ASCE **Lifelines** Conference 2021 2022

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San Fernando Earthquake Conference

50 Years of Lifeline Engineering

Understanding, Improving, & Operationalizing Hazard Resilience for Lifelines

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ASCE INFRASTRUCTURE RESILIENCE

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ABSTRACT

There has been 50-years of progress in lifeline earthquake engineering since its inception as a primary field of practice following the 1971 San Fernando Earthquake in Los Angeles, California. Over that time lifeline engineering has been applied worldwide and extended to address additional hazards beyond earthquakes. Lifeline engineering is now recognized as a critical aspect to ensuring the resilience of communities against any and all hazards. It is therefore important to recognize the advancements in lifeline engineering over the past half-century on the occasion of the 50-year anniversary of the 1971 San Fernando earthquake. To understand, improve and operationalize hazard resilience for lifeline infrastructure systems we must recognize where we are in the practice, how we got here, and where we should be going. We must also recognize its continued increasing importance for improving community resilience. The Lifelines 2021-22 conference brings together practitioners, researchers, educators, material suppliers, innovators, service users, and other experts related to improving the lifeline infrastructure systems. The abstracts assembled in this volume represent the state-of-the-practice and the state-of-the-art, and describe future needs in lifeline infrastructure systems.

FOREWORD

The February 9, 1971 San Fernando California Earthquake was a devastating yet seminal event which, for the first time, demonstrated the seismic threat to lifelines that fundamentally support our modern livelihoods. Knowledge gained from this event initiated the study of lifeline systems worldwide, including water, wastewater, electric power, gas and liquid fuels, communications, transportation, and solid waste management systems. The founding efforts of the ASCE Technical Council on Lifeline Earthquake Engineering, a predecessor unit to the current ASCE Infrastructure Resilience Division (IRD), by international leaders like the late Charles Martin Duke from the University of California, Los Angeles (UCLA) established lifeline systems into a mainstream discipline, now accepted as fundamental for community and regional resilience.

To celebrate the advancement of lifeline earthquake engineering made over the past 50 years since this landmark seismic event, the ASCE Infrastructure Resilience Division (IRD) and The University of California, Los Angeles (UCLA) entered into a partnership in 2018 to organize and host the San Fernando Earthquake Conference – 50 years of Lifeline Engineering (Lifelines2021) in February 2021, focusing on "Understanding, Improving & Operationalizing Hazard Resilience for Lifeline Systems."

The 50th anniversary of the San Fernando Earthquake provides us with an opportunity to reflect on the need to increase the resilience of our critical infrastructure systems to earthquakes and other hazards. The conference will provide a retrospective of where we are today and how we got here. It will also contribute to a global vision for where we are going in our quest to create resilient infrastructure systems that support community and regional resilience within interdisciplinary and multihazard environments.

The conference was originally planned to be held at UCLA on February 7-10, 2021. However, impacts from the COVID-19 pandemic required the conference to be delayed to February 2022 (Lifelines2021-22). This delay impacted the timely release of information authors had initially planned to provide during the original conference dates. As a result, to accommodate author interests to provide citable references for their work, the conference organizers added this Book of Abstracts publication. This set of abstracts is intended to stand alone and describe the authors' work and be independent of the final paper and presentation, which will be provided at the conference.

This publication release includes abstracts submitted for presentation-only and those intended to be published as papers in the proceedings. Additional abstracts associated with work to be described at the conference will be added to this publication periodically. Abstracts for special sessions are planned to be added in the future.

The Lifelines2021-22 conference activities were launched on February 9, 2021 with a webinar commemorating the 50th Anniversary of the San Fernando Earthquake. Prior to the in-person conference on February 7 to 11, 2022 at UCLA, the conference is holding several on-line activities throughout the 2021 calendar year related to the conference theme of Understanding, Improving and Operationalizing Hazard Resilience for Lifeline Systems.

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Research Review Summary of the San Fernando Earthquake

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ABSTRACT

San Fernando Earthquake in 1971 was one of the significant devastating hazards despite a moderate magnitude. Therefore, a substantial number of studies were performed from different perspectives to understand the impact of the earthquake and the behavior of the structures that had structural and non-structural damages. In this study, 383 research documents from 749 authors were downloaded from the web of science and analyzed between the years of 1971 and 2019. This way, the variety of the contents of these researches, linkage between them, the contribution of different countries and institutions were established. This study conducts a bibliometric analysis and a review of existing literature on the San Fernando Earthquake, focusing on the last five decades intending to achieve a better understanding of the research work on this subject. Bibliometric analysis was chosen as a methodology, which enables understanding of the relationship between successive studies that were performed within the last half-century. It presents the annual contribution, author and country production and collaboration, citation details, keyword, and content-based analysis in both digital and visual format. It is believed that the study will provide useful information to the researchers, and connect the individual studies to others, and identify the gaps.

The Alquist-Priolo Earthquake Fault Zoning Act at 50: Lessons Learned and New Developments Regarding the Assessment of Surface Fault Rupture Hazard in California

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ABSTRACT

The Alquist-Priolo Earthquake Fault Zoning (AP) Act was passed in California in 1972 following the 1971 Mw 6.6 San Fernando earthquake. The law was motivated by the recognition that surface fault rupture disproportionally damaged structures located across traces of faults that moved during that earthquake. The AP Act prohibits most structures for human occupancy from being placed over the traces of Holocene-active faults, which are faults that have moved during the past 11,700 years. The State Geologist, through the California Geological Survey (CGS), is mandated to issue Earthquake Fault Zone (EFZ) Maps, which delineate areas where fault investigations are required prior to development. Site-specific fault investigations are conducted by project geologists which are then reviewed by local lead agencies for approval. The AP Act provides a relatively simple and effective means to protect lives and property through regulation: If a fault is found at a site, then only the recency of activity needs to be determined and setbacks are required for faults identified as Holocene-active. Despite the simplicity of mitigation by avoidance, complex regulatory language and inconsistencies in standards of practice during investigations and review have led to frustration among geoscience practitioners, lead agencies, and property owners. Guidance documents such as CGS Special Publication 42 serve to bring more consistency to the implementation of the AP Act. One issue facing those affected by the AP Act is that, in some circumstances, fault activity cannot be determined at a site due to limitations of site geology, or practical considerations that limit subsurface investigative methods. Recent surface-rupturing earthquakes such as the 2019 Ridgecrest earthquake also highlight the challenges of characterizing the potential of surface rupture on distributed active fault systems.

The complexity of the surface rupture, which occurred on a fault system with low cumulative slip (<5 km), is typical of other recent surface ruptures in the Eastern California Shear Zone. In contrast, recent large surface-rupturing earthquakes on plate boundary faults with large (>10s of kms) cumulative offset have comparatively simple surface rupture patterns. Cumulative offset may be a first-order control on rupture complexity, and empirical data sets developed should consider this as a potential parameter to forecast the distribution of surface faulting.

New methods such as Probabilistic Fault Displacement Hazard Analysis offer potential insights to current approaches, and are being evaluated by CGS as potential additional tools for assessing surface rupture hazard for sites affected by the AP Act.

Seismic Safety of Large Storage Dams, Key Structures of Water and Hydropower Supply Systems

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ABSTRACT

Large storage dams are a cornerstone of water supply and irrigation systems and hydropower generation. Most of them serve multipurpose projects that have additional purposes like flood protection, navigation, aquaculture, recreation, etc. The dams must be able to withstand the strongest ground motions expected at the dam site to ensure that these lifelines function after an earthquake and, more importantly, protect the people downstream of the dam from catastrophic release of water from the reservoir. Therefore, the seismic safety criteria for these structures are governed by the protection of life and may be significantly different than criteria for the interconnected lifelines.

The current seismic design and safety criteria of the International Commission on Large Dams are discussed. The work also describes a) the impacts on the dam industry of the damage to embankment and concrete dams caused by the 1971 San Fernando earthquake, which has led to changes in the seismic analysis of dams from the pseudostatic analysis concept introduced in the 1930s to modern methods of dynamic analyses of dam-reservoir-foundation systems, and b) the methods of seismic analysis and design of large concrete and embankment dams. For large dams, the seismic hazard is a multi-faceted hazard including, ground shaking, fault movements, mass movements etc. Examples of recently completed embankment dams located in highly seismic regions in Iran, Pakistan and Panama, which were designed for ground shaking and fault movements are used to illustrate current methods of seismic design of large dams.

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A Comprehensive Re-Evaluation of the Seismic Performances of the Upper and Lower San Fernando Dams Using Current State of Practice Procedures

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ABSTRACT

The well-documented field performance case histories of the Lower San Fernando Dam (LSFD) and the Upper San Fernando Dam (USFD) during the 1971 San Fernando earthquake have been foundational to the development of the field of modern seismic dam engineering, and to the inception of the U.S. national seismic dam safety programs still ongoing today. The liquefaction-induced upstream flow failure of the LSFD, and the only small to moderate deformations that occurred for the similarly constructed USFD, provide an unusually valuable pair of case histories for back-analyses of the behaviors of embankment dams subject to soil liquefaction and strong near-field seismic loading. Together, these two similarly constructed dams, but with two very different performance outcomes, represent an important and challenging pair of tests for analytical methods. State of Practice procedures for nonlinear seismic deformation analyses (NDA) depend on many factors, among which seven key factors include (1) cyclic pore pressure generation relationships, (2) constitutive models for seismic response, cyclic pore pressure generation, and resulting cyclic strains, (3) criteria and protocols for transition to post-liquefaction residual strength, (4) potential strain softening of cohesive soils, (5) criteria and protocols for continuation of analyses (and deformations) beyond the end of seismic shaking, (6) methods for modeling of post-earthquake volumetric reconsolidation, and (7) suitable evaluation of the results of seismic deformation analyses to draw overall engineering conclusions. Back-analyses results from both the USFD and the LSFD, using exactly the same sets of analytical models, relationships, and modeling protocols are addressed. These analyses correctly predicted (1) the upstream flow failure of the LSFD, (2) the non-failure and only limited deformations of the downstream side, (3) the elevation of the "lip" of the upstream liquefaction flow slide heel scarp that represented the remaining post-earthquake effective "top of freeboard" that narrowly prevented reservoir overtopping. This work provides new methods for extension of the analyses through full runout of the upstream liquefaction flow slide, with cross-checking of final geometry based on limit equilibrium analyses and empirical relationships. The post-shaking analyses, extending the analyses through full runout and evaluation of residual crest conditions, is new material not yet presented in previous conferences. These same analyses also correctly predicted (1) only small to moderate seismic displacements and deformations of the USFD, and (2) the main USFD embankment translating laterally towards the downstream side along a deep-seated basal shear mechanism during strong inertial seismic shaking, but remaining statically stable at the end of the earthquake. Both sets of NDA analyses represented usefully accurate engineering "predictions" of the two very different sets of observed performances of the two dams; results that would provide good engineering insights and a suitable basis for both (1) engineering evaluations of expected seismic performance and dam safety, and (2) seismic mitigation design for both existing and new dams.

A Retrospective Evaluation of the Performance of the Lower San Fernando Dam

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ABSTRACT

As a result of the **M** 6.6 1971 San Fernando earthquake the Lower San Fernando Dam (LSFD) suffered significant damage that could have resulted in a breach of the dam and uncontrolled release of the reservoir (URR). A number of events, some directly related to the earthquake and other random events, collectively intersected to successful avoid a catastrophic failure. The LSFD embankment was damaged significantly as a result of liquefaction that led to a massive slide of the upstream slope into the reservoir. The slide lowered the crest of the dam well below the maximum reservoir level, leaving a small section of the downstream side of the embankment with about 5 feet of freeboard. Fortunately, the reservoir was lowered soon after the earthquake, avoiding a potential collapse of the embankment and URR into the heavily populated San Fernando Valley below. Experience suggests that systems failures are typically the result of a combination of events or circumstances (a sequence of events) that collectively conspire to produce the outcome that was observed. The events in a sequence may be a combination of causally related events (dependent on a common initiator) and/or the occurrence of random, unrelated events that happened at just the right time and place to contribute to the sequence. This study models the events at the LSFD as a result of the 1971 earthquake to assess just how rare (in terms of its likelihood of occurrence) it was. In this study we perform a retrospective probabilistic seismic risk analysis for the Van Norman Complex (VNC) where the LSFD is located. The analysis includes a systems evaluation of the VNC to assess how the system would perform during a seismic event, including the potential for URR of the Upper and/or Lower San Fernando Dams. The seismic risk model allows us to evaluate the performance of the VNC during the 1971 San Fernando Earthquake and the likelihood of occurrence. The study involves three steps. First, we identify the sequence of events that played out during and after the earthquake to successfully avoid a breach of the LSFD. Second, we build a systems model to evaluate the performance of the VNC to seismic events. Third, we quantify the model to estimate the probability of the observed sequence of events that involved the 1971 earthquake, damage to the upstream slope of the embankment of LSFD, the non-breach of the Upper San Fernando Dam, timely lowering of the LSFD reservoir and eventual avoidance of a breach. This study indicates the sequence of events that occurred at the VNC during and after the earthquake and lead to the avoidance of a catastrophe was a very low likelihood, a rare event; annual frequency of occurrence less than 10^{-3}. While this study is retrospective in nature, the systems modeling provides a unique insight to how the VNC performed during the earthquake and lessons as to how similar systems should be evaluated - using a systems-based approach that includes not only the failure modes of individual structures, but rather the system-level sequences of events – such as those that transpired during the near-failure of the LSFD.

Role of Cyclic Softening in the Response of the Lower San Fernando Dam

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ABSTRACT

The Lower San Fernando Dam has served as an important case history for geotechnical earthquake engineering for nearly 50 years. Liquefaction of the hydraulic fill in the upstream shell is the widely agreed primary cause of the slide at the Lower San Fernando dam and this case history is often used for the validation of constitutive models developed for liquefaction analyses of dams. It also has served as an important case history for estimating residual strengths for liquefied soils. Most previous analyses have modeled the hydraulic fill clay core with a single undrained shear strength and a simple Mohr-Coulomb constitutive model. This neglects potential cyclic softening, which likely occurred within the core and may have influenced the overall deformation response of both dams. Thisstudy uses the PM4Silt constitutive model to represent the cyclic response of the clay core and PM4Sand to represent liquefaction of the sandy shells. The potential for strength loss in both the core and the shells after shaking is considered. The proposed modeling approach is expected to lead to improved predictions of potential deformations of dams that are affected by strain-softening clays in the foundation or within the body of the dam. Accurately representing the response of these materials is essential to ensuring that accurate deformation estimates are obtained for use in designing remediations or performing risk assessments.

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Upper San Fernando Dam Construction Methods and Implications on the Modeling of Its Seismic Performance

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ABSTRACT

The slides within the Upper and Lower San Fernando Dams had among the most significant effects on lifeline infrastructure from the 1971 San Fernando Earthquake. These dams were constructed using hydraulic fill processes over 100 years ago. Post-earthquake investigations of these dams owned and operated by the Los Angeles Department of Water and Power (LADWP), significantly influenced dam and reservoir safety policy and geotechnical earthquake engineering worldwide, continuing to this day. These dams are the most studied in the world. Except for being severely shaken and deformed by the 1971 San Fernando and 1994 Northridge earthquakes, the Upper San Fernando Dam (USFD) has not been substantially altered since its original construction. Extensively analyzed, this dam has become a landmark case study for validating numerical models, despite its poorly documented construction methods. Following the 1971 earthquake, most analysts assumed a semi-hydraulic fill method of construction as well as a firm foundation. They also thought that the outlet line, damaged in 1971, was within the hydraulic fill materials and deformed with them. These assumptions have influenced the interpretation of the USFD performance and every numerical simulation of its seismic behavior.

However, this investigation uncovered and documents essential data on the USFD construction methods, including descriptions, original photographs, and diagrams from field survey records pulled from LADWP archives. Based on a thorough review of these LADWP records, the USFD is confirmed to have been constructed using the full hydraulic fill method, the same method used for building the Lower San Fernando Dam, but with some crucial differences relevant to seismic performance. Further, the outlet line was placed within foundation alluvium soils and suffered damage in 1971 when those deformed. The hydraulic fill methods, in general, are known to produce materials susceptible to liquefaction. But the semi-hydraulic fill method, which was initially assumed, is known to produce different pre-event strain distributions and much weaker dam materials than the standard hydraulic fill method. These documented results are essential to include in any numerical evaluation of the USFD. Cross-sections are proposed to refine numerical models and describe what aspects are needed to validate the dam's seismic performance accurately.

Lessons Learned From the Observed Seismic Settlement at the Jensen Filtration Plant in the San Fernando Earthquake

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ABSTRACT

The Joseph Jensen Filtration Plant of the Metropolitan Water District is located in the area of strongest shaking generated by the 1971 San Francisco Earthquake. One or more concrete basins which had been precisely leveled settled by amounts of up to six inches rendering the plant inoperative. These basins were supported on compacted sandy material derived from the Saugus Formation and one of the secondary lessons learned was that compaction to 90 percent of the DWR standard was insufficient to prevent settlement in a major earthquake, but, from a more academic point-of-view, the primary lesson that was learned is that the amount of settlement that was observed could not have been predicted by using the estimated history of cyclic shear strains using a single component of earthquake motion.

This work recounts the sequence of events that led up to this finding and then the subsequent events that led to the conclusion that the settlements caused by each component acting separately could be added to approximate the settlements that would be cause by two-component, that is multi-directional, loading. This second finding was then used to estimate the average effect of multi-directional shaking on the occurrence of liquefaction of fully saturated cohesionless soils. In that exercise it was assumed that, on average, two arbitrary components of motion would be equal, so that the predicted settlement of a dry sand subjected to multi-directional shaking would be double that cause by a single component of shaking but it was never suggested that you should double the settlements caused by one component of motion if the components were not equal.

Because in the 1970's it was not practical to conduct site response analyses in ordinary geotechnical practice, various simplified methods for predicting seismic settlements were developed. These are very approximate and generally very conservative and so that it is not at all clear that the resulting estimates should be increased to account for multi-directional shaking. However, it is now practical to conduct nonlinear effective stress site response analyses in ordinary practice and it is recommended that these be run for two components simultaneously, and that the settlements or excess pore pressures that are calculated for each component be added at each timestep. and that the accumulated settlements or latent settlements be used as a measure of the accumulated strain history and its effect on the rate at which further settlements or excess pore pressures are generated. This provides a robust and reasonably accurate method for estimating the likely magnitude of seismically induced settlements.

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Evolution of Seismic Analysis of an Embankment Dam with Approaches and Insights from Back-Analyses of the Seismic Performances the Upper and Lower San Fernando Dams

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ABSTRACT

Back-analyses of the performances of the Upper and Lower San Fernando Dams (USFD and LSFD) during the 1971 San Fernando earthquake have been important in evaluating the ability of current State of Practice analytical models, relationships, and procedures to predict seismic performances of both existing and new embankment dams during earthquakes. An embankment dam constructed in the 1950's was recently evaluated using current State of Practice methods for seismic hazard characterization, site and embankment characterization, and nonlinear seismic deformation analyses. Even though the dam shells and transition zones were constructed with potentially liquefiable coarse grained materials, placed with lifts of 2 to 12 feet thick layers and compacted with only one dozer pass for leveling, a re-evaluation of the expected seismic performance of the dam performed in the late 1980's indicated small to negligible seismic deformation potential. More current approaches, using more recent seismicity characterization and input ground motions, site characterization, and numerical modeling approaches produced significantly different seismic deformation estimates. The updated probabilistic seismic hazard analyses included development of input ground motions using scenario-based target spectra. Site characterization included selecting an appropriate Becker Penetration Testing to Standard Penetration Testing conversion method based on an evaluation of three common methods currently in use, and then cross-comparing the results with (1) available actual in-situ relative density testing test data and (2) construction history and developing an alternative method for conversion. The nonlinear seismic deformation analysis models, relationships, and procedures using FLAC were selected based on demonstrated predictive ability to estimate deformations in well-documented case histories such as the seismic performances of the LSFD and USFD during the 1971 San Fernando earthquake. Even though the successful models and relationships used in FLAC correctly predicted the failure mechanisms, upstream flow failure, and remaining freeboard in the heel scarp area of the LSFD. FLAC can have difficulties, however, in predicting the full extent of post-earthquake runout conditions. Therefore, forward analytical approaches require further post-earthquake deformed shape analyses to assess the final deformed shape and effective remaining freeboard. An assessment of the potential final post-earthquake deformed geometry was performed through a set of pre- and post-earthquake deformed shape analyses that predict the potential runout distance of the predicted upstream flow slide, and the geometry and stability of the remaining crest conditions. A comprehensive analytical approach has been developed coupling the FLAC modeling with secondary post-earthquake deformed shape analyses to assess the final deformed shape and remaining effective freeboard of the dam.

Road to Resilience – Seismic Upgrades of Water Treatment Facility Damaged in San Fernando Earthquake

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ABSTRACT

The Metropolitan Water District of Southern California (MWD) is a regional wholesaler that provides water for 26 member agencies to deliver – either directly or through their sub-agencies – to nearly 19 million people living in Los Angeles, Orange, Riverside, San Bernardino, San Diego and Ventura counties. MWD's Joseph Jensen Water Treatment Plant was under construction when the San Fernando Earthquake hit the region 50 years ago. Only 10 miles away from the epicenter, the nearly completed plant sustained substantial damage and resulted in redesign and retrofit of multiple structures. Following the San Fernando Earthquake, MWD started assessing its overall seismic risk and initiated a seismic upgrade program for existing structures, which has evolved into a comprehensive program intended to improve seismic resilience of the entire water delivery system.

Two decades later, the Jensen Plant went through another test as the 1994 Northridge Earthquake shook the region with the epicenter again less than 10 miles from the plant. The lessons learned from the 1971 earthquake resulted in multiple design changes in the subsequent upgrade and expansion of the facility, and had a profound effect on MWD's policy emphasizing seismic resilience in its infrastructure reliability program. The 1994 event provided a rare opportunity to demonstrate effectiveness of the mitigation measures taken after the first earthquake, and the value of investing in seismic risk mitigation projects. Experience from the San Fernando Earthquake has had a lasting effect in shaping MWD's seismic resilience strategy. The hard-learned lessons and the accumulated knowledge through numerous seismic upgrade projects over decades will benefit other regional water agencies facing similar seismic risks to develop their own seismic resilience strategy.

The audience will learn the damage to different structures within the Jensen Plant caused by the 1971 San Fernando Earthquake and the subsequent repair/mitigation measures taken to upgrade the facility. The effectiveness of some typical mitigation measures will be examined by comparing performance of the structures in the 1994 Northridge Earthquake. They will also learn about the evolvement of MWD's comprehensive strategy to improve seismic resilience of a complex water delivery system, and how an unfortunate event could have a positive and lasting impact on shaping long-term policies when the right lessons were learned.

Caltrans Seismic Retrofit Program after the 1971 San Fernando Earthquake

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ABSTRACT

Prior to the February 9, 1971, California's Department of Transportation (Caltrans) bridges were designed with very limited seismic design criteria. Consequently, several bridges and interchanges were severely damaged during the San Fernando earthquake. Within a few days after the earthquake, Caltrans managers had written change orders that all bridges under construction were required to have much more transverse reinforcement in the columns, end the practice of using undeveloped starter bars between foundations and columns, and increase seat lengths to at least 18 inches; all to prevent the types of damage that was observed after the earthquake. However, at that time the interstate highway system was almost completely built. Consequently, most of California's bridge inventory had been designed with little resistance to large earthquakes. Caltrans has been playing catch-up ever since, retrofitting and re-retrofitting vulnerable bridges as new lessons are learned after every earthquake.

Caltrans' bridge retrofit program began after the 1971 San Fernando earthquake with cable restrainers to prevent superstructure unseating and to protect vulnerable columns. However, the 1987 Whittier earthquake demonstrated that restrainers alone were not adequate and so a new retrofit program began that included column casings. Subsequent earthquakes tested Caltrans' retrofit programs and identified new hazards and vulnerabilities. Research was funded to better understand seismic hazards and to test retrofit devices. Screening algorithms were developed to identify Caltrans' bridges at the highest risk from earthquakes. Screened-in bridges were evaluated in pre-strategy meetings where licensed engineers determined if a retrofit was necessary (and at what cost).

California's 12 transportation districts could then choose between different highway safety projects, including seismic retrofits. Retrofit design criteria has been updated every few years in the Structure Technical Policy Document 'Seismic Retrofit Guidelines for California Bridges.' Recent earthquakes have shown the efficacy of all this work.

The Sierra Madre Fault System: What have we Learned Since the 1971 San Fernando Earthquake?

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ABSTRACT

On February 9, 1971, the M6.6 San Fernando earthquake ruptured the San Fernando fault, a small portion of the ~130 km (80 mi)-long the north-dipping, reverse Sierra Madre fault system that includes the Santa Susana, San Fernando, Sierra Madre, and Cucamonga faults. Permanent ground deformations from this earthquake disrupted many lifelines in the northern San Fernando Valley. In the 50 years since the 1971 earthquake, our understanding of this complex fault system has continued to evolve. Paleoseismic trench exposures of the San Fernando fault reveal three moderate (~ 1 m (~3 ft)) slip events, including the historic 1971 earthquake, during the late Holocene.

Trenching studies on the central portion of the fault system reveal much larger surface displacements (≥ 5 m (≥16 ft)) during large (~M7.5), infrequent magnitude earthquakes along the northern margin of the Los Angeles basin. The central Sierra Madre fault last ruptured in the early Holocene and may have involved fault sections to the west (San Fernando) and/or to the east (Cucamonga). The behavior of large, infrequent earthquakes appears to vary in space and possibly time. Slip rate studies utilizing displaced alluvial surfaces with radiocarbon, cosmogenic, and luminescence dating suggest late Quaternary slip rates of 1-2 mm/yr for the San Fernando, Sierra Madre, and Cucamonga sections. A long-term (post-Miocene) published slip rate for the westernmost Santa Susana section of ≥ 6 mm/yr is used in current seismic source models (e.g., UCERF3), however, geomorphic observations and cosmogenic studies in progress appear to suggest a much lower late Pleistocene rate. A lower slip rate on the Santa Susana fault and the presence of multiple active reverse and blind reverse faults in the northern San Fernando Valley imply that modern north-south tectonic shortening is distributed across a much broader zone and highlights a more complex zone of fault crossings and potential ground deformation for lifelines in the northern San Fernando Valley.

Seismic Response of Pipelines from Multi-Point Shaking Table Tests

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ABSTRACT

Buried pipelines are an essential underground infrastructure of modern societies, which is susceptible to damage during earthquake events. The characteristics of seismic excitation that impact pipelines are affected by the spatial distribution of seismic waves and the large extent of long pipelines. A shaking table testing program was conducted on scaled buried pipeline model to investigate its seismic response under non-uniform ground motion. The pipelines-sand model was enclosed in a suspension continuum soil box excited using three shaking tables that can induce uniform and non-uniform seismic excitations. The soil bed was uniform dry sand and the model pipeline was 6.0 m in length and 150 mm in diameter. The soil was instrumented with accelerometers along the soil profile, while the pipeline was instrumented with strain gauges and accelerometers around the pipeline. The soil-pipeline model was subjected to twenty-four different ground motions. The recorded data from all instrumentation were analyzed to evaluate the influence of non-uniform seismic excitation on the pipeline response. The results demonstrated that the pipeline response to longitudinal acceleration was larger than the response of surrounding soil under non-uniform excitation. In addition, the peak pipeline tensile and compressive strains to non-uniform ground motion was about twice that under uniform ground motion.

The Seismic Responses of Shallow-Buried Pipeline on 1D Soil Liquefaction Shaking Table Test

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ABSTRACT

According to the economic development and land use requirement, the depth of buried underground pipelines is gradually limited. Therefore, the seismic response of shallow-buried pipeline during earthquake is very important issue for seismic design. However, the few shaking table tests have been carried out in the past pipeline studies. In this study, a 1-dimensional laminar box on the shaking table is used to simulate the shallow-buried pipeline during the earthquake event. The input motion applies in axially direction with the pipeline to focus on the influence between liquefaction, land subsidence and pipeline uplifting. Two PVC pipes with the 3m in length were embedded in the saturated standard quartz sand at 45cm depth from the ground surface. The pipes were filled with water and air respectively to compare the uplift behavior during the soil liquefaction. The measurement of accelerometers, strain gauges and pore pressure gauges were used to describe the dynamic behavior of pipes and soil. From the test results, the soil liquefaction occurs from a small area to fully liquefaction with the increase of input motion intensity from 200 gal to 400 gal. The pore pressure increase during the soil liquefaction induces both pipes uplift. The results can better understand the soil liquefaction effects and ground shaking responses of shallow-buried pipeline. Moreover, these data are valuable for establishing liquefaction evaluation criteria and improving seismic design and disaster prevention concerning on pipeline system.

Uncertainty Quantification in Resilience Analysis of Complex Systems

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ABSTRACT

Realistic analysis and design of physical and engineering systems require not only a fine understanding and modeling of the underlying physics, but also the quantification of the various sources of uncertainty and their influence on the quantities of interest. In the context of regional risk and resilience analysis, the collection of physical (structures and infrastructure), social and economic systems constitute a complex interconnected dynamical system whose performance is influenced by large numbers of uncertain system characteristics and external stressors. Uncertainty quantification in risk and resilience analysis aims to characterize and propagate the sources of uncertainty through the components of the complex system and quantify the effects on selected measure(s) of interest (e.g., measures of impact or resilience.) Specifically, to measure regional resilience, the work presents a set of resilience metrics that capture the temporal and spatial variations of the recovery process. Despite growing interests in uncertainty quantification, it remains a major challenge to characterize and propagate all the relevant sources of uncertainty in the mathematical models of complex systems, where the so-called curse-of-dimensionality is yet an unsolved problem. A novel multi-fidelity approach is developed that leverages less expensive, lower-fidelity models (e.g., a simplified physics approximation) together with dimensionality reduction techniques to first identify the important sources of uncertainty. Given a small subset of important uncertain input data, high-fidelity models preserve desired accuracy in predicting the metrics of interest along with their uncertainties.

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Nonlinear Dynamic SSI Analyses of a Caisson Wall to Protect 10' Diameter Filter Outlet Conduit at Diemer Plant in Yorba Linda, California

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ABSTRACT

The Metropolitan Water District owns and operates five regional water treatment plants including the Robert B. Diemer Water Treatment Plant in Yorba Linda, California. The plant, which serves approximately 4 million people in Los Angeles and Orange Counties, was constructed in 1963 in accordance with standards in place at the time. The plant is in a seismically active region and is approximately 0.3 miles from the Whittier Fault, which can generate a 6.8 moment magnitude earthquake. The Diemer plant site was constructed by cutting off the top of a ridge and placing the excavation materials in the adjacent ravines to produce a level pad. The plant's 121-inch diameter filter outlet conduit is buried about 7 feet while crossing about a 400-foot length of the northeast fill slope. The fill materials were placed without removing colluvium and slop wash of very low shear strength, and were compacted to the practices of the early 1960's. As such, it was not benched into competent sedimentary rock as modern practice would dictate. In addition, the fill slope has an inclination of 1.5H:1V, which is steeper than the current practice of 2H:1V. Previous studies and field explorations have indicated that the fill slopes placed in ravines around the plant site including the northeast fill slope are only marginally stable under static loading conditions and do not have adequate stability under the MCE event. This led to concerns about seismic slope instability which was confirmed by various analyses. Seismic performance of the filter outlet conduit was evaluated by performing dynamic soil-structure-interaction analyses using the FLAC 3D computer program. Based on nonlinear seismic deformation analyses, constructability, and consideration of minimum interference with plant operation, a caisson wall with a length of 370 feet was selected to laterally support the fill slope housing the filter outlet conduit. Analysis results indicated that 6-foot diameter caissons spaced at 8-foot on center would stabilize the upper portion of the fill slope supporting the conduit. Analysis results are presented in terms of lateral displacement, moment, and shear distributions for the caisson wall, the maximum shaking-induced displacements of the conduit and the top of caissons. The effectiveness of the caisson wall in terms of ensuring the structural integrity of the conduit during earthquake shaking is also provided. The results indicated that shaking-induced axial stresses along the conduit are well below the best-estimate buckling stress and the envelope of maximum principal wall stresses of the conduit remain in the elastic range.

Data Management for Multi-Hazard Analysis of Lifelines

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ABSTRACT

Lifeline managers rely on data and information for managing the lifecycle of systems and assets, including the analysis of potential hazards and threats to system operations. Lifeline organizations are collecting and processing more data than ever before to gain new and useful insight into how they can operate, maintain and protect systems and assets more effectively. Moreover, organizations are investing in and incorporating standards and guidelines in practice to improve their data management capability. However, lifeline managers have expressed concern that data management, quality and resourcing challenges continue to limit their ability to make informed asset and risk management decisions in practice.

This work will introduce the methods and findings from a research project that developed a process to assess the extent to which data quality and information fragmentation in lifeline organizations is impacting the ability to effectively manage risk exposure to multiple hazards. Individual semi-structured interviews and group workshops were conducted with participants from case study organizations to understand how assets, risks and data are managed within the organization, and what challenges arise in these management processes. Specifically, the research focuses on three risk types: (1) Asset degradation/deterioration; (2) Climate-related risk, and; (3) Pandemic risk. Although this research does not explicitly focus on earthquake risk and management, its hopes to encourage discussion around the effective management of multiple risks and hazards that have the potential to negatively impact lifelines in all regions. The insights gained from this research process are used to support the development of a diagnostic approach for improving data quality and data management in lifeline organizations. The aim of this research is to reveal where changes to data management practice in lifeline organizations, for example, in data collection and/or sharing, may significantly improve asset and risk management capability.

Industry is providing lifeline organizations opportunities to transform current asset and risk management practice by using bespoke data and system analytics. This work will illustrate how fundamental data quality and information fragmentation issues in lifeline organizations need to be addressed first if the benefits of this digital transformation are to be realized.

Experimental-scale Fault Rupture Test on Buried Pipeline Reinforced with Segmental Protective Shield

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ABSTRACT

Pipelines are used for the transportation of water, gas and oil. A pipeline system usually traverses a large geographical area; thus, it is likely to be exposed to a wide variety of geo-hazards or Permanent Ground Deformations (PGDs). Large deformations induced by landslide, lateral spreading, or fault movement can cause damages to buried pipelines. To increase the ability of pipe for accommodating significant PGDs and sustaining large plastic deformations without failure, standards and guidelines suggest using mitigation measures for buried pipelines crossing faults. This investigation primarily focuses on performance of transmission oil and natural gas pipelines under permanent ground deformations induced by reverse faulting. This work experimentally explores a mitigation method that can be used to minimize the effect of permanent ground deformation on pipeline-fault crossing. This study presents the results of laboratory-scaled fault rupture tests to investigate the axial elongation, shearing, and bending performances of pipelines surrounded by a segmental shield protection and subjected to abrupt ground deformation. An experimental setup is developed and described for physical modelling of the pipeline crossing reverse fault. Moreover, the effect of pipe wall thickness, relative burial depth, and relative pipe and shield diameters on the behavior of reinforced pipe subjected to reverse faulting will be investigated. Finally, practical implications of the study is discussed, and recommendations are made for applying the experimental results for mitigation of buried pipelines vulnerable to permanent ground deformations.

Formulation of an Improved Hybrid Method to Develop Seismic Fragilities for Seismic Risk Assessment of Power Plants and Industrial Infrastructure

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ABSTRACT

Seismic fragility evaluations of structures, systems, and components (SSCs) are often performed to support seismic probabilistic risk assessment (SPRA) of nuclear power plants (NPPs) and other industrial infrastructure facilities. Early NPP SPRAs permitted screening of SSCs judged not to have significant contributions to risk. Recent SPRA requirements encourage the explicit development of fragilities over judgment-based screening for the majority of SSCs and accident sequences in the plant response logic model. For realistic risk estimates, these fragilities may be approximate and conservative for non-risk-significant SSCs, but must be refined and detailed if the SSC risk contribution is significant. The Electric Power Research Institute (EPRI) is a leading developer of NPP industry guidance on performing SPRAs. SPRAs of other industrial infrastructure is a less established industry, and as such often relies on EPRI guidance given their similarity with many NPP SSCs. The current state-of-the-art guidance for performing seismic fragility evaluations for SPRAs is documented in EPRI 3002012994. Two analytical methods are recommended in EPRI 3002012994 for developing detailed seismic fragilities: the Separation of Variables (SOV) approach and the Hybrid method. The SOV approach is more rigorous and often only used for dominant risk-contributing SSCs, while the more simplified and cost-effective Hybrid method is often used for the remaining majority.

The EPRI Hybrid method estimates a seismic capacity $A_{1\%}$, which corresponds to about 1% non-exceedance probability (NEP), using calculations similar to deterministic design standards familiar to engineers. A1% is expressed in terms of a ground motion parameter, e.g., peak ground acceleration (PGA), that corresponds to a 1% probability of SSC failure. The EPRI Hybrid method then recommends generic values for aleatory and epistemic variability parameters to estimate a conservatively biased median capacity, i.e., a PGA that corresponds to 50% probability of SSC failure. This simplification aims to streamline calculations on the basis that risk contribution from potential failures at ground motions corresponding to the low-NEP capacities is typically higher than the less frequent ground motions corresponding to the median capacity. Insights from a recent SPRA project demonstrated that this simplification could lead to significant conservative bias if the generic variability parameters are systematically lower than the SSC-specific variabilities, and to potential unconservative bias if the variability in seismic demands significantly outweigh the strength variabilities in violation of the assumptions implicit in the method.

This study presents the formulation of an Improved Hybrid fragility method that significantly improves accuracy while only marginally increasing the required computations. The median capacity is calculated explicitly following similar steps to those used to calculate $A_{1\%}$ while using median demands, strengths, and deformation limits. The variability parameters are estimated explicitly from the median and $A_{1\%}$ capacities. A minimum variability check is performed to enforce consistency with the underlying assumptions. This Improved Hybrid method was successfully implemented in an SPRA of a commercial NPP that was accepted by the U.S. Nuclear Regulatory Commission.

Measures for Enhancement of Earthquake Resilience of Water Front Industrial Parks

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ABSTRACT

During past earthquakes in the world, industrial parks in waterfront areas have been repeatedly damaged. The main causes of the damages to the industrial facilities were the soil liquefaction of the artificial ground reclaimed from waters, it's induced large ground displacements, and the earthquake ground motion due to soft reclaimed soil. Heavy damages to industrial facilities by future earthquakes will seriously affect the living and safety of the people, as well as the worldwide economic activities. The enhancement of earthquake resistance of industrial parks is one of the most urgent national subjects around highly urbanized areas such as the Tokyo and Osaka bays in Japan. Various kinds of countermeasure for industrial facilities against the soil liquefaction and large ground displacements have been developed through internationally cooperative researches, particularly between Japan and U.S. The U.S. - Japan joint research on the liquefaction induced ground displacement was started in 1985, and developed the methods to estimate the magnitude and the distribution of ground displacements, and the measures to protect the foundations of structures against the ground movements. Based on these research results, the Japanese government initiated a national project since 2015 to enhance the earthquake and tsunami-resistance of energy production and supply systems in the nationwide, such as oil, gas and electricity. Damage of industrial parks caused by past earthquakes is reviewed and outlines the development of countermeasures of industrial facilities against liquefaction and large ground displacement. The national project by the Japanese government and its outcomes is also introduced.

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Multistep Analysis of the Steel and HDPE Pipes for the Golden Ears Forcemain and River Crossing, Vancouver British Columbia

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ABSTRACT

Metro Vancouver (MV) plans to install new sewer forcemains under the Fraser River as essential pipelines (Class IV Pipeline) which are intended to remain functional and operation during and after a 2,475-year return earthquake. The new forcemains will consists of twin 914 mm inner diameter steel and HDPE pipes to be installed via the horizontal directional drilling (HDD) method and open cut method. Major seismic hazards along the forcemain alignments consist of soil liquefaction induced permanent ground deformations (PGD) of vertical settlement (on the order of 0.1 to 0.5 m) and lateral spreading movements up to 4 m.

A pipe-soil interaction finite element model of the entire alignment, approximately 2.1 km, was completed using Abaqus software. The pipeline was modeled using a shell-type element which can respond to bending loads with significant ovalization of the pipe cross-section. Ovalization gives the element elastic flexibility substantially greater than a pipe element unable to ovalize when in bending. In the model, PGDs were applied at multiple steps to account for the sequential loading stages (site preloading settlement, long term static settlement, "during event" ground movement and "post event reconsolidation settlement"). The stress accumulated in each loading step was carried into subsequent steps. Both steel and HDPE pipes were analyzed in the model, and appropriate pipe sections, joints and connections were selected based on the modeling results.

Functional Damage of Water Supply Systems due to Power Outages during Recent Natural Disasters in Japan

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ABSTRACT

The Hokkaido Eastern Iburi earthquake occurred on September 6, 2018 with a moment magnitude (Mw) of 6.6. A coal-fired power plant in Atsuma, which is located near the epicenter, was heavily damaged because of this earthquake. The power plant stopped producing electricity, and imbalance in the supply and demand of electricity was caused in Hokkaido. This resulted in the blackout. The earthquake cut power to all 2.95 million households in Hokkaido.

A powerful typhoon Faxai, the 15th typhoon in 2019, made landfall in Tokyo's neighboring Chiba Prefecture around 5:00 a.m. on September 9. It caused severe structural damage especially in the southwestern part of Chiba Prefecture. It also triggered extensive and continued power outage in Chiba Prefecture. Power supply was disrupted at approximately 640 thousand houses in Chiba Prefecture as of 10:30 am on September 9. The power failure continued for about two weeks mainly in the southern part of Chiba Prefecture.

The water supply systems were disrupted during these two natural disasters. The functional damage to water supply systems during the two events were mainly due to the power outages. This study makes a report on functional damage of water supply systems after the 2018 Hokkaido Eastern Iburi earthquake and that in Chiba Prefecture after Typhoon Faxai. In Japan, it is anticipated that extensive power outages may occur after the Tokyo Inland and the Nankai Trough earthquakes in the near future. This study will be helpful to establish a resilient water supply system against future earthquakes.

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Seismic Vulnerability Assessment of Pipelines and Critical Facilities

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ABSTRACT

This work reports on a half-year study to assess the seismic risk of Sacramento Regional County Sanitation District (SRCSD) and Sacramento Area Sewer District pipelines and critical facilities. While the Sacramento area is not subject to the same level of seismic hazard as neighboring San Francisco, it has experienced the effects of earthquakes in the past (e.g., 1989 Loma Prieta earthquake). Since 1950, there have been roughly two dozen events that have occurred within 100 km of Sacramento. In order to understand the risk that these systems currently face, the following questions were addressed:

- What is the likelihood that an earthquake will cause significant damage and disruption to Districts' underground pipelines and critical facilities in the next 50 years, 100 years and longer?
- Which parts of the Districts' underground pipeline system are subject to the highest levels of seismic risk?
- What are the expected seismic risks to underground pipelines – that is, expected repair costs & repair times
  - on an annualized basis and in large, credible earthquake scenarios?
- Are there critical facilities that are vulnerable to damage and which could impair the whole system?
- What recommendations, strategic and technical, can be made that will help improve seismic resilience andreduce potential losses in the future?

The above questions were addressed in a high-level desktop study that incorporated our best understanding of seismic hazards in the region and how pipelines will respond to various levels of earthquake effects, including strong ground shaking and liquefaction-induced ground failure. One of the more notable features of this study was the use of ImageCat's earthquake event set which simulates the occurrence of earthquakes over 500,000 years, wherein earthquake events and associated intensity footprints are constructed through a random-walk process. This stochastic catalog of simulations is consistent with the USGS models that produce earthquake design maps used in building codes. To supplement this probabilistic approach, a deterministic worst-case scenario was elaborated.

In this study, we first quantified current risks and then evaluated whether cost-effective solutions existed to mitigate these risks. To present a comprehensive view of seismic risk to Districts' pipelines, four different products were produced. These included:

- Losses and Repair Times from M7.3 Great Valley Earthquake Scenario
- Average Annualized Losses and Repair Times
- Expected Losses and Repair Times Associated with Different Return Periods
- Effectiveness of Various Mitigation Options in reducing Expected Losses and System Downtimes

Each product was useful in evaluating different mitigation strategies to reduce future seismic risks. In some cases, the information above was important in determining whether earthquake insurance was a viable means of risk transfer or not. Additionally, we designed planning strategies to reduce overall impacts by relying on effective response or recovery planning activities.

Seismic Resiliency Evaluation of a Structural Cured in-Place Pipe Liner for Water Mains

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ABSTRACT

This work describes a structural Cured-in-Place-Pipe (CIPP) technology for water main renewal and strengthening against earthquake and natural hazard effects. It focuses on a product named ALTRA™ (referred to as the Product hereinafter), the second generation of Aqua-Pipe™, available through Sanexen Water. This Product is an epoxy resin impregnated composite lining consisting of an inner and outer layer, or jacket. The outer jacket consists of a seamless, circular woven fabric with continuous high tenacity polyester yarns in both longitudinal, or warp, and circumferential, or weft, directions. The inside jacket consists of proprietary yarns in the weft direction which have the ability to elongate upon loading, and of high tenacity polyester yarns in the warp direction. Prior to resin hardening as a result of thermally activated crosslinking, the weft yarns allow the lining to conform, during installation, to the host pipe surface and diameter with a tight fit while avoiding the formation of folds in the liner.

Building on the know-how gained from the almost 1,400 miles of first generation of Aqua-Pipe™ installed in more than 400 cities throughout North America, ALTRA™ was launched in the spring of 2020 as soon as it had received its NSF/ANSI Standard 61 certification and was installed in several projects since. Field installations confirmed the ability of the Product to conform to host pipe diameter of cast/ductile iron pipe segments varying in diameter between 148 mm and 162 mm, without the formation of a longitudinal fold in the liner (manufactured with an outside diameter of 147 mm). Tensile and flexural testing confirmed its structural properties as a standalone pipe based on strength and elastic modulus measurements, but more importantly, it revealed the high deformation capacity of the Product, specifically in the longitudinal direction, which exceeds 20%.

The Product was evaluated through a series of large-scale tests at Cornell University's Large-Scale Lifelines Laboratory. These tests included direct tension, friction, direct shear, four-point bending, shear offset, and large-scale fault offset tests. A report of the testing project at Cornell was published recently [1]. The ultimate large-scale fault offset test proved the ALTRA™ Cured in-Place Pipe (CIPP) technology to resist the large extension (joint opening by 0.36 m) and bending (joint opening and rotation of 0.36 m and 14° respectively) involved during testing. Despite such large deformations, the Product remained structurally sound and retained water pressure. Post- fault-rupture testing performed on liner samples taken from highest deformation joint area indicated that residual mechanical properties were similar to pristine liner properties. This behavior is at the root of the high resilience of ALTRA™ in large underground deformation events.

[1] T. D. O'Rourke, J. E. Strait, N. Mottl, B. Berger, B. Wham, H. E. Stewart and D. Price. Performance Evaluation of Aqua-Pipe under Earthquake-Induced Ground Deformation, Interim Report, Cornell University, June 2020. https://cpb-us-w2.wpmucdn.com/sites.coecis.cornell.edu/dist/a/38/files/2020/06/1-June-20-InterimSanexenReport_MNB_TDO_JES_b.pdf

A Novel Steel Pipe Joint for Enhancing Pipeline Seismic Resilience I: Development and Validation

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ABSTRACT

The structural performance of lap welded joints is essential for safeguarding the structural integrity of steel water pipelines in seismic areas. Over the last four years, an extensive experimental project was launched to determine the performance of lap welded joints under severe ground-induced deformations. The research consisted of full-scale physical experiments on 24-inch-diameter pipe joints, supported and validated by rigorous numerical finite element simulations. The experimental results have indicated the standard lap welded joints are both strong and capable of sustaining substantial deformation without loss of water containment. Questions related to local lap weld joint deformation were also elucidated and the corresponding strains developed under extreme tensile or compressive loads at critical locations were quantified, demonstrating the ability of those joints to sustain a significant amount of local strain at critical locations.

The present work describes the most recent phase of the above research, focusing on the behavior, analysis and design of a new seismic-resistant lap welded joint, towards further enhancing the resilience of welded steel water pipelines. This new concept comprises the standard lap weld configuration, but contains a small geometric projection, introduced at a specific location near the circumferential fillet weld. Experimental results from full-scale experiments on pressurized 24-inch-diamter pipe joints, supported by finite element numerical simulations, indicate that the new lap welded joint, when subjected to severe axial and bending loading, is capable of sustaining a remarkable amount of deformation, while maintaining its strength and without loss of water containment. Furthermore, this small modification is proven to result in consistent buckling of the steel pipe cylinder and not the lap weld joint.

The proposed joint, referred to as "Atlas Seismic Resilient" or "ATLAS SR-joint" (patent pending), offers an efficient, reliable, yet economical solution for welded joints in steel water pipelines in seismic and in other geohazard areas.

Scenario Simulation of Hsinchu Water Supply System for Seismic Hazard Mitigation

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ABSTRACT

Taiwan is located on the circum-Pacific seismic belt, one of the most earthquake-prone regions in the world. Many of its densely populated cities and industrial clusters are exposed to high seismic hazards. Evidence indicates that the widespread disruption of water supply on this island, which has occurred in the past in the presence of major earthquakes, will occur again in future earthquake events. It will not only cause inconvenience to the people and businesses in the affected areas, but also generate large impacts to elsewhere in the world through the disconnection of high-tech supply chains. Therefore, it is very important for the utilities to assess their water supply systems, through which seismic hazard mitigation can be implemented more adequately. This investigation focused on the seismic scenario simulation of the water supply system in Hsinchu, where the Hsinchu Science Park, the first and largest science park of its kind in Taiwan, is located. Unfortunately, there are three known active faults right beneath it. The analyses employed the Twater software system developed by the National Center for Research on Earthquake Engineering (NCREE). Twater is able to predict the damage to the component pipelines and facilities of a water supply system, as well as the system's serviceability given an earthquake scenario. As the input data, Twater utilizes the inventory and hierarchy of relevant system components including raw water aqueducts, water treatment plants, major clear water conveyance trunks, and water transmission and distribution pipeline networks, along with their relationship with the water supply areas in a system. The analyses considered four earthquake scenarios. The simulation provides the estimates of numbers of pipeline damages and households without water, together with the damages in water mains and major facilities in Hsinchu. Key observations from the simulation results indicate that: (1) the clear water main from the Paoshan Water Treatment Plant, the largest in the system, needs a retrofit against fault offset for securing its functionality; (2) the smaller but crucial Hsinchu First and Second Water Treatment Plants and their shared raw water aqueduct need a upgrade for surviving any earthquake right beneath them; (3) the Hsinchu Science Park, now a hub of semiconductor manufacturing in the world, may suffer severe water outage due to the vulnerability of relevant water transmission trunks and its own water pipe network. Eventually, this investigation justifies that the scenario simulation following the approach the Twater software adopted may quantitatively reveal the seismic weaknesses of a water supply system for hazard mitigation.

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Verification of Applicable Range of Underground Steel Pipeline Design Formula for Large-Diameter Pipes Subjected to Fault Displacement

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ABSTRACT

The Chi-Chi Earthquake (Mw 7.6) which occurred in Taiwan in 1999 caused tremendous damage to structures, as fault displacement reaching 10 m or more. Many pipelines cross faults in the affected area, and were heavily damaged, including rupture and blockage of pipes due to fault displacement, forcing a cutoff of the water supply. In recent years, much research on issues related to design methods for steel pipelines crossing faults has been reported, such as prediction of fault displacement, setting of the fault countermeasure (effect) range, and development of fault countermeasure construction methods. This design has the feature that advance countermeasures can be taken easily because the assumed position of the fault, tolerance angle, etc. with the pipeline are known. However, while countermeasures for pipelines that cross faults are clearly needed, specific design methods and countermeasures are not currently indicated in the guidelines for pipeline seismic design of Japan.

The Sub-committee of JSCE has proposed a design formula that enables easy calculation of the strain that occurs in an underground steel pipeline under the action of a fault displacement. In this design formula, the pipeline was modeled by beam elements, where the effect of deformation in the cross-sectional direction of large-diameter, thin-walled pipes such as water pipes is a concern.

In this work, the applicable range of the design formula for large-diameter pipes was verified by experimental and numerical analysis.

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Study of Analysis Method on Behavior of Seismic Type Ductile Iron Pipes Considering Decrease of Ground Stiffness in Embankment Failure

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ABSTRACT

In this study, we proposed an analysis method considering decrease of ground stiffness to analyze behavior of pipeline composed of seismic type ductile iron pipes when the pipeline was buried in large ground deformations induced by embankment failure, with the beam and spring elements used generally to simulate behavior of buried pipeline. In addition, we confirmed a validity of the proposed method in comparison of the results of analysis with measured values of pipeline behavior in actual embankment failure.

We built an analysis model with beam elements as pipes and spring elements as pipe joints and soils around the pipeline. We connected spring elements to the pipeline model in an axial direction and a transverse direction. We used two kinds of soil spring elements to build ground models. One is the soil spring proposed by American Lifelines Alliance outside embankment failure section. It is generally used in the finite element method. It is used in no embankment failure section. On the other hand, we proposed another soil spring considering decrease of soil stiffness in embankment failure section. We supposed that the soil spring constants to express soil stiffness and the load acted to pipeline were decreased, as the relative displacement between soil and pipeline increased in embankment failure. Therefore, we used results of single-plane shear tests of soil conducted by Nonoyama, et al. to express the characteristic of the proposed soil springs. Moreover, we directly applied soil load to pipeline from a transverse direction in embankment failure section in the analysis to assume that soil load influenced pipeline displacement in embankment failure.

We analyzed the pipelines in embankment failure by using the proposed soil spring constants and general soil spring constants, respectively, and compared the results of analyses with the actual measured values of pipelines exposed by embankment failure. The transverse pipeline displacements obtained from the analysis used the proposed soil spring constants were nearer to the measured values than those in the analysis used the general soil spring constants. However, the section where pipeline displacements in transverse direction actually occurred was larger than that of analysis used the proposed soil spring constants. So, we considered decrease of ground stiffness in a little bit outside of embankment failure section in the analysis. As a result, we confirmed a validity of the analysis method because the results of analysis could coincide with the measured values well.

Life-Cycle Analysis of Water Infrastructure Incorporating Physics-Based Deterioration and Recovery Modeling

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ABSTRACT

Water mains provide fundamental services to communities. These services might be impacted by the gradual deterioration processes affecting the system and by instantaneous hazard occurrences (earthquakes in particular). A proper life-cycle analysis of water mains should account for the effects of such phenomena on the performance of the infrastructure. Currently available methods for the quantification of damage on water mains use empirical fragility and repair rate curves, calibrated based on historical data. Accounting for the physical characteristics with approximate correction coefficients, these curves do not allow for a physics-based quantification of the effects of gradual and shock deterioration. In addition to a proper modeling of the impact, a proper modeling of the recovery actions required after the disruption of service can provide the operators with accurate estimates of the down-times that the infrastructure will experience and of the costs that should be sustained throughout the life-cycle. Most models available in literature tend to differentiate between deterioration and recovery modeling. With independent modeling, important interactions between deterioration and recovery might not be captured. However, both types of processes can be interpreted in terms of the change in the same state variables and as such they can be modeled together. In this work, we propose to use recently developed, state-of-the-art models for deterioration and recovery of water infrastructure to develop a unified framework for the life-cycle analysis of the system. The framework includes a physics-based formulation for the damage on water mains following the occurrence of seismic excitations. Namely, the damage experienced is formulated as a function of multiple state variables including material properties, soil properties and age of the pipes. Finite Element formulations are used to compute the strain on the pipelines during the seismic event and predict the expected damage. Similarly, the recovery model consists of a detailed schedule for the repair or replacement of damaged pipes while considering the required crews, resources, and other scheduling constraints. The proposed framework can be used to accurately quantify the performance of the water infrastructure over time, to device optimal maintenance strategies on the system, and to help communities prepare for the interruption of service following a hazardous event.

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Utility-Academic Collaborative Partnership to Test, Evaluate, and Install an Innovative Seismic Pipeline Replacement Solution

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ABSTRACT

The East Bay Municipal Utility District (EBMUD) is a publicly-owned utility that supplies water to 1.4 million customers in the San Francisco Bay Area. To address replacement of EBMUD's 4,200 miles of aging pipelines, the organization embarked on a major initiative to increase the replacement rate of the distribution system from 10 to upwards of 40 miles per year. To accomplish this, a research team at the District was formed to identify efficiencies, develop metrics, and evaluate innovative methods, technologies, and materials used in pipeline replacement projects. Essential to this sustainable pipeline replacement program is considering various AWWA certified pipe materials, products, and fittings for pilot installations to evaluate where cost-effective efficiencies can be gained during design and construction as well as mitigate risk to hazards posed by the District's proximity to active seismic features, including the Hayward fault which intersects the entire service area.

To mitigate and reduce the risk of distribution pipeline breaks during a seismic event, the District recently installed AWWA C900 iPVC pipe with RCT Flex-Tite self-restraining fittings. Project locations varied within the District's diverse geographical service area from a flat and well gridded neighborhood, to a steep hillside area near the Hayward fault, to a location with windy roads and adjacent hills with active landslides. In parallel, the Center for Infrastructure, Energy, and Space Testing (CIEST) at CU Boulder and the District initiated a collaborative study to examine the combination of iPVC pipe and RCT coupling with experiments to evaluate seismic response under axial tension, axial compression, and axial cyclic loading as well as four-point bending. The study includes full-scale tests on 6-in diameter DR-14 iPVC pipe specimens and the results indicate excellent performance of the pipeline system.

Results of this utility-academic collaboration between the District and CU Boulder, highlight experimental testing results, an overview of project specific geohazards, and lessons learned during construction and installation of this innovative seismic resilient pipe system. Critical research findings established during this collaborative partnership ensure sustained system reliability, sound infrastructure investment strategies, and long-term customer satisfaction.

Planning for Seismic Resilience of Water Networks: Working with Local Government Sectors in New Zealand

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ABSTRACT

Planning for resilience of lifeline systems has several drivers including preparing adequately for future events to minimize the impact on community living and socio-economic sectors of a region. Water networks in New Zealand are largely managed by local government sectors represented by councils. Risk assessment for seismic hazard is usually carried out to procure insurance cover. However, resilience planning has gained increasing attention among councils. This study demonstrates a scenario-based resilience assessment of water networks of Rotorua district council, New Zealand, where a participatory approach was adopted to work with the council to meet their needs and to make informed decision throughout the process.

Many active faults are present in the study region. To choose a credible earthquake fault scenario, probabilistic seismic hazard analyses were carried out for 100, 500 and 2500 year return periods. Ngakuru Southwest fault source consistently showed maximum contributions at three hazard levels and it was chosen in consultation with the council for the scenario-based assessment. The risk assessment process included: (i) damage modelling to identify vulnerable parts of the network; and (ii) estimating service outage time adopting preferred recovery strategies. Damage modelling considered the effects of ground shaking, liquefaction and lateral spreading and adopted published vulnerability models including the models developed from Canterbury earthquake sequence to predict damage within the network. The priority and order of recovery of various parts of the network as determined by the council authorities were adopted to estimate the outage times. Outage time for wastewater network was much longer compared to the water supply network as wastewater pipes were required to be flushed with water to remove deposits of liquefied material.

Service outage times are key indicators of resilience initiatives and they form effective means of communicating the impact of loss of services to the community and the stakeholders who are key financial decision makers. There are many factors that influence outage times including: (i) number of crews available and repair strategies adopted; and (iii) interdependencies on the recovery of other networks such as road, and electricity. As modelling interdependencies of all the networks is a complex exercise, it is recommended that each network can be modelled for its damage and outage of services independently at any time preferred by the council and the effects of interdependent network can be assessed in a systematic and logical manner.
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Deterministic Optimization Model for Budget Allocation to Seismic Risk Mitigation for Water Distribution System

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ABSTRACT

Damages to the water supply system after earthquake events such the San Fernando earthquake have illustrated the high vulnerability and risks associated with failure of these sensitive water distribution systems. This is more critical due to the possibility of the Fire following earthquake events and potential increase in water demand immediately after the event. Recently, significant advancements have been achieved in the development of retrofit and strengthening systems for water distribution systems such as using a structural liner or FRP reinforcement to reduce such risk of seismic damage and to ensure continuity of water distribution operations following an earthquake. Considering the limited budget of most municipalities, seismic risk mitigation typically involves appropriate planning and prioritization to address the critical pipelines that produce the most impact.

An optimization model is described that can be utilized for budget allocation to implement retrofitting measures for steel and concrete water pipelines. This model can be used by decision-makers to develop budget allocation strategies and determine which strengthening or retrofitting method or methods that the most practical, economical and safe to be used considering a predefined set of limitations and criteria. The deterministic model provides the optimal retrofit measures based on minimizing the retrofit costs, post- earthquake replacement costs, and especially seismic large losses. A case study is used for a small pilot area based on the return of certain earthquake to demonstrate the practical aspects and application of the proposed model.

Pipeline exposure database, built environment occupancy type, pipeline vulnerability functions, and regional seismic hazard characteristics are used to calculate a probabilistic seismic risk for the pilot area. The results are developed in terms the variation of retrofit costs for pipelines located in the pilot area based on their geographical location and the selected strengthening methods.

Development of a Real-Time Estimation System for Damage of Water Supply and Sewage Infrastructure Immediately after an Earthquake

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ABSTRACT

A real-time estimation system to seismic damage of water supply and sewage infrastructure such as distribution and sewer pipelines immediately after an earthquake was developed as a web-GIS oriented system. The whole system consists of four sub-systems: sub-system A for capturing spatial data on ground motion intensities; sub-system B for estimating pipelines damage distributed in a targeted region; sub-system C for telecommunicating associated disaster digital information; sub-system D for visualizing damage estimation data. In sub-system A, spatially discretized data of ground motion intensities are downloaded and captured as a 250 m * 250 m mesh-data to the system's memory. Peak ground acceleration (PGA), peak ground velocity (PGV), instrumental seismic intensity defined by Japan Meteorological Agency (IJ) and spectrum intensity (SI) are used as a ground motion intensity measure. In less than half an hour immediately after an event the system accesses to the associated web sites provided by NIED and Real-Time Earthquake & Disaster Information Consortium (REIC). In sub-system B, pipelines damage is estimated by applying an empirical sophisticated fragility curve representing the relationship between ground motion intensity and damage probability / damage rate from view of points of pipe type, pipe diameter, classification of microtopography and potential of liquefaction occurrence. The damage data is stored in the system. In sub-systems C and D, the system is designed to enhance usability and human-system interface among users for the system. The disaster digital information on locations of pipelines damage in a mesh-data or point-data format and that on pipelines damage probability / damage rate are shared interactively between a system administrator and lifeline management sectors by sending and receiving text style emails aggregated for each targeted area. Those are also showed on a user side interface for the system automatically by the web-GIS online tools.

Study on SPF Application for Ground Settlement

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ABSTRACT

Ever since 1995 Kobe Earthquake, earthquake damage to buried pipelines due to fault movement, liquefaction, ground settlement has been seen in large-scale earthquakes. After a large-scale earthquake occurs, restoration of water transmission main is considered a priority, but this is time consuming when large deformations and water leakages occur. Steel Pipe for Fault (SPF) settlement type was developed to absorb ground displacement and prevent water leakages at connections in ground structures and buried pipelines in order to maintain water flow without cracks, even if ground settlement occurs. The development of this SPF is based on the technology of the SPF original type, which is a solution for infrastructure and pipelines in fault zones.

The SPF settlement-type is a special steel pipe developed to absorb ground displacement, and it can maintain water flow function without cracks and water leakage, even if large displacement occurs. Since the pipe thickness of SPF settlement-type is the same as that of the main pipe, the reaction force is larger when compared to that of general flexible pipes. In order to reduce the reaction force (and the influence on adjacent structures) numerical analysis and modeling were carried out to improve SPF shape. Toward the application of the SPF settlement-type, values studied included: the performance of water-flow cross-section; the performance of coating elongation; the effect of reaction force to the wall of ground structure; and the effect of hydraulic thrust force; all of these have been analyzed and verified not to exceed the limit stated, even in cases where twice the design values were loaded. In addition, to verify the change of ground settlement and the performance of SPF settlement-type, measuring instruments were installed and continuously recorded. The measurement data is provided.

Focusing on the serious damages caused by large-scale earthquakes, a case study of SPF settlement-type is provided, to contribute to the resiliency of water infrastructure. We hope that this work may help to prevent earthquake damage in water infrastructure in the near future.

Enhancing Chances for Water to Cross the San Andreas Fault in the Elizabeth Tunnel

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ABSTRACT

The Elizabeth Tunnel has been in service since 1913 as that part of the Los Angeles Aqueduct (LA Aqueduct) that crosses the San Andreas fault. The Fairmont Reservoir provided head for flow through the tunnel and a downstreampower plant. Aqueduct design began shortly after the 1906 San Francisco earthquake, and its designer was aware ofthe location and importance of the San Andreas fault in Southern California. The Fairmont Reservoir Dam was constructed at the same time and with the same methods as the Lower Van Norman Dam at the southern terminus of the LA Aqueduct, which failed during the 1971 San Fernando earthquake. The Fairmont Reservoir was taken outof service and a new Fairmont Reservoir No. 2 constructed to provide head with appropriate piping that included a bulkhead to prevent water from flowing from the tunnel into the out-of-service reservoir. The 2008 Great Southern California Shakeout Scenario was a M 7.8 earthquake on the Southern San Andreas fault that ruptured toward the northwest, dying out near the Elizabeth Tunnel. This disaster simulation revealed that all three aqueducts bringing water to Southern California could be damaged in a single earthquake. The Los Angeles Department of Water and Power began considering constructible "enhancements" that might allow water to flow through the tunnel after faultdisplacement. Water systems that used HDPE pipe remained in service in the 2010-2011 Christchurch earthquakes, suggesting that an effective enhancement might be a simple section of HDPE pipe placed across the fault zone inside the tunnel. As-built geology notes from the 1907-1911 tunnel construction indicated some unstable locations,but geology notes for most of the concrete-lined tunnel had been lost. No historical earthquakes have happened nearthe tunnel since before it went into service in 1913, so roof collapse caused by strong shaking needed to be addressed. Design considerations began in 2012 for anchoring HDPE pipe in the semicircle invert of the tunnel so itwould remain in place during normal aqueduct operation and not obstruct the tunnel during maintenance shutdown periods. The existing bulkhead was to be replaced with a new removable-door bulkhead to allow construction access from the out-of-service reservoir bottom. Alternatives were studied and steel ribs were added for structural support across the 480-foot-wide zone of most recent faulting; shotcrete overlays were added in zones of very poor rock quality identified with an innovative seismic refraction survey inside the tunnel. Contact grouting was added through the entire fault zone and where shotcrete overlays were needed. During final design, which was completed by Los Angeles Department of Water and Power engineers, the HDPE pipe was eliminated from the design concept. Design was completed in 2020, and construction was planned to begin in 2021.

A Novel Steel Pipe Joint for Enhancing Pipeline Seismic Resilience II: Applications

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ABSTRACT

Welded lap joints are widely used in steel water pipelines. Previous experiments on full-scale specimens, supported by finite element calculations have demonstrated the strength and deformation capacity of standard lap welded joints. This work is a continuation of the above research and describes the second part of an extensive project aimed at determining the performance of lap welded joints, under severe ground-induced deformations. It refers to the behavior, analysis and design of a new seismic-resistant lap welded joint, which increases the resilience of welded steel water pipelines. This new concept, referred to as "Atlas Seismic Resilient" or "ATLAS SR-joint" (patent pending), consists of the standard lap weld, equipped with a small geometric projection, introduced at a specific location near the circumferential fillet weld, so that local buckling occurs at the steel pipe cylinder and not at the lap weld joint. In the companion abstract, this new concept is validated, using full-scale experiments and finite element numerical simulations.

The ATLAS SR-joint is applied in two case studies associated with the design and construction of buried steel water pipelines in areas where significant severe actions on the pipelines is expected because of ground deformation. The first case refers to a large-diameter buried steel pipeline in a settlement area and the second case refers to a seismic fault-crossing area. In both cases, the proper use of ATLAS SR-joint results in a decrease of bending and stretching deformation in the pipeline, and mitigates the effects of ground-induced actions, towards enhancing pipeline resilience and increasing the level of pipeline safety, so that water containment is assured and pipeline functionality is maintained after a severe ground motion event.

This work, together with the companion effort, demonstrates that the proposed ATLAS SR-joint constitutes an efficient, reliable, yet economical solution for welded joints in buried steel water pipelines, constructed in seismic and in other geohazard areas.

Earthquake Response, Vulnerability Assessment and Rehabilitation of Water Conveyance Tunnels in High Seismic Hazard Regions: Whitewater Tunnel No. 2 Seismic Resilience Study

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ABSTRACT

The Metropolitan Water District of Southern California (Metropolitan) owns and operates an extensive conveyance, storage, treatment and distribution system, which provides water to approximately 19 million people over a 5,200 square mile service area. Metropolitan's Colorado River Aqueduct (CRA) conveys on average approximately 25% of its service area annual demand. The CRA, which is comprised of 5 pumping plants, 29 miles of siphon, 63 miles of canal, 58 miles of conduit and pipeline and 92 miles of tunnel, crosses multiple faults along its route including multiple segments of the southern San Andreas Fault (SSAF) system.

As part of its seismic resilience strategy, Metropolitan has conducted studies to assess the seismic hazards from a Moment Magnitude (Mw) 7.8 earthquake on the southern SAF, estimate the potential damage to the CRA, and assess the potential impacts to water delivery. Of concern is the CRA Whitewater Tunnel No. 2, which lies between the Garnet Hills fault and Banning fault segments of the SAF zone. A splay of the Garnet Hills fault crosses the tunnel approximately 1/3 mile from its west portal.

While it is generally perceived that underground structures perform better during major seismic events when compared to their above ground counterparts, the response of underground structures to recent earthquakes (e.g., Kobe 1995, Duzce 1999, Chi-chi 1999, Wenchuan 2008) suggest the need to investigate the vulnerability and rehabilitation strategies of critical tunnels to future seismic activities. In the case of the Whitewater Tunnel No. 2, repairing the damage from a rupture within the tunnel would likely be the critical path to restoring CRA deliveries. This work covers the methodology utilized in the risk assessment, development of performance criteria, structural evaluation, pre-earthquake mitigation and post-earthquake rehabilitation strategies for the existing Whitewater Tunnel No.2 based on anticipated damage from a Mw 7.8 SAF earthquake that ruptures through the tunnel. The effects of large displacements (both vertical and horizontal) on the tunnel due to strong ground shaking from the earthquake is also discussed.

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Colorado River Aqueduct Seismic Resilience: A Century of Evolution

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ABSTRACT

The Metropolitan Water District of Southern California (Metropolitan) owns and operates a complex water conveyance, storage, treatment, and distribution system that covers a 5,200 square mile service area in a seismically active region and is depended upon to provide approximately one-half of the water needed by its 19 million residents. Metropolitan's infrastructure includes the Colorado River Aqueduct (CRA), originally constructed in the 1930s, stretching 242 miles from the Colorado River to Lake Mathews in Riverside County and crossing multiple fault zones along its route. Constructed as part of the original CRA, the Casa Loma Siphon Barrel No.1 is a 148- inch diameter concrete pipe that extends five miles across the San Jacinto Valley and crosses the Casa Loma Fault Segment of the San Jacinto Fault Zone—a major branch of the San Andreas Fault System.

Despite very limited knowledge of seismic activities in the 1920s, Metropolitan engineers took proactive measures to address seismic resilience in the design of the CRA, including the incorporation of articulated joints in the original Casa Loma Siphon Barrel No.1 crossing the active San Jacinto Fault System. In the 1960s, cracks and leakage developed in the pipe as a result of earth movement where the siphon crosses the Casa Loma Fault. 300 feet of the 148-inch diameter concrete pipe were replaced with steel pipe, joined by external sleeve-type couplings. These couplings were installed across the fault to permit minor movement to mitigate leakage caused by ground subsidence due to groundwater withdrawal and possible fault creep.

Benefiting from the latest advancements in earthquake engineering, pipeline design and lessons learned from major seismic events around the world, Metropolitan engineers and consultants conducted extensive research on the latest seismicity data, pipeline design standards, recently developed seismic-resistant products, and modern computer modeling techniques. Aimed at achieving greater levels of seismic resilience beyond the conventional measures of prevention and protection, 1,200 feet of the existing 148-inch diameter steel and concrete pipe segments crossing the Casa Loma Fault are to be replaced with a combination of steel pipes and earthquake-resistant ductile iron pipes. This newly designed pipeline is anticipated to remain functional and operational during and following a design seismic event. Strategies for repairing the pipe is also developed should the pipeline be damaged in an earthquake that exceeds the design seismic event.

LADWP's First 54-inch Earthquake Resistant Ductile Iron Pipe Project

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ABSTRACT

The Los Angeles Department of Water and Power (LADWP) is committed to creating a seismically-resilient pipe network. A network with pipe material that withstands ground movements such as earthquakes and ground subsidence. One material that was evaluated is the Earthquake Resistant Ductile Iron Pipe (ERDIP) which was originally developed and manufactured by a Japanese-based company. ERDIP has been installed in Japan for over 40 years with no documented failures. With Japan's history of seismic activity and stringent standards, ERDIP has proven to withstand earthquakes and ground movements, thus making it a suitable candidate for LADWP's first ERDIP large diameter pipeline, the Foothill Trunk Line project.

The Foothill Trunk Line is a large pipeline used to transport water to the Sunland/Tujunga area of the City of Los Angeles. LADWP will replace a 3-mile section of the pipeline, which was originally built in the 1930s. The existing pipeline, ranging in diameter from 24 to 36 inches, will be replaced with two miles of 54-inch diameter ERDIP and 1 mile of welded steel pipeline. To minimize impacts to the community, a new 12-inch diameter earthquake resistant ductile iron distribution water mainline will also be installed alongside the 54-inch ERDIP. This 54-inch diameter ERDIP project is being installed with open trench and tunneling methods, and LADWP in-house crews have been installing this 54-inch diameter ERDIP since January 2018. This project is an important water infrastructure investment that will ensure resiliency and reliability resiliency and reliability of the water supplies within the San Fernando Valley, and the surrounding communities in the City of Los Angeles.

This project was strategically placed in portions of LADWP's distribution system that have been targeted for replacement, serve critical areas/facilities, and are located in seismic fault or liquefaction zones. LADWP's designers evaluated fault displacement characteristics of the area and potential displacement of existing faults within the proposed alignment. Through the design process, the design team was confronted with various design challenges such as profile development, designated pipe types for seismic resistance, and designing for operational needs. In addition, to design challenges, our LADWP in-house crews had many construction challenges, such as new installation methodology versus our typical welded steel pipe method, hydrostatic joint testing, and dealing with unforeseen substructures that impacted the ERDIP appurtenances.

Practical Dependence-Based Strategies for Improved Resilience of Water Systems

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ABSTRACT

Adequate performance of lifeline infrastructure systems is at the core of community resilience. However, lifeline systems are particularly vulnerable to hazards, such as earthquakes, hurricanes, and floods, given their large geographical coverage and long design lifetimes. Moreover, lifeline systems operate under various interdependent conditions, introducing complex feedback loops among them that are particularly hard to manage during extreme events. At the same time, these interdependencies may offer strategies to improve resilience across utilities and communities that together achieve unified restoration and performance goals. In this study, we quantify the effectiveness of field-informed and dependence-based strategies to improve the resilience of water supply systems through practical computational modeling techniques. The upstream and downstream dependence-based measures considered here build upon real practices elicited by interviews we conducted with eight large water utilities across the United States between 2017 and 2018. The computational modeling includes system damage state estimation, recovery modeling, system performance quantification, and resilience assessment. System performance is defined here as hydraulic service availability, which implies operability but not necessarily full functionality. We perform hydraulic modeling using open-source software WNTR (Water Network Tool for Resilience), which allows for what-if scenario analyses. Our results reveal that joint dependence-informed restoration strategies yield performance improvements that exceed their independent benefits. In the processes, dependency effects also reveal priorities among mitigation measures. Our computational modeling, informed by state-of-the-practice strategies to manage contingencies, offers unique opportunities to quantify the impact of diverse adaptation measures across utilities today, some generally applicable, while some remain particular to specific utility types, but all geared to support effective decision making under uncertainty within the water industry.

Seismic Resilience in Design of New Water Supply Systems: A Natural Disaster Resilience Framework Informed by Lessons Learned from the 2011 Tohoku Earthquake and Tsunami Crisis

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ABSTRACT

Seismic events can create complex problems and challenges for the built environment. Water infrastructure is one of the most critical utilities in support of community resilience. To prepare for future seismic events, effective resilience frameworks informed by lessons from past disasters will help address complex problems. This work discusses a seismic resilience design approach for a new water infrastructure system supported by an effective framework and lessons learned from the 2011 Tohoku Earthquake and Tsunami Crisis. This work discusses four main topic areas. The first part describes the $1.3 billion Willamette Water Supply System (WWSS) and the seismic hazard it faces in the Pacific Northwest Region. The second part discusses key insight drawn from a 2019 public administration research program that focused on learning lessons from the 2011 Tohoku earthquake and tsunami crisis in Japan. This provides important foundation to help inform the third part that discusses an overall resilience framework that addresses the complexities and interconnected elements associated with natural disasters. The fourth part then applies the resilience framework, the lessons learned from the Tohoku Earthquake and Tsunamic Crisis program and other related thinking to the WWSS to illustrate how the framework can be practically and effectively implemented to improve the resilience of water infrastructure systems. This work targets leadership, managers, operators, and engineers associated with the development, design, and operation of critical water infrastructure systems. It provides useful broader context of major seismic disasters, lessons learned and an overarching framework to address these complex issues, provides a case study of how these measures can be implemented in the development of a new seismically resilient water infrastructure system, as well as highlights fundamental policy decisions related to establishing level of service priorities.

A Practical Approach to Improving Seismic Resilience for Critical Water Infrastructure Systems

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ABSTRACT

Knowing where to start with the implementation of measures to improve seismic resilience of critical water infrastructure systems can be overwhelming. Seismic hazards like other natural disasters can create complex problems that require appropriate multi-dimensional solutions to effectively address them. Many times, the various disciplines involved use specific language and jargon that, if one is not familiar with it, essentially makes the needed information inaccessible to those not practicing within that particular discipline. While many good sources of literature to address the problem exist in the industry, typically they seem to treat the subject matter at either a very high (or conceptual) level or at a very focused and detailed level, neither of which provides adequate and balanced guidance for practically improving resilience. This work provides a practical step-by-step guide to improve water infrastructure system resilience. It addresses high level planning types of issues in a way that they can be implemented. It also captures the essence of some of the more detailed seismic concepts that must be considered to achieve greater seismic resilience. It considers social-technical aspects that supports broader contextual understanding for issues associated with seismic design for water infrastructure while providing direction where greater areas of specialized expertise are needed. The content described by this work is based on (a) a new chapter being prepared for AWWA's M41 *Ductile-Iron Pipe and Fittings Manual of Water Supply Practices* focused on seismic guidelines for ductile iron pipe as well as (b) seismic guidelines and minimum design requirements developed for a new large water infrastructure system in the Pacific Northwest Region. This work targets leadership, managers, and engineers associated with the development, design, and policy decisions related to critical water infrastructure systems. It provides a discussion of the topics that are related to this complex problem. It incorporates high level planning concepts in a way that are practical to implement. It provides practical steps that support achieving improved water system resilience. Finally, it serves as a bridge for the industry between the high-level planning concepts and the detailed specialized areas of focus.

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Probabilistic Seismic Functionality and Recovery Sequence Analysis of Water Distribution Systems

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ABSTRACT

Earthquakes cause considerable damage to pipelines in Water Distribution Systems (WDS). Such damage can significantly disrupt the performance of the systems. Moreover, the presence of corrosion on pipeline walls significantly weakens the seismic capacity over time and increases the susceptibility to failure. Seismic risk assessment for water infrastructures is typically performed using a scenario-based approach. In this study, a novel approach is proposed to probabilistically evaluate the functionality of WDS during earthquakes and plan the recovery process. The annual frequency of exceedance of functionality loss of WDS is estimated using seismic hazard curves. The probability of seismic damage to pipelines is estimated based on the American Lifeline Alliance (ALA 2001) guideline. The ALA repair rates are modified based on the observed effect of corrosion on pipeline performance after a recent earthquake (2014 Napa Earthquake). Each component's damage state is then determined stochastically by comparing the repair rate and a uniform random variable assigned to the component. The functionality of the WDS is measured in terms of global network efficiency and hydraulic availability. Global network efficiency measures the effectiveness of the network's physical connectivity under various disruptive scenarios, whereas hydraulic availability measures the fractional hydraulic capacity of the system. A pressure-driven hydraulic simulation capable of estimating the hydraulic performance of WDS under partial failure condition is performed to estimate the system hydraulic availability. Finally, a sequential recovery method is presented to assist utility managers in prioritizing repair tasks to optimize the WDS functionality. The proposed method is illustrated using a hypothetical WDS.

Three-Dimensional Numerical Modeling of Cured-In-Place Pipe

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ABSTRACT

The results of three dimensional (3D) numerical modeling are compared with the results of full-scale tests on a pipeline reinforced with cured-in-place pipe (CIPP) performed at the Cornell Large-Scale Lifelines Facility. The results pertain to axial elongation to accommodate earthquake-induced ground deformation of a 6-in. (150-mm) – diameter ductile iron (DI) pipeline lined with Aqua-Pipe™ Generation 1 (AP1) as the CIPP. The full-scale lab tests were designed to evaluate the axial resistance to relative movement between the host pipe and CIPP. A 24-in. (610 mm)-long section of DI pipe was pulled 36 in. (914 mm) across the CIPP under different rates of axial movement and internal pressure. The pipe and lining were sealed and pressurized with end caps. The CIPP diameter was measured carefully and replicated in the numerical analyses. This work provides information about the model setup, representing the pipe and liner as elastic isotropic materials, and pipe/liner interface properties. Both DI pipe and CIPP were modeled as elastic isotropic material with Young's modulus and Poisson's ratio from tensile coupon test results. Three-dimensional, 8-node, linear interpolation, full integration elements (C3D8) were used for the pipe and the liner. The number of elements along the pipe and liner circumference is 32. From the large-scale tests axial loads are plotted with respect to axial displacement for internal pressures of 0, 30, 45, and 75 psi (0, 0.17, 0.31, and 0.52 MPa) and shown to compare favorably with the numerical results. The numerical results are used to investigate the effects of initial CIPP diameter, changes in diameter with length, and diameter changes as a function of internal pressure. Rate of loading is shown experimentally to have negligible effects on axial load as a function of axial movement.

Fault Rupture on Pipeline with Cured-in-Place Pipe

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ABSTRACT

An approximately 36-ft (11-m)-long, five-piece section of a ductile iron pipeline was lined with Aqua-Pipe™ Generation 2 (AP2) and tested in fault rupture at the Cornell Large-Scale Lifelines Facility. The pipeline had a total of four joints located 5 and 15 ft (1.5 m and 3.6 m) north and south of the fault. The fault angle was 50º. The pipeline was instrumented with 96 strain gages at 20 locations along the pipeline to evaluate axial forces and bending moments as well as determine de-bonding between the pipe and lining as a function of fault displacement. The pipe was pressurized to an average 81.3 psi (561 kPa), and buried in partially saturated sand compacted with an average direct shear, peak friction angle of $\phi = 40º$, equivalent in strength to that of a medium dense to dense granular backfill. The depth of burial to top of pipe was 32 in. (813 mm). The test basin was displaced until the full 4-ft (1.20–m) of actuator travel. The lined pipeline maintained its integrity and water pressure throughout the test. The axial forces at the south and north end of the test basin were about 27 and 30 kips (120 and 134 kN), respectively. The axial force was 25 kips (110 kN) at 6 in. (152 mm) of fault displacement, after which de-bonding between the pipe and lining occurred.

Fault rupture in the test is also representative of the most severe ground deformation that occurs along the margins of liquefaction-induced lateral spreads and landslides. Pipeline extension was accommodated by longitudinal movement at the joints, with maximum movement measured at 14.0 in. (356 mm) at the joint closet to the southern side of the fault. Maximum north joint rotation closest to the fault was about 14.0°. The measured and theoretical rotations are in good agreement. The pipeline was able to accommodate a maximum average 30.85 in. (784 mm) of axial extension, corresponding to average tensile strain of 6.3 % along the pipeline. No loss of water pressure or structural failure of the lined pipeline was sustained. Axial extension during the test is large enough to accommodate the great majority (well over 99%) of liquefaction-induced lateral ground strains measured by high resolution LiDAR after each of four major earthquakes during the recent Canterbury Earthquake Sequence (CES) in Christchurch, NZ.

A Seismic Fragility Framework for Earth Dams

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ABSTRACT

Dam owners often need to assess the seismic risk for large portfolios of dams, and the large size of these portfolios can make site-specific analyses unrealistic. Fragility models predict the probability of different damage states for a given ground shaking intensity measure, and can be used to assess the potential seismic risks to a dam given the regional seismic hazard or to quickly evaluate the potential of damage after an earthquake. Fragility models can easily be applied to large dam portfolios, but they must accurately represent the relevant damage states and they must account for the variability among the dams across the portfolio. This study outlines a seismic fragility framework for earth dams that is modeled after the approaches used for other types of infrastructure, such as bridges. The framework uses the relative crest settlement (i.e., settlement normalized by the dam height) as the engineering demand parameter and involves two statistical models, an engineering demand model and a seismic capacity model. The engineering demand model predicts the relative settlement as a function of ground motion intensity, and the seismic capacity model predicts the probability of a damage state given the relative settlement.

These two models are used together within a Monte Carlo simulation to compute the resulting fragility model. This study focuses on developing seismic capacity relationships for three damage states (minor, moderate, and serious) using databases of seismic dam performance developed in previous literatures. These relationships predict the probability of a damage state as a function of relative settlement and, distinct from previous studies, are based on the original damage description for each dam without consideration of the observed relative settlement. The proposed seismic capacity relationships can be coupled with different engineering demand models to develop fragility relationships. The development of a seismic fragility relationship is demonstrated through an example that uses the proposed seismic capacity relationships and a simplified engineering demand model.

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Seismic Performance Assessment of Water Pipelines Retrofit with Corrosion-Protection-Liner Technology

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ABSTRACT

Aging and corrosion of underground lifeline systems significantly impair their structural integrity and reduce their service life. The seismic damage to underground lifeline systems reported in the past earthquakes, especially to those structurally deteriorated lifelines, induced serious secondary disasters, which led to significant life and economic losses. Seismic retrofit of critical underground water pipelines, serving as a key component of lifeline networks, has become an urgent need in engineering practice to improve the performance and serviceability of these critical lifelines. The corrosion protection liner (CPL) technology consists of installing flexible plastic liners with V-shaped anchoring studs inside existing pipelines and subsequently filling cement mortar to the gap between the waterproof liner and the pipeline. With the excellent chemical resistance, impermeability and fast construction cycles, CPL provides an economic and environmentally friendly alternative for pipeline rehabilitation without large-scale excavation. However, the lack of verification and quantification of the seismic performance of pipelines rehabilitated with CPL remains a critical deficiency for its application as an effective seismic retrofit method for underground pipelines. This study focuses on the response of CPL-strengthened ductile iron (DI) push-on joint by evaluating the liner stress, relative joint openings and rotations produced by axial and lateral repetitive loadings simulating the seismic loading experienced by the pipeline during an earthquake event. Full-scale quasi-static tests were performed on three water-pressurized DI pipelines with push-on joints before and after reinforced with the CPL. Moreover, based on the joint response under quasi-static loading, numerical models were developed for capturing the axial and bending behaviors of CPL-reinforced joints that considers strength degradation and energy dissipation. Nonlinear dynamic analyses were performed on the pipeline models incorporated with the new joint models to assess the seismic performance of the pipeline after retrofit with CPL technology. Both the test results and numerical analyses indicate that CPL provides substantial axial and rotational strength to the joints of DI pipelines and improve their seismic behavior under high intensity ground motions. But the quality of the heat melting welding of CPL remains a critical uncertain factor, and poor-quality control may be adverse to the seismic performance of the retrofitted pipeline.

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Probability-Based Seismic Resilience Assessment Method for Water Supply Networks

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ABSTRACT

Urban water supply network (WSN) is one of the most vital lifeline systems that maintains the normal operation of modern society. The seismic performance of WSNs has recently attracted the attention of academia and industry, in particular, the recovery capacity from external events. This capacity is referred to as seismic resilience, which is defined as the ability of a system to resist, recover from, and adapt to an earthquake impact. It is quantified as the change in functionality over time. However, it is challenging to quantify the optimum recovery process dynamically due to earthquake induced pipe damages and consequent leakages. In this study, a new probability-based method is proposed to assess the seismic resilience of WSNs, focusing on an important issue, i.e. recovery strategies to restore system functionality. The method contains four steps: (1) the description of the system, consisting of the network topology with the necessary components, including nodes, pipes, reservoirs, tanks, pumps, and valves; (2) hydraulic analysis with a focus on earthquake-induced damage, i.e., pipe breaks and leaks; (3) assessment of system functionality, considering the nodal demands and pressure; (4) assessment of system resilience with different recovery strategies that consider different priorities. A case study on a WSN in a medium-sized city is performed. The WSN includes 190 nodes and 323 pipes, supplying an area of 345 km2 and a population of 690,000. The PGA corresponds to a design-basis earthquake (DBE), and the maximum considered earthquakes (MCEs) are 0.10 g and 0.22 g. The Monte Carlo simulation technique is used to generate the damage scenarios of the WSN, including the number and locations of pipe damage, as well as the types of pipe damage. During the hydraulic analysis, the nodes with negative pressure are eliminated in an iterative process until no negative pressure nodes exist in the system, as suggested by the GIRAFFE software. The system functionality is calculated as the satisfaction rates of the water flow demand and water pressure of nodes after and before an earthquake. The effects of different recovery strategies on the seismic resilience of WSNs were discussed. The seismic resilience of the WSN can be significantly increased using a functionality prioritization recovery strategy compared to a pre-determined one based on empirical opinions.

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Can Cured-In-Place Pipe be Seismic Resilient? An Innovative Collaboration between EBMUD, SFPUC, Sanexen Water, and Cornell University

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ABSTRACT

The East Bay Municipal Utility District (EBMUD) supplies water to 1.4 million customers in the San Francisco Bay Area. To address replacement of EBMUD's 4,200 miles of aging pipelines, the organization embarked on a major initiative to increase the replacement rate of the distribution system from 10 to upwards of 40 miles per year. To accomplish this, a research team at EBMUD was formed to identify efficiencies, develop metrics, and evaluate innovative methods, technologies, and materials used in pipeline replacement projects. Essential to this sustainable pipeline replacement program is the challenge to mitigate risk to hazards posed by EBMUD's proximity to active seismic features, including the Hayward fault which intersects the entire service area.

The San Francisco Public Utilities Commission (SFPUC), the third largest municipal utility in California, serves 2.7 million residential, commercial, and industrial customers in the Bay Area. During the past decade, the SFPUC has upgraded transmission water pipelines serving wholesale and retail customers to meet seismic criteria and levels of service goals for water service following large seismic events. The SFPUC is seeking innovative strategies for increasing seismic resilience within its distribution system in San Francisco, consisting of over 1,200 miles of mostly smaller diameter cast iron and ductile iron pipe. Due to the high street restoration cost for full pipe replacement within San Francisco's streets, trenchless construction alternatives that also provide seismic resiliency, meet water quality standards, and are cost effective are being investigated.

In recent years, Cured-In-Place Pipe (CIPP) has become recognized as a trenchless alternative for renewing water distribution pipelines with sustainable long-term benefits. The utilities share interest in learning more about the seismic performance of various types of CIPP technologies. For this collaboration, Sanexen Water installed their CIPP product Aqua-Pipe into various vintage cast-iron pipe sections supplied by both EBMUD and another California based utility (Los Angeles Department of Water and Power). These specimens were tested in various loading modes at Cornell University's Large-Scale Lifelines Testing Facility to evaluate and characterize the results for seismic resiliency. Cornell performed a variety of other tests on the Aqua-Pipe, including a large-scale fault rupture test, to summarize the performance of the CIPP liner under tensile, bending, and earthquake induced ground movement scenarios. Results of this collaboration highlight the partnership, involvement, and roles of each party, experimental testing at Cornell, typical and extreme geo-hazards that both EBMUD and SFPUC may encounter, and lessons learned during planning, designing, and installing Aqua-Pipe as a seismic resilient pipe system. Outcomes of this collaboration include critical research findings to ensure sustained system reliability, sound infrastructure investment strategies, and long-term customer satisfaction.

A Unique Approach and Lessons Learned for Mitigating Geotechnical/Structural Hazards for the Willamette Water Supply Program Raw Water Facility Project

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ABSTRACT

The Willamette Water Supply Program is a consortium of local agencies in the Tualatin Valley that aim to develop a new resilient water supply for the region. This work involves new pipelines, reservoirs, water treatment plants, and seismic retrofits/expansions to existing raw water facilities. This work focuses on the existing Raw Water Facility and present design and construction efforts to retrofit and expand the facilities at the crest of the Willamette River near Wilsonville, Oregon. The work focus is on how the design incorporated the program's unique level of service goals into a site-specific basis of design that met the intent of ASCE design guidelines for both retrofit and new structures. Key design aspects include a site specific PSHA, significant contributions to the hazard from long duration Cascadia Subduction Zone ground motions, program specific design guidelines and modifications to ASCE ground motions, and a detailed peer review process. The work also focuses on cyclic direct simple shear testing, 2-D numerical FLAC models, and soil structure interaction approaches for evaluating the deformations, proposed ground improvement, and stresses of a 56 ft diameter caisson embedded approximately 90 ft below grade. The project is utilizing a CM/GC contractor to construct the project and an overview of construction considerations and lessons learned will be presented.

Comparative Study on Seismic Performance Analysis Methods of Water Distribution Systems

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ABSTRACT

Seismic performance analysis of water distribution system (WDS) is an essential step in the seismic design and resilience evaluation of WDS. Network connectivity reliability evaluation and the flow-based hydraulic simulation evaluation methods are widely used in the seismic performance analysis of WDS. In the existing research, one of the methods is usually selected to evaluate the seismic performance of WDS, but there is a lack of comparison of the application results of these two methods. This work compares the analysis results of the two methods through the application of benchmark WDS cases in which the connective reliability and the availability of water demand of nodes are used as quantitative measures of these two methods; the analysis processes of the two methods are based on the Monte Carlo Simulation to consider the uncertainty of seismic damages of pipelines. The two methods were applied to the seismic performance analysis of three benchmark WDSs (C-Town, Exnet, Modena) with different characteristics. These benchmark WDSs are representative and widely used in the research of hydraulic model calibration and measurement location optimization of WDS. Through the connectivity reliability and water demand serviceability of the benchmark WDSs under different seismic damage levels, the correlation, consistency and statistical characteristics between the results of the two analysis methods were compared. The application results showed that the correlation and consistency between the connectivity reliability and the water demand serviceability of nodes was low. For a specific user node, the index value of seismic connectivity reliability was usually greater than that of the water demand serviceability. According to the ranking by the index values of seismic connectivity reliability, user nodes with lower seismic reliability may not necessarily have lower levels of water demand serviceability. For user nodes with higher values of water demand serviceability, their seismic connectivity reliability level may not be higher. The hydraulic simulation method based on water flow analysis was considered to be a more realistic analysis method because it contains both the topological structure and the actual hydraulic characteristics of WDS. Therefore, it is recommended to use a flow-based hydraulic simulation method to evaluate the seismic performance of WDS. It should be noted that the total amount of water supply at the sources of the WDS, the operating condition of pumps, the water demand patterns and pressure dependent demand of user nodes all have non-negligible influences on the results of the hydraulic simulation methods, and reasonable parameters need to be set before application.

Damage Mechanism on the Large-Diameter Water-Supply Pipe during the Earthquake in Osaka, Japan

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ABSTRACT

An earthquake occurred in northern Osaka, Japan, on June 18, 2018, with a maximum seismic intensity of 6 on the JMA scale. Although the earthquake was a relatively moderate earthquake with M6.1, large- diameter water-supply pipes was damaged and water supply to the surrounding residents was stopped.

Damage to other infrastructures such as roadways and railways was minor. Even in buried water and gas pipes, damage to small-diameter pipes was minor. In addition, there was almost no damage such as joint disconnection, which is often seen as the damage to buried pipeline in an earthquake. The damage to ductile iron pipe with a diameter of 800 to 900 mm was significant having large cracks on the pipe body. The several factors were considered: the lack of material strength of the early ductile iron pipe, which was manufactured during the transition when the high-grade grey cast iron pipe was replaced to current ductile iron pipe. The pipe thickness was not constant due to external corrosion. Abnormal water pressure in the pipe occurred during the earthquake.

This study clarified the material properties of ductile iron pipes by conducting material strength tests and microscopic observation of tensile fracture surfaces for the excavated damaged pipes and new pipes. It was turned out that the excavated pipe does not meet the material strength in the standard of the current ductile iron pipe and it has brittle material property. In addition, due to the unevenness of the pipe surface and the inhomogeneity of the spherical graphite that can be produced in the ductile iron pipe, the arc-shaped test piece with the pipe surface has a lower tensile strength than the round bar test piece that has been machined inside the pipe thickness.

Seismic response of large-diameter pipe in the cross-section was simulated by FEM analysis modeling pipe and soil elements together. The generated section forces of the pipes with different dimeter were compared between the case with material strength based on the above material tests and the case with material strength of current standards.

Effects of Ground Strain and Pipeline Orientation on the Pipeline Damages during Earthquakes

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ABSTRACT

Pipeline damage correlations are used for the risk studies of water distribution systems. One of the parameters that is correlated with damages of pipelines situated in permanent ground deformation zones is horizontal (lateral) ground strain. Most damage correlations prefer to use the maximum absolute value of the two principal strains around the pipelines as the lateral ground strain parameter. However, strains caused by differential lateral ground movements can be resolved into two components: ground strains parallel and transverse to pipelines. Performing such a process for a large urban water distribution system is a relatively complicated task and development of damage relationships requires a comprehensive ground deformation and pipeline database. During the several earthquakes in 2010 and 2011, named as Canterbury Earthquake Sequence (CES), Christchurch infrastructure was affected by severe liquefaction with large PGD levels. In addition to land residential housing damage, there was severe liquefaction-induced damage to the water distribution system in Christchurch. The unprecedented database compiled following the Canterbury Earthquake Sequence provided the opportunity to explore the effects of ground strain and pipeline orientation on the pipeline damages during earthquakes. This research utilized geographical information systems (GIS) and primarily the 2011 Christchurch earthquake pipeline damage and ground deformation data. The present study uses the most recent and improved water distribution network and repair records provided by the Stronger Christchurch Infrastructure Rebuild Team (SCIRT), as sourced originally from the Christchurch City Council (CCC) and provides the most complete picture of the system as of 4 Sept. 2010. GIS database for the 22 Feb. 2011 earthquake include approximately 1730 km of water mains and trunk lines, typically ranging from 75 to 600 mm in diameter, with internal pressure of about 100 kPa. There were 1502 repairs in Christchurch and the majority of the pipelines and repairs belong to asbestos cement, cast iron and PVC pipelines. This study presents the results of the research regarding the use of the parallel and transverse ground strains in developing pipeline damage correlations.

Geologic and Geotechnical Interpretation and Finite Element Modeling Basis for Design and Installation of Three Large-Diameter Earthquake Resistant Ductile Iron Pipes (ERDIP) to Accommodate 9.4 feet of Landslide Displacement

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ABSTRACT

The Penitencia Delivery Main and Penitencia Force Main Seismic Retrofit project consisted of the design and installation of three large-diameter Kubota earthquake resistant ductile iron pipes (ERDIP) to accommodate up to 9.4 feet (2.9 m) of compression strain and lesser amounts of extensional strain due to seismic landslide displacement in response to a design level earthquake on the Hayward Fault. Shortly after construction of the Valley Water District's Penitencia Water Treatment Plant (PWTP) in the late 1960s, it was determined that the PWTP is situated on an actively creeping 240-acre landslide, in addition to being about 1 mile (1.6 km) from the Hayward Fault. The PWTP's three 60- to 72-inch-diameter supply and distribution pipelines extend downslope from the PWTP, crossing from the landslide to stable ground beyond the landslide toe.

This lifeline project comprised an interdisciplinary team that completed studies, analyses, and design to prevent catastrophic seismically induced failure of the pipelines. Work completed by the team of geologists, geotechnical engineers, structural engineers, and civil engineers included a landslide study, a Landslide Displacement Hazard Analysis (LDHA), subsurface exploration, historic instrument data evaluation, instrument monitoring, evaluation of alternatives, and soil structure interaction finite element modeling of the pipeline and backfill. The estimated displacement for a single large earthquake event was determined using finite element modeling, and earthquake ground motions records scaled to the design level. Additionally, a creep increment was determined based upon 40 years of instrumentation and monitoring. Supplemental investigation determined the likely location and geometry of failure where the landslide basal plane intersects the existing pipelines. The complex geologic interpretation and modeling generated the recommended parameters that were used in the soil-structure interaction finite element modeling of the pipelines.

The selected retrofit project incorporated large diameter Kubota ERDIP and pipe collars to accommodate movement. Before manufacturing the pipe, Kubota completed in-house modeling and testing to determine allowable load limits for the pipe joints. The project enhances regional public safety by improving the reliability/resilience of water delivery infrastructure needed following an earthquake and reduces the potential for local flooding of the neighborhood and a nearby school in the event of a seismically induced pipe break. The worthy project received a CalGeo 2018 Outstanding Project Award and an ENR 2018 Best Project Award for the California Region. The project was also featured in a 2018 ASCE magazine article entitled, "Pipeline Protection."

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Quantifying Earthquake Hazards to Lifeline Systems at a Regional Scale with a Study of the City of Los Angeles Water System Pipeline Network

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ABSTRACT

In order to efficiently maintain and operate seismically resilient water lifeline systems, it is crucial to characterize the damage potential of the pipeline system in future earthquakes. Mitigation strategies to address known vulnerabilities can then be identified and prioritized in risk reduction programs to meet system performance criteria. Assessing water pipeline damage potential involves considering both the probabilistic geographic distribution of earthquake-induced shaking and ground deformations, and the locations of the pipe network within the geographically variable shaking and potential ground displacement. This study of hazards on a regional scale, rather than a site-specific scale, is a necessity of lifeline engineering. A recent major study was undertaken to evaluate system-level consequences for the entire City of Los Angeles water pipeline network, measured by the estimated total number of pipeline repairs and subsequent repair costs and times due to earthquakes. In order to compute such consequences from earthquakes, new methods were required for quantifying surface fault rupture, liquefaction, and landslide hazards at a regional scale. This study involved mapping zones of surface fault rupture hazard and assigning probability of fault rupture displacement, mapping zones of liquefaction hazard and assigning probability of liquefaction and median estimated liquefaction-induced settlement and lateral spread displacement as a function of peak ground acceleration (PGA) and moment magnitude (M), and mapping zones of landslide hazard with associated probability of earthquake-induced landslide and median estimated landslide displacement as a function of PGA and M. The methods and results of this study enable a detailed analysis of the City of Los Angeles water pipeline network's resilience to seismic hazard and deaggregation of the risk by hazard type (surface fault rupture, ground shaking, liquefaction, and earthquake-induced landslide), by source faults, and by pipeline service zones.

The Design Approach to the Cross-Harbour Pipeline, Wellington, New Zealand

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ABSTRACT

The existing water supply to Wellington (New Zealand's Capital City) relies on water transmission pipelines that cross the active Wellington Faultline in several locations. These pipelines are expected to break or sustain significant damage in a major Wellington Fault rupture event resulting in extensive parts of Wellington being left without water for up to 100 days whilst repairs are completed. The unexpected failure of the water transmission pipelines during normal operation may also result in limited supply, water restrictions, or potentially even loss of supply to areas of Wellington.

The construction of a Cross-Harbour Pipeline (CHP) will significantly improve the disaster resilience and the operational resilience of Wellington's water supply by providing an alternative pipeline route that does not cross the Wellington Fault. The project consists of a new water transmission pipeline (approximately 800mm diameter and 20km in length) that connects Waterloo Water Treatment Plant in Petone to the Carmichael Reservoir in Wellington via a pipeline across Wellington Harbour and will be designed to remain in service after an earthquake event with a 1% probability of exceedance in 2,500 years.

As the CHP is located within a seismically active environment there is also the risk of damage from other natural hazards such as permanent ground deformation and tsunami. To quantify these effects on the pipeline, an innovative design approach was required that involved significant geotechnical work at an early stage in the project life cycle to inform the selection of a resilient pipe route and pipe design. Geotechnical activities comprised of:

- A high-level geotechnical desktop study and route geo-hazard vulnerability assessment.
- An advanced desktop and preliminary engineering assessment of the high vulnerability areas. This concluded that site investigation was required to allow the quantification of Peak Ground Deformations and the subsequent Soil-Pipe-Interaction stress analysis.
- A risk based, staged site investigation program that commenced at high vulnerability locations first.

The work addresses the approach to a lifelines pipe route selection process was developed (to assess over 700 routes); that was informed by considerable geotechnical assessment and targeted site investigations at an early stage in the project, such that pipe routes being considered were the most resilient available (a primary project objective). It also addresses how the design requirements were developed (and documented in the Design Philosophy Statement) to ensure the CHP design approach was robust, that it would achieve the project objectives and how this informed the geotechnical assessment progressing at an early stage.

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The Cross-Harbour Pipeline Geotechnical Challenges, Wellington, New Zealand

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ABSTRACT

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Several geo-challenges that may affect the construction and performance of the marine segment (over 11km in length) of the new pipeline are identified. This, and its alternatives, straddle over soft marine fine-grained sediments, liquefiable coarse-grained soils, the shallow aquiclude layer that caps the aquifer that is the main source of water for Wellington, and some active faults. Each of these individual challenges and their combinations under static and seismic loading conditions is taken into consideration and assessment to inform the selection of a resilient route and the design of it.

A task force was formed, and a comprehensive geosciences program were put together to inform the lifelines pipe route selection and design. The main focus of the program comprises:

- A Site-Specific Probabilistic Hazard Assessment
- A study of fault rupture potential
- A study of tsunami potential
- A marine site investigation program comprising Cone Penetration Tests, boreholes, undisturbed sampling, down the hole shear vane, and laboratory testing
- The development of a detailed geological model which is compatible with the geotechnical properties and material behavior
- The development of the geotechnical material properties for various loading conditions

This work covers how this approach is implemented and how it is expected to be used as an indispensable tool to inform the lifelines pipe route selection process and design.

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Design of Metropolitan Water District's Replacement of Casa Loma Siphon Barrel No. 1 Project, San Jacinto, California

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ABSTRACT

The Metropolitan Water District of Southern California (Metropolitan) initiated the Replacement of Casa Loma Siphon Barrel No. 1 (Project) to improve the seismic resilience of the Colorado River Aqueduct (CRA) facilities. The Casa Loma Siphon Barrel No. 1 is one of three large diameter pipelines that conveys potable water supply from the CRA to Metropolitan's distribution system and is a critical lifeline facility. The existing siphon crosses the Casa Loma Fault near San Jacinto, California (within the San Jacinto fault zone) and is susceptible to damage due to fault rupture and ground subsidence. The siphon was originally constructed in 1935 and is a 148-inch diameter concrete pipe.

The most critical objectives of the Project are to retrofit the existing siphon for the anticipated fault displacement and long-term settlement and to allow Metropolitan to quickly return the pipeline to service should damage occur during an earthquake. The Project will replace the existing siphon with dual 104-inch diameter, earthquake resistant ductile iron pipelines (ERDIP) manufactured by the Kubota Corporation in Japan.

The project team evaluated several alternatives during design including different pipeline alignments, alternative backfill materials, and various pipeline joint configurations. Because of the large fault deformation, the preliminary analyses led to a design that incorporates ERDIP with Expanded Polystyrene (EPS) Geofoam backfill material to distribute the fault displacement across many pipeline joints. The Project team developed a novel approach to modeling the ERDIP joints by utilizing the finite element analysis program ABAQUS to simulate the pipeline joint deformations along axial and rotational degrees of freedom combined with a traditional soil-pipe interaction modeling to examine the pipeline performance.

This project has several unique challenges, including: (1) design for large fault displacements estimated at 12.8 feet horizontal and 2.6 feet vertical (coseismic surface displacement) and 3.0 feet of settlement over the 50-year design life; (2) novel application of EPS Geofoam as pipe backfill at the fault crossing to distribute displacement and reduce stress in the pipeline joints; (3) sophisticated finite element analysis using a 3-D model of the fault and pipeline interactions; (4) full-scale testing of the 104-inch pipeline joint performance to verify the maximum rotation and moment capacities.

Seismic Reliability Assessment of Buried Pipelines Subjected to Significant Permanent Ground Deformations in an M9 Cascadia Subduction Zone Earthquake

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ABSTRACT

Pipelines in regions with moderate and high seismic hazard may be at risk of structural damage and service disruption due to permanent ground deformations (PGD), including earthquake-triggered landslides and liquefaction-induced lateral spread and settlement. Efficient methods of reliability assessment may be required when finite element soil-structure interaction and detailed fragility-based analyses are not possible. This study presents such methods based on a seismic reliability assessment study of large diameter buried pipelines as part of a comprehensive water system seismic study for the Portland Water Bureau (Portland, Oregon). The target audience for this study are engineers as well as water system owners and operators.

A case study is presented of three approximately 20 mile long steel pipelines ranging in size from 44 to 66 inches that transport water to East Portland from the Bull Run watershed, and five Willamette River crossings that transport water from East to West Portland. The river crossings include 30 to 60-inch diameter buried pipelines of material types ranging from cast iron and ductile iron to welded steel and bar-wrapped concrete cylinder pipes with welded joints. Segments of these pipelines are subject to as much as 10 feet of combined landslide and lateral spread permanent ground deformations for an M9 scenario earthquake on the Cascadia Subduction Zone. The locations, widths, and magnitudes of the PGD demands on the pipelines were calculated in a GIS framework at the intersection of the pipelines with locations susceptible to landslides and liquefaction.

Using available information on the pipeline size, internal pressure, and nominal wall thickness, a simplified analytical analysis was performed to compute maximum strains in the pipelines resulting from transverse PGD. Analytical analysis results were confirmed using nonlinear finite element analyses for representative pipeline segments. Uncertainties in the PGD estimates, width of PGD zones, analytical procedures, and peak ground acceleration were used to perform Monte Carlo simulations to compute individual and joint failure probabilities for the pipelines. Reasonable parameter distributions and values for the analytical pipeline strain and Monte Carlo simulation analyses are provided. The methodology presented in this study uses analytical procedures to assess pipeline vulnerability and provides likely locations of damage compared to more general evaluations typically performed using empirical pipeline fragilities. This approach can be used by engineers performing similar studies to better quantify pipeline vulnerability and provide a more realistic assessment to the owners.

Regional-Scale Seismic Vulnerability Assessment for a Medium-Sized Water and Wastewater System

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ABSTRACT

Regional-scale vulnerability studies are essential for resiliency planning and prioritization of seismic retrofit projects for a spatially distributed infrastructure. The regional seismic vulnerability study performed for the Elsinore Valley Municipal Water District (EVMWD) is described. The study focused on EVMWD's critical water and wastewater system facilities including 68 miles of water transmission pipes, 80 miles of wastewater transmission pipelines, five reservoirs, three reclamation facilities and one water treatment plant. The EVMWD service area is located in a region of very high seismic hazard dominated by the San Andreas, San Jacinto, and Elsinore fault zones.

The EVMWD service area is bisected by the Elsinore fault zone, resulting in water pipeline fault crossings at more than 20 locations and wastewater pipeline fault crossings at more than 40 locations. The 200-km-long Elsinore fault has not had a major earthquake in recent history. However, fault rupture ranging from 3 to 10 feet of horizontal surface offset poses a major hazard to the water and wastewater system. For this study, existing mapping for the Elsinore fault was modified using recent LiDAR and historical aerial imagery to prepare detailed block-by-block maps of pipeline fault crossings. The maps included identification of known fault splays, zones of uncertainty for each fault trace, pipeline fault crossing locations, length of pipeline within the fault deformation zone, and pipeline fault crossing angle. In addition to fault rupture hazard, portions of the service area are subject to high liquefaction-related hazards. A liquefaction hazard map developed for the study incorporated both the age and depositional environment of the soils as well as likely groundwater levels. The study highlighted areas of highest hazards and provided prioritized recommendations to effectively target vulnerabilities. In addition, areas were identified where more detailed studies would likely lead to significant reduction in uncertainty and reduce the extent of retrofit mitigation. The recommendations considered redundancies in the system as well as the relative risk from the fault rupture hazard and liquefaction hazard as the latter can be triggered by earthquakes on any of the major faults in the greater region.

Detailed seismic evaluations of medium-sized water and wastewater systems are not always economically viable. Regional-scale vulnerability studies provide a cost-effective approach to characterize hazards with consideration for the full system while identifying areas of uncertainty to inform more detailed and targeted studies. The approach used in this study can be applied by engineers and owners to vulnerability studies for other distributed systems to inform resiliency planning and prioritization of mitigation projects.

Seismic Vulnerability Assessment and Repair Time Estimates of Major Water Pipeline System in Southern California

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ABSTRACT

Seismic reliability of the San Diego County Water Authority's (Water Authority) water system is performed. The Water Authority is a wholesale water supplier to its 24 retail water agencies serving 3.3 million people in the San Diego Region. Pipelines serving the region originate at Lake Skinner in southern Riverside County and extend to the southern end of San Diego County near the international border. The water system includes five major north-south pipelines that include two approximately 42 mile long 48-inch reinforced concrete pipelines and three steel, prestressed concrete cylinder pipe (PCCP), and steel-lined PCCP approximately 43, 63 and 85 miles and ranging in size from 66 to 108 inches. Several east-west pipelines of up to 120 inches consisting of steel, PCCP, and bar-wrapped concrete cylinder pipes totaling about 47 miles extend service to the member agencies. The system is located in a complex geologic environment consisting of crystalline bedrock terrain of the Peninsular Range to the east, and sedimentary formation of the coastal plain to the west. The study area is dissected by numerous east-west drainage channels and rivers with unconsolidated material and shallow groundwater resulting in a high liquefaction hazard. Locally steep canyons have slope instability and landslide hazards. To the north, the water system is impacted by the seismically active San Andreas, San Jacinto and Elsinore Fault Zones, and near its southern end by the Rose Canyon Fault Zone. The Water Authority completed a seismic vulnerability study in 1993, which provided the basis for its Emergency Storage Project (ESP) that is in operation today. The 1993 study is updated by incorporating latest advancement in pipeline engineering, regional geology, and seismology. Specifically, probabilistic assessment of seismically-triggered landslides, liquefaction and fault rupture and resulting estimates of permanent ground deformation is performed. Site specific geotechnical investigations at targeted locations are being used to quantify seismic hazards. Pipeline vulnerability assessment is performed using strain-based finite element analyses at critical locations coupled with empirical fragilities. Repair time estimates update includes detailed consideration of uncertainties in potential damage to the system, damage detection and reporting, temporary or permanent repair, repair resources, repair means and methods, critical material stockpile, existing contracts, contractor availability, mutual aid agreements, and nature and extent of damage to supporting lifelines.

Probabilistic analysis, through detailed treatment of uncertainties, using Monte Carlo simulations and process simulation techniques are performed to develop realistic estimates of restoration time. A detailed approach for the assessment of a large water system with little redundancy is provided. It will be of interest to engineers, and owners in the use of probabilistic techniques to system evaluation and a realistic assessment of restoration times.

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Seismic-Resistant Pipeline Design: Parametric Study of Axial Connection Force Capacity

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ABSTRACT

This study supports ongoing efforts to develop seismic design guidelines and pipeline performance classifications for water and wastewater systems. The only existing design classification system for seismic performance is specific to ductile iron (DI; ISO 16134, 2006), and does not apply to other common pipe materials, connection types, or system components. Previous studies have defined the axial Connection Force Capacity (CFC) of segmented PVCO (oriented polyvinyl chloride) pipes relative to ERDIP (earthquake-resistant DI pipe) systems that have performed well during past seismic events and associated earthquake-induced permanent ground deformations. This study expands on previous work by adapting the ISO 16134 classification system for quantifying the CFC to additional pipeline materials and connections that are prevalent in water distribution and wastewater collection systems. Pipeline materials and system characteristics, such as joint/connection geometry, burial depth, and backfill soil conditions, have a direct and critical impact on seismic demands and deformations by influencing the frictional resistance along the pipe length and connection face as it undergoes axial deformations.

These effects are not explicitly considered in current seismic design procedures, nor has a parametric study been performed to investigate which factors are most influential to system performance. In this study, we quantify a ratio between the CFC of a particular system of interest to the ISO ERDIP CFC, defined as the K1 factor. The K1 factor is a conversion factor, calculated based on analytical and experimental results, to determine which CFC performance class various pipeline systems fall under. An understanding of the generated frictional forces is intended to support industry guidelines for the seismic design of buried water and wastewater pipeline systems.

Vulnerability Assessment of Portland Water System in an M9 Cascadia Subduction Zone Earthquake

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ABSTRACT

The City of Portland's water system is the largest in the state of Oregon. It serves a population of more than 935,000, almost one-quarter of the population of Oregon. The system covers a service area of approximately 225 square miles. It services 165 pressure zones and has over 2,000 miles of pipelines, two major dams, 38 pump stations, 59 distribution system tanks, and 10 terminal storage reservoirs with the largest being the 50 million gallon Powell Butte reservoir. Some of the oldest components of the system (circa 1911 and 1925) consist of three approximately 20-mile-long large diameter supply conduits, ranging in size from 44- to 66-inch diameter, that convey water from the Bull Run watershed to the Portland metropolitan area. The system also includes a wellfield that is the second largest source of water in the state of Oregon. In 2009 dollars, the replacement value of the system was estimated to be $6.7 billion. A comprehensive seismic reliability study was performed that included seismic hazard mapping including permanent ground deformation (PGD) maps for liquefaction-induced lateral spread and differential settlement, ground shaking and earthquake-triggered landslides in an M9 earthquake on the Cascadia Subduction Zone. The PGD maps were developed using information obtained from thousands of boring logs and 3D geology from Oregon Department of Geology and Mineral Industries. Seismic fragilities for pump station and tanks were developed thorough site walkthrough and simplified fragility analysis. The work included definition of a backbone system and assessment of its pre- and post-earthquake performance through hydraulic analysis. Distribution pipelines were evaluated using a range of published fragilities including data from recent Christchurch and Napa earthquakes. Post-earthquake seismic demand was estimated by considering post-earthquake fire and emergency water supply demands from hospitals and emergency centers. Results of the study were used to develop recommendations for reliability improvement such that, if implemented, the PWB water system will meet the goals set forth in the Oregon Resilience Plan. This work can be used as a case study for the assessment of one of the largest water systems in the Pacific Northwest. The study implemented a practical methodology for seismic assessment of a complex system of supply, transmission, distribution, pumping and storage subjected to geographically distributed hazards. The approach used in this study may be applied by engineers, owners and operators of water systems and provides practical approaches to vulnerability assessment and reliability improvement of such systems.

Resilience-Based Water Infrastructure Rehabilitation Planning Using Bayesian Network

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ABSTRACT

Water supply systems (WSSs) are among the most critical lifeline infrastructures which have been significantly damaged by earthquakes in the past. Many of the water mains in the United States are aging beyond their lifespan of 75 to 100 years (ASCE, 2017) which makes them even more vulnerable to earthquakes. Therefore, it is of paramount importance to consider the effect of deterioration on seismic resilience of WSSs. In this regard, the novel Bayesian Network (BN) approach is employed to assess the resilience of WSSs against both deterioration and seismic hazards. BN is usually used to handle causal relationships between different variables in probabilistic terms. Using BN approach, different rehabilitation strategies can be analyzed through forward and backward propagation. By understanding how different rehabilitation strategies affect the resilience of overall systems, infrastructure owners can make a decision towards creating more resilient infrastructure systems that withstand more stresses and recover quickly. The proposed framework is demonstrated using a reasonably large WSS operating in the earthquake-prone Charleston region of South Carolina.

Seismic Resilience: Orange County Sanitation District is Planning For 2030 and Beyond Through a Risk-Based Evaluation of Their Process Facilities

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ABSTRACT

Seismic resiliency is a major concern for the stewards of our wastewater infrastructure throughout California. This particularly includes the Orange County Sanitation District (OCSD), who provides wastewater collection, treatment, and disposal services for approximately 2.6 million people in Southern California. OCSD has wastewater treatment plants located in Fountain Valley (Plant No. 1) and Huntington Beach (Plant No. 2). Because OCSD's facilities are exposed to local seismic hazards, including local faulting, liquefaction, and lateral spread, the potential for earthquake damage and associated service disruptions is a significant threat to their $11 billion infrastructure.

Many structures at OCSD's plants were constructed before the adoption of modern building codes. Older codes (prior to 2000 International Building Code [IBC] and subsequent 2001 California Building Code [CBC]) generally had lower estimates for seismic hazards and did not require mitigation of seismic-induced ground deformations. With this realization, OCSD has taken a proactive approach and conducted a study to evaluate structures at both treatment plants for potential seismic hazards, including identification of mitigation strategies to improve operational resiliency following a large earthquake. Based on the findings from this study, a plan was developed to identify and prioritize mitigation projects using a risk-based methodology. This is the foundation for integrating seismic resilience into OCSD's overall capital improvements program.

OCSD's seismic resiliency study evaluated 63 facilities in total, covering a wide range of structures, including buildings, pump stations, clarifiers, and digesters. The study began in August 2017 and the final report was completed in July 2019. The focus of the study was to identify potential failure modes (PFMs) for each of these facilities, including risks from strong ground shaking, liquefaction induced differential settlement, and lateral spread. Based on the PFMs, mitigative measures were identified to address deficiencies in the structures. Because of the number of facilities that were evaluated, it was necessary to develop a unique approach that identified exemplar structures that represented common design and construction techniques that would demonstrate similar performance during a seismic event. The exemplar structures were evaluated using a 3D finite element analysis to model performance. The results of this analysis were extrapolated to other structures with similar characteristics to identify vulnerabilities.

It was also necessary to develop an approach to categorize the risk associated with the potential failure modes, including an evaluation of the likelihood of occurrence and the consequence of failure. A risk-based prioritization was utilized to integrate seismic resilience into OCSD's on-going planning for their $5 billion capital improvement program (CIP) over the next 20 years. This work expands on the unique methodology used by OCSD to evaluate their facilities and how this process was integrated into their capital improvements program.

When the Shaking Starts, Are You Prepared? TVWD's Plan to Incorporate an Early Earthquake Warning System

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ABSTRACT

Tualatin Valley Water District (TVWD) is a water district which currently serves a population of nearly 230,000 people in Washington County, Oregon. The District has a goal of becoming seismically resilient and meeting the metrics of the Oregon Resilience Plan by 2064. As aging infrastructure is replaced, TVWD continues to install technologies which can help TVWD respond before, during, and after a seismic event, with the goal of bringing the water system online shortly after a seismic event. Technologies continue to change, and the ability to detect an earthquake prior to the actual shaking is becoming available. This work covers what TVWD has done in the past to prepare for seismic events, the early warning system it is in the process of implementing, and other work planned for implementation in the near future.

Approach to Evaluation of Liquefaction and Lateral Spreading, and Application to Assessment of Potential Failure Modes for Seismic Risk Reduction at Wastewater Treatment Plants

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ABSTRACT

The Orange County Sanitation District's (OCSD) wastewater treatment plants located in Fountain Valley (Plant No. 1) and Huntington Beach (Plant No. 2), California were the subject of geotechnical evaluations as part of a program to identify seismic vulnerabilities and recommend mitigations for over 60 existing structures. Many of these facilities are exposed to liquefaction and lateral spreading hazards, and geotechnical approaches were developed to assess the potential for these hazards to cause structural damage and associated service disruptions. The study began in August 2017, and the final report was completed in July 2019 with a focus on identifying potential failure modes (PFMs) for each of these facilities along with associated recommended mitigation measures.

The geotechnical portion of the project began with a comprehensive review and databasing of available geotechnical information. The team then planned and executed a geotechnical investigation to supplement the historical data provided by the client. An analysis groundwater level was selected, and the geotechnical datasets were combined with ground shaking inputs to allow for systematic liquefaction triggering and associated settlement and lateral spread magnitude assessments. These assessments were used to develop profiles of liquefaction and lateral spread induced deformations associated with each structure. Structural analysis was then performed by others to assess the structural response to differential settlement and lateral spread patterns in parallel with the evaluation of the structures' response to ground shaking. Deformations were assessed and inputs to structural evaluations were developed for the wide range of structures at the two plants, including steel moment-resisting frame buildings, tilt-up concrete buildings, pump stations, cylindrical concrete digester tanks, rectangular concrete clarifiers, and concrete and steel surge towers. These structures were founded on a range of different foundation types, including deep foundations with some structures relying on tiedown anchors.

Proposed geotechnical mitigations were developed to address potential failure modes identified for the structures and were prioritized using an approach that categorized the risk associated with each potential failure mode, with consideration given to the likelihood of occurrence and the consequences of failure.

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Hetch-Hetchy Water Supply Reliability Across Sunol Valley

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ABSTRACT

Fault crossing design of a 66-inch Alameda Siphon 4 of the San Francisco's water transmission system is discussed. The predominant source of water to 2.7 million residential, commercial, and industrial customers in the San Francisco Bay Area originates in the Hetch-Hetchy watershed and transported across the Central Valley the Coast Range Tunnel (CRT) located on the eastern edge of a half mile wide Sunol Valley. Water is transported across the valley in four 66 to 96 inch siphons. The siphons are connected to the CRT portal through a 53-foot long 120-inch diameter steel manifold. Approximately 500 feet from the portal, the siphons cross the Northern Calaveras Fault. The fault is one of the most active faults in the Bay Area, with the expected rupture displacement of more than four feet lateral and one foot vertical. The three older siphons were not explicitly designed to withstand fault displacements. Damage to the siphons will cutoff Hetch Hetchy supply to San Francisco. A new 66-inch fourth siphon was designed to withstand the expected fault rupture displacement to provide a continuous supply of 120 million gallons per day. The fault crossing design was developed to accommodate fault rupture through slip and controlled plastic behavior as well as anchorage to the existing 1933 era manifold at the CRT portal. Design specifications included special metallurgical requirements for pipeline material, shop and field welding and material traceability requirements to control the plastic response of the pipeline. The performance criteria for water supply reliability accepted the potential failure of older siphons but required a confirmation of their reliable shutdown. However, an emergency shutdown of the older siphons would cause the CRT to overflow due to the lag time associated with the corresponding reduction in flow from Hetch-Hetchy and the available capacity through the new siphon. The overflow system consisting of 80-foot tall vertical overflow shaft was evaluated for over 1.0g of shaking and a new 66-inch overflow pipeline crossing the fault was designed. Reliability of the overflow shaft and the overflow pipeline were critical because an uncontrolled flow from either could result in substantial damage and erosion of the surrounding hillside. The new siphon was fitted with continuous fiber optic strain gages to monitor strain in the pipeline from long-term creep on the fault. This study will provide valuable guidance to engineers and owners of water infrastructure subjected to extreme loading conditions.

Design of Pipeline River Crossing for Large Lateral Spread Displacements

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ABSTRACT

This study describes the design considerations for a large diameter pipeline crossing the Russian River in Sonoma County, California. The river crossing is located approximately 10 km from the seismically active Rodgers Creek fault, the northern extension of the Hayward fault. The fault is capable of generating a magnitude 7.0 earthquake, which results in estimated lateral spread displacement along the riverbanks of several feet. The cement mortar lined and coated steel cylinder pipeline with welded bell and spigot joints originally designed in 1975 is not capable of withstanding the imposed deformation. Due to concerns with impacts of construction on the aquifer, ground improvement to limit deformations was ruled out by the owner. The pipeline includes a 200-foot-long segment beneath the river bottom and below the lateral spread zone. Outside of the river footprint, a 600-foot long section of the pipeline rises through the liquefiable zone with significant profile changes, and includes several bends and connections, including connection to a large diameter concrete caisson of the Ranney well for ground water collection. Due to changes in profile and alignment, the pipeline goes from competent material below the liquefiable zone across the lateral spread zone and into a non-liquefiable crust above the water table near the ground surface. After multiple design iterations and non-linear soil structure interaction analyses, a creative design solution was developed to accommodate lateral spread displacements. This study developed a viable design with significant constraints and construction-related challenges. Design challenges were addressed through multiple design iterations consisting of more than six pipeline configurations to accommodate more than six feet of lateral spread displacement accommodated through bending of an approximately 30-foot-tall riser and torsion in an S-configuration of pipeline. Owner's involvement included development of pipeline design drawings and consideration for tie-details with existing infrastructure, placement of valves and meter vaults. Geologists and geotechnical engineers provided detailed assessment of potential ground failure modes and estimates lateral spread displacements.

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Developing a Non-Invasive Methodology to Assess the Vulnerability of Sacramento-San Joaquin Delta Levees Protecting Natural Gas Infrastructure

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ABSTRACT

The Sacramento-San Joaquin Delta (Delta) and its levees are both a critical infrastructure itself and a host to a suit of other infrastructure systems such as natural gas storage and transmission. Many of the Delta levees were built as simple peat dikes resting on marsh soils, before modern engineering analyses and methods were available and are vulnerable to damage from floods, wave action, seepage, subsidence, earthquakes, and sea level rise. We are developing a non-invasive, and cost-effective integrated methodology by leveraging the existing wealth of information to optimize non-invasive geophysical data acquisition and processing for conditions specific to levees and the underlying sediments unique to depositional environments in the Delta. Specifically, our methodology will aim to improve characterization of spatial variability of soil deposits and levee materials in the Delta necessary to improve fragility analyses by utilizing remote sensing methods, geologic and geomorphic mapping, geophysical data acquisition, geotechnical modeling, and modeling-based structural performance assessment of infrastructure components. Geophysical surveys are a cost-effective and effective method of subsurface exploration without disturbing the ground or structure; however, they are not without their shortcomings due to the significant heterogeneity of natural deposits and levee composition within the Delta complicated by compromises between data resolution and depth. Our approach employs multiple methods of complementary geophysical explorations to provide a comprehensive understanding of the current levee system conditions and aid in advancement of the understanding of the most appropriate non-invasive exploration techniques in the Delta environment.

Lifeline Infrastructure Systems for Your Water Supply, Transmission, and Distribution Systems - A Step-Wise Approach to the Design and Construction of Seismic-Resistant Pipe, Fittings, Valves, and Fire Hydrants

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ABSTRACT

This is an industry-focused review, and an accompanying text can be supplied as well if the Committee desires. The study focuses on a pipe, fitting, valve, and fire hydrant system for water supply, transmission, and distribution which employs joint systems that deflect, expand, contract, and provide end-wise thrust capacity. The system has been tested by Cornell's Large Scale Geotechnical Facility and certified in compliance with ISO 16134,and those results will be reviewed.

The intended audience is design engineers and municipal water system owners and operators who are committed to system resilience during and after a seismic event. The audience will learn of recent product development and performance testing through 30-inch diameter that includes pipe, fittings, valves, and fire hydrants.

This investigation will be useful for municipal water system owners and operators and their design consultants in writing performance-based material specifications to ensure water system resiliency. Utilizing current and common materials available to everyone plus modern and innovative joint technology, this is a very useful and user-friendly system from an installation, operation, and maintenance standpoint. Specifically, it utilizes AWWA Standards and joints familiar with utilities and installing contractors.

A step-wise approach to system-wide design and construction will be presented which addresses areas of highest risk and moves outward to areas of lower risk. This study of a new system for ductile iron pipe, fittings, valves, and fire hydrants through 30-inch diameter will document longitudinal joint expansion and contraction within limits of positive restraint and radial joint deflection. Performance characteristics of the joint assembly will be investigated and discussed, and the performance of ductile iron pipe, valves, and fire hydrants during seismic activity will be reviewed.

Preliminary National-Scale Seismic Risk Assessment of Natural Gas Pipelines in the United States

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ABSTRACT

The United States manages the largest natural gas pipeline network in the world. As of 2018, distribution, transmission, and gathering lines comprise respectively about 87.5%, 11.8%, and 0.7% of the total mileage. Much of this pipeline infrastructure was installed underground before modern seismic codes and may therefore be vulnerable to the seismic hazards of (i) strong ground shaking and (ii) ground failures induced by surface faulting, liquefaction, or landslides. Many different stakeholders are involved in ensuring the safety of natural gas pipelines; e.g., the Pipeline and Hazardous Materials Safety Administration (PHMSA) works with state agencies and over 1,000 pipeline operators to mitigate the risks to gas transmission lines caused by many other threats beyond seismic hazards.

In this research study, we began paving a path forward for identifying and systematically evaluating the long- term seismic risk of natural gas pipelines at a national scale. Specifically, we examined the seismic risk of transmission pipelines in the conterminous United States using the U.S. Geological Survey's latest 2018 National Seismic Hazard Model (NSHM). First, we discretized the 2018 pipeline data from PHMSA into segments of roughly 1 mile or shorter in length. Next, we obtained peak ground velocity (PGV) and peak ground acceleration (PGA) hazard curves for each pipe segment from the 2018 NSHM. We then integrated the PGV hazard with a candidate fragility model from the literature to forecast the average annual loss (i.e., number of repairs, leaks, and breaks) due primarily to strong ground shaking. To preliminarily approximate the average annual loss due primarily to ground failures, we separately integrated the PGA hazard, which is related to permanent ground deformations from liquefaction and landslides, with another candidate fragility model from the literature. Although both fragility models were empirically derived from a comprehensive database of observed damage to gas pipelines from past earthquakes, the resulting risk estimates are likely conservative because the damage data excludes pipelines with modern welds of high quality.

We find that, on an average annual basis, there are more breaks from ground failures compared to those from strong shaking, which is consistent with the literature; however, the distributions of repairs as breaks and leaks are quite different from the commonly assumed 20:80 distributions. Although the two fragility models yield noticeably different estimates of absolute risk, the relative distribution of seismic risk between different geographic regions remains stable across the models.

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Development of Digital Twin of Gas Pipelines Embedded in Ground for Seismic Safety Evaluation Using Physics-Based Simulation

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ABSTRACT

For comprehensive evaluation of seismic safety of gas pipelines, we are developing a digital twin of pipelines and grounds with which a full three-dimensional non-linear seismic response analysis of pipelines can be made by considering soil-structure interaction effects. The digital twin is a high fidelity model of the pipelines and the grounds, and a finite element method enhanced with high-performance computing capability is used. We constructed a digital twin for an actual pipeline of a few ten kilometers and made trial evaluation of the seismic safety using past records of strong ground motion. It was shown that physics-based simulation of the digital twin clarified high safety of the pipelines that were designed according to the current design code. The use of the digital twin enables us to make seismic response of highest resolution and accuracy, together with the uncertainty evaluation of the underground structures. The comprehensive evaluation that uses the digital twin will be a key technology to realize an advanced energy supply system that is both secure and efficient.

Evaluation of Flooding Potential on Gas Pipelines

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ABSTRACT

There is a lack of study in the literature for flood evaluation of gas pipelines. This study shows the practical evaluation of flooding potential on the high-pressure gas pipelines located within flood zone per FEMA maps. The gas pipelines passing the creek are divided into two categories: the elevated pipelines and the buried pipelines. The proper vertical distance between the thalweg and the elevated pipeline is determined per the flood depth. The optimized cover of buried pipeline also is determined per the scour depth of flood. To calculate the scour depth, the recommend equations by (API Recommended Practice 1133 2017) are used in this study. The results of study show the inconsistency of the equations. It is suggested the more data needs to be collected to fit a better equation for calculating the scour depth. The maximum flood and debris force are also calculated, and the graph is provided to determine the minimum cover depth with the constant sample median of the soil particles for the buried pipelines and the minimum distance from the thalweg for the aboveground pipelines based upon the flood forces.

Evaluation of Numerical Methods for Modeling the Performance of Natural Gas Pipelines under Permanent Ground Displacements

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ABSTRACT

Earthquakes can generate substantial surface fault displacements which threaten the integrity of buried transmission gas pipelines at fault crossings. Such fault displacement hazards can cause severe plastic deformations and gas pipeline rupture, resulting in environmental pollution, fires, and widespread disruptions of gas supply. Historically, numerous numerical methods have been developed to predict pipeline response to fault displacement and other earthquake-induced permanent ground displacement hazards. These methods have varied from linear elastic to plastic models for material behavior, from beam to elbow to shell elements for modeling the pipes, from uniaxial springs to continuum finite elements for modeling the soils, and with and without the consideration of many other features such as frictional behavior of the soil-pipe interface, internal pressure of the pipe, buckling, etc. Present practice largely relies upon nonlinear (material and geometric) finite element analyses using pipe elements with uniaxial springs to account for soil restraint. The use of continuum modeling techniques that can explicitly account for localized pipe behavior, such as pipe buckling, are becoming more prevalent in certain applications. However, a comprehensive comparison of these methods is lacking. This work covers the results of a study undertaken to systematically examine the performance of three different numerical methods, in terms of both accuracy and efficiency, and recommendations of when advanced techniques apply are also provided. The study focuses on modeling soil-pipe interaction for different fault displacement scenarios. Parametric sensitivity analyses are conducted on models with varying degrees of complexity, with the objective of devising recommendations for selecting proper methods in simulating pipe response to permanent ground displacement.

California State-Wide Natural Gas Infrastructure Seismic Hazard Analysis Including UCERF3, Directivity, and Non-Ergodic Models

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ABSTRACT

We have recently performed a California state-wide seismic hazard study focusing on the resiliency of the natural gas infrastructure including the transmission and storage facilities. This large inter-disciplinary study includes technical experts in geology, seismology, geotechnical engineering and other related earthquake engineering fields. The results are focused on the ground motion aspects, with other efforts focused on geotechnical and structural aspects of the state-wide infrastructure study. Ground motions are estimated following a standard probabilistic seismic hazard analysis (PSHA) methodology. The UCERF3 seismic source model was implemented within the PSHA approach including the multiple segment and complex ruptures associated with large magnitude linked fault ruptures contained in the UCERF3 dataset. The PSHA uses the current state of practice NGA-West2 ground motion models for crustal events. For sites located in the northwestern region of the state of California, the recently developed NGA-Subduction ground motion models were included for estimating ground motions from the Cascadia Subduction seismic source. For selected sites in the near source region, the potential impact associated with rupture directivity was assessed and the PSHA calculations included the application of multiple directivity models. PSHA calculations were presented in terms of mean and fractile hazard curves to evaluate the uncertainty in the hazard results. Finally, an approach for the calculation of non-ergodic seismic hazard was implemented for this state-wide study. These last steps in the methodology represent a non-standard approach for general PSHA studies and the assumptions, limitations, applicability, and observations from these non-standard approaches will be presented.

Challenges to the Seismic Design and Evaluation of Energy Pipelines-Dealing with Missing or Uncertain Information

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ABSTRACT

The first comprehensive guidelines for the seismic design of oil and gas pipelines (energy pipelines) was produced by the Gas and Liquid Fuels Lifelines Committee of the ASCE Technical Council on Lifeline Earthquake Engineering in 1984. At that time, the state of practice was to utilize non-linear finite element analyses to understand the response of buried, welded steel, high-pressure pipelines to seismically-generated permanent ground displacement. These analyses utilized pipe elements with non-linear uniaxial springs to represent soil restraint. This is still the standard practice today. The seismic ground displacement hazard definition requires stipulation of the amount of ground displacement, the direction of ground displacement, the length of pipe within the zone of ground displacement. Evaluation of the pipeline response requires relating the computed pipeline strains to a level of seismic performance ranging from continued safe operation, maintenance of pressure integrity, or rupture. Determining what level of seismic response is acceptable requires definition of a threshold likelihood for the consequences of unacceptable response. In typical practice, none of these parameters is well defined and numerous assumptions are required, often leading to multiple layers of conservatism. This work covers a practitioner's view of the current state of practice, based upon nearly 40 years of experience, with an emphasis on shortcomings that exist in defining seismic ground displacement hazard and evaluating pipeline response and the implications on the ability to reliably quantify seismic risks for energy pipelines.

Ridgecrest M 7.1 Earthquake of July 5 2019 - Performance of Gas Lifelines

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ABSTRACT

The Ridgecrest M 7.1 main shock earthquake of July 5 2019 was a strong earthquake with extensive surface fault rupture that affected the communities of Ridgecrest and Trona, California. The main shock was part of a complex sequence of earthquakes and surface faulting including a M 6.4 foreshock with surface fault rupture and many M 3 to M 5.7 aftershocks. Pacific Gas and Electric (PG&E) Company operates the natural gas system in this area. Surveys were conducted to evaluate what worked well, and what type of damage occurred. Survey data was analyzed to develop fragility models that explain the observed damage. The gas system in the area includes several types of infrastructure: transmission pipelines, distribution mains, service laterals and meters, and gas regulating stations.

Transmission pipes. Surface faulting occurred through two gas transmission pipes; one rupture (left lateral slip) across a 150-mm (6-inch nominal diameter) pipeline related to the July 4, M 6.4 foreshock, and the second (right lateral slip) across a 250-mm (10-inch nominal diameter) pipeline associated with the M 7.1 mainshock. The amount of offset at the two pipeline fault crossing locations ranged between about 30 and 50 cm. Both pipes are heavy-wall welded steel, and responded to fault rupture by bending and deforming without leakage. Within a week after the earthquake, both of these buried pipes in the vicinity of fault offset were uncovered and inspected; no gas leaks were noted. Then, segments of both pipelines were replaced with unstressed new pipe extending about 45 m (150 feet) to either side of the fault crossings. The level of ground shaking along the transmission pipes was as high as PGV = 85 cm/sec; no leaks were observed anywhere along the transmission pipes.

Distribution pipes. About 440 km of distribution pipe were exposed to shaking with PGVs up to 40 cm/sec. High sensitivity gas leak surveys were conducted after the earthquake. Leaks were found along about a dozen gas distribution mains, mostly of 50 to 100-mm (2 to 4-inch nominal diameter); some leaks may have predated the earthquakes. In the Trona area, the bulk of the distribution mains are steel. In the Ridgecrest area, the bulk of the distribution mains are MDPE (plastic).

Service Laterals and meters. About 270 km of gas service laterals and thousands of meters were exposed to shaking with PGVs up to 50 cm/sec. Over 300 leaks were found in the first few days after the earthquake; increasing to nearly 500 a year after the earthquake. Many of these reflected minor leaks in the distribution system that occur over time from non-seismic effects (e.g., corrosion, age-related issues). Service laterals were found to have a much higher leak rate as compared to distribution mains. About 60% of these leaks were on the risers to above ground meters.

Gas Regulating Stations. There are gas regulating stations in the vicinity to reduce pressure between the transmission and distribution systems. One of these was located in Trona, in an area that underwent a few inches of settlement and lateral spread due to liquefaction. No leaks were observed at any of these stations.

Pipeline Route Optimization Using Integrated Geohazard Screening Methods Across the Roof of the World, Central Asia

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ABSTRACT

A route optimization study for a 900-km long gas pipeline extending from west to east through a corridor bound by the Pamir Mountains and Tien Shan, also known as "The Roof of the World", was performed using integrated remote sensing technologies. Ongoing collision between the India and Eurasia plates has resulted in the Tien Shan orogenic belt and the Pamir Mountains. Thus, the proposed transmission route crosses one of the most seismically active regions in the world. Rapid uplift, erosion, and steep slopes give rise to widespread landsliding and massive rock slope failures in both the Pamir and Tien Shan Mountains. We performed a detailed geohazard investigation by mapping and integrating satellite based DEMs, high-resolution imagery, LiDAR, aerial photography, and helicopter-based electromagnetic resistivity. Analysis of these data sets integrated with detailed surficial geologic mapping allowed us to delineate route soil conditions and potential geohazards. Initial desktop geohazard screening included mapping for potential active fault crossings, landslides, and liquefiable deposits. Traffic light- style susceptibility maps were developed for route refinement and hazard mitigation. Airborne electromagnetic resistivity data was acquired and incorporated with surficial geologic mapping in GIS facilitating development of a three-dimensional geologic framework that used resistivity data to estimate subsurface conditions at pipeline trenching depths. Based on this integrated approach we developed the framework for an optimized geotechnical borehole program to maximize the informational value of each borehole site compared to a traditional evenly spaced layout along the selected pipeline route.

Seismic Design of Pipeline Considering Pressure and Tensile Properties

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ABSTRACT

This work proposes a design method to calculate the inelastic deformation of pipelines induced by temporary ground deformations. The proposed design method consists of an elastic solution and a strain conversion procedure which was developed to predict the inelastic strain distribution by using the elastic solution and a strain conversion procedure. Roundhouse type and yield-plateau type stress-strain curves are considered. Validation of the proposed method is conducted by comparing the results predicted by the proposed method with the results obtained by finite element analyses (FEA). The effectiveness and accuracy of the method are discussed by comparison with The critical compressive strain (CCS) in compression of unpressurized or pressurized pipes subjected to axial compression is discussed. Roundhouse type and yield-plateau type stress-strain curves are also considered.

Empirical and semi-empirical design formulas to predict the CCS in compression of unpressurized pipes have been presented in current regulations, guidelines, and publications. The current design formulas are represented as a function of D/t (D: pipe diameter, t: wall thickness), however, do not contain any terms to consider the effects of pressure and tensile properties. Hence, analytical solutions effective to predict the CCS in compression considering the effects of pressure and tensile properties are described. The effectiveness and accuracy of the analytical solutions are investigated by comparison with the results obtained by FEA and the design formulas presented in some design guidelines.

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Practical Use of Risk Assessment and Management System for Power Lifeline Against Typhoon (RAMPT)

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ABSTRACT

In Japan, severe meteorological disasters including typhoon have recently continued to occur and have been intensifying damage to infrastructures. Simultaneous multiple accident cases and their countermeasures for electric power system against Typhoon are presented. For example, as typical typhoon disaster in metropolitan area, the electric power distribution equipment was heavily damaged by Typhoons occurred in 2018 and 2019. From these experiences, particular attention is paid to issues related to “Resilience” for disaster mitigation of electric power systems. When a large scale Typhoon occurs, the emergency response headquarters are supposed to be established to collect the disaster information including typhoon information. However, in general, the damage information sources are highly limited due to the damages to other infrastructures and residential facilities.

In order to support the decision makings for actual restoration works during such less disaster information condition, the “Risk Assessment and Management System for Power lifeline against Typhoon (RAMPT) “, has developed by the Central Research Institute of Electric Power Industry (CRIEPI). RAMPT is a system for predicting and estimating damages on distribution equipment caused by typhoons. RAMPT utilizes two types of information as inputs; equipment dynamic characteristics data and typhoon information. The equipment dynamic characteristics data are installed beforehand. On the other hand, the typhoon information is input by users as sequentially updated information during typhoon approaches. That information includes the typhoon position, central pressure for typhoon sequence, and its course, which are obtained from the Japan Meteorological Agency (JMA) through the Internet. As output, RAMPT provides the typhoon forecast and estimated equipment damage information for every sub-branch business office. This information supports and is very useful for the electric power companies during the emergency restoration works against typhoon disasters.

Application examples of RAMPT are illustrated during actual restoration works of electric power distribution equipment in 2018 and 2019. It is emphasized that typhoon damages of electric power distribution equipment are mainly caused by the damages of their surrounding facilities such as flying objects, and tree collapse. Finally, damage prediction accuracy of RAMPT and future subjects for improving the residence of electric power distribution system are discussed.

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Analysis of the Power Distribution Facilities Damage by the Great Hanshin-Awaji Earthquake

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ABSTRACT

Lifeline operators are expected to reduce the amount of damage and restore them as soon as possible in preparation for major disasters such as large-scale earthquakes in the Nankai Trough, which are feared to occur in the near future. Since power distribution facilities is a huge amount in all areas, once a large-scale earthquake occurs, it take time to understand the amount of damage to the facilities and take longer for an efficient recovery system to be established. As a result, there is a concern about the delay in the restoration of electricity, which is one of the lifelines.

As a countermeasure, we studied a risk assessment management system with the ability to immediately estimate damage to power distribution facilities. The system can estimate damage immediately after an earthquake from earthquake information such as epicenter, magnitude, and epicenter depth originated from the Japan Meteorological Agency. The system is also named risk assessment management system for Power lifeline Earthquake real time (RAMPEr), which is being studied with The Central Research Institute of Electric Power Industry. If RAMPEr is introduced, it is possible to quickly estimate the damage situation of our power distribution facilities after the earthquake occurs, and it is possible to quickly arrange the support recovery system, and it is possible to quickly and accurately introduce recovery workers to the area where the damage is large.

Estimation of power distribution facilities damage by RAMPEr is based on the mechanical strength of the seismic motion and power distribution facilities. However, damage to power distribution facilities in urban areas is often due to indirect damage caused by the collapse of houses. If the mechanism of indirect damage can be added to damage estimation of RAMPEr, it can be expected to improve the estimation accuracy and improve the effectiveness more.

Results are reported on analyzing the relationship between damage to power distribution facilities and damage to houses using the results of the Hanshin-Awaji Earthquake (1995 Hyogo Prefecture Southern Earthquake), which caused significant damage to power distribution facilities.

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Investigating Power Grid Reliability Through an Analysis of Post-Earthquake Experience Data

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ABSTRACT

Seismic-induced loss of off-site power (LOOP) can prevent critical facilities from delivering their function and result in grid outages. These adverse effects can cascade over multiple infrastructure systems and lengthen the recovery efforts. As such, quantifying the likelihood of losing power at important sites following an earthquake can valuably inform resilience-based risk decisions.

Characterizing the LOOP probability is a non-trivial task. Grid outages can result from power imbalances and failures along any grid links and nodes (e.g., generation, transmission, distribution, local switchyard), sometimes far away from the site under consideration. The literature has typically tackled the problem using "bottom-up" approaches where the entire grid nodes and links are preliminary assigned fragilities, which are then combined into a single point estimate for a given site. Similar detailed approaches may be rigorous but tend to be site-specific and associated with increased costs, which are not desirable when analyzing large areas containing multiple critical facilities. Instead, this study investigated the grid reliability using a "top-down" approach based on a review of actual experience data on post-earthquake grid performance. The data are obtained from the Electric Power Research Institute (EPRI) database developed from 30+ worldwide earthquakes in the last forty years. The "top-down" approach has several advantages, e.g.:

- Describes the grid performance at large, therefore implicitly accounts for the failure probability from all grid subcomponents.
- Represents the performance of a diverse population of grid systems and components exposed to a broad set of earthquakes.
- Reduces the implementation effort for resilience-based risk decisions or plant-specific seismic probabilistic risk assessments.

Lessons learned from this study significant to resilience efforts include, for example:

- Different approaches to quantify the likelihood of losing electric power at important sites following an earthquake.
- Understanding what makes a grid seismically resilient or vulnerable.
- Identifying what kind of data we need to further collect and research to improve grid reliability.

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Seismic Analysis and Design of Offshore High-Voltage Cable in Young Bay Mud for M7.8 Earthquake on San Andreas Fault

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ABSTRACT

Seismic analysis performed in support of design of the offshore segment of a high voltage (230 kV) transmission line that connects two substations in San Francisco, California is the focus of this study. The offshore portion of the transmission line is located approximately 2,000 feet from the western shoreline of the San Francisco Bay, has a total length of approximately 2.5 miles, and consists of three parallel double armored cross-linked polyethylene (XLPE) cables. The transitions from the offshore portion to onshore portions occur in high density polyethylene (HDPE) conduits, approximately 1,500 feet each, installed from the land using horizontal directional drilling (HDD) and are included in the seismic analysis of the offshore segment. Seismic design criteria for the line are based on 84th percentile ground motions from an Mw 7.8 earthquake on the San Andreas Fault, which is located approximately 9 miles to the west.

Geologic conditions along the offshore portion of the line were evaluated by a review of bathymetric and geotechnical data and consist of very soft to soft fine-grained sediment of Young Bay Mud underlain by older alluvium deposits over bedrock. Nonlinear geotechnical analysis was performed to calculate the expected permanent ground deformations along the cable alignment.

Seismic assessment of the offshore marine cable was performed using non-linear soil-structure interaction analysis to compute maximum axial force under the earthquake-induced permanent ground deformations. The analyses included consideration of material and geometric nonlinearity of the cable, nonlinear response of the surrounding soil, as well as the effects of the operating cable temperature and the friction between the cable and the conduit within the HDPE pipes. Cable properties were obtained from mechanical and electrical cable tests on a prototype cable performed by others. Several parameter sensitivity studies on cable-soil interaction, compression stiffness, and anchorage capacities were performed. Multiple alignments with S-shape slack were evaluated for optimal combined seismic and thermal loading. Overall seismic reliability of the cable was evaluated through analysis that considered uncertainty in earthquake ground motions, geotechnical response, and the corresponding response of the cable. Monte Carlo simulations were performed to estimate the scenario and annual probabilities of failure. The target audience for this study includes engineers as well as public utility company stakeholders, who can benefit from the methods and lessons learned as presented here.

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Landslide Triggering for Transmission Power Lines In Southern California

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ABSTRACT

Power transmission and subtransmission lines in Southern California often face unpredictable climate change, high seismic activity, and geohazards such as slope instability. One such line is a transmission line which traverses over fifty miles of mountainous terrain from Ventura County to Santa Barbara County. Most of the transmission line structures along this line are located in remote mountainous locations, and founded on sedimentary bedrock formations. Some are in landslide terrain, adjacent to mapped landslides, on steep slopes, or on ridgetops. The instability risk for these structures increases with significant precipitation and/or seismic events. Loss or damage to any of these structures due to ground deformation would result in disruption of service to all subtransmission and distribution lines in the service territory. Since the structures' remote locations make prompt repairs impractical, mitigation is often necessary. However, mitigation is expensive, and so measured and targeted mitigation becomes essential. Through a geological desktop study and site visits, SCE identified the locations most prone to landslides. Groundwater mounding modeling, field investigations, and other geotechnical and hydrologic studies were conducted at these sites. The project team estimated peak ground and spectral accelerations (PGA and SA) with a range of probabilities exceeding over 50 years. The team used the historic precipitation data to generate landslide-triggering precipitation criteria and create a monitoring tool to predict rainfall. The probability of exceedance depends on the project life cycle. The team first calculated the FOS under saturated conditions, due to precipitation, and then they calculated the seismic load. Seismic vulnerability was assessed excluding the impact from storm events. The FOS was calculated based on the project life cycle, where line resiliency is determined using relationships between FOS and the Probability of Exceedance, considering storm recurrence intervals. The team recommended the most efficient mitigation based on structure resilience and the Probability of Exceedance during the project's life cycle.

In short – this transmission line is a single-point service interruption system prone to landslides and due to it being in a remote location, it is difficult, time-consuming, and expensive to fix. Well-calculated mitigation measures were developed and implemented, but with discretion. This requires first to determine which locations are at highest risk, and then define the circumstances that require mitigation, and eventually figure out the most efficient mitigation method.

A Key to Community Earthquake Resilience Is Neglected

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ABSTRACT

Electric power is the single most important lifeline affecting community resilience because its loss impacts other lifelines, commerce, manufacturing, and jobs, which are needed for a community to function. For most members of the community the operation of computers and refrigeration will be lost.

Historically, from a users' perspective, the performance of power systems has been good. The 1971 San Fernando (6.5 Mw) earthquake ended almost forty years without damaging urban earthquakes in the U.S. and was the genius of the term, "lifeline earthquake engineering." It was also the genesis of the Technical Council on Lifeline Earthquake Engineering within ASCE to address what appeared to be a failure of these critical systems to operate acceptably in earthquakes. However, the perceived good power system performance is unjustified when they have only been subjected to 7 Mw earthquakes or less and have repeatedly suffered severe damage in moderate earthquakes. Power systems are designed with redundancy in substations and the power delivery network. Larger earthquakes affect larger regions that can overwhelm system redundancy.

The 1994 Northridge earthquake (6.7 Mw) subjected a power system that is not much different from existing systems, considering 30-year expected equipment life. One utility had twenty-five 230 kV bushing fail disrupting transformers that cannot be bypassed and have limited spares available. It was only through the dedication and ingenuity of utility personal and the use of unconventional mitigation practices that avoided immediate bushing replacement that power was quickly restored. Without these procedures and the luck of transformer fires caused by bushing failures, widespread disruptions could have lasted several weeks, assuming that spare bushings, maintenance resources, and limited specialized restoration equipment was available.

Within the Institute of Electrical and Electronic Engineers standards organization, "IEEE Recommended Practice for Seismic Design of Substations", IEEE Std, 693-1997 was developed. The third edition of the standard, IEEE Std. 693-2018, has still not addressed the problem of avoiding the amplification of the bushing's support (transformer tank) from exceeding the qualification capacity of bushings. While most switchyard equipment can be bypassed to restore service, this is not the case for transformers.

Procedures used to measure the as-install frequencies of bushings on transformers will be described and test results will be summarized. In addition, transformer characteristics will be described to show that the lack of performance requirements in the standard can contribute to lengthy power disruptions.

Effects of Earthquakes on Transmission Lines and their Major Components

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ABSTRACT

Seismic effects are not generally considered in design of transmission lines and their major components (i.e., support structure-foundation system, wire conductors, and ground wire), which are a vital link in the power transmission system. The design is typically governed by wind/ice combinations and broken wire loads. However, performance of transmission lines from recent and past earthquakes demonstrated the seismic vulnerability of these structures. This study reviewed numerous case histories regarding the seismic performance of transmission line structures that documented the primary source of damage to transmission lines resulted from geotechnical related seismic hazards. In addition, this study conducted a survey to gather information from utilities about damage to their transmission structures from earthquakes and assess their design practices for seismic events. The results of the survey generally show no consideration of seismic loading and associated geotechnical hazards by the majority of the responding utilities in design of new or retrofitting existing transmission structures. The study also presents a method to evaluate the seismic effects on major transmission line structures and includes example problems that provide an overview of the procedures employed for evaluating transmission lines and the structural response of support structures (lattice tower and tubular pole) due to liquefaction-induced vertical, lateral, and rotational displacements.

Assessment Methodology for Buried High Voltage Power Lines for Post-Earthquake Power Supply Reliability

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ABSTRACT

Reliable power supply following a major earthquake is critical for emergency response and rapid restoration of essential functions. This study presents the methodology used for assessment of 230 kV and 115 kV buried power lines connecting various substations in San Francisco, California. The power lines traverse highly variable subsurface conditions. Prior to the development of present-day San Francisco, the landscape consisted of dune sands inland of historic shoreline. Several major creeks drained into marshes along the margin of the San Francisco Bay. The historic marshlands are associated with layers of peat and very soft, plastic, organic silty clay called Bay Mud. Over the years, the marshes and creeks were filled with non-engineered fill that are highly liquefiable. In the 1906 Great San Francisco earthquake and the recent 1989 Loma Prieta earthquake, these areas, especially the Sullivan Marsh and Mission Creek areas, suffered several meters of liquefaction-induced permanent ground deformations that resulted in extensive damage. The seismic risk assessment methodology considered uncertainties in strong shaking and permanent ground deformation, type of construction, material properties, and failure modes. The power lines include high pressure fluid filled (HPFF), high pressure gas filled (HPGF) and cross-linked polyethylene (XLPE). Failure modes can range from leak or rupture in the pipe casing; excessive bending or kinking of the cable or the pipe; failure of the cable insulation from moisture or water intrusion resulting from rupture of the pipe; or excessive deformation of the pipe leading to damage to the cable insulation. A set of failure criteria for the lines was developed by considering different failure modes for the lines, observations of failures in past earthquakes, material and component tests on the casing pipe assembly, and application of engineering principles. Hundreds of nonlinear soil-structure interaction (SSI) analyses were performed for a range of permanent ground deformation estimates, pipe material strength assumptions, and soil parameters. Analysis also considered interaction with manholes and utility crossings. Monte Carlo analysis was performed to develop fragility curves for each segment to compute the overall failure probability for each line.

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Approach for Development of Seismic Fragility of Hydroelectric Powerhouse Buildings

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ABSTRACT

Hydroelectric power generated in seismically active parts of California are a renewable and vital part of the state's electric grid capacity and stability. This study developed seismic fragilities for critical building and non-building structures in ten California hydroelectric powerhouses to investigate improving the resilience of electricity generating assets. Seismic hazards to the powerhouses included ground shaking and rockfall. Seven of the powerhouses are more than 100 years old, two of them constructed in the 1950s and one in the late 1980s. In many cases, building drawings were not available. Seismic fragilities were developed with limited data and large uncertainties. Data collection methodologies included detailed site reconnaissance, limited field measurements, and observations of building's current condition including any deterioration, understanding of seismic load paths in structures not originally designed for earthquakes and potential geologic hazards including landslides, liquefaction and rockfall. Seismic assessments were conducted and the complexity of these assessments were presented to the owners for a better appreciation of inherent risk. The study made educated engineering decisions under a high degree of uncertainty and translated the information into realistic analytical models used to develop seismic fragilities. These fragilities were incorporated in the overall power generation system risk assessment. Given the abundance of old infrastructure, information provided in the work will be helpful in seismic assessment of other similar structures.

Seismic Risk Assessment of Transmission System at Portland General Electric

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ABSTRACT

Portland General Electric and its team are currently executing a risk-based analysis, quantifying seismic risk to the transmission system and evaluating upgrades to determine which are cost effective. This work will be of interest to electric utilities and regulators. It describes a methodology for cost/benefit with a scalable level of effort, resulting in upgrades that are justified in terms of avoided risk to customers, the most important criterion for evaluating spending by a regulated utility. PGE identified two objectives. First, PGE has committed to asset management-based decision making, emphasizing cost/benefit from customers' perspective. Top-down policy or code-driven plans that cannot demonstrate customer benefit are not acceptable. As another utility was asked by a commissioner in a public meeting, "How do you know when to stop?" Second, the approach should be incremental, meaning the level of effort should be driven by the value of the information provided and can be scaled depending on the precision needed.

There are three major elements comprising the methodology.

- Ground-Shaking Analysis included selection of ground-motion models, determination of soil parameter,and calculation of ground shaking intensities. Initially, easily-available information and broad assumptions were used to manage the level of effort.
- Structural Analysis included development of fragility curves defining probability of failure versus shakingfor representative asset/structure combinations. The curves consider interaction of adjacent equipment multiple failure modes: damage to insulators or foundations and anchor rods, rocking or tipping.
- Risk and Economic Analysis comprising four parts: 1) Monte Carlo analysis of equipment failure and outages using a load-flow model, 2) evaluation of simulations to estimate outage durations, 3) determination ofupgrade options, and 4) calculation of consequence cost, risk, and upgrade benefits.

The team first completed a proof of concept, using a single earthquake scenario. This analysis emphasized speed and learning over accuracy to demonstrate that the approach will work and to iron out any wrinkles before applying it at scale. PGE concluded that the method met their objectives. The team incorporated lessons learned and is currently working on the system-wide analysis, focusing on Cascadia Subduction Zone events.

Telecommunications Impacts from the HayWired Scenario

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ABSTRACT

The US Geological Survey's HayWired scenario—a moment magnitude (Mw) 7.0 rupture of the Hayward Fault and an aftershock sequence—is named, in part, to recognize society's increasing dependence on wired and wireless communication technologies. The communications chapter of the HayWired scenario considers how communication services may be disrupted and restored after a large earthquake. Analysis of impacts to communication networks is complex due to multiple competitive service providers in a largely unregulated industry, convergence of voice and data systems, dependence of equipment on electric power, and a dynamic landscape as technologies continue to evolve.

This work provides an overview of insights into the methods and strategies used to engage in dialogues with the communications industry, develop the analysis and restoration models, and create opportunities for governments, businesses, and the public. The research topic and industry-focused efforts include:

- Mitigation of earthquake hazards including attention to telecommunications infrastructure standards for ground failure hazards and fire, and consistency of equipment installation standards.
- Identification of secondary impacts of collateral damage to fiber optic cables (e.g., from bridge damage, derailed trains, pipeline (water, oil, gas) breaks), and restoration of communication services affected by widespread electric power outages.
- Potential effects to building-mounted cellular sites in light of building codes, backup power, and yellow/red-tag inspection protocols.
- Coordination with other lifeline infrastructure around damage, repair, and restoration interactions—especially electric power and transportation systems.
- Discussion of the communications industry's preparedness for restoration contingencies, especially fuel and labor shortages in the San Francisco Bay Area.
- Management of user/subscriber behavior after a disaster by carriers, and education of subscribers to both conserve bandwidth and to prepare for sustaining communications during and after a major disaster.
- Considerations for local governments around community vulnerabilities in light of the trend towards cellular small cells (which typically do not have backup power), the implications of regulatory constraints, planning for loss of 911 system functionality, managing population displacements (especially groups with access functional needs and socially vulnerable populations with limited services), and expansion of support for telecommuting.
- Considerations for legislative/regulatory measures that could improve outcomes and address issues.

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Experimental and Numerical Investigation of Submarine Telecommunication Cable Responses to Earthquake-induced Seabed Movements

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ABSTRACT

Submarine fiber-optic cables have been widely used to connect the international communications throughout the world. Nowadays, over 95% of international telecommunications are routed via the submarine telecommunication cables crossing the oceans. The submarine telecommunication cables are usually buried shallowly in the seabed and are thus vulnerable to seabed movements. In recent years, damages of submarine telecommunication cables have been noticed after the occurrence of seabed movements induced by significant offshore earthquake, e.g., offsets of strike-slip faults and submarine landslides. However, the understanding of the failure mechanisms of submarine telecommunication cables under such geohazards is quite limited, and the methods to evaluate safety status of the cables after the geohazards are still in a paucity. To fill the gap between engineering practice and understandings and to provide a basis for numerical simulations on the cable-seabed interaction under submarine geohazards, a series of physical model tests was conducted in this study to investigate the change of internal forces along the submarine telecommunication cables subjected to abrupt lateral seabed movements. A light weight (LW) cable for deep-sea deployment is instrumented with strain gauges along the route and buried in a split box to model the effect of strike- slip offset on the cable response. The sensitivities of offset distance and fault-cable crossing angle are investigated. The results show that under the same offset distance, a decrease of crossing angles leads to a remarkable rise of the tension strain along the cable route, which can further result in the exceeding of the designed cable breaking load and the failure of cables. Based on the test results, a series of finite element parametric analysis based on a beam-on- spring model is carried out to further study the effect of cable length, cable-fault crossing angles, and soil resistance, etc., on the cable safety. A regression analysis is carried out on the numerical results. A simple but effective regression formula is proposed, which can predict the maximum cable strains induced by lateral seabed movements, considering the effects of the related dominating factors. Using the regression formula, a safety evaluation procedure is established for evaluating the cable safety under lateral seabed movements.

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Development of the Passive Damper System Realizing the Negative Stiffness Control

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ABSTRACT

The negative stiffness control is one of the structural control methods where the control force is negatively proportional to deformation. It has been clarified by past researches that negative stiffness control makes it possible to decrease the total stiffness of the structure, thereby suppressing the absolute acceleration and absolute displacement. One of the promising applications of the negative stiffness is to use with rubber isolation bearings, by which drastically elongates the natural period while keeping the supporting stiffness in a vertical direction. Whereas reduction of the absolute acceleration by the negative stiffness contributes to the damage reduction of civil engineering structures, suppressing the absolute displacement would be another desirable feature particularly for railway structures, since the damage of the track on which the vehicles are running is affected by the absolute displacement.

When it comes to build an actual negative stiffness damper device, however, it can only be achieved by using sophisticated but complicated active controlled actuators or semi-active devices. For application to real structures, those control systems are not regarded as alternatives to the widely-used passive control devices, in terms of the long- term robustness and the costs of installation and maintenance. Simpler and more economical devices are needed.

In order to overcome the difficulties, a new vibration control device realizing negative stiffness in a passive manner was proposed. The developed device consists of a sliding plate with a PTFE portion, and they are vertically pressurized by gas springs. Unlike ordinal friction pendulum device, shape of the sliding plate is convex to generate the control force that is negatively proportional to the deformation. That is to say, the response displacement would be accelerated as the response increases. In addition, the proposed device comes with supplemental friction energy dissipation between the sliding plate and the PTFE in order to prevent a significant increase in the displacement of the damper. The prototype of the proposed device was assembled, and its performance was investigated through sinusoidal loading tests. It was found from the periodical loading tests that the proposed device generated the designated negative stiffness as well as friction energy dissipations in a good accuracy. It consequently follows that the proposed mechanism could successfully realize a negative stiffness control in a passive manner.

A Study of Hong Kong MTR Network Node Criticality

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ABSTRACT

Public transport networks (PTNs) are critical in densely populated gigantic megacities such as Hong Kong. Public transportation plays an indispensable role in urban resilience with an integrated, complex and multiplex structure. The term vulnerability is defined as the capability of PTNs to resist disruptions, including the removal of one or more targeted nodes. Consequently, measuring the node criticality in complex PTNs is of great practical significance. Despite the proposition of a variety of node criticality criteria to address this problem, few succeeded in more comprehensive aspects. Therefore, this work covers a more effective and thorough method of assessing node criticality by considering the node features based on the complex network theory. Then it analyses the network robustness demonstrated on the Mass Transit Railway in Hong Kong by removing the top-k critical nodes by descending order based on degree centrality (DC), betweenness centrality (BC), closeness centrality (CC), and the proposed EWM-TOPSIS method and quantifies the effectiveness of the proposed method. Four evaluation indicators, including the frequency of nodes with the same ranking (F), global connectivity (E), size of the largest connected component (LCC), and average path length (APL) are computed to compare the performance of the four methods and measure the network robustness with respect to the intentional attacks. The results demonstrate that the EWM-TOPSIS method has more obvious advantages than the others under the static attack strategies, especially in the initial removal stage.

Seismic Response of Container Cranes and Effects on Wharf Response and Crane Structure Performance

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ABSTRACT

Adequate seismic performance of marine container terminals is critical to supply chain resilience. Seismic performance of container cranes and wharves are key factors in the seismic performance of a container terminal. This study describes the seismic response of container cranes and their effect on the wharf seismic response. Results are based on hundreds of time history analyses and include a variety of crane and wharf structures. Effects of the relative dynamic properties of the crane and wharf are summarized.

Recommended crane seismic design criteria and expected performance of container cranes are detailed, addressing different design approaches, e.g., designing the crane to "rock" or "tip" back and forth elastically, seismically compact detailing, providing isolation/damping systems. Seismic retrofit concepts for existing cranes are also described.

This study will interest stakeholders in the container shipping industry, as well as those involved in supply chain resiliency planning, providing a basic understanding of:

- How cranes and wharves interact and respond in earthquakes, including the significance of certain factors.
- How cranes can reduce or increase the wharf seismic response.
- Expected seismic performance of container cranes and contributing factors.
- Concepts for designing new cranes and retrofitting existing cranes to improve their seismic performance, and to limit adverse effects on the wharf structure in an earthquake.

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An Integrative Framework to Measure the Impacts of Earthquake-Induced Landslides on Transportation Network Mobility and Accessibility

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ABSTRACT

Landslides not only undermine the structural integrity of roadways but also deposit a significant amount of material on the road surface, usually resulting in partial or complete road closure to traffic. This work undertakes an integrative analysis framework combining natural hazards with network mobility to provide insights on disaster preparedness and relief. In particular, this framework characterizes the impact of seismically induced landslides on network mobility to reveal the mobility changes immediately after the events and throughout the course of restoration and recovery efforts. Based on transportation network's structure property, the network is considered as a graph, and its topographic feature are transformed into link attributes. The simulation uses a scenario-based analysis approach. By comparing the travel time pre- and post- the occurrence of seismically induced landslides, the mobility change on the network can be measured and visualized, helping identify the impacted regions. The determination of future landslide locations and volumes is primarily challenged by uncertainty in the magnitude of seismic hazards, hydrologic conditions, and soil variability. To limit these uncertainties, and to avoid selecting a specific earthquake scenario during this initial assessment, for the sake of this exercise landslides were assumed to originate from all unstable soil or rock masses within the deposits of previously occurred landslides. The highly populated Portland Oregon Metro is selected as a case study to demonstrate this framework given that the Pacific Northwest is highly prone to large earthquakes as part of the Cascadia Subduction Zone as well as highly susceptible to landslides given its high topographic relief and wet climate. In this case study, travel time to the west and east sides of Willamette River, which divides the Portland Metro area, shows an abrupt change in mobility. In particular, the Portland Hills region with its steep topography is identified as the most vulnerable region. Although immediate post-landslide mobility is critical for the initial disaster response, the mobility during recovery phase is also important for the business restoration and risk control in planning. Based on a temporal analysis of recovery, the majority of the network mobility is expected to be restored after 30 days. The results of this study serve as a preliminary assessment of the impact of landslides on network mobility and can facilitate decision making in emergency planning.

Studies on the Deployment of Sustainable Practices using Lightweight Aggregates for Bridge Infrastructures

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ABSTRACT

The state of bridge infrastructures in the United States has received a mediocre grade which indicates the vulnerable condition of these lifelines in response to extreme events as well as their poor serviceability during normal conditions. This assessment manifests challenges in the areas of condition, capacity, funding, and future needs, as well as innovation. Aging and structurally deficient bridges require prompt attention to enhance their performance and extend their service life. Presented case studies discuss opportunities to achieve these objectives for existing and new bridges through application of sustainable practices for both superstructure and substructure components. These applications cover a wide range of techniques to 1) enhance the service life of bride decks, 2) improve the capacity of the superstructure, and 3) reduce demands on the abutment walls, all contributing to the resilience of bridge infrastructures and their performance during extreme events. Further discussions include ratings and assessment of various practices and their interdependencies with the infrastructure resilience measures, as well as environmental and social resilience, and sustainability objectives.

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Use of Corridors to Manage Transportation Networks Subject to Seismic Hazard

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ABSTRACT

We explore the use of Corridors as a concept to support a bridge retrofitting strategy for transportation networks subject to seismic hazard, using the San Francisco Bay Area as a testbed. The authors define a Corridor as a set of bridges that works together to deliver a transportation service. In order to detect a corridor, we explore the use of different clustering techniques, and select the Markov Clustering Algorithm as the most suitable for the task. Once sets of Corridors are defined, we perform a two-step stochastic optimization to choose actions to manage the transportation network. Two actions for each bridge are considered: retrofitting the bridges in a corridor before the disruptive event or repairing the damaged bridges after an event. After proposing a set of bridges to retrofit, the evaluation of the policy comes from a probabilistic assessment of travel time increase for hazard-consistent seismic scenarios. Given that the retrofitting strategy is subject to the results of the clustering process, we also present different trends and guidelines of Corridors selection. In particular, we observe a change in the performance of the network as a function of the size of the individual clusters and the distribution of the retrofitted bridges relative to the shortest paths that connect the Origin and Destination pairs that define the demand. As a conclusion of this study, we observe that the implementation of the Corridors Optimization approach in the San Francisco Bay Area yields a better relative performance than other management approaches, such as considering bridges as individual entities or using graph centrality measures to rank them. Besides the improvement in performance, the use of corridors as a technique to select bridges to perform a seismic retrofit is closer to the current processes followed by decision-makers in transportation agencies.

Evaluation of Equivalent SDOF Method for Nonlinear Dynamic Response Analysis of Railway or Highway Embankments

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ABSTRACT

A Newmark's sliding block analysis has been generally used for evaluating the seismic response (sliding displacement) of railway embankments in Japan. However, the Newmark's sliding block analysis oversimplifies the actual phenomena, and some related defects have been pointed out. A simple method is proposed for evaluating the nonlinear dynamic response of embankments subjected to large earthquakes. Specifically, a static push-over analysis method was employed to assess nonlinear behavior of embankments. Then, based on the results of the analysis, a simple method for carrying out dynamic nonlinear seismic response analysis of an embankment using an equivalent-single-degree-of-freedom (SDOF) model was proposed. It was confirmed that seismic response of embankment calculated using the proposed method showed good agreement with that obtained using the finite element method. Comprehensive static push-over analyses were conducted for embankments with various specifications such as height and gradient. The obtained parameters to be used for a SDOF model were then classified as functions of these configurations. Using the results obtained from the process, it was now possible to construct an equivalent SDOF model from a few parameters such as embankment height that could be obtained without detail inspections. It is thus demonstrated that the proposed method made it possible to carry out the dynamic responses of embankments in an economical manner compared to the conventional two-dimensional finite element method. The method is thus considered as efficient and expedient procedure for evaluating the seismic

Seismic Fragility Assessment of Seismic Isolated Bridges in Cold Climate

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ABSTRACT

Seismic isolation has been extensively used around the world for seismic protection of structures. Different types of elastomeric and friction based isolation devices have been developed and successfully implemented with a common objective of period shift and increased energy dissipation of structures. Several high seismic regions around the world experience seasonal freezing that can drastically alter the isolation bearing properties and structural response under earthquake loads. Under subfreezing temperature, mechanical properties of elastomeric and friction bearings are affected as well as the properties of concrete and steel reinforcement. The objective of this study is to evaluate the seismic performance of a base isolated bridge equipped with sliding and elastomeric isolation device located in cold climate where temperature below -300C is expected. The Friction Pendulum System and Lead Rubber Bearing will be considered as representative examples of sliding and elastomeric isolators, respectively. Considering the change in mechanical properties of isolation bearings such as, shear stiffness, yield strength, and friction coefficient, due to temperature change, the performance of isolated bridges will be evaluated considering two sets of near-fault and far filed ground motions. A detailed nonlinear three dimensional finite element model of the bridge considering the material properties at cold temperature will be developed. The performance of the isolation bearings and the isolated bridges will be evaluated in terms of isolator force-deformation relationship, force demand in the substructure, deck acceleration, and shear strain in the isolation bearing. Finally, fragility curves will be developed for seismic vulnerability assessment isolated bridges at subfreezing temperature.

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Seismic Performance Assessment and Retrofit of Bridges for Enhanced Resilience of New Zealand Highway Infrastructure

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ABSTRACT

For over two decades New Zealand Transport Agency (NZTA) has been implementing measures to reduce vulnerability and achieve robust seismic performance of the highway bridges. An overview of the significant initiative is presented here with examples of some of the measures implemented. Screening procedure developed in the mid-1990s has been followed for preliminary assessment of thousands of bridges. Following established strengthening criteria some of them were placed in inventory of structures recommended for further investigation. Detailed investigations of those structures are undertaken as part of continued assessment process. For those requiring intervention, retrofit work is prioritized based on specific criteria. Once selected for detailed assessment the structure is analyzed for response to expected seismic demands. If found deficient then retrofit options are considered to elevate the response to meet acceptable performance objectives. The underlying philosophy behind retrofit is to reduce damage to acceptable level such state that functionality can be restored at reasonable cost and time after an earthquake. The retrofit works include structural improvements such as strengthening of members, addition of ductile elements for energy dissipation and measures to maintain structural integrity. Different geotechnical aspects such as foundation strengthening for increased bearing capacity, ground improvements to prevent liquefaction and slope protection at abutments and approaches are undertaken to achieve effective and comprehensive improvement of the complete arrangement. Over the last two decades, majority of the bridge stock has either been assessed or been through different levels of retrofit. With focus on strategies for optimum benefit, details of various types of retrofit measures are presented as examples. Resilience of the network evaluated based on expected performance and vulnerability as well as relative importance of individual structures. It has been determined that retrofit of the bridges has led to significant improvement in resilience of the transportation network. The whole process is elaborated and discussed with case studies.

Modeling Road Blockage Due to Building Collapse Following Earthquakes

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ABSTRACT

Transportation infrastructure in general, and roads more specifically, are one of the critical infrastructure that support social and economic activities of communities. In addition, other critical infrastructure are highly dependent on transportation infrastructure. The most common impact of disruptions of roads is the obstruction of emergency services (e.g., ambulance, firefighting, evacuation). Furthermore, the recovery process of a community following an extreme event (e.g., a natural hazard) depends on the functionality of the transportation infrastructure. Therefore, risk and resilience analysis of transportation infrastructure is critical to assist a community to minimize the initial impact of a hazard and recover rapidly. Current approaches model the probability of road blockage due to building collapse by using high-resolution optical satellite images and aerial photographs that are collected in the past event. However, the data used by these methods are limited and few data have been collected before 2010. Besides, data may not be available for specific regions which have not experienced recent earthquakes. Thus, a probabilistic estimation method is required for risk and resilience analysis of roads. This study proposes a probabilistic model to predict the footprint of the debris from the collapsed of buildings. The model is calibrated using a Bayesian approach and data from the 2010 Haiti Earthquake. The model is then used to construct fragility curves for estimating the conditional probability of road blockage at a given road section for a given seismic intensity (i.e., the peak ground displacement). The proposed model considers the relevant factors impacting road blockage probability including building types, damage level, and road characteristics. Probability of road blockage at a given road section are estimated the four general road section types, considering buildings on only one side of the road or both sides, and with or without a traffic islands. The probability of road blockage for an entire road is then calculated with a system reliability analysis. The proposed models are applicable to any general urban area without the dependence on historical data from past earthquakes.

Lifetime Risk Assessment of Highway Bridges subject to Earthquake and Flood Hazards

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ABSTRACT

Floods and earthquakes are the two major extreme events that can lead to severe damage at highway bridges. Within the lifetime of a bridge located in a seismically-active flood-prone region, it may be subject to the single-hazard of floods or earthquakes, or a possible multi-hazard condition combining the effects of these two independent events, while the performance of various bridge components can decay in time due to various aging effects. In the flood- alone hazard condition, flood-induced hydrodynamic loads and scour can instigate structural damage on bridge piers with reduced soil resistance at the foundations. Meanwhile; besides the vulnerability of a bridge under the earthquake- alone hazard, a multi-hazard condition may emerge from the occurrence of flood-induced scour followed by an earthquake causing an increased risk of failure due to the altered bridge dynamic characteristics under seismic excitations. This study presents the outcomes obtained from our research project which is carried out for assessing the risk of highway bridges under the single and multiple hazards of earthquakes and floods, as well as evaluating the time-varying risk considering aging effects. Within the analysis framework, finite element models of a typical highway bridge are generated and the uncertainties in modeling, soil, deterioration, and scour input parameters are taken into consideration in this process. Nonlinear static analyses are conducted to develop flood-alone fragility curves and nonlinear time-history analyses are conducted to produce earthquake-alone and multi-hazard fragility curves. As a further attempt, the developed fragility functions are employed along with the accepted hazard curves and loss functions in a simulation-based stochastic framework to compute the distribution of failure probabilities and losses throughout the lifetime of the bridge. The outcomes of this research project are planned to be used as a base for the improvement in design procedures and decision-making methodologies for optimum maintenance planning of bridges subject to the considered hazard conditions.

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Experimental and Numerical Study of Winding Rope Device Aseismic System for Continuous Bridge

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ABSTRACT

Continuous bridges account for a large scale in the total length of the bridges. With the rapid development of theory and construction, the span of continuous bridges between adjacent expansion joints has been expanded from the original 3-4 spans to the current 10-12 spans. However, under the action of longitudinal earthquake, the seismic loads are still mainly borne by the single fixed pier, and the potential seismic capabilities of sliding piers are not fully utilized. In the past earthquake events, severely damaged continuous bridges accounted for a large proportion of the damaged bridges, so it is necessary to investigate the seismic performance of the continuous bridges. In order to solve this problem, the winding rope device (WRD) aseismic system which includes the winding ropes and the vicious fluid damper is proposed. The winding ropes are connected in series with both ends of the viscous fluid damper. Under the action of earthquake, the damper force increases with the increase of relative speed between the sliding piers and superstructure, thereby activating the winding ropes and produce large friction forces. In this study, the constitutive model and the working mechanism of the WRD were introduced. Meanwhile, a pseudo-dynamic experiment of the vicious fluid damper was carried to investigate the performance. Based on the above research, a shaking table test of a scale model with a three-span continuous bridge employing the WRD aseismic systems was designed and performed. Finally, the test model was simulated using ANSYS and both the results of numerical simulation and test were compared. The analysis results reveal that:1) The WRD could make the sliding piers bear the earthquake loads with the fixed pier cooperatively, which can effectively reduce the seismic requirement of the fixed pier and improve the seismic performance of the bridge; 2) The numerical simulation results proved the correctness of the finite element model and the effectiveness of the WRD, which are identical to the test results; 3) The WRD has good performance in dissipating energy and limiting the displacement of superstructure under the action of earthquake. Meanwhile, the WRD increase the seismic response of the sliding piers, but the sliding piers will not be destroyed before the fixed pier through reasonable design and arrangement. This study highlights the aseismic effect of the WRD, which is expected to provide a reference for the seismic design of continuous bridges.

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Nonlinear Seismic Response and Damage Analysis of a Prefabricated Subway Station Structure

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ABSTRACT

There were two main characteristics in prefabricated subway station located in Changchun, northeast China, compared with subway station constructed by traditional open-cut and cast-in-place method. One was that assembled components of the prefabricated subway station were connected by tenon-groove joints. The other was that traditional solid components were replaced by thin-walled closed-cavity components to achieve the lightweight of assembled components. To examine the dynamic properties of the prefabricated subway station, a finite-element model was developed to simulate interaction among the soil, the envelope structure and the underground subway station during earthquakes. Numerical simulation and analysis of the nonlinear seismic responses of the prefabricated subway station under inputting only horizontal seismic motion and simultaneously horizontal and vertical seismic motions were implemented. The dynamic horizontal relative displacement of structure and the stress responses on the components were analyzed in detail. The seismic damage features of prefabricated subway station under horizontal seismic motion and simultaneously horizontal and vertical seismic motions was discovered and compared preliminarily. The results indicated that the additional influence of vertical ground motion on the seismic response of this subway station could not be ignored. Compared with inputting only unidirectional horizontal ground motion, the mechanical and deformation characteristic values of the station were increased under bidirectional coupling ground motions. With the increase of the ground motion intensity, the impact rate of the vertical ground motion showed an increasing trend. For instance, the Mises stress, maximum principal stress and minimum principal stress of the prefabricated subway station under bidirectional coupling ground motions compared with unidirectional horizontal ground motion increased by 39%, 26% and 49%; the axial force, shear force and bending moment increased by 45%, 51% and 52%; the relative horizontal displacement and the joint opening increased by 60% and 79%. Within the seismic fortification levels, the prefabricated subway station had excellent seismic performance and the design of thin-walled closed-cavity components were safe and reliable, which met the requirements of the current specifications for seismic performance. However, due to the significant increase in damage under the strong earthquakes, the side walls, the crown arch and the envelope structure were the weak positions for earthquake resistance, which should be given sufficient attention.

Overview and Outlook for the Development of Prefabricated Subway Station Technology

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ABSTRACT

The construction technology of prefabricated subway station (PSS) is an important part of industrialization and intelligence of construction, it is the development direction of future subway station construction. The origin, development, application, and technical progress of PSS technology is introduced and the development process and representative engineering examples of developed countries in this field are summarized. Comparison shows that the assembly technology of Europe and Japan is relatively advanced, with high prefabrication rate, high assembly precision and advanced waterproof technology, but there is a big difference between the engineering structure type and the underground engineering of Chinese subway; the precast level of PSS in the former Soviet Union is relatively low, and cast-in-place concrete is needed for component connection, which limits the prefabrication degree, assembly efficiency, automation level and overall waterproof effect of the structure. Compared with the traditional cast-in-place station structure, the seismic research of PSS is still in its infancy, lacking systematic theoretical method and engineering design experience. The research and engineering practice in this field in China is introduced. Some thoughts and suggestions for the development of PSS technology in the future are identified based on the research and development and successful application case of the first PSS in China – Yuanjiadian station of Changchun Metro Line 2.

Connecting with Community Need: Building a Resilience Program at the Port of Portland

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ABSTRACT

This work addresses industry-focused development of a resilience program at the Port of Portland (Port) in Oregon. The Port owns and operates Oregon's only large commercial hub airport and marine terminals on the Willamette and Columbia Rivers. The Port's facilities connect Portland, SW Washington, and the Inland NW to the world by providing critical transportation and logistics facilities.

First, thing addressed is why a resilience program, not just a series of projects, is necessary for long-term resilience. Often initial interest in resilience at an organization is driven by an executive champion, but building resilience requires up-front investment and, if one is lucky, no demonstration of its benefits. As leadership changes or other new topics emerge, resilience investments can be pushed or cost-engineered out. Having a program helps normalize resilience as a given "good." The core program elements such as a shared and concrete understanding of why your specific organization needs a resilience program needs to be addressed; this is an essential component of understanding how your agency can contribute to community resilience. Next, the usefulness of an organizing construct or tool, such as the Port's "Little Airport" concept, to help evaluate project options, make sound investment decisions and consistently communicate objectives will be addressed. Also address the importance of strong internal and external partnerships that recognize that lifeline resilience cannot take place in a vacuum. The Port's program provides examples including work with local public sector partners, and work with the National Institute of Building Sciences and Oregon State University on the on- going Resilient Runway Project.

Target audiences of this work include public sector employees and private sector consultants with public sector practices with an interest in advancing investment in, particularly large-scale, resilience projects. Key takeaways include: a resilience program helps provide context for making informed decisions about costly and sometimes cutting-edge investments and helps keep resilience investments from being cost-engineered out; your resilience program needs to play to your organization's strengths (this is not the place to take on a new role); and it is essential to build shared purpose and understanding across a range of audiences—from engineers to executives to the public. This work is intended to help people build support for a resilience program and provide pointers on how to build a program.

Study on Self-centering Seismic Isolation at the Bottom of Fixed Pier in Continuous Bridge

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ABSTRACT

In general, only one fixed pier is set in a continuous bridge. It is difficult to satisfy seismic demand of the fixed pier in a strong earthquake area. To solve this problem, a pier-bottom seismic isolation structure with self-centering (PSIS-S) was set at the bottom of the fixed pier, whose contact surface was elliptical. Under a strong earthquake, there was a relative swing between the bottom of the fixed pier and bearing platform, preventing the seismic energy from transferring to the fixed pier and superstructure. After the peak value of the ground motion, continuous bridge can basically return to the initial equilibrium position under the action of the self-weight and seismic residual energy. A shake table test and simulation of a three-span continuous bridge were conducted. Then, taking a typical five-span continuous bridge as an example, the influence of main parameters of the PSIS-S structure on its seismic isolation effect were studied. The results showed that the PSIS-S structure can effectively reduce the seismic response of the fixed pier, and after the earthquake, the residual deformation of continuous bridge was small, meaning that the PSIS-S structure had a self-centering capability. The ratio of long radius to short radius of ellipse had a great influence on the seismic isolation effect of PSIS-S structure, but the influence of friction coefficient could be ignored.

Functional Damage and Recovery of Highway Networks in Major Earthquake Disasters in Japan

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ABSTRACT

In the past earthquake disasters in Japan, highway network systems were suspended due to both emergency closure as initial response and restoration of physical damage to facilities. Therefore, the spatial extent and duration of road closure strongly dependent on distribution of shaking intensity and resultant physical damage. We compiled post-earthquake functional performance of highway network systems during major earthquake disasters in Japan. Examples are shown for the Great Hanshin-Awaji Earthquake Disaster, 1995, the Great East Japan Earthquake Disaster, 2011, the Kumamoto Earthquake, 2016 and the North Osaka Prefecture Earthquake, 2018. Firstly, the spatial extents of immediate road closure due to initial response based on seismic monitoring and road inspection are compared. On this basis, functional fragility curves are developed for each earthquake disaster; the curves describe the relationship between shaking intensity and the probability of occurrence of road closure. Secondly, time history of daily traffic volumes on highway networks are spatiotemporally visualized. Then, the highway network performance is compared in terms of three kinds of highway network performance measures: 1) total number of sections open to traffic, 2) total distances open to traffic, and 3) total traffic volumes weighted by travelled distance. The third measure tends to be almost consistently lower than the previous two measures. In future development, the compiled dataset will be utilized to model resilience functions for rapid assessment of post- earthquake highway network performance based on seismic monitoring systems.

Developing a Resilient Runway at Portland International Airport

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ABSTRACT

Following a major seismic event, severely damaged transportation infrastructure in Oregon, will initially isolate the Portland region and western Oregon from receiving critical aid during the first response. PDX, Oregon's only large hub commercial airport has the potential to connect the region to essential response services, and to drive rebuilding and economic recovery. However, to fulfill these roles, PDX needs a runway that is large enough to support military and commercial jets and is functional immediately following a major seismic event. The Resilient Runway Project is the cornerstone in the Port's Seismic Resilience Plan. This industry-focused work reviews the processes used, and the critical questions asked during preparation of a 30% design milestone for a seismically resilient runway at Portland International Airport (PDX). PDX is located on dredged fill in an historic floodplain along the Columbia River creating a significant challenge in resilience planning. One of the largest hazards facing PDX is the liquefaction-induced settlement and lateral spread prompted by a CSZ event. Mitigating a runway's vulnerability to liquefaction is not a small or simple project, nor is it a common one in the US. This work addresses the steps taken to identify the specific risks to PDX's runways, including when consulting support was required, what was analyzed, and decisions to invest in developing innovative data to help guide the Port's decisions. This work focuses on the approach taken by a public sector engineering department, and how academic and private sector consultants contributed to the development of a defensible project. Take-aways for engineers and project managers will include concrete examples of the cost benefit of data collection, how to maximize investment dollars, and steps that build leadership-level confidence in unusual projects.

Target audiences include project engineers and project managers who need to know what questions to ask, and when seeking external advice and support can help bolster the efficacy and defensibility of your project recommendations, particularly for innovative or less common projects with high costs.

Tsunami-Induced Loads and Demand in Structural Members of Skew Bridges

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ABSTRACT

Bridges are essential components of coastal transportation systems playing a critical role in the economic prosperity of coastal communities, and are vital to rescue and recovery efforts following disasters, such as tsunamis. Unfortunately, recent extreme events, including the 2004 Indian Ocean Tsunami and the 2011 Tsunami in Japan, destroyed hundreds of coastal bridges revealing their vulnerability to extreme hydrodynamic loading. This observed damage indicated the need for developing a fundamental understanding of tsunami-induced effects on bridges, and development of simplified predictive load equations and design methodologies. To avoid the limitations of small-scale experiments and simplified two-dimensional computational fluid dynamics, which cannot adequately simulate the structural dynamics and fluid-structure interaction, the authors conducted 1:5 scale tsunami experiments of a skewed bridge in the Large Wave Flume (LWF) at Oregon State University. The bridge had a skew angle of 45o and realistic properties, with the superstructure consisting of three steel I-girders, cross-frames and a reinforced concrete slab. The hydrodynamic experiments involved different bridge configurations and a series of solitary waves and bores that represented a wide range of tsunami scenarios.

The experimental data revealed that as in straight bridges, skewed bridges witness significant lateral and vertical forces, as well as overturning moments. In addition, skewed bridges witness also large yawing and rolling moments, which are generated by the gradual application of the transient tsunami loading on the superstructure.

These moments lead to an unequal distribution of the tsunami loading to the two abutments, with one of them having to withstand on average 73% of the total lateral load and 80% of the total uplift load. Even more interestingly, the combined effects from the applied uplift force and the overturning and rolling moments lead to overstressing of some bearings, with the ones below the offshore acute and obtuse corners attracting on average 33% and 66% of the total uplift load respectively. This percentage is much larger than the 16.7% predicted by a commonly used assumption of an equal load distribution to all the bearings. In summary, given the lack of tsunami design guidelines for bridges presently, the findings of this work are expected to be of high significance to bridge engineers and researchers, because they demonstrate the complexity of the inundation mechanism and associated loading on skewed bridges. These complex effects result in the overstressing of certain structural components that can increase the probability of a progressive collapse mechanism.

Fifty Years of Progress in Seismic Design of California Bridges (1971 to 2021)

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ABSTRACT

San Fernando earthquake of 1971 was a turning point for California Seismic Bridge Design. The collapse of I-5/SR14 interchange and many other area bridges was an awakening moment for bridge designers at Caltrans. Bridge seismic design up to this time included occasional Response Spectrum Analysis and reduction of forces based on predefined reduction factors. Caltrans has made major advances in Seismic design since that time and has developed Seismic Design Criteria (SDC) that has been used and referenced by numerous agencies and countries. Some major advances include a shift from force-based to displacement-based design, better characterization of design seismic hazards, and improvements in bridge designs such as balancing stiffness and periods, ensuring superstructure continuity, providing redundancy, joint-shear design, use of isolation bearings, minimum ductility requirements, upgraded details of seismic critical members, and most recently moving to performance-based design. Meanwhile, Caltrans undertook an aggressive seismic retrofit program through which more than 2000 bridges have been upgraded to higher seismic safety standards. These advances have been a result of the knowledge gained from post-earthquake damage investigations, partnerships with research institutions and universities, and continued engagement of bridge designers at Caltrans and consulting firms.

The latest Seismic Design Criteria includes provisions for cast-in-place and precast concrete bridges, new design and analysis methods, and a class of enhanced performance (Recovery) bridges which are designed for both functional and safety evaluation earthquakes. The Caltrans Office of Earthquake Engineering, Analysis and Research is currently undertaking a pioneering work on implementing probability-based design provisions through which engineers will be able to estimate the probability of bridges exceeding various performance levels (Damage States) when subjected to all possible earthquakes.

Historical Progression of Los Angeles Metro Seismic Design Criteria

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ABSTRACT

The Los Angeles Metro transit system has been undergoing a rapid expansion since the 1980's. The expansion includes complex structures including elevated structures with major bridges, circular tunnels, oval caverns, rectangular tunnels, and underground stations. In addition, the Metro transit system overlaps with the lifelines of other jurisdictions, including the California Department of Transportation, Los Angeles Bureau of Engineering, and many others. The Los Angeles area is also subject to a significant seismic hazard. The seismic hazard creates risks of damage due to fault rupture, ground shaking, liquefaction, landslides, and seismic settlement. Nevertheless, Metro provides Supplemental Seismic Design Criteria as part of its overall Design Criteria in order to provide for design of new structures for seismic hazards. Metro's design criteria has progressed over time based on capabilities in the engineering community, new research, and changes in parallel standards such as the Caltrans standards, and ASCE-7. Metro's criteria has served as a model for other lifeline system design criteria, and is anticipated to continue to change its standards over time with additional engineering capabilities and knowledge in the community. This work reviews the history of changes of the Metro Supplemental Seismic Design Criteria. Metro's criteria anticipates changes to computational methodologies commonly used for design of Metro structures, including three-dimensional seismic response analysis and structure-soil-structure interaction with Metro facilities. The Metro criteria could be applicable to other codes and standards of practice utilized by the profession for transportation and other lifelines structures in seismic regions.

Seismic Design of Los Angeles Underground Transit Stations

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ABSTRACT

The Los Angeles Metro transit system has been undergoing a rapid expansion since the 1980's. The expansion includes extensive segments with tunnels and underground stations. The Los Angeles area is subject to a significant seismic hazard, the greatest impact being ground shaking, which affects a large area compared to more localized earthquake effects such as fault rupture. Therefore, all underground stations in the Metro system are designed according to high standards of analysis and design to accommodate ground shaking. With the restraint provided by the ground, underground subway stations are inherently more resilient when subject to ground shaking than above-ground building structures. Nevertheless, Metro provides Supplemental Seismic Design Criteria as part of its Design Criteria to ensure reliable and robust design of new underground structures for resilience to ground shaking. The Supplemental Criteria requires designing for the fundamental racking (side sway) impact of ground shaking due to vertically propagating shear waves. However, some subway stations are adjacent to large building structures with deep basements that modify the racking deformations that otherwise would occur in the free-field without major adjacent structures. The change in racking deformations is due to inertial effects of the adjacent structure mass during shaking. A further complication is the reflection of shaking energy up into the adjacent structure and back down, with an associated period of vibration influenced by the stiffness and mass of the adjacent affected structure known as kinematic effects. Therefore, some computational seismic analyses of subway station response must include the impacts of nearby structures in the overall structural model as simplified single- or multi-degree-of-freedom (SDOF and MDOF, respectively) systems. The methodology used in seismic analysis of stations is described and examples are provided for selected stations.

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Seismic Design Approach for Underground Structures of LA Metro Regional Connector Transit Corridor Project

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ABSTRACT

The Regional Connector Transit Corridor (RCTC) Project is a design-build project currently being constructed by the Los Angeles County Metropolitan Transportation Authority (Metro). The 1.9-mile-long light rail subway includes major underground elements of twin bore tunnels, cut-and-cover box tunnels, three cut-and-cover underground stations, and a rail crossover cavern. Final design of the underground structures has been completed and construction has substantially advanced with an opening for revenue service planned for late 2022. Located in downtown Los Angeles, one of the most active seismic regions, the RCTC Project underwent comprehensive seismic design for its underground structures complying with the Metro Rail Design Criteria. The overviews of Metro's seismic design criteria and the project-specific approach that has been taken for the major underground elements of the RCTC Project are summarized and documented, in order to enhance understanding of Metro's criteria and requirements and lead potential improvements in Metro's future underground developments.

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Bridge Structural Health and Performance Monitoring: Rapid Post-Earthquake Assessment

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ABSTRACT

The Digital Twin (DT) created and maintained in operational SHMP (Part I) is employed here to develop a framework for Rapid Post-Earthquake Assessment (RPEA). Despite the recent revolution in digital technology and related scientific research, manual inspection is still the most reliable plan-of-action in the U.S. for post-event assessment of civil infrastructure and situational awareness. Such an approach to assess geographically distributed critical infrastructures after a potentially large-scale disturbing event, e.g., an earthquake, is an expensive effort requiring human resources that might not be readily available after the disaster. Without a granular knowledge of infrastructure situations, disaster management efforts in large metropolitan areas can easily lead to the chaos resulting in extended fatalities, recovery time, cost, and social and economic consequences that can go well beyond the region to affect the whole nation. Considering the current condition of infrastructures (nearly 40% of 600,000 US bridges are 50+ years old), it is crucial to develop a robust, reliable, self-improving, and automative RPEA. In this study, we propose using Digital Twin idea from which needed thresholds or fragilities can be pre-determined for the RPEA assessment right after an event. Also, the updated DT can provide us with detailed information about the location, extent, and severity of the probable damages.

Assessing Direct and Indirect Long-term Economic Impacts from Earthquakes to the U.S. National Bridge Inventory

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ABSTRACT

Using the U.S. Geological Survey's 2018 National Seismic Hazard Model and the 2018 National Bridge Inventory compiled by the Federal Highway Administration (FHWA), we perform an annualized earthquake loss (AEL) study for over 600,000 bridges in the conterminous United States, quantifying both direct and indirect economic losses. The typical AEL framework has been adjusted to use new replacement unit cost data and modifications have been made to the default damage fragility functions to use bridge-specific parameters. Earthquake hazard is defined in terms of a spectral acceleration hazard curve at a vibration period of 1.0 sec, accounting for the site-specific soil conditions. Hazard is integrated with the bridge-specific fragility curve to compute annual probabilities of exceeding various damage states. Further, we perform economic loss analyses using the repair costs associated with specific damage states as well as indirect costs incurred due to downtimes using Hazus methodology, resulting in an estimate of mean total annual financial loss for each bridge. Quantitative assessments of seismic risk, especially those that account for downtime-related impacts, enable us to illustrate the distribution of overall financial risk with respect to geographical region, era of construction, or type of bridge.

Assessing Cost Efficacy of the Caltrans Phase I, Phase II Bridge Retrofit Program

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ABSTRACT

In the last 40 years, earthquakes in California have caused freeway bridge collapses in urban areas resulting in considerable economic disruption and fatalities. Following the 1989 Loma Prieta earthquake, where 43 people died as the result of a single bridge failure, the State of California embarked on a significant bridge retrofitting program to help curb future impacts. Under the MMC project, the cost efficacy of these efforts was assessed using REDARS (Risk from Earthquake DAmage to Road Systems), a software tool that estimates damage to bridges and analyzes disruption experienced road networks after an earthquake event. The analysis also considered secondary economic impacts, which in many cases are far greater than the direct impacts, resulting in a benefit cost ratio of 3 to 1. This work presents the results of this analysis, and suggests methods of preserving this early 2000's era computational framework using cloud-based technologies.

Evaluating the Impact of Equipment Selection on Debris Removal and Dependent Lifeline Infrastructure Recovery

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ABSTRACT

Post-disaster debris removal is one of the critical activities that needs to occur in the aftermath of natural disasters such as earthquakes and tsunamis to enable community recovery. This initial stage of recovery can affect recovery of other lifeline infrastructure and is often hampered by numerous logistical bottlenecks including the non-availability of heavy equipment; inadequate capacity of temporary debris management sites (TDMS) for debris sorting and reduction prior to final disposal; and competing priorities such as medical and temporary housing relief operations. This work provides a means of analyzing such long-term debris removal and lifeline repair operations by considering the logistical constraints on the site to quantify recovery times and thus enable decisionmakers to make data-driven and informed decisions before the disaster. Specifically, a simulation-based methodology is presented that uses debris quantity estimates from HAZUS and debris haul distances from GIS as input to a discrete event simulation (DES) model to simulate the debris removal operations. Output is obtained in terms of operation recovery time and this framework enables a sensitivity analysis to be performed by varying the decision variables of heavy equipment fleet configurations and TDMS site selection. Furthermore, repair operations for lifelines infrastructure that are dependent on debris removal are identified and quantified to obtain measure of full system recovery. The developed framework was applied to the case studies of a Cascadia event for the coastal towns of Newport and Astoria in Oregon to determine the ideal fleet configurations to meet resilience targets. The proposed framework enables decision-makers with an objective means of evaluating decision alternatives both before and after disasters to optimize their community's capability of handling disaster debris. The presented framework also provides the means of optimizing the location of TDMS sites based on the predicted spread of debris under differing disaster scenarios.

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Use of a Slot Cut Approach During a Major Landslide Hazard Reduction Project at a Frank R. Bowerman Landfill

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ABSTRACT

Solid waste landfills are frequently located in areas where continued development requires addressing hazards posed by static or seismic slope instabilities. Slot-cut excavations have been widely used to maintain stable slopes during excavations adjacent to structures or at the toe of steep slopes. It is well known that the observed improvement of slope performance in slot-cut excavations over what would be expected based on two-dimensional evaluations is due to the contribution of out-of-plane resistance or the three-dimensional (3D) effect on slope stability. The evaluation of slot-cut stability in practice, however, is often based on a highly simplified single-block wedge analysis valid only for simple slope geometry and homogeneous soil conditions.

This work included the remedial design and construction for a major landslide in formational materials at the Frank R. Bowerman Landfill in Orange County, California, that incorporated the slot cut approach. The construction of this remediation was completed in 2018. Plans called for a staged development with segmental excavation and buttress filling along the toe of an existing creeping landslide. The segmental excavation included 42 slots that are each a maximum 50-ft wide along the toe of landslide slope.

Using 3-D slope stability software, the critical slots along the toe of the landslide were evaluated to provide input into the project specifications. The project team evaluated the landslide from several different orientations (i.e., backcut, side cut in landslide debris, and side slopes of engineered fill). Based on these evaluations, recommendations regarding minimum and interim fill elevations were needed prior to starting adjacent slots. Ultimately a slot cut approach was successfully used to construct the project. Geotechnical monitoring of the landslide movements during construction informed the execution.

Experimental Study on Convective Mode of Storage Liquid in Tanks under Near-fault Ground Motions

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ABSTRACT

The long period velocity pulse is recognized as one of the characteristics of near-fault ground motions, and hence the response of lower frequency vibration will be amplified owing to the resonant effect. In general, the frequency of convective mode of storage liquid in tanks is low and the period is similar to the pulse period of near-fault ground motions. Therefore, it is worth paying attention to the near-fault effect on the convective mode of storage liquid in tanks. Based on the long-stroke and high-speed shaking table at NCREE, an experiment was implemented to study the resonant response of convective mode of storage water in rigid rectangular tanks. The purpose of this study is to estimate the slosh height and the associated total volume of water splashing out of the tank under near-fault ground motions, and also to determine the relationship between the resonant response and the seismic parameters of input motions.

In this study, the impulse motion was developed for free vibration analysis to identify the fundamental frequency and damping ratio of convective mode under different tank size and water level conditions. It is found that the damping ratio of convective mode of storage water is about 0.35%. In addition, the proper near-fault ground motions were selected, and the velocity pulse and band-pass signal were extracted from the original ground motion for resonance analysis. It is noted that, owing to the resonant effect, the sloshing response is sensitive to the frequency content of the excitation rather than the exist of velocity pulse.

Two tank specimens with the same length and width but different height were located on the shaking table and tested simultaneously under the same test condition, such that the sloshing height and total volume splashing out of the tank for one earthquake event can be determined from the higher and shorter ones, respectively.

Compared to the conservative estimation as specified by industrial standards and guidelines (e.g. EPRI guidelines for spent fuel pool in nuclear power plants), the more rational analysis procedures to estimate the total volume of water splashing out of the tank are proposed in terms of the time histories of sloshing height and timely adjusted freeboard under the consideration of cyclic excitation, and the geometric shape of splashing water at each time is assumed by a triangular prism for 1D excitation and a triangular pyramid on corner for 2D excitation, respectively. In addition, the method to estimate the time histories of sloshing height for general cases without experimental data is also proposed in this study using SDOF analysis according to the fundamental frequency of convective mode.

Seismic Strengthening Strategies for Sprinkler Piping Systems in Hospitals

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ABSTRACT

Potential failure of fire protection systems might be caused by damaged supply tanks, pumps or piping systems. Among these components, damage of sprinkler piping system might most affect occupancies of buildings. For instance, the leakage of piping systems in hospitals during small earthquakes could results in shortage of fire protection and malfunction of medical equipment. The break of sprinkler systems caused by strong earthquakes could even harm the life safety. However, there is no specific seismic standards for sprinkler piping system in Taiwan. Taking a sample sprinkler piping system in a medium-scale hospital as an example, this research aims to improve seismic strengthening strategies for piping in critical buildings based on NFPA 13. The content of this research is summarized below:

1. Three damage states for failure modes of a sprinkler-piping system: (1) failure of the ceiling causedby the impact of the sprinkler head which might result in dusts full of medical space; (2) Damaged threaded joint of the branch which might resulted in flood on the floor level while the resulted moment on the joint exceeds its capacity; and (3) drop-off of piping segments which might obstruct escape egress while verticalhangers or anchorage exceeds its tensile and shear capacity.
2. Numerical analysis of seismic strengthened sprinkler piping systems: Strengthening devices include braces of main pipes, steel wires for branch lines and sprinkler heads, and flexible hoses at possible impactregions. Detailed numerical analyses were conducted to compare seismic performance of pre- and after- strengthened systems under DBE. The results of a series of component tests were conducted to verify simplified numerical models with SAP2000 v.20 software for vulnerable piping joints and seismic devices.
3. Shaking table tests of the sample sprinkler piping system: A series of shaking table tests has been conducted to verify the accuracy of numerical results. A test region of 10m by 10m area of the sample sprinkler piping system with damage potential was picked out based on preliminary numerical analysis. It shows that significant effects of seismic spatial interactions caused by an adjacent ceiling system and partition walls. Flexible hoses at possible impact regions effectively decrease impact forces. Besides, steelwires has minor effects due to necessary slackness to keep the same levelness as the adjacent ceiling system.Most of all, the braces of main pipe is necessary to control most inertia force of the piping system.

Based on the comparison of test results of strengthening and original sprinkler piping system, the seismic efficiency, installation applicability and economic consideration of seismic strategies for sprinkler piping systems are discussed to propose an applicable seismic design guidelines in Taiwan.

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Considerations for the Application of Risk Informed Decision Making on Dam Safety Projects

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ABSTRACT

Various states and other agencies are developing risk-informed decision making (RIDM) guidelines for dams. FERC is also in the process of integrating RIDM into its dam safety program and has promulgated interim RIDM Guidelines. The RIDM process typically includes an assessment of the likelihood of loading, the dam's fragility under loading, and the consequences of uncontrolled release to estimate life safety risk. This risk estimate can be used to decide if dam safety improvements are warranted. As part of the FERC rollout, several dam owners are conducting pilot projects as trials of the process that will provide valuable input to others who will use RIDM in the future. One of these projects is Southern California Edison's pilot project for one of its dams. The facility is a concrete-faced rockfill dam constructed in the early 20th century.

The RIDM work on this facility thus far has included a Semi-Quantitative Risk Analysis and Quantitative Risk Analysis Workshops. Assessments have included stochastic hydrology, assessment of potential overtopping-induced embankment erosion in the probable maximum flood, the potential for spillway erodibility, facing slab stability, potential for deformation of the dam under seismic loading, and HEC-LifeSim evaluation of downstream consequences. The results of these evaluations have provided a clearer understanding of dam safety issues for the owner. Previously, potential failure mode analysis processes had identified several potential dam safety concerns. The RIDM process expedited an identification of a single failure model as driving the risk and allowed for the assessment of a range of mitigation options. Additionally, the application of the Interim FERC Risk Guidelines has assisted in evaluating the proposed risk methodologies and developing a group of facilitators and subject matter experts who can serve on future risk assessment projects. A number of lessons were learned during the course of the project regarding the overall RIDM process which will be informative for those in industry who plan on applying similar approaches in the future.

Centrifuge Modeling of Hydrodynamic Loads in Water Storage Tanks

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ABSTRACT

Buried water storage reservoirs are now the primary sources of water in cities along the highly seismic western coast of the U.S. They are usually placed at elevated locations within an urban area to deliver water by gravity and are the primary sources for post-earthquake firefighting water supply as well as drinking water. As such, they are critical to limiting post-earthquake fire damage and for any recovery efforts. These reservoirs are a relatively new class of structures. As such, they have not yet experienced large earthquakes, code-based or simplified methods are not directly applicable or technically justified for them, and any advanced three-dimensional nonlinear soil-structure- fluid-interaction analysis has no experimental or case history validation basis. One of the mechanisms that is typically overlooked or addressed in a simplified manner is that of hydrodynamic loading from the oscillations and occasional sloshing of the enclosed water. In particular, the impact of the forces transmitted from the water to the adjacent retaining structure and the retained soil, as well as their coherency with dynamic earth pressures, and their scaling with ground motion intensity, remains unclear.

This investigation features a series of five centrifuge model tests performed at the Center for Geotechnical Modeling at UC Davis with the goal of understanding and thus reducing the uncertainty associated with capturing hydrodynamic loads within the broader problem of soil-structure-water interaction in buried storage tanks. The centrifuge tests comprised a reduced scale modular tank wherein the properties that have been found to affect the problem most were varied. The response of the system was captured by inducing first, second, and third modes of sloshing under harmonic motions, as well as exciting the system with broadband earthquake motions. The response was recorded with pressure transducers, tactile pressure sensors, and high-speed cameras. The results are compared to theoretical and numerical simulations for the free oscillation of liquids and suggest the pressures developed during sloshing are significant even long after the motion has ceased. For non-sloshing inducing motions, the pressure response at the base of the container is proportional to the acceleration of the input motion. It is expected that this study will advance our fundamental understanding of how water behaves in these configurations, inform future numerical modeling and validation efforts, advance tools used by research and practice, and more broadly improve the earthquake resiliency of cities that utilize buried storage tanks.

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Multi-Hazard Seismic Risk Assessment of a Cooling Water Delivery System

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ABSTRACT

This study describes a seismic probabilistic risk assessment (SPRA) of a supplemental cooling water delivery system at a nuclear power plant subjected to multiple earthquake-induced hazards. The system consists of an offsite groundwater well used concurrently for municipal water supply, submersible pumps, an adjacent pumphouse, a pipeline that transports water to a storage reservoir on a hilltop at the plant site, the hilltop reservoir structure and equipment, and buried piping that runs downhill to the plant. During a potential earthquake, all the system components are subjected to ground shaking hazard. Several of the system components are also be subjected to the following seismic-induced ground failure hazards during or immediately following an earthquake: liquefaction, lateral spreading, and slope failure. The system relies on both long-existing infrastructure and recently added components. As a result, in addition to the varying susceptibility of the system components to different earthquake-induced hazards, these components embody a spectrum of construction vintages and prevailing seismic design criteria. This study summarizes the seismic fragility evaluations performed to assess the system component contributions to the overall system failure probability at increasing levels of seismic hazard. Seismic fragility functions were used to characterize the conditional probability of component failure as a function of seismic input. Component failure criteria were explicitly identified or screened out for potential seismic-induced failure modes considering that success of the system function requires the ability to deliver cooling water from start to end. Risk insights from the SPRA identified the relative importance of individual components to the overall system risk. These insights can be used to support risk-informed decision-making.

Quantifying the Resilience of Interdependent Infrastructure

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ABSTRACT

Societal well-being and economic prosperity of modern society depend on critical infrastructure and their provision of essential resources and services to communities. Goal of Regional resilience analysis is to promote strategies that can reduce the spatial and temporal extents of disruptions to the flow of essential resources and services to communities.

Resilience analysis typically consists of 1) rigorously modeling the post-disaster recovery process, and 2) quantifying the resilience associated with a given recovery process. For regional resilience analysis of infrastructure both the recovery modeling and resilience quantification present several challenges. The challenges arise from the spatial and temporal disparity of the recovery process over the region of interest. The challenges in the modeling of the post-disaster recovery process of infrastructure include 1) scheduling the physical recovery of infrastructure, 2) translating the physical recovery of infrastructure into the recovery of disrupted services, and 3) developing a computationally manageable approach for the recovery modeling and optimization. The challenges in quantifying the resilience associated with recovery process of infrastructure include 1) defining aggregated performance measures of spatially distributed infrastructure, and 2) defining metrics for resilience quantification that can account for the spatial and temporal disparity of infrastructure performance over the region to promote distributive justice, in addition to promoting a rapid recovery of infrastructure.

This study covers a comprehensive formulation to quantify the resilience associated with spatially distributed interdependent infrastructure. The formulation combines multiple aggregated performance measures in a matrix representation to generate a consolidated assessment of regional resilience. The formulation is then illustrated by quantifying the resilience associated with the post-disaster recovery of interdependent infrastructure for a benchmark example. Resilience quantification enables policy and decision makers to both define and identify resilience characteristics, and design strategies to promote regional resilience.

Measuring Community Lifelines Resilience Using Regional Inoperability Input-Output Modelling

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ABSTRACT

Lifelines are always interconnected with each other and their interdependency could be gauged using economic models. Input-Output (IO) modelling is part of macroeconomics used to measure interdependency between economic sectors. The modified form of IO modelling is Inoperability Input-Output (IIO) modelling, which is used to determine how dysfunctionality of one sector propagates among interrelated infrastructures and sectors. In this study, Dynamic IIO modelling is performed for two scenarios, San Francisco in the United States and National Capital Delhi in India. Inventory and other resilience measures adopted by the community are accounted for in Dynamic IIO. Critical economy lifelines such as Water Distribution, Gas Distribution, Electricity transmission system, Transportation, and communication networks are considered. In this method, countrywide IO data is used and downscaled to a specific region of interest using regional Gross Domestic Product (GDP) data. It was found that the recovery pattern of both the area varies with each other. From the economy view, the mitigation efforts of the regions should be different. This study helps in identifying the variation in recovery patterns corresponding to different resilience measures. This study would be useful for creating and developing effective regional mitigation strategies, identifying the sectors which are more vulnerable to the lifeline distribution.

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Identification and Assessment of Critical Dependencies for Rapid Post-Event Response and Recovery

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ABSTRACT

To better support and meet the Eugene-Springfield metropolitan area community's social and economic needs following a major earthquake or flood, the Metropolitan Wastewater Management Commission (MWMC) has completed development of a Disaster Mitigation and Recovery Plan. The planning process included an assessment of the expected performance of MWMC's regional wastewater conveyance and treatment facilities and outlining actions and upgrades needed to achieve Oregon Resiliency Plan level of service goals following a Cascadia Subduction Zone (CSZ) earthquake and MWMC's internal goals following a catastrophic flood. Additionally, as a part of this major planning process, MWMC dependencies were identified and evaluated to develop actions that could be taken to minimize the potential for cascading failures following a major earthquake or flood event. This work focuses on three aspects of this effort – (a) an approach used by management and operations staff members to explore and rank what will be most needed for disaster response and recovery, (b) the ten most critical dependencies identified by MWMC, and (c) assessment of each critical dependency through a partnership between consultants and staff members. MWMC has found this effort very valuable to gain a better awareness and understanding of the organization's critical dependencies and engage staff to proactively develop and implement construction- and administrative-based solutions that will improve their ability to rapidly respond and recover from disasters.

Systemic Seismic Vulnerability and Risk Assessment of Urban Infrastructure and Utility Systems

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ABSTRACT

The seismic vulnerability and risk assessment of infrastructure and utility systems is essential to prevent or mitigate sufficiently the negative consequences, implement resilience management strategies and recover efficiently after a major earthquake. In a complex urban environment, having multiple interacting and interdependent infrastructure, this becomes even more important. Earthquake hazards not only affect a single asset, but their impact is much greater because of the inter- and intra-dependences among various infrastructure, utility systems and lifelines. Therefore, we urgently need efficient tools to quantify and assess the systemic vulnerability and risk of urban infrastructure and utility systems. This is a challenging topic that is nowadays receiving more attention by the research community, the industry domain and the policymakers. In this respect, one of the few efforts worldwide is the European funded SYNER-G project that encompasses interdependencies, delivers a holistic methodology and implements a comprehensive framework (Pitilakis et al. 2014). The approach embraces detailed taxonomy of infrastructure systems, seismic hazard and intensity measures appropriate for spatially distributed systems, fragility assessment of components, modeling of interdependencies between components and networks, definition of systemic performance indicators, socioeconomic impacts and relevant uncertainties. SYNER-G method is based on the Object-Oriented Modelling paradigm. Even though there exist other modeling approaches, among them SYNER-G method includes a broader scope of systemic analysis that incorporate interdependencies. This study reviews the available modeling approaches and tools for the seismic risk analysis of interconnected systems, including advantages and limitations. Furthermore, the capacities of the SYNER-G framework are illustrated through a selected application regarding the risk analysis of interconnected infrastructure and utility systems in the city of Thessaloniki, in Greece. Among other aspects, the hazard modelling is discussed, including drawbacks and advantages of the two common approaches, the probabilistic and the scenario-based procedure. In this case study, the most critical components are identified, and different mitigation strategies are examined, on the basis of their effect in the performance of the interconnected systems and the overall loss reduction. The integration of interdependencies into the risk analysis and resilience strategies, facilitates better understanding of critical infrastructure operation and enables well-informed proactive and reactive decision-making and efficient disaster risk management, by infrastructure owners and operators, insurance companies, consulting agencies and local authorities.

Pitilakis, K., Franchin, P., Khazai, B., & Wenzel, H. (Eds.). (2014). SYNER-G: systemic seismic vulnerability and risk assessment of complex urban, utility, lifeline systems and critical facilities: methodology and applications (Vol.31). Springer Netherlands, DOI 10.1007/978-94-017-8835-9.

Evaluating the Importance of Interdependent Civil Infrastructure System Components for Disaster Resilience of Community Housing

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ABSTRACT

Housing disaster resilience is crucial for community disaster resilience as it provides two essential functions: shelter from the elements and functional housing. We present a methodology to quantify community housing disaster resilience considering the unmet post-disaster community demand for both shelter and functional housing. Total Sobol' indices are used to evaluate the importance of the vulnerability and recoverability of individual components of community infrastructure systems and building stock units for community housing disaster resilience, while requiring no prior knowledge of these component properties. We illustrate the application of the proposed importance analysis on a virtual community considering the functionality of the electric power supply, water supply and communication infrastructure systems, and a number of building stock units.

Assessing Lifeline Interdependencies and Restoration Performance in San Francisco Using Qualitative Methods

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ABSTRACT

The purpose of this project is assess the interdependencies and restoration performance of lifeline systems serving the City and County of San Francisco following a major earthquake. In 2014 and again in 2020, expert interviews with lifeline providers and cross-sector workshops were used to understand how lifelines will be impacted by a major earthquake, what the restoration timelines and processes will be for each lifeline system and how lifelines depend on one another. New issues, improvements and degradations in restoration performance between the first and second study were assessed. The project resulted in current and target restoration timelines for all San Francisco lifelines using a common metric of level of service disruption and a clear understanding of interdependencies between lifelines. The project helped identify geographic areas with concentrations of lifeline systems or other vulnerabilities, key actions needed to achieve target restoration timelines, and high priority mitigation opportunities that benefit multiple lifeline systems. The project demonstrates the value of qualitative and collaborative approaches to assessing lifeline interdependencies and restoration performance at a community scale.

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Seismic Fragility of Water Pipelines

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ABSTRACT

The performance of water lifelines during seismic events is an area of ongoing research. In this study we evaluate three different seismic events and the impact that ground shaking and ground deformations had on the water pipeline systems. This information is then used to develop generalized and specific fragility curves that track different pipeline; material types, code standards, orientations to deformations, limit-states, etc. The resulting fragility curves are then used within a predictive infrastructure systems model and tested against two other seismic events to examine the utility of this model for forecasting damage and disruption. Results indicate that connections and joints are often the weak link in the water pipeline, particularly when there is a bend or intersection that acts as a stress concentrator. More realistic geometry of the pipelines and the loading functions should be considered when designing or retrofitting pipelines as simplified fragility estimates often underestimate the hazard. The overall goal of this work is to provide municipalities and utility providers with tools for mitigating the consequences of seismic hazards on water lifeline systems.

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Using Global Variance-Based Sensitivity Analysis to Prioritize Bridge Retrofits in a Regional Road Network Subject to Seismic Hazard

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ABSTRACT

We present a novel method for prioritizing bridge retrofits within a regional road network subject to uncertain seismic hazard, using a technique that accounts for network effects and disruptions while avoiding the combinatoric computational costs of exhaustive searches. This method uses global variance-based sensitivity analysis (SA) to compute a probabilistic ranking of bridges according to how much their retrofit statuses influence the decision variable of interest. Given a set of bridges, we treat their individual retrofit states as binomial random variables. The expected cost of the road network performance – as approximated over a hazard-consistent set of ground-motion maps, each associated with a particular rupture scenario, and multiple damage maps per ground-motion map – is our decision variable and includes both direct costs (due to bridge repairs) and indirect costs (due to delays and infeasible trips). We use the hybrid-point Monte Carlo approximation method developed by Sobol to estimate bridges' total-order sensitivity (or, Sobol') indices. A bridge's total-order Sobol' index measures how much its retrofit status influences the variance of the expected cost of the road network performance and accounts for the effect of its interactions with other bridges' retrofit states. We compute bridge Sobol' indices on a hazard-consistent set of 30 ground-motion maps. We then test a strategy in which bridge retrofits are prioritized in decreasing order of their total-order Sobol' indices on a hazard-consistent set of 45 ground-motion maps.

We present results for a set of 71 highway bridges in the San Francisco Bay Area. We show that a retrofit strategy based on bridges' total-order Sobol' indices outperforms strategies in which we rank bridges by age, fragility, daily average traffic volume, a combination of the three aforementioned characteristics, and the results of a one-at-a-time analysis in which we damage individual bridges and compute the impact of each bridge's closure on the road network performance. We discuss considerations for implementing the proposed method and show that it remains computationally tractable while accounting for the probabilistic nature of the seismic hazard, the uniqueness of individual bridges, the network effects that stem from the (non-linear, non-additive) links between the states of individual bridges and the performance of the overall road network, and decision-makers' priorities.

This method leverages existing tools and models (e.g. ground-motion intensity maps with spatial correlations, a regional travel model), without imposing further assumptions – it should therefore be extensible to other types of networks under different types of hazards and with consideration given to different decision-makers' priorities.

Building Seismic Resilience into a Regional Water System

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ABSTRACT

The Metropolitan Water District of Southern California (Metropolitan) provides approximately 1.6 billion gallons of water every day to 19 million people over a 5,200 square miles service area within southern California. Metropolitan's system includes the 242-mile Colorado River Aqueduct, 830 miles of conveyance and distribution pipelines and tunnels, 20 dam and reservoir facilities, and 5 water treatment plants. The system traverses an area with numerous faults capable of generating large earthquakes that have the potential to impact water deliveries. As an owner and operator of a critical lifeline system, Metropolitan has long recognized the importance of preparing for earthquakes and the associated seismic hazards. Accordingly, the organization has taken steps to improve the seismic resilience of the system to limit the impacts on water deliveries to our customers. Metropolitan employs a defense-in-depth approach for its seismic resilience strategy with the goal of preparing for and effectively responding to seismic events. The major components of this strategy include maintaining adequate emergency water supplies, hardening facilities to limit damage from seismic hazards, and maintaining a robust emergency response program. This work covers the implementation of Metropolitan's seismic resilience strategy, focusing on how the activities support the organizations goals for seismic resilience.

Fragility Function Viewer for Oregon Lifelines

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ABSTRACT

A comprehensive taxonomy and database of region-specific fragility functions appropriate for Oregon were solicited by a research cooperative of Oregon-based lifeline providers. Objectives included the following: (i) identify available and missing fragility functions suitable for Oregon lifelines, (ii) evaluate the quality of the collected fragility functions, and (iii) provide recommendations where refinement is needed for future fragility function development studies. Initially, a literature review and expert survey were conducted to: (a) identify relevant hazards, infrastructure, and multi-hazard scenarios of interest to Oregon stakeholders, (b) identify potential in-house and proprietary fragility functions, and (c) develop metrics to evaluate the quality of the collected fragility functions. Based on the literature review and expert solicitation, a fragility database was structured using a hierarchy of infrastructure systems (electric power systems, water and wastewater systems, and transportation systems), hazards (earthquake, tsunami, etc.), and fragility function attributes (fragility development method, probabilistic distribution, damage states, and other relevant metadata like infrastructure description, regional applicability, and source reference). In addition, a fragility function rating scheme was developed and validated through expert solicitation. To enable easy access to the database, a Python-driven fragility function web application was developed using Pandas and Dash. The web application allows one to select, visualize, search, compare, and export fragility functions in the database. The database and web application may prove useful to utility managers to assess risk and make informed decision about their facilities.

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Probabilistic Seismic Risk Evaluation of the City of Los Angeles Water System Pipeline Network

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ABSTRACT

A seismically-resilient water lifeline system is critical for ensuring effective post-event response and rapid community recovery after disastrous earthquakes. To design, construct, and maintain seismically-resilient water systems, it is crucial that the damage potential of a pipeline system be quantified in future earthquakes. Mitigation strategies to address known vulnerabilities are essential in ensuring that system performance goals and criteria can be achieved with available resources. To assess the damage potential of a large water pipeline network, the following factors must be addressed: regional seismicity, spatial distribution of earthquake-induced shaking, and ground deformation (event footprint) in future events, pipeline fragilities, and department resources for emergency response. In this study, a large stochastic catalog of earthquake simulations, or an “event set,” that adapts the Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3) model is developed to represent the regional seismicity of the Los Angeles Basin. Random event footprints for each earthquake simulation are constructed by utilizing empirical ground motion models (GMMs) that are consistent with the 2014 United States Geological Survey (USGS)’s National Seismic Hazard Mapping Project (NSHMP). The spatial correlation of ground shaking intensity is also established by utilizing empirical spatial correlation models. This set of earthquake simulations more comprehensively captures the large uncertainties (both epistemic and aleatory) in seismic hazard models than simplified methods and is utilized to evaluate system-level consequences for the entire City of Los Angeles water pipeline network, measured by the total number of pipeline repairs and subsequent repair costs and times due to strong ground shaking and ground deformations. These estimates of damage and impact are based on empirical pipeline fragility models and restoration data from two past events that affected the water system in the past (1971 San Fernando and 1994 Northridge Earthquakes). System-level performance is then evaluated at various targeted probability levels and influential seismic sources are identified. This study was performed as part of a long-term program administered by the City of Los Angeles Department of Water and Power to quantify and ultimately enhance the seismic resilience of all city trunklines and distribution pipelines.

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A Taxonomy of Hazard Types: Classifying Lifeline Infrastructure System Failure Events between 1906 - 2019

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ABSTRACT

To enable urban settlements, infrastructural systems are planned and constructed to yield critical resource units of food (kCals), communication (mHz), energy (kWh), and water (MGDs), while also discharging units of waste (tons). The resource units produced, transmitted, and distributed by these lifeline systems have historically been generated beyond municipal extents and at industrial scales. As both transmission lengths and resource unit volumes increase, there is a corresponding level of risk to sustained operations of lifeline systems. This risk emanates from loads or forces that are either categorically intrinsic within the system's physical operation, or extrinsic from the larger environment in which the lifeline system is placed. These loads or forces are otherwise known as hazards.

Research engagement on hazards to lifeline systems is characterized by varying degrees of either disciplinary or geographic emphasis. Today, however, the expanded disciplines responsible for conceiving, developing and implementing lifeline infrastructure systems (Planning, Civil Engineering, and Architecture among others) seek non-biased design-actionable research featuring relevant hazard-based data sets and usable classification tools for informing resilient design requirements of future lifeline solutions operating in the 21st century. From an era in which the range of hazard types affecting lifeline systems is expanding, then all disciplinary stakeholders will benefit from an updated taxonometric assessment of hazard types for mitigating both regionally-familiar hazards of increasing frequency / strength, while also preparing for plausible hazards without regional precedent.

Hazards have been nominally classified as Natural, Anthropogenic or Technological. However, such broad classifications afford low design-actionability. What is the range of contemporary hazards any new infrastructure solution must anticipate for persistent operation in 21st century contexts? In other words, what are the types of hazards against which 21st century lifeline infrastructure solutions ought to consider and be designed to withstand?

This investigation yields a taxonometric table of hazard types and historical failure incidents exceeding current list-based categorizations. This engagement has canvassed (120) historical lifeline system failure incidents between 1906 and 2019, and each have been positioned into quadrants according to the hazard source (Natural or Unnatural) and the hazard location of origin (Internal or External). These quadrants reveal four primary orders of hazards: Natural Catastrophes, Mechanical Faults, Human / Animal Interventions, and Resource Depletions. Using classificatory techniques, these hazards and their subsets are sorted and classified into relational families, genus, and species. This taxonomy is then validated through the bottom-up situating of event-specific lifeline failure incidents as documented through both popular and scholarly sources. This taxonomy seeks to represent the demonstrated range of hazard types experienced globally between 1906-2019, and organizes them in a disciplinary-agnostic way for improved usability by planners, designers and engineers of future lifeline infrastructural solutions with resilient features.

Seismic Maintenance of Water Pipe Networks Using Stochastic Combinatorial Optimization

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ABSTRACT

Water pipe networks are one of the lifeline networks of modern cities. Despite the importance of these networks, empirical evidence shows substantial chance of these networks being damaged by seismic events causing significant disruption to their serviceability. To avoid such disruptions, utility managers often need to identify effective maintenance schemes while minimizing the use of limited rehabilitation budget. This identification is often made challenging by the inherent uncertainties associated with seismic events, uncertainty associated with seismic fragility estimation of water pipes, exponentially increasing decision space, and limited maintenance budget available to the utilities. Hence, there is a critical need of an effective approach to identify optimal seismic maintenance plans for minimizing post-earthquake serviceability loss. In this study, a stochastic combinatorial optimization formulation was used to model the problem. Monte Carlo simulation integrated with quasi-pressure driven hydraulic analysis was used to evaluate the serviceability of the network for each maintenance scheme. Two commonly used metaheuristics, namely genetic algorithm and simulated annealing, were used to identify the optimal maintenance scheme that minimizes the post-earthquake serviceability loss. The effectiveness of the methodology was demonstrated by using two city-scale water pipe networks as the test-beds. The performance of these metaheuristics were then compared in terms of their computational runtime and solution quality with each other and other commonly used algorithms in state-of-practice. The comparison showed that both genetic algorithm and simulated annealing based optimization can effectively identify economical seismic rehabilitation plans for city scale water pipe networks. The findings of this study are expected to be highly valuable to utility managers managing water pipe networks exposed to significant seismic risks.

Role of A Critical Infrastructure in Seismic Resilience of Multiple Lifeline Systems

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ABSTRACT

The Bangabondhu Bridge (originally named Jamuna Multipurpose Bridge) in Bangladesh is a critical connection between the east and west of the country. The 5 km long bridge across Jamuna, one of the largest rivers in the world in terms of flow volume, carries a 4-lane roadway, a rail track, a gas pipeline and a power transmission line. Opened in 1998 after decades of planning and nearly five years of construction the bridge was the first and up to this point the only fixed link between the two halves of the country. The road and railway carry significant volumes of passengers and freight within country of nearly 180 million people. Additionally, the link is being used by traffic to and from outside the country as part of South Asian Regional Road and Rail Network. The gas pipeline supplies natural gas from the east to the western part of the country for industrial and domestic use. The power lines are part of national grid distributing power among regions. Located within a region of considerable hazard and history of significant earthquakes, seismic resilience of the bridge is of paramount importance. Resilience of the infrastructure is evaluated in light of its significance within the four lifeline networks. Key risks and potential vulnerabilities are identified. Strategies for mitigation and contingencies are suggested.

Agents of Change for Resilient Infrastructure

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ABSTRACT

The effects of hurricanes with respect to infrastructure resilience are reviewed with reference to Hurricanes Katrina and Sandy. The effects of Hurricane Sandy on New York City and subsequent programs to improve the City's infrastructure are described. Special attention is focused on the restoration of the L Line Tunnel, which was flooded by Hurricane Sandy. A team from Cornell and Columbia Universities was assembled at the request of Governor Andrew Cuomo to help re-engineer a $1/2 billion project to rehabilitate the tunnel, and still keep the subway in service. The new approach integrates several advanced technologies, including distributed fiber optics and LiDAR. The project was a breakthrough in infrastructure restoration resulting from interdisciplinary work between civil and electrical engineers. No closure was necessary with the new design. The work was completed with weekend and nighttime closures of only one tube at a time, with two tubes operational during the daytime on weekdays. The project was completed successfully three months ahead of the revised schedule, six months ahead of the original design that required full tunnel shutdown, and under budget with more than $100 million of savings. The agents of change that lead to improved policies and approaches are explored, including the technical, institutional, and social challenges of introducing new technologies and engaging community support.

Next Generation Hazard Resilient Infrastructure

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ABSTRACT

The resilience of underground infrastructure to large ground deformation depends on the ability of pipelines, cables, and conduits to accommodate the geometric nonlinearities in soil by changing shape through axial elongation/compression, flexure, and rotation at joints. This work focuses on the development of the next generation hazard resilient infrastructure through large-scale testing and analytical and numerical modeling. With the assistance of the Cornell Large-Scale Lifelines Testing Facility, ten new pipeline and conduit systems have been developed and commercialized using a protocol of large-scale tests and fault rupture experiments that define and confirm performance under extreme conditions of ground deformation. Resilience involves the capacity of the pipelines to accommodate large ground deformation from earthquake-related movements associated with fault rupture, liquefaction, and landslides. It also involves the accommodation of ground movement caused by hurricanes, floods, tunneling, excavations, and subsidence related to mining and dewatering. The development and validation of analytical and numerical models for soil-structure interaction are described. The performance of the new systems is described, and examples of ductile iron, steel, polyvinyl chloride, and high and medium density polyethylene pipelines as well as pipelines reinforced with cured-in-place pipe and pipe liners are used to illustrate the performance of next generation hazard resilient infrastructure. Next steps in the development of hazard resilient infrastructure are discussed, which include the incorporation of smart sensor technologies and signal processing.

Fortifying Lifelines in Oregon's Coastal Communities

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ABSTRACT

Oregon's Coastal communities will be geographical isolated due to damaged highways after a Cascadia magnitude 9 earthquake at a time when providing medical care and shelters for residents and visitors including tsunami victims will be urgently needed. Efforts to help understand and mitigate earthquake risks to coastal hospitals are underway and coastal resilience priorities have been identified. Fortifying the 11 hospitals, including power and water supplies needed for their functionality, is critical for protecting lives and enhancing community resilience.

Identifying, or where lacking, creating facilities that can be used for sheltering tsunami refugees and mass care will help prepare the 11 communities with hospitals as well as the coastal population at large. Emergency response and recovery efforts will be conducted on transportation systems that have been severely damaged; nonstandard transportation methods and options will evolve after the disaster. Immediate response will be limited to locals and involve both official publicly-owned and privately-owned vehicles including boats, all-terrain vehicles and heavy machinery. Evacuation by air for the critically wounded will be limited due to insufficient resources. Initial response from State and Federal assistance will be by air. It will involve, but not be limited to, dropping medical and mass care supplies.

At this same time, reconnecting geographically isolated "coastal islands" caused by shaking and tsunami damage (e.g., collapsed bridges and landslides) will be required. Temporary road improvements and work-arounds that do not meet current standards-of-practice will be necessary. Examples include: installing culverts across open streams together with road fill materials; transporting people via all-terrain vehicles; and, ferrying people across waterways using private boats. A "push to connect" approach to connect disconnected routes (ie. "islands") from staging areas to supply critical facilities and communities is being explored. Fuel, which will be in high demand (e.g., for emergency generators) will be pushed out from fuel points of distribution (ie. FPODS) to hospitals.

Recovery will likely require temporary new modes of transportation that involve using beaches for vehicles and establishing a North-South waterway highway parallel to portions of U.S. coastal Highway 101. Priorities to improve coastal resilience are: 1) creating a lifeline backbone mitigation plan that would provide water and power to hospitals and may involve new water tanks and microgrids; and 2) developing a multimodal transportation plan for respond and recovery using a "push to reconnect" approach.

Seismic Resiliency Planning for Wastewater and Stormwater Infrastructure

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ABSTRACT

The City of Portland, Bureau of Environmental Services (BES), completed a Resiliency Master Plan (RMP) to develop a prioritized approach to improving resiliency to earthquakes and climate change for the City's stormwater and sanitary system infrastructure. Resiliency includes both reducing the risks of critical infrastructure failure prior to a natural disaster and improving the recovery time of the system after an event. With respect to seismic hazards, the RMP focuses on the risks associated with a Cascadia Subduction Zone Magnitude 9.0 earthquake. The RMP includes identification of backbone infrastructure, recovery targets to meet or exceed those established by the 2013 Oregon Resilience Plan, a seismic vulnerability analysis of pipes and critical pump stations, guidance for best design, construction, and administrative practices, and early and long-term actions including prioritized capital project for resiliency. The work covers 1) how an asset management framework was used to identify high risk infrastructure and build business cases for resilient investment; 2) how the RMP has strengthened BES' Continuity of Operations Plan; 3) the steps BES took to work with external infrastructure managers to address interdependencies; and 4) the communication methods used to raise awareness among ratepayers and staff to better prepare for earthquakes at home and in their work.

Digital Twin-Based Approach for Improving Infrastructure Resilience

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ABSTRACT

Over decades, cities have been growing. In the meantime, Cities are facing challenges to sustain economic and social development. Among the top challenges, infrastructure and its related are on the top of the list. For a city to be resilient, communities must be able to respond to a disaster after it strikes, so that the impact can be mitigated and communities can quickly recover, therefore resilient infrastructure is essential. To improve infrastructure resilience with adequate capacity for recovering to the designed performance after a hazard event, such as earthquake, hurricane etc., infrastructure must be well maintained, and community needs to be well prepared for hazard events so it can quickly recover to the designed performance or even better. This study presents Digital Twins (DT)-based approach and framework to help us to achieve the goal. Since it was originally introduced, the objective of a digital twin is to mitigate the undesirable emergent behavior. DT has been mostly employed by manufacture industry for Product Lifecycle Management (PLM), especially by NASA. DT is evolved from digital model with automatic data flow between virtual and physical space. For lifeline infrastructure systems these days, various data, including physical, mechanical and ambient data, are collected over time for constructing digital twin, represented by a set of digital models, including 3D reality model, data-driven model, physics-based models and decision-support models. The information derived from these models is to diagnose the potential undesirable behavior, evaluate and predict the performance, and eventually prescribe the solutions for improving the resilience of infrastructure. A few examples will be given to demonstrate how DT-based approach for rapid detection and location of urban water system anomaly, assessment of structural integrity with high-fidelity DT for monitoring structural systems and deep learning-assisted inspection in virtual space of digital twin. Therefore, it is believed that DT as an emerging trend is increasingly become the holistic approach for digital transformation of infrastructure industry, Although it does require for additional effort at data collection and mastering new technologies, it brings multiple benefits of cost- effectiveness and risk reduction for owners and stakeholders, eventually improves the resilience of lifeline infrastructure.

Impact of CyberShake on Risk Assessments for Distributed Infrastructure Systems

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ABSTRACT

In developing a seismically resilient infrastructure network, it is crucial to characterize the potential for system-level damage in future earthquakes. The probabilistic seismic risk analysis (PSRA) approach is typically used to account for 1) the correlation of system components damage that results from earthquake-induced shaking and ground failure hazards, and 2) the vast uncertainty in forecasting earthquake occurrences, ground shaking intensities and system responses. Conventionally, empirical ground motion models (GMMs) are used to quantify the spatially correlated ground motion hazard. One current weakness of such empirical GMMs is that they are typically developed from global ground motion datasets. They represent “average” source, path attenuation, and site response characteristics of global earthquakes, and are associated with large variability components that reflect a variety of crustal structures and conditions. The average ground motions in a specific region are often different from those from the global average and are expected to exhibit lower variability. Such differences in median and variability can lead to poorly centered and wider than necessary distributions of the risk metrics.

One approach to address the need for regional assessment of ground motions is to replace the global GMM output with simulated motions. Provided that the simulations have been properly validated, they should, in theory, include the source, path and site effects of a specific region. The Southern California Earthquake Center CyberShake platform was designed for that purpose as the first simulation-based probabilistic hazard model. CyberShake simulates over 400,000 earthquake ruptures and propagates waves through 3D velocity models, generating full time series. The approach is consistent with PSRA in which we use CyberShake results as the hazard component.

For this work, we build on a recent comprehensive PSRA study of the underground water pipeline network for the City of Los Angeles, where the system-level performance (measured by the expected number of pipeline repairs) was established as a function of exceedance probability based on a large set of events sampled from the UCERF3 earthquake source model. The study utilized the NGA-West2 GMMs to compute randomly sampled ground motions with a level of spatial correlation that is consistent with observations. By repeating our study using the events and simulations from CyberShake, we are exploring the impact of region-specific simulations on seismic risk and resilience assessments of distributed infrastructure. This work will serve as a proof-of-concept and is expected to provide guidance to the research and PSRA user communities.

Hazard-Resilient Infrastructure: An ASCE Manual of Practice on Analysis and Design

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ABSTRACT

According to the United Nations Office for Disaster Risk Reduction (UNDRR), half of the world's inhabitants, expected by 2025 to increase to roughly two-thirds, and the vast majority of property and wealth are concentrated in urban centers situated in locations already prone to major disasters, such as earthquakes and severe droughts, and along flood-prone coastlines. The "Sendai Declaration", among other things, called for the strengthening of disaster risk reduction to mitigate loss of lives and assets worldwide. In other words, a call to strengthen critical infrastructure. Infrastructure systems are essential for supporting communities, changing the equity imbalance, and increasing resilience. It is therefore essential to develop means for increasing infrastructure system resilience against severe hazards.

Civil infrastructure systems traditionally have been designed, constructed, operated and maintained for appropriate probabilities of functionality, durability and safety while exposed to extremes during their full-service lives. Examining systems in the context of resilience would add proper considerations for adaptability to changing conditions including recovery.

This work introduces an ASCE Manual of Practice (MOP) on Hazard-Resilient Infrastructure. The purpose of this MOP is to provide guidance for and contribute to the development or enhancement of standards for hazard-resilient infrastructure. The goal is to transform our infrastructure and make them hazard resilient. The framework provided in this MOP emphasizes infrastructure systems and how they support community resilience.

The underlying approaches in this MOP are based on using probabilistic methods for risk analysis and management for infrastructure projects in order to effectively address uncertainties within a planning horizon timeframe. The approach provided herein focuses on identifying and analyzing hazards, system failure, associated probabilities and consequences including direct and indirect losses, failure and recovery profiles, quantification of resilience, impacts on communities, the economics of resilience, and technologies for enhancing resilience for new as well as existing infrastructure.

Probabilistic Resilience Distance Indices and Application for Power-distribution Systems

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ABSTRACT

Holling in 1973 first introduced the concept of system resilience for ecological systems; then, the notion of resilience was defined for civil structures, infrastructure systems, and communities by Bruneau et al. in 2003. To quantify system resilience, four essential properties are recognized, including resourcefulness, robustness, redundancy, and rapidity in the physical, technical, organizational, and socioeconomic dimensions. Since then, several system resilience assessment methodologies (such as tools, software, models/framework, indices, and scorecards) have been developed for communities or different categories of infrastructure systems or structures considering different hazards. It is notable that numerous quantitative or qualitative resilience measures, or ambiguously termed as metrics, are found in the literature, which aim to quantify the 'amount' of resilience in a system leading to resilience measurement. However, objective decisions based on such measurements are not ready to make. First, such measurement is random in nature as a result of incorporating uncertainties from hazardous inputs, material properties, and epistemic ones from modeling assumptions (e.g., physical models for structures and social-economical models for resourcefulness). Second, the ingrained drawback of such measurements is its lack of theoretical basis in discriminating relatively that how a parametric infrastructure system is more resilient than a different one or the same one subject to some changed conditions.

This study thus presents a twofold purpose. First, several statistical or information-theoretic resilience-distance (RD) measures and strictly defined mathematical metrics are proposed termed as Resilience Distance Indices (RDIs). Among studying the effects of different system resilience parameters, it provides a rigorous basis for hypothesis testing if a resilience measure due to resourcefulness improvement or material retrofitting is acceptable or how close when compared to the targeted resilience of the same system. More significantly, a resilience aggravation analysis (RAA) model is proposed for objectively characterizing how system resilience dynamically varies with critical resilience parameters. Second, we will present the application of this RDI framework to an electric power distribution system in a rural area and demonstrate its effectiveness in measuring the contribution of material protection methods and organizational/technical resourcefulness to probabilistic gains in resilience.

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San Andreas Fault Displacement Hazard Characterization of the Los Angeles Aqueduct at Elizabeth Tunnel

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ABSTRACT

The Los Angeles Aqueduct serves an important function within the Los Angeles Department of Water and Power (LADWP) system by transporting water from Owens Valley to the northern San Fernando Valley. The aqueduct is vulnerable to multiple geological hazards along its route, but a major engineering challenge to risk mitigation is the aqueduct's crossing of the San Andreas fault (SAF) in the five-mile-long Elizabeth Tunnel near Lake Hughes. Future earthquake ruptures on the SAF have the potential to completely sever the ~10 ft-wide tunnel and disrupt theoperation of one of LADWP's critical lifelines. Fault characterization studies and fault displacement hazard analyses were performed for the SAF at the tunnel crossing to support the development of design concepts to improve the resilience of the tunnel and the water system. The location, width, and complexity of the SAF at the tunnel crossing were poorly understood prior to field investigations due to indistinct geomorphic expression and historical grading. Following extensive geologic and geomorphic mapping, cone penetration testing, rock coring, petrographic analysis, and down-hole geophysical data collection, an integrated geological model was developed that characterizes the SAF locally as a steeply south-dipping zone of faults that narrows and coalesces from the surface to tunnel depth. Angled core borings penetrated a wide zone (>550 feet) of fault-damaged rock containing a few thick zones of cataclasite and ultracataclasite that represent major fault strands. Surrounding these major fault strands are a multitude of very thin faults and shears within the rock mass. Probabilistic fault displacement hazard analyses utilized a source characterization for the Mojave section of the SAF that is consistent with nearby paleoseismic data constraints, and mean hazard and hazard fractiles were generated to explore the annual exceedance frequency-net displacement relationship and model uncertainties. New LADWP performance-based seismic design guidelines classify the Elizabeth Tunnel in the highest criticality category and specify both a 2,475-year probabilistic fault displacement and deterministic fault displacement based on an **M**8.3 SAF scenario earthquake. The extremely large calculated displacement hazard values developed in accordance with the design guidelines were compared with average and maximum surface displacements from a global data set of large, continental strike-slip earthquakes to develop final estimates of fault displacement hazard at the tunnel crossing. The SAF location, width, and complexity at Elizabeth Tunnel, as well as the displacement hazard results, are being used as input to develop design alternatives for a more resilient Los Angeles Aqueduct crossing of the SAF.

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Monte Carlo Simulation to Perform Liquefaction Evaluation of Conveyance Systems

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ABSTRACT

A commonly accepted procedure in evaluation of liquefaction potential of a building site in a seismic zone is to perform field investigations including standard penetration tests (SPT), and use simplified analysis to estimate the cyclic resistance ratio (CRR) and cyclic stress ratio (CSR) with depth of saturated young alluvium. Comparing CSR and CRR profiles, liquefaction of soil deposits is evaluated. Field investigations can be very expensive for the evaluation of buried pipelines, which may traverse through miles of liquefaction zones and would require numerous tests. Liquefaction phenomenon as a natural process is inherently random and affected by the earthquake magnitude, ground acceleration, soil type and relative density, overburden pressure, thickness of liquefiable soil, and depth to groundwater and their corresponding variabilities. The state of such processes is naturally indeterminate and thus cannot be described with certainty. For these reasons, decisions required for emergency planning of possible pipeline failure are invariably made under similar conditions of uncertainty. The quantification of the uncertainties and proper evaluation of their effects on the performance of a pipeline can be estimated by the Monte Carlo simulation (MCS). MCS provides a mathematical basis in which uncertainties are identified, quantified, and combined in a rational manner. The process can provide a more complete picture of the liquefaction hazard along a pipeline alignment. MCS to estimate liquefaction hazard includes metrics from the pipeline alignment, a liquefaction susceptibility map, locations of active faults, earthquake recurrence models, magnitude-rupture length models, ground motion prediction models, a magnitude-farthest distance of liquefied sites model, a non-liquefied surface layer thickness-liquefied layer thickness model, and a frequency distribution of normalized post-liquefaction reconsolidation settlements. A computer program is developed to perform MCS while considering faults and modeling the pipeline by 3-D linear elastic beams connected by nodes. Each node has six degrees of freedom; three translations and three rotations. Engineering properties and bending/shear/tension capacities of the pipeline are specified. In each simulation, post- liquefaction reconsolidation settlements are calculated and provided as input into the finite element (FE) analysis to estimate bending/shear/tension demands. Comparing demands with capacities, the program identifies which nodes would fail. By repeating the simulation over million times, the program estimates an annual probability of liquefaction/pipeline failures, which are then converted to the probability of exceedance for a given exposure time using the Poisson Model. This study discusses the MCS/FE analyses for the response of a hypothetical pipeline crossing liquefaction zones in San Fernando Valley and Los Angeles basin due to earthquakes from the San Andreas Fault and Newport-Inglewood Fault.

Monte Carlo Simulation to Perform PFRHA of Colorado River Aqueduct Crossing Southern San Andreas Fault at San Gorgonio Pass

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ABSTRACT

Deterministic fault rupture hazard analysis (DFRHA) provides a straightforward framework for evaluating the potential extent of horizontal and vertical surface fault displacements at a pipeline crossing for specific magnitude earthquake scenarios. However, this approach is limited in quantifying the aleatory and epistemic uncertainties that come with characterizing the parameters that control the amount of slip occurring across a fault, the frequency of different magnitude events occurring during the design life of a facility, and the distribution of the different amounts of surface displacements that occur along a rupturing fault relative to the location of a pipeline. As such, fault rupture phenomenon as a natural process is inherently random. The states of such processes are naturally indeterminate and thus cannot be described with certainty. For these reasons, decisions required for emergency planning of possible pipeline failure are invariably made under similar conditions of uncertainty. The quantification of the uncertainties and proper evaluation of their effects on the fault rupture at pipeline crossings can be estimated by the Monte Carlo simulation (MCS). MCS provides a mathematical basis in which the uncertainties are identified, quantified, and combined in a rational manner, while providing a more complete picture of the fault rupture hazard at the pipeline crossings. MCS includes metrics from the pipeline alignment at fault crossings, locations of the faults, earthquake recurrence models, magnitude-rupture length models. This work covers a probabilistic fault rupture hazard analysis (PFRHA) as a compliment to the DFRHA of fault displacements at a pipeline crossing. A computer program is developed to perform PFRHA using the MCS. MCS accounts for uncertainties in the PFRHA by using the principal of probability and furnishes a fault rupture hazard curve at the pipeline crossing, which is then converted to the probability of exceedance for a given exposure time using the Poisson Model. The analysis results are shown in terms of annual probabilities, average return periods, and magnitude range for horizontal/vertical offsets. The method is illustrated by an application to the Metropolitan Water District of Southern California's Colorado River Aqueduct (CRA), where it crosses the San Andreas fault system at San Gorgonio Pass.

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Geologic Hazard Characterization for Metropolitan Water District's Replacement of Casa Loma Siphon Barrel No. 1 Project, San Jacinto, California

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ABSTRACT

The Casa Loma Siphon Barrel No. 1 is a critical lifeline within Metropolitan Water District of Southern California's (Metropolitan) water delivery system. The 148-in diameter siphon was constructed in the 1930s as part of the Colorado River Aqueduct and conveys water through the San Jacinto valley across the San Jacinto fault zone (SJFZ) in Riverside County. Evidence of cracking and leakage due to non-tectonic settlement (0.6–1.0 in/yr) was noted in the 1960s and appears concentrated where the siphon crosses a strand of the SJFZ named the Casa Loma fault (CLF). Continued settlement and leakage suggest the siphon is potentially susceptible to failure due to tectonic and non-tectonic displacements. The SJFZ presents a significant engineering challenge for pipeline retrofit design because it is one of the most seismically active faults in southern California and paleoseismic studies suggest it has produced large coseismic surface displacements (>8.2–13.1 ft).

This study presents the results of a geologic characterization conducted for a retrofit project designed to improve the siphon's seismic resiliency against potential future ground deformation. Work included paleoseismic trenching at the siphon fault crossing, analysis of historical settlement data, and deterministic and probabilistic fault displacement estimates to develop key fault crossing parameters (displacement amount and direction, fault zone location, distribution of deformation, and style of faulting) used in the retrofit design. This study estimates deterministic and probabilistic coseismic displacements that range from 12 to 14 ft, which agrees with other paleoseismic estimates along the fault. Ultimately, the pipeline was designed to accommodate 12.8 ft of coseismic horizontal surface displacement (2,475-year return period) on the CLF and 3.0 ft of settlement for a 50-year design life.

The project's chosen retrofit design includes the Kubota Corporation's earthquake-resistant ductile iron pipe (ERDIP) to accommodate both the tectonic and non-tectonic ground displacements. To help distribute potential narrow "knife edge" tectonic ground displacements, the project team explored using Expanded Polystyrene Geofoam backfill in conjunction with ERDIP. The rate of surface rupture propagation ("rise time") was estimated to confirm the suitability of geofoam backfill material since this material has a strain-rate dependent behavior. This project illustrates the importance of detailed geologic investigations in seismic retrofit projects for the design of pipelines to accommodate large coseismic surface displacements. See companion efforts by Chau et al. (2021) and Baune et al. (2021) for further details about Metropolitan's seismic resilience efforts and details of this project's engineering design.

West Shore Lake Oroville Lineament Geologic Investigation, Northern California

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ABSTRACT

The ML5.7 1975 Oroville earthquake occurred seven years after construction of Oroville Dam, the tallest earth-fill embankment dam in the United States. The Oroville earthquake and aftershocks resulted in recognition of Quaternary activity along the Cleveland Hill fault (CHF), Swain Ravine fault zone (SRF), located west of the Foothills fault system, where the seismic hazard is relatively low based on moderate earthquake activity and small co-seismic displacements. For relicensing, LiDAR data was acquired to evaluate the possible northward extension of the CHF. An approximately 10 km-long, north-south oriented zone of topographic lineaments were identified in the LiDAR along the West Shore of Lake Oroville (WSLO) north of Oroville Dam. The lineaments are coincident with the northern projection of the CHF and are expressed as scarps, benches, and saddles along the steep slopes of WSLO. In order to assess the origin of the lineaments, and determine whether or not the prominent lineament is related to recent fault activity that could pose a co-seismic surface rupture potential at Oroville Dam, our study integrated geomorphic mapping, field reconnaissance, and four trenches across the lineament. Detailed mapping documented a roughly north-south oriented bedrock fabric throughout the region associated with a series of parallel lineaments. Field reconnaissance and trench exposures revealed a robust correlation between strength of the Jurassic meta-volcanic bedrock and localized erosion and slope failures. These surface processes exploit weaker zones within the bedrock, resulting in differential erosion and stepped topography. The stepped topography is accentuated by side-hill benches formed by colluvium that infills areas between resistant bedrock zones. The result is a youthful zone of topographic lineaments. Furthermore, a clay-rich saprolitic unit (~175 ka) was mapped in trench T3 that crosses the lineament in Bear Meadow. No faulting or deformation was observed in the saprolite; therefore, precluding an active fault consideration.

2.5D Ground Motion Effects from Excitation of Underground Tunnels by Obliquely Incident Seismic Waves

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ABSTRACT

The ground motion around underground tunnels can vary significantly from the free-field ground motion due to wave scattering which can influence the seismic demand for the design of the aboveground structures. Although wave scattering has received considerable interest by geophysicists, seismologists and engineers, neither building codes nor seismic design guidelines have yet considered this matter. Considering wave scattering by underground tunnels, the majority of existing studies examine two-dimensional (2D) plane-strain models assuming that the incident seismic waves propagate perpendicular to the longitudinal axis of the tunnels, which accounts for scattering effects in a 2D manner only. It is a common perception that considering vertically incident seismic waves is a conservative assumption for seismic design. Nevertheless, the propagation direction of seismic waves is arbitrary and not necessarily perpendicular to the tunnel axis, with the wave scattering effects having a three-dimensional (3D) character.

This study presents findings from a 2.5D hybrid Finite Element-Boundary Element (FE-BE) numerical simulation of an underground tunnel subjected to obliquely incident seismic waves propagated from the bedrock with arbitrary angles. The soil is assumed to be saturated and modeled as a two-phase medium based on the Biot's theory. The soil nonlinearity is dealt with an equivalent linear approach. The objectives of this numerical study are to: (1) investigate the amplification of the ground motion due to the presence of the underground tunnel, by examining the differences in the peak ground accelerations and acceleration response spectra between the ground motion around the underground tunnel and the free-field motion; (2) develop practical factors that can adjust the free-field predictions to account for obliquely incident seismic waves around the underground tunnel for seismic design.

It is shown that the presentence of the underground tunnel can cause significant amplification of the peak ground accelerations, and the amplification factors are larger for the oblique incidence cases than the vertical incidence case. The effects of the underground tunnel on the acceleration response spectra are also noticeable, and in particular, the oblique incidence cases may give rise to large spectral accelerations for long periods, especially for the vertical spectral accelerations. It is also shown that the vertical ground motion is significant and cannot be overlooked, and the traditional vertical-to-horizontal ground motion ratio 0.65 can result in either underestimates or overestimates of the expected vertical ground motions, depending on the angle of incident seismic waves. The findings highlight that the influence of underground tunnels should be carefully considered in order to improve the seismic design of the aboveground structures which relies on proper input motions that account for below-ground effects.

Seismic Performance of PVC-U Pipe and Design Prediction Tool

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ABSTRACT

The 2010-2011 Canterbury Earthquake Sequence (CES) in New Zealand caused significant damage to the region's buried horizontal infrastructure. Based on the authors' investigations following the earthquake events, they observed that the underground pipes have signature failure modes that are unique to the material that the pipe is made from. They noted that some pipes, such as those made of PVC, do not fail under one mechanism alone, but have multiple failure modes depending on material characteristics, soil conditions, and direction of the earthquake forces acting on the pipeline.

In New Zealand, the pipes used are generally tested with respect to all expected significant loadings as specified by material standards, such as AS/NZS 1477 for PVC pipes. However, the amount of damage to pipe joints observed following the CES appear to indicate that adding an axial joint load to the tests already mandated would greatly enhance the seismic design of pipes.

For this purpose, an experimental investigation is completed on DN225 mm PVC-U pipe joints to ascertain the serviceability and ultimate limit state allowable loads when a pipe joint is subjected to axial seismic-simulated actions. The experimental results are able to replicate the observed earthquake damage by incorporating forces simulating peak ground accelerations in both the horizontal and vertical directions in the testing. Based on the observations, a theoretical framework was developed to illustrate how seismically-induced axial forces can be generated in the joint of an underground pipe. While it is acknowledged that the joint capacity of pipe is conventionally assessed through fragility predictions of peak ground velocity (for wave propagation issues) and peak ground deformation (for ground strain issues), the incorporation of peak ground acceleration may be necessary to complete the design. While the approach presented is considered as a first-order check and does not account for ground strains, ground displacements, or tensile actions, it allows simplistic multi-scenario comparative analysis to be done with relative ease.

This research output suggests that the existing compliance pipe standards can be easily modified to better replicate the observed seismic pipe damage and the proposed theoretical framework could be used to improve decision-support-systems models used by buried infrastructure asset owners to provide better post-disaster functionality information on their pipelines.

MICP Treatment to Mitigate Soil Liquefaction Induced Building Settlements

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ABSTRACT

Liquefaction induced building settlement can cause extensive damage to buildings and infrastructure, and therefore ground improvement of the underlying soil can be necessary. Microbial induced calcium carbonate precipitation (MICP) is a natural and sustainable soil improvement method that increases the strength, stiffness and liquefaction resistance of soils. The efficacy of MICP treatment to reduce foundation settlement was studied in a centrifuge test. The test was performed on the 9 m radius centrifuge at the UC Davis Center for Geotechnical Modeling at a gravitation acceleration of 60g. The model was divided to three sections, an untreated zone, a MICP zone treated to 6 m depth, and a MICP zone treated to 13 m depth. The cemented zones were prepared pluviating sand to Dr = 40% and applying MICP treatment to achieve a moderate cementation level (Vs = 500 m/s). The soil profile contained loose sand pockets at different depths within a dense sand.

Accelerometers, pore pressure transducers, bender elements and linear potentiometers were used to measure the soil and structure response during shaking, while CPT profiles were used to characterize the soil conditions. Six pairs of shallow foundations were place in each of the three sections, which each foundation applying a contact pressure of 230 kPa. The model was subjected to five sinusoidal dynamic shaking events with the acceleration amplitude ranging from 0.03g to 0.5g. The MICP treatment improved liquefaction resistance of the soil and the presence of loose and dense sand layers near the MICP treated sand affected the dynamic response and settlement of the soil and foundation systems. The MICP treatment significantly decreased the total and differential settlement of the shallow foundations. The mechanisms that contributed to the foundation settlements placed on MICP treated soils include volumetric settlement, punching settlement and bearing capacity failure.

Techno-Economic Assessment of Liquefaction Mitigation by Microbially Induced Desaturation

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ABSTRACT

Microbially induced desaturation (MID) is a novel, minimally disruptive biogeochemical technique for mitigating the potential for triggering earthquake-induced soil liquefaction. In MID, native microorganisms are stimulated to produce relatively insoluble nitrogen biogas, thereby desaturating the soil. Its minimally disruptive nature makes MID particularly attractive for mitigating liquefaction triggering beneath and around existing facilities, where current mitigation techniques are generally either not applicable due to their disruptive nature or too costly to be economically viable for all but the most critical facilities. Considering the large inventory of existing infrastructure built on or in potentially liquefiable soil, a cost-effective means of mitigating triggering of liquefaction in a minimally disruptively manner could significantly enhance seismic resilience worldwide. The key technical factors influencing the effectiveness of MID for mitigation of liquefaction triggering include delivery of the nutrients for generation of biogas in the liquefaction susceptible soils, the persistence of the induced desaturation, and the impact of local environmental conditions, including groundwater pH and the presence of alternative electron acceptors, e.g. sulfate. Economic analysis suggests that if these technical factors can be managed, MID can be a cost-effective means to mitigate liquefaction triggering beneath and around existing infrastructure.

Field Monitoring of the Persistence of Microbially-Induced Desaturation in Silty Soils for Mitigation of Earthquake Induced Soil Liquefaction

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ABSTRACT

Earthquake liquefaction hazard in silty soils is a critical problem for infrastructures in Portland, Oregon, and other areas around the world for which there currently exists no cost-effective solution to improve the soils beneath and around existing facilities. This is particularly important for the lifelines within the Critical Energy Infrastructure (CEI) hub in northwest Portland, where 90% of Oregon's liquid fuel and all jet fuels for Portland's airport are handled. It is essential from both a seismic safety and seismic resilience perspective to be able to mitigate liquefaction potential in these areas in a cost-effective manner. Recent studies suggest that liquefaction mitigation using microbially induced desaturation (MID) may provide the capability to do this. The objective of MID is to reduce the generation of earthquake-induced excess pore water pressure compared to saturated soils, and thereby reduce the potential for triggering liquefaction. A field trial study of liquefaction mitigation using MID was performed at two sites in Portland in the summer of 2019 as a collaborative effort between Portland State University, Arizona State University researchers from the Center for Bio-mediated and Bio-inspired Geotechnics, and the University of Texas at Austin. The low-plasticity, liquefiable silts were treated using MID by injecting nutrients to stimulate native bacteria for a duration of four weeks. Crosshole pressure-wave velocity measurements, a vertical array of embedded sensors that measure water content and electrical conductivity, pre- and post-treatment seismic cone penetration tests, and direct soil sampling from treated soils indicated that liquefiable soils were successfully desaturated at both sites. Monitoring the persistence of desaturation is ongoing at one site and was performed for 9 months following treatment at the other site. The results indicate that the induced desaturation persisted through seasonal fluctuations of the ground water table since the end of treatment. These data, which document the longevity of MID, are particularly important to establish this innovative technique as a viable option for liquefaction mitigation of silty soils underneath the fuel tanks in the CEI hub and in liquefiable silty soil that threaten lifelines worldwide.

Evaluating Cyclic Loading Response of a Low Plasticity Silt with Laboratory and In- Situ Cyclic Loading Tests

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ABSTRACT

The cyclic response of saturated soils to earthquake loading can cause ground failures which can severely damage lifeline infrastructures. The earthquake-induced ground failure in saturated soils is attributed to two mechanisms: sand-like generation of excess pore pressure or clay-like cyclic softening. However, the cyclic behavior of soils that are intermediate to sands and clays ("intermediate soils") such as non-plastic or low plasticity silt is not well understood. It is particularly important to study the cyclic behavior of low plasticity intermediate soils in the Pacific Northwest because many critical infrastructures and lifelines in this region overlay young, fine grained, low plasticity silty soils. Furthermore, the anticipated magnitude 9.0 Cascadia Subduction Zone earthquake is expected to result in high intensity shakings with long durations. This research describes a laboratory and in-situ cyclic testing program to characterize cyclic behavior for a fine grained low plasticity soil (plasticity index less than 15) at a site in Portland, Oregon. The soils at the site are similar to those at the Portland International Airport and those that underlie levees along the Columbia River. The cyclic behavior of these soils was characterized with cyclic direct simple shear (DSS) tests, resonant column torsional shear tests, and in-situ cyclic testing with the NHERI@UTexas large mobile shakers TREX and Rattler. The results of this testing program are used to evaluate the soil's potential to develop excess pore water pressure with cyclic shear strains ranging from 0.0001% to 3%. The results of cyclic DSS laboratory tests are compared to resonant column torsional shear and in-situ cyclic tests to discuss the effects of different cyclic loadings on the soil's cyclic behavior during earthquakes. These data will contribute to the larger body of knowledge of the cyclic behavior of low plasticity silts.

Site Specific Seismic Ground Motion Analysis in New York City Area – A Case Study

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ABSTRACT

This project is part of the planned reconfiguration of terminal at LaGuardia (LGA) Airport in Flushing, New York. Based on the results of subsurface exploration program, the stratigraphy of the site consists of fill underlain by organic silt/clay, underlain by sand, underlain by varved clay and silt, underlain by sand, glacial till, and bedrock. Initial liquefaction susceptibility evaluation using the New York City Building Code (NYCBC)-based liquefaction screening tool indicated that the Fill stratum may be susceptible to liquefaction. The site is assigned Seismic Site Class F, therefore in accordance with the NYCBC, it requires a site-specific response analysis to determine seismic parameters for the Site.

In order to develop design seismic soil profiles, additional Seismic Cone Penetration Tests (SCPT) were performed to collect shear wave velocity data. A site-specific ground motion analysis was conducted to develop a design acceleration response spectrum in accordance with the applicable provisions of ASCE 7 and NYCBC, using dynamic soil properties. Based on the results of the site-specific analysis, the liquefaction analysis was revised.

Liquefaction risk and liquefaction-induced settlements were reduced significantly utilizing site-specific analysis results. The case study demonstrates in addition to Code compliance, how performing site-specific seismic studies can be cost efficient solutions for projects to potentially reduce site classification, spectral acceleration, dynamic loads, thus reduce design and construction costs.

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Comparing Existing and Novel Methodologies for Estimating Risk of Liquefaction Triggering and Damage

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ABSTRACT

Estimating the probability that liquefaction will occur at a given site (i.e., whether liquefaction will be triggered in the soil profile) is a critical first step in calculating the seismic risk on lifelines and structures, such as lateral spreading and ground settlement. Several methodologies for estimating this probability exist in the literature. The majority of these methods are based on estimating the factor of safety against liquefaction triggering throughout the soil profile and condensing that information into an index such as the liquefaction potential index (LPI). After formulating the index, the probability of liquefaction-induced damage can be estimated qualitatively (e.g., "severe" liquefaction damage is expected for indices above a threshold) or quantitatively through fragility curves developed using global databases of observations of surficial liquefaction manifestations. Although insightful, these methods don't consider layer-to-layer interaction, and their reliability has been questioned in previous case histories involving substantial stratigraphic variability. We propose two novel methods and compare them with the traditional methods, such as LPI. The first involves probabilistic estimation of the excess pore pressure ratio and shear strain in the soil profile. These probabilistic models include the influence of layer-specific properties (such as the thickness, relative density, and proxies for the hydraulic conductivity of susceptible layers), profile-specific properties (such as the total deposit depth), ground motion characteristics, and layer-to-layer interaction proxies. The second applies a method common in performance-based earthquake engineering (PBEE) of structures – incremental dynamic analysis – to analysis of a soil profile. This approach consists of performing nonlinear site response analyses at multiple ground motion intensity levels, with or without consideration of site-specific hazard during ground motion selection. We apply the existing and novel methods to a hypothetical site in Los Angeles, California and discuss the advantages and disadvantages of each approach in design. The implications of these advantages and disadvantages for the design and analysis of lifeline systems are also discussed.

Evaluation of the Liquefaction Hazard for Sites and Embankments Improved with Dense Granular Columns

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ABSTRACT

Over the past few decades, dense granular columns (DGC) have become a common soil improvement strategy for critical embankment structures founded on potentially liquefiable deposits. The state-of-practice for the design of DGCs is limited to simplified methods that consider, separately or in a de-coupled manner, the three primary liquefaction-mitigation mechanisms provided by these columns: (i) installation-induced densification; (ii) enhanced drainage; and (iii) shear reinforcement. Critical aspects, such as the effects of soil-column-embankment interaction, site characteristics and layer-to-layer interaction, ground motion characteristics beyond the peak ground acceleration, and the total uncertainty (to name a few), are not included in current engineering design procedures.

This shortcoming prevents a more reliable, performance-based evaluation of the liquefaction hazard in sites improved with DGCs. In this work, we present results from a numerical parametric study, previously validated against dynamic centrifuge test results, to evaluate the liquefaction hazard in layered profiles improved with DGCs. The criteria for various degrees of liquefaction is based on excess pore pressure ratios and shear strains observed within each layer. Our study includes different properties and geometries for both soil and DGCs, various confining pressures induced by an overlying embankment, as well as a large collection of ground motions from shallow crustal and subduction earthquakes. We performed a total of 30,000 3D, fully-coupled, nonlinear, dynamic finite-element (FE) simulations in OpenSees using a state-of-the-art soil constitutive model (PDMY02), whose properties were calibrated based on both element level laboratory tests and a free-field boundary-value problem modeled in the centrifuge. The results from this parametric study are used to propose a probabilistic predictive model for the triggering of liquefaction in embankment sites treated with DGCs.

Support for Peak Ground Velocity in the U.S. Geological Survey National Seismic Hazard Model

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ABSTRACT

The U.S. Geologic Survey (USGS) routinely updates the National Seismic Hazard Model (NSHM) for the United States and its territories. The NSHM has historically supported calculation of probabilistic seismic hazard for pseudo-spectral accelerations at three periods (0, 0.2, and 1 s) and one reference site condition (a time-averaged 30-m shear-wave velocity of VS30 = 760 m/s) as required for the design ground motion maps of the NEHRP Recommended Seismic Provisions for New Buildings and Other Structures and other building-code documents.

With the recent 2018 update the NSHM expanded support in the conterminous United States to 22 spectral periods and 8 site conditions ranging from VS30 = 1500 m/s (Site Class A) to VS30 = 150 m/s (Site Class E), as required by the 2020 NEHRP Provisions. Expanding support to more periods and site conditions was made possible largely by adoption of the NGA-East ground motion models (GMMs) for the stable craton of the central and eastern United States. The USGS is now expanding support to additional intensity measure types. Here, we present the incorporation of peak ground velocity (PGV) in the NSHM. The NGA-East models include PGV, as do many GMMs used to estimate earthquake ground motions in the active crust and subduction zone tectonic environments of the western United States. For those GMMs considered in the NSHM that do not natively support PGV, we use a newly developed conditional model to estimate PGV given values of pseudo-spectral acceleration (PSA). Unlike prior models that are conditioned on a single spectral period, the period used in the new model is magnitude dependent. The model introduces a parameter TPGV, which refers to the spectral period with the highest correlation between PSA and PGV at the given magnitude. This feature captures the magnitude scaling observed in the corner frequency of the earthquake source and also leads to an improved model of aleatory variability. The model is derived from observations in an active tectonic regions and we explore its application to other tectonic environments. We also provide an overview of USGS web services and applications that provide online access to PGV estimates from the NSHM.

An Introduction to the Modeling of Active Fault Zones Width's Effect on the Qualitative Deformation of Lifelines and their Routing (Case Study: Buried Gas Pipelines in East of Iran)

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ABSTRACT

Among the many factors causing damage to lifelines, there are active faults along the pipeline route that can cause fracture and breakdown of the pipeline if it is justified. Thus, during pipeline route study phase, detailed geological work on the route should be undertaken and fault paths identified. It is therefore essential to study the structures of the study area in order to select the appropriate path.

Due to crossing of Iranshahr-Mirjaveh gas pipeline in the eastern part of Iran at the intersection with the southern terminals of the Nehbandan fault system, careful study of the geology and structural interpretation of these faults in terms of damage to the pipeline is necessary. Therefore, in this study, using tectonic seismic studies, field surveys and etc., active faults are accurately identified and differentiated by modeling displacement and damages considering fault width at intersection with lifelines (buried gas pipelines) have been measured and evaluated.

On the other hand, it is very difficult to prevent seismic events and predict the exact time of earthquakes. However, with public education, there can be a significant reduction in earthquake damage. Detailed geological and seismio-tectonic examination of each area and the combination of these findings with the results of statistical and probabilistic studies on earthquakes occurring in each area, have the important role in maintaining sustainability as well as continuing the exploit of some things we are going to build.

Therefore, in this study, considering a specific area in eastern Iran and using available software to simulate the active fault and analyze their effects on pipelines and considering the impact of active fault zones on three issues selected (strike slip, strike slip- reverse and reverse faults) have been investigated to improve the design parameters routing of lifelines (buried gas pipelines) in the future.

Approach for the Fundamental Mode Shape of Layered Soil Profiles

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ABSTRACT

The fundamental mode shape of layered soil profiles is a key site response parameter, it has been adopted into the Japanese seismic code to represent the shape of soil displacement response along the vertical direction. In this study, a simple approach for estimating the fundamental mode shape of layered soil profiles was developed. The equilibrium between the inertial and elastic forces at the soil-layer interface is used. The proposed approach can directly model the fundamental mode shape and can be conveniently implemented using a hand, thus making it suitable for use by practicing engineers. The assessments of the proposed approach using a series of layered soil profiles demonstrates that it can produce results in close agreement with the actual results.

Deep, Dynamic In-Situ Excess Pore Pressure Response of a Medium Dense Sand

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ABSTRACT

The Port of Portland has identified the deep and thick deposit of medium dense sands underlying its runways and terminals as a significant risk to post-earthquake recovery. Efforts to design mitigation of liquefaction- and lateral spreading below its runways have been complicated by the inability to easily sample these soils and the lack of case history data on the performance of medium dense sands at depth. This study describes a joint agency-industry-university collaboration to quantify the dynamic response of such soils at depth using controlled blasting tests conducted at the Port of Portland. The experimental field-testing program is described, including the geotechnical characterization of the deposit, instrumentation, and blasting program. The typical characteristics of the blast-induced ground motions are quantified to highlight the reduced significance of P-waves, owing to their frequency content, in the dynamic response of the sand. Following the presentation and discussion of typical shear strain and corresponding excess pore pressure time histories for various blasts, the relationship between shear strain and excess pore pressure is quantified in the medium dense sands at an average depth of 25 meters and 2.5 atmospheres of vertical effective stress. The relationship between shear strain and excess pore pressure will be used by the Port and its consultants to calibrate constitutive models used to assess various ground improvement alternatives.

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Macro & Micro Liquefaction Hazard Mapping for Electronic Power Utility Tunnel In Korea

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ABSTRACT

The largest earthquake in Gyeongju Occurred in 2016 since the earthquake observation. And the following year, there was the Pohang earthquake that caused the largest earthquake damage ever. Especially, the Pohang Earthquake caused the liquefaction phenomenon in the sedimentation area of the coast.

In this study, we investigated the seismic vulnerability of the liquefaction in the electric power utility tunnel in the whole area of South Korea. In the analysis of seismic liquefaction vulnerability, the earthquake with return period 1,000 years and liquefaction potential index are used. The liquefaction vulnerability analysis was conducted in two stages. In the first stage named Macro mapping, the vulnerability was analyzed by calculating the liquefaction potential index using the survey data of the location of electric power utility tunnels in the whole area of South Korea. In the second stage named Micro mapping for vulnerability analysis, the seismic response analysis was performed for the locations determined to be dangerous in the Macro mapping, and the final liquefaction potential index was recalculated. At this time, the site investigation data over 150,000 were used from the National Geotechnical Information DB Center and three earthquake acceleration time histories were used in the site response analyses.

As a result of the study, the macro liquefaction hazard map showed that the possibility of liquefaction vulnerability was high in some regions of the southeastern region of South Korea where the Gyeongju and Pohang earthquakes occurred. Through re-evaluating the potential of liquefaction vulnerability based on the site response analysis, it was found that some regions did not have a high risk of liquefaction vulnerability unlike the macro results. Also, areas that were found to be unsafe in both macro and micro liquefaction vulnerability assessments were followed up by field investigations. Based on these results, it is found that the macro and micro liquefaction vulnerability assessment can give the effective measurement to electric power utility tunnel against liquefaction. Also, the macro liquefaction hazard maps according to the various peak earthquake acceleration can greatly help in the selection of regions that will prioritize the improvement of the seismic performance of the electric power utility tunnel within a limited budget.

Earthquake Ground-Motion Simulation using Sparsely Distributed Observed Motions for Analysis and Design of Lifeline Structures

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ABSTRACT

We present a Gaussian Process Regression (GPR) method to quickly interpolate the surrounding observed ground-motion (GM) time-series to estimate the GM at an adjacent unobserved location. The interpolation process is done using a GPR which models the real and imaginary parts for various frequencies as random Gaussian variables. At present, the number of earthquake ground-motion (GM) recording stations is generally sparse. As an example, there are only about 2000 recording stations in CA. The spatial variation of GMs could affect the response of the distributed lifeline structures such as bridges and natural gas pipelines within a seismic region. It is required to have the GM at the fine-scale locations of the lifeline structures to have a reliable loss or damage estimation as the post-earthquake investigation. There are several developed GM simulation processes, such as physics-based GM simulation and conditioned simulation, to name a few. Although the physics-based GM simulations are well employed by researchers in the past, it could be highly time-consuming and computationally expensive, especially when generating of GM time-series at the fine-scale grid of locations is desired. Therefore, we establish a GPR model to be able to predict the GM time-series at the desired locations conditioned on their neighboring observed motions. To do so, we employ the 3D fully deterministic simulated motions developed by Rodgers et al. for M7.0 Hayward fault scenario earthquake at the San Francisco bay area. The GM dataset is randomly partitioned to train and validation/test subsets. Then, the GPR model is trained deploying the train dataset. The accuracy of the trained model is then evaluated using the validation/test subset for which we compare the estimated GM time-series given by the GPR model and the simulated ones at the corresponding locations.

Regional-Scale Liquefaction Modeling for Water Supply Systems

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ABSTRACT

Regional-scale liquefaction hazard analyses are necessary for resilience planning and prioritization of seismic upgrades for critical distributed infrastructure such as levees, pipelines, roadways, and electrical transmission facilities. However, conventional regional-scale liquefaction hazard analyses typically only use ground surface data to approximate the complicated subsurface mechanics and spatial variability of liquefiable soil deposits. For example, HAZUS only uses surficial geologic maps as input to estimate liquefaction hazards, neglecting the influence of groundwater, soil plasticity, and soil penetration resistance. Such methods also require extrapolation for large magnitude earthquakes, like a potential Mw = 9.0 Cascadia Subduction Zone earthquake.

We have developed probabilistic, regional-scale liquefaction models using data from hundreds of borings to better understand subsurface conditions that could influence liquefaction. We use the subsurface data to train 3D random fields of phreatic groundwater depth, soil plasticity, and penetration resistance for several geologic units. The probabilistic random fields converge to the recorded subsurface data at sampling locations and can also be used to quantify uncertainty regions where boring data are limited. The random fields provide the necessary input parameters for site-specific liquefaction triggering analyses, and since they are continuous throughout the model domain, they unify site-specific and regional-scale liquefaction trigging procedures.

We demonstrate the effectiveness of the random field models in a 460 km2 area near Portland, Oregon. We compute the probability of liquefaction triggering on a 5 m-grid and identify localized areas with high liquefaction hazard. Seasonal variations in groundwater level measurements are quantified as a source of variance in the random fields and are included in the probabilistic calculations. We also demonstrate the regional-scale random field models match site-specific analyses in a blind hold-out dataset with about 80% accuracy. Thus, the 3D random fields provide an important step towards quantitative liquefaction hazard assessments for regionally distributed infrastructure.

A Partially Non-Ergodic NGA Subduction Ground-Motion Prediction Equation

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ABSTRACT

We present an NGA-Subduction ground-motion model (GMM) based on the 2018 PEER NGA-Sub global database. We use about 16,500 records from 247 events, both interface and intraslab, to estimate the model parameters. The model is regionalized to account for differences in the constant, anelastic attenuation, linear site amplification, and basin effects. Seven regions were considered: Alaska, Cascadia, Central America and Mexico, Japan, New Zealand, South America, and Taiwan. The regional adjustment terms are modeled as regional random effects, which assumes that the regional coefficients are samples from a global coefficient distribution. This allows an extension of the model to a new region using the global model. The magnitude scaling is modeled as a bilinear function, becoming less steep at larger magnitudes. The magnitude break point depends on the geometry of the subducting slab and on event type (interface or intraslab). The model parameters are estimated via Bayesian inference using Markov Chain Monte Carlo sampling. The Bayesian approach allows us to include prior information and assess uncertainty in a probabilistic way. Epistemic uncertainty associated with the model parameters and median predictions are taken into account via a posterior distribution of coefficients. Each region has a different number of events and recordings, which affects the uncertainty of the regional coefficients. Regions with a larger number of earthquakes and recordings have smaller epistemic uncertainty associated with the median predictions. Similarly, the epistemic uncertainty in median predictions increases for large magnitudes and long distances, since data is sparse in these ranges.

An Efficient Ground Motion Selection Platform for Multi-Damping-Ratio Spectra

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ABSTRACT

Ground motion selection plays an important role in simulating the response of structures to earthquake shaking. In the design and evaluation process of structures with vertical irregularities or those that contain components whose dynamic response are associated with a damping ratio that is different from the parent structure, sometimes it is necessary to subject the structure to ground motion sets selected for multiple-damping-ratio target spectra. We have developed an efficient computational platform to select and consistently scale recorded earthquake ground motions for multiple target response spectra. Given a set of target response spectra for horizontal and vertical ground motion components, considering different damping ratios and period-dependent record-to-record variabilities, a set of ground motions is selected and scaled such that: (1) the mean spectra of the selected and scaled horizontal motions would follow the target horizontal spectra for all specified damping ratios; (2) the mean spectra of the selected and scaled vertical motions would follow the target vertical spectra for all specified damping ratios; (3) the selected set of horizontal spectra would preserve the prescribed period-dependent record-to-record variability for the horizontal component; (4) the selected set of vertical spectra would match the prescribed period-dependent record-to-record variability for the vertical component; and (5) for each set of horizontal and vertical components, a single scaling factor is used; thus, preserving the relative amplitude and phasing of the original recorded horizontal and vertical components.

Additionally, significant improvement in computational efficiency is achieved by employing a modified version of a greedy record selection algorithm. More specifically, the run time of the modified algorithm is significantly reduced by utilizing the parallelization capabilities that are present in most modern desktop and laptop computers. The process is demonstrated for sites where the hazard is dominated by shallow crustal earthquakes.

Machine Learning-Based Selection of Efficient Parameters for the Evaluation of Seismically-Induced Slope Displacements

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ABSTRACT

Seismically-induced slope displacements (D) are often considered as a performance index in the seismic design of slope systems. Although previous studies have developed predictive relationships for estimating D, a rigorous selection of the most efficient parameters to estimate D has not been thoroughly performed yet. This study uses modern machine learning based techniques to identify the most efficient features that may influence the estimation of D in shallow crustal tectonic settings. The candidate features considered in this study include: slope parameters (e.g. the yield coefficient), earthquake parameters (e.g. magnitude and distance), intensity ground motion parameters (e.g. spectral accelerations), and site conditions. Feature selection techniques such as stepwise selection, least absolute shrinkage and selection operator (Lasso), and Random Forest are implemented to perform the feature selection. Our results show that the Forward Selection algorithm with only six features exhibits superior performance in the aspect of prediction accuracy and cross-validation error as compared to the results of other applied statistical techniques. The influential features consist of system's yield coefficient, initial fundamental period Ts, earthquake moment magnitude, peak ground velocity, and ground motion spectral acceleration at degraded periods equal to 1.4Ts and 1.1Ts seconds. The detected significant parameters provide insight and a basis for developing more efficient prediction models.

Spectral Damping Scaling Factors for the Next Generation Attenuation (NGA) Subduction Earthquakes

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ABSTRACT

This study presents two new magnitude-distance-dependent global damping models for interface and intraslab subduction earthquakes. The Next Generation Attenuation for subduction earthquakes (NGA-Sub) project has recently developed a comprehensive database of recorded ground motions from seven subduction regions: Alaska, Cascadia, Central America and Mexico, South America, Japan, Taiwan, and New Zealand. This database is the largest uniformly processed ground motion database for subduction events and is used to develop a new set of subduction ground motion models (GMMs) at 5% damping ratio. We worked with the NGA-Sub project to develop an extended database that includes pseudo-spectral accelerations (PSAs) for 11 damping ratios between 0.5 and 30%, as well as measures of significant duration of motion for each record. We used this database to develop a damping scaling factor (DSF) model that can be used to adjust subduction GMMs from a referenced 5% damping ratio to other damping ratios. The DSF is strongly influenced by the response spectrum shape and the duration of motion. Previously, as part of the "NGA-West2" project, we had developed a DSF model for shallow crustal earthquakes in active tectonic regions, which was a function of the damping ratio and spectral period, as well as magnitude and distance, which were used as surrogates for spectral shape and duration of motion. Two newly developed global DSF models are presented for the horizontal component of PSA ("RotD50" component representing an "average" horizontal component), one for interface and one for intraslab subduction earthquakes. The parameters and functional forms for the median and standard deviation of DSF are the same as the "NGA-West2" DSF model, but the coefficients are calibrated to the NGA-Sub database. Comparisons between subduction and crustal DSF models are presented. The differences arise from the considerably longer duration of interface records for very large magnitude events and the rich high-frequency content of intraslab records compared to the shallow crustal earthquakes. Regional differences are discussed by comparing the proposed global models to the data from each subduction region, and recommendations on the applicability of the global models are provided. These models can be used to scale any subduction zone GMM for a damping ratio of 5%, including the newly developed NGA-Sub GMMs, to calculate ground motions for damping ratios other than 5%.

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Updated Seismic Hazard Screening of the Contra Costa Canal, San Francisco Bay Area, California

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ABSTRACT

Canals play an integral role in water conveyance to municipalities. In the San Francisco Bay Area, the potential for seismic events present a significant hazard to large segments of canals, requiring significant reconstruction efforts and time. Located on the east side of the San Francisco Bay, the Contra Costa Canal (Canal) delivers fresh water from the Sacramento-San Joaquin Delta, to the Contra Costa Water District's (District) service area. Previous seismic hazard assessment, performed during the late 1990's, identified roughly 13 kilometers and 30 kilometers of canal length with "high moderate" and "moderate-low" liquefaction potential, respectively. Based on the previous assessment, a long-term canal modernization program was implemented by the District. To provide an updated seismic hazard assessment, our study includes a phased approach, probabilistic (Phase I) and deterministic (Phase II), using modified published liquefaction susceptibility and landslide susceptibility mapping, District geotechnical borehole data, and publicly available LiDAR, for approximately 36 kilometers of the Canal. After eliminating sections of the Canal with low or insignificant geologic and seismic hazard, we performed simplified quantification of the hazard combined with assessment of the seismic fragility of Canal structures located in areas with moderate to high liquefaction and landslide hazard. Results of this study include updated maps of canal segments susceptible to landslides and liquefaction that document less than 3 kilometers of the Canal is likely exposed to moderate to high liquefaction potential, with the remaining 33 kilometers of Canal having low to very low liquefaction potential. The main differences in seismic risk estimated in the previous assessment and this study are 1) lower ground motions based on updated characterization of earthquake sources 2) reduction in calculated ground motion values by use of modern attenuation relationships, and 3) reduction of the Canal lengths exposed to liquefaction and landslide hazards based on updated hazard mapping and analyses of available geotechnical data. Structural assessment indicates the majority of the Canal lining, tunnels, and nine of the fifteen siphons have capacity to accommodate PGVs well above scenario earthquakes. This case study demonstrates how improvements to seismic hazard models and updated mapping requires re-evaluation of critical infrastructure. Revised assessments at appropriate frequencies may reduce costs by replacing total system mitigation measures with specific at risk locations. Methods presented are applicable to canal engineers and owners for assessing seismic vulnerability by combining simplified analytical techniques and developing seismic fragilities of lined canals and buried concrete siphons.

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Near-Real-Time Prompt Assessment for Regional Earthquake-Induced Landslides Using Recorded Ground Motions

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ABSTRACT

Earthquake-induced landslides (EQILs) can cause unacceptable economic loss and casualties. The prompt assessment of EQIL can provide an important reference for emergency rescue. Based on recorded ground motions and the Newmark sliding block method, a near-real-time prediction method for the EQIL is proposed, and the corresponding prompt assessment system is developed. First, the seismic network is used to obtain the ground motion records near the epicenter immediately after the earthquake. Subsequently, the slope of the target region is determined based on a global digital elevation model (DEM). Meanwhile, the mapping relationship between the global lithology map (GLiM) database and the engineering lithology classification is established to determine the geological parameters for the target region. Furthermore, the critical slope of each station can be determined using the Newmark sliding block method. Finally, the slope distribution of the target region and critical slope are displayed together on the GIS platform to present the areas with high landslide probability. The commonly used Newmark displacement models and the Newmark sliding block method are compared in this work to demonstrate the necessity of time-history analysis. The proposed method is validated through the 1979 Coyote Lake earthquake and 2016 Kumamoto earthquake. The 2018 Hokkaido earthquake is used as a case study to illustrate the detailed procedures and advantages of the proposed method. With high efficiency and convenience, the characteristics of the ground motion can be fully considered using the proposed method, which provides an important reference for post-earthquake emergency rescue.

Accounting for Site Effects to Improve Seismic Hazard Resilience of Lifeline Systems

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ABSTRACT

Improving the seismic performance of lifelines is fundamental to achieving resiliency of urban environments against extreme natural events. The vulnerability of lifelines is inevitably associated with their exposure to diverse regional and local site effects. Seismic hazard assessments of lifelines are uniquely challenged by varying local soil conditions, as evidenced by multiple past earthquakes; from the damage due to liquefaction-induced ground deformations to the concentration of damages in areas prone to ground motion amplification. However, the hazard associated with transient seismic waves affects the entire lifeline system, as opposed to the localized effects imposed by ground failure. Observations are summarized from the 1989 Loma Prieta earthquake, the 2010- 2011 Canterbury sequence of earthquakes, and the 2011 Tohoku earthquake where local soil conditions affected the seismic performance of different types of lifelines. An evaluation of current practices to incorporate site effects into seismic hazard assessment of lifelines is then provided. Strengths and limitations of simplified methods to estimate soil strains around pipelines are revised, and compared to microzonation efforts which target the quantification of site effects on a broad regional scale. Within the framework of challenges and opportunities associated with accounting for site effects covered in this work, areas of future research are identified as potential paths toward improved resiliency of lifelines to seismic hazards.

Evaluating Impact of Adjacent Tall Buildings on Seismic Response of Underground Structures

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ABSTRACT

Underground structures are commonly constructed near existing or new tall buildings in dense urban areas. Tall buildings, during earthquake shaking, generate base shear that is carried by the building foundation and surrounding soils. This base shear may be transmitted to adjacent underground structures. A previous study was conducted by combining dynamic centrifuge tests and numerical simulations to evaluate the impact of highly idealized adjacent tall buildings on the seismic response of underground structures. The numerical model can reproduce the seismic behavior observed in the centrifuge including the additional loading demands imposed by adjacent building on underground structures.

A large-scale parametric study using three-dimensional (3-D) nonlinear finite element analysis with more realistic soil-structure-underground structure (SSUS) representation is performed and presented to evaluate the impact of variability in the SSUS system on the seismic response of underground structures. The effects of different building heights, building foundations, underground structure configurations, and soil profiles are evaluated using a suite of ground motions. These configurations represent the range of conditions that are likely to be present in dense urban environments. The results show that (a) as the adjacent building became taller and hence the base shear increased, greater dynamic earth pressures were transmitted to the underground structure, (b) the dynamic earth pressures were reduced with increasing building to underground structure distance, and (c) the racking displacements of underground structures were strongly dependent on building foundation and underground structure configurations such as basement depth, pile length, and the depth of the underground structure. For design purposes, these interactions need to be considered by modeling a realistic building and underground structure representation in SSUS system to evaluate the added demands that a given building will impose on underground structures including cut- and-cover boxes and bored tunnels.

Mitigation of Fault Crossing Hazard for Large Diameter Pipelines Crossing the Concord Fault

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ABSTRACT

Contra Costa Water District's (District) treated water service area (TWSA) supplies water to a population of approximately 500,000 people living in Contra Costa County in the eastern San Francisco Bay Area. The seismically active Concord Fault runs in the northwesterly direction through the cities of Walnut Creek and Concord bisecting the District's TWSA into eastern and western halves. Several of the District's large diameter pipelines cross the fault and are susceptible to breaks in the event of a large surface rupturing earthquake. These pipelines are critical to water transmission southwards and westwards from the District's two water treatment plants located in the cities of Concord and Oakley east of the Concord Fault. Customers located west of the fault would be impacted by reduced conveyance capacity if the pipelines crossing the fault were unavailable following a large earthquake on the Concord fault, and water losses would affect the treated water system until broken transmission mains were isolated.

The Concord fault exhibits 3 to 4 mm/year of fault creep manifested by curb offsets and en-echelon cracking of pavements at several locations within the District's service area, and damage to a 24-inch diameter transmission main located parallel to and above the fault. The fault has a long-term (geologic) slip rate of 3.4 ± 0.3 mm/yr estimated from a 6,000-year record of stream channel offsets. Although Concord fault does not have a historic record of large surface rupturing earthquakes since 1776, when the written record began in the Bay Area, associated microseismicity and published fault trenching studies indicates it is active. The United States Geological Survey estimates probability of a major earthquake ranging from a little over one percent to approximately eight percent in the next 30 years. While the near term probability of a major earthquake on the fault is moderate to low, it is a high consequence scenario in terms of its impact on the water supply for a large population.

A cost effective strategy was developed to mitigate the fault rupture hazard for ten large diameter pipelines ranging in size from 20 to 48 inches. This case study demonstrates the use of isolation and bypass as an effective and practical mitigation strategy that can be employed by owners of water systems in lieu of an expensive pipeline replacement or retrofit program.

Mitigation of Fault Crossing Hazard for Water Conveyance Infrastructure Upgrades, Sonoma County, California

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ABSTRACT

Fault rupture evaluation and mitigation design for upgrade of Sonoma Water's backbone aqueduct system to improve reliability in future large earthquakes included detailed pipeline fault crossing studies. The system consists of large-diameter pipelines, storage tanks and booster pump stations that provide water to over 600,000 people in Sonoma and Marin Counties. The system is bisected by the active Rodgers Creek fault (RCF) in Santa Rosa and by the potentially active Bennett Valley fault (BVF) at Spring Lake. The BVF is part of a broad right-stepover connecting the RCF with the active Maacama fault. Upgrades to the aqueduct system included replacement of a 36-inch Aqueduct crossing the Rodgers Creek fault and upgrade of the Sonoma Booster station near the mapped trace of the BVF. The RCF pipeline fault crossing was designed for operational continuity following a major surface-rupturing earthquake on the fault. Nonlinear soil-structure interaction analyses were performed to develop the replacement design. Geologic assessment of the fault included review of unpublished consulting reports, interpretation of LiDAR and 2D seismic reflection data, and subsurface exploration consisting of closely spaced CPT and geotechnical borings to locate and characterize the fault. Similar design considerations resulted in fault trenching and geophysical studies to document presence or absence of fault-related deformation associated with the Spring Valley strand of the BVF, located east of the RCF. Fault trenching of the BVF north and south of the Booster Station exposed faulted and unfaulted sediments across the inferred trace of the fault. Combined with results of a geophysical survey along the Spring Lake Dam south of the Booster Station and interpretation of available pre-dam aerial photography and post-dam LiDAR data, results of the Spring Lake study helped constrain the location and activity of the BVF relative to the Booster Station. Using the fault investigation techniques, tight constraints along the active traces of the fault and secondary zone of deformation were provided to the engineers for a reliable fault crossing design. Design challenges included presence of existing infrastructure and tie-in to the existing aqueduct.

Ground-Motion Databases & Tools at the UCLA Natural Hazards Risk and Resiliency Research Center (NHR3)

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ABSTRACT

The Natural Hazards Risk and Resiliency Research Center (NHR3) is a multidisciplinary multi-university research center with headquarters at UCLA. NHR3 is developing several earthquake ground-motion datasets, databases and tools to support research and engineering practice, and making them available for public download on a web portal. These ground-motion datasets, databases and tools are intended to provide continuity and integration in the different fields of earthquake science and engineering. One example of the data is the extensive set of ground-motion records (dataset), as well as computed intensity measures, such as response spectra, and source, site, and path metadata (database) for the 2019 Ridgecrest Earthquake Sequence. This vast and dense dataset can be used by researchers to develop and validate new ground-motion models for various intensity measures, as well as be used by practicing engineers to evaluate the response of structures distributed in a region. In addition to these datasets and databases, both the NGA-East and NGA-Subduction ground-motion models have been implemented into various computer platforms and have been released to the public at the NHR3 portal. These models have been implemented in MS Excel (Visual Basic), Matlab, Python and R. Both researchers and practitioners have been taking advantage of these advanced tools. The ground-motion datasets, databases, and tools can be accessed at: https://www.risksciences.ucla.edu/nhr3.

Variations in Ground Motion Amplification in the Los Angeles Basin due to the 2019 M7.1 Ridgecrest Earthquake: Implications for the Long-Period Response of Infrastructure

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ABSTRACT

Coherent patterns and large variations in ground shaking amplification were observed in the Los Angeles basin during the 2019 M7.1 and M6.4 Ridgecrest earthquakes. In particular, 3 s to 6 s responses showed variations due to shallow basin geological structure that have implications for the response of mid-rises, high-rises, long-span bridges, and fuel storage tanks to large earthquakes, even if epicentral distances are several hundred kilometers. The Ridgecrest strong-motion data were recorded by seismic stations from the spatially dense Community Seismic Network, the Southern California Seismic Network, and the California Strong Motion Instrumentation Program. The mainshock observations are compared at the same locations with ground motion simulations to examine the regions that experienced the largest shaking, and to investigate the geological sources of large- amplitude shaking. The simulations were computed for the two most commonly-used regional community seismic velocity models, CVM-S4.26.M01 and CVM-H 15.1.0. Both observations and simulations are used in dynamic analysis with a finite-element model of an existing high-rise with ~6-second fundamental horizontal periods, located in downtown Los Angeles. The geographical variation in maximum story drift, shear force, and moment values show that if high-rise structures had been located only a few km north in the San Fernando Valley, or west in West Los Angeles where some of the largest amplifications were recorded, more significant response and damage may have been observed.

Seismic Slope Stability Analysis and Mitigation for Transmission Power Lines In Southern California

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ABSTRACT

Many of the high voltage transmission line towers in Southern California are located in hilly terrains and in a high seismic hazard environment which requires assessment of these towers during a major seismic event. Some of these towers are located within historic landslide features making them quite vulnerable for large deformations during seismic shaking. Permanent ground deformations due to slope failures during and after a seismic event could result in losing some of these towers and their functions.

In this study, a seismic assessment in terms of slope stability was performed for several high voltage towers along a transmission power line corridor from Tejon Pass to Cajon Pass in Southern California. Incidentally, this corridor runs along the Southern San Andreas fault. Based on an initial study including review of geology maps and site visits, out of 2,269 structure locations along the corridor, 17 locations were selected for further evaluations for seismic slope stability. Field investigations consisting of borings were performed at some of these sites and soil/rock samples were obtained for laboratory testing. At some locations, field survey was performed to establish elevation contour lines in order to develop appropriate cross sections. In addition, at some locations, towers were assessed for both a local slope stability and a global slope stability. Local slope stability concerns were raised because some towers are located next to a cut slope which was made primarily for access roads. The analyses involve, developing ground motions using UCERF3 seismic source model, developing cross sections (both local and global), assigning strength properties to each layer, and performing seismic slope stability analysis. Ground motions were developed for probability of exceedance of 5, 10, 20, and 50 percent in 50 years and parametric studies were performed to establish design level earthquake. Seismic deformations were estimated using Bray and Travasarou (2007) method. For locations, where deformations exceeded a certain threshold, different mitigation methods were proposed including but not limited to soldier pile and lagging walls and soil-nail walls. Challenges for this study include high ground motions resulting in about 1g of PGAs, anticipated large slope deformations, and difficult terrain to implement mitigation methods. This study will present the thought process to select the design level earthquake based on the parametric studies, results of analyses in terms of FOS and seismic deformations, and details about mitigation methods used at certain locations.

Behavior of the North Anatolian fault and Expected Marmara Earthquake in Turkey Illuminated by an Offset Byzantine Aqueduct

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ABSTRACT

The northern branch of the North Anatolian Fault (NAF) presents the greatest natural hazard for the Marmara Megapolis and specifically the İstanbul Metropolitan area. The Sea of Marmara section of the NAF is a ~180-km-long seismic gap bound by the M ~7.4 1912 Mürefte earthquake rupture in the west and M7.4 1999 İzmit earthquake rupture in the east. The eastern and western terminations of the 1912 and 1999 ruptures, respectively, define the length of the seismic gap and consequently the magnitude and rupture extent of the expected Marmara earthquake. This study focused on the western termination of the M7.4 Izmit surface rupture on Hersek Peninsula where a 2.6-km-long suspension bridge was built across the Izmit Bay. In this study, we integrated high-resolution onshore and offshore data from Hersek Peninsula and its vicinity in İzmit Bay to assess the seismic hazard risk for the Marmara region. Detailed geologic and geomorphic mapping, paleoseismic trenching, geophysical and geotechnical subsurface data and archeoseismologic investigations demonstrate that the M7.4 1999 İzmit earthquake did not rupture the surface and possibly died off at or east of the Hersek Peninsula due to structural complexity of the NAF at this location. Existence of a restraining bend and bifurcation of the NAF at Hersek Peninsula suggest that this location might be a persistent asperity acting as a segment boundary since Pleistocene. Surface ruptures documented in paleoseismic trenches north of the Hersek Lagoon and an offset 6th century Byzantine aqueduct; however, suggests that this section of the NAF has ruptured the surface multiple times in the past and is highly likely to rupture again during the expected Marmara earthquake. The Byzantine aqueduct which crosses the projection of the NAF is offset 14 +/-1 meters and yields 13.6 +1/-3.5 mm/yr dextral slip rate indicating that the northern branch of the NAF accrues and releases the majority of the stress between Eurasia and Anatolian block in the Marmara region. If the ~180-km-long seismic gap between the 1912 and 1999 ruptures during a single event the expected Marmara earthquake can range between M7.3 and M7.6. These observations have fundamental implications on critical infrastructure planning and emergency response planning for the expected Marmara earthquake.

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Parametric Investigation of Ground Failure at Balboa Blvd. During the 1994 Northridge Earthquake via Nonlinear Deformation Analyses

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ABSTRACT

Nonlinear deformation analyses are becoming increasingly common in geotechnical practice for evaluating the performance of geosystems. The seismic performance of the Balboa Blvd. during the 1994 Mw 6.7 Northridge earthquake is examined through nonlinear deformation analyses (NDAs) using state of the art tools to (1) evaluate the sensitivity of the resulting failure mechanism and estimated maximum horizontal displacements to reasonable variations of poorly constrained input parameters and alternative input ground motions; and (2) draw conclusions with regards to our ability to employ the adopted modeling protocols and engineering procedures in forward predictions of ground deformation patterns.

Prior work by the authors consisted of NDAs targeting at providing insight into the failure mechanism, and earthquake-induced ground deformation patterns at Balboa Blvd. The geotechnical characterization of the site was assessed based on field and laboratory data obtained from two investigation campaigns. Transitional probability geostatistics were used to develop stratigraphic models that capture the heterogeneity and the spatial variability patterns of sand-like and clay-like soils present at this site. The stratigraphic models were implemented in the finite different software FLAC and the behaviors of sand-like and clay-like soils were simulated using the PM4Sand v3.1 and PM4Silt v1.0 constitutive models, respectively. Results from these NDAs suggested that a compounded effect of both liquefaction of sand-like soils and cyclic softening and shear failure of clay-like soils led to the excessive ground deformations at Balboa Blvd.

This study presents a series of sensitivity analyses that address uncertainties or alternative considerations that were previously not accounted for. Those include the potential variation of input ground motions, some aspects of the spatial variability of soils, and the consideration of additional semi-empirical correlations for cyclic mobility deformations and excess pore pressure thresholds in the calibration of the constitutive models. This study (1) sheds light on the effect of these factors on the seismic response at this site; (2) emphasizes the importance of using appropriate engineering procedures and numerical modeling protocols in the prediction of deformation patterns; and evaluates the bounds of uncertainty of these predictions and procedures such that they can be more readily adopted and/or advanced by stakeholders, practitioners, and researchers.

Constraining Near-Surface Fault Displacements Using Physics-Based Dynamic Simulations

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ABSTRACT

Coseismic fault displacements in large earthquakes have caused significant damage to structures and lifelines located on or near fault lines. Examples include severely damaged bridges, dams and tunnels in the 1999 Chi-Chi earthquake, pancaked buildings in the 1999 Kocaeli earthquake, distorted railroads in the 1975 Guatemala earthquake, and ruptured water lines during the 2019 Ridgecrest Earthquake Sequence. Fault displacements therefore represent an important seismic hazard, especially for distributed infrastructure systems that are more likely to cross fault lines. Compared to well-developed empirical ground-motion models (GMMs, a.k.a. GMPEs), empirical fault displacement models are sparse and poorly constrained partly due to the paucity of detailed fault displacement observations. Advancements in physics-based simulation models make them an attractive approach to address this important problem. Once validated against well-documented case histories, the models can be used to predict displacements for scenarios and events we haven't experienced yet. Those synthetic displacement datasets can then be used alone or combined with empirical observations to develop ground displacement models, which are then integrated into probabilistic fault displacement hazard analyses (PFDHA). For our physics-based approach, we develop an ensemble of dynamic spontaneous rupture simulations, which construct dynamic earthquake rupture evolution and seismic wave propagation under plausible physical conditions (e.g., fault geometries, friction constitutive properties, stress conditions and surrounding earth media). In contrast to kinematic sources used in simulation-based ground-motion models (e.g., CyberShake), dynamic rupture simulations predict fault displacement through physical causative parameters instead of empirical pre-descriptions of resultant slip distributions. Dynamic models can also capture off-fault inelastic distributed fault displacements such as those observed by recent aerial imaging (e.g., 1992 Landers, 1999 Hector Mine, 2016 Kaikoura, and 2019 Ridgecrest earthquakes). In this work, we summarize our model validation and initial forward modeling results. The validation is performed against on- and off-fault displacement data of the 1992 Landers earthquake, one of the events with the most detailed documentation of displacement over a wide area. We also perform a sanity-check validation of ground motions against recordings from the event, to ensure that all physics important to modeling has been properly parameterized. This combination of validation and calibration of the model is critical to its use for the forward modeling of new events. Finally, we show sample forward simulation results for scenario events not captured in the current empirical datasets.

Fully Nonergodic Ground Motion Model in Southern California Using SCEC CyberShake Dataset

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ABSTRACT

In earthquake engineering, it is crucial to ensure a structure can withstand a certain level of ground motion while maintaining a desired level of performance. It is common practice to rely on probabilistic seismic hazard analysis (PSHA), to define those ground motions. In traditional approaches, PSHA consists of the integration of the expected level of ground motions (through ground motion models or GMMs) over all the expected events, including their probabilities over time. The variability of ground motions expected at one site for a given event is a key component controlling the shape of its associated hazard curve. In practice, such variability is represented by the total standard deviation of the residuals between ground motion measurements and the median predictions from the GMM. However, much of the variability comes from the ergodic assumption that the variability of ground motions at one site over time equals the variability of ground motions over all sites in a short period of time. The variability from ergodic models tends to be large and larger variability leads to higher ground motions at any given annual frequency of exceedance, especially at longer return periods. Moreover, the median ground motion prediction given by GMMs is a global average, which may deviate significantly from local observations of interest.

Therefore, the most promising way to improve the seismic hazard assessment at a given location is to develop non-ergodic GMMs, which more accurately represent the region of interest. Despite the rapid growth of strong motion networks, empirical datasets are still too sparsely populated to fully define the source, path and site effects. However, numerical ground motion simulations, such as those from the CyberShake platform, can generate enormous datasets for any site of interest, making them an ideal tool to explore non-ergodic modeling. Before such simulations can be incorporated in engineering applications as in PSHA, it is vital that they are validated against observed data.

In this study, we focus on CyberShake Study 15.4, which was conducted for southern California with a tomography-inverted 3D velocity structure. We first validate CyberShake's ability to capture the median ground motions and total variability from empirical GMMs adjusted for regional effects using a subset of the NGA-West2 database. Then, we apply the spatially varying-coefficient model to the CyberShake dataset. We use the simulation-based non-ergodic GMM to predict ground motion and its variability in the state of California and compare the results from the empirical dataset.

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Seismic Site Characterization Data for Lifelines and Other Applications – A 50-Year Retrospective in Los Angeles, California

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ABSTRACT

The study of the effects of damaging earthquakes on the built environment has made significant strides in the 50 years since the 1971 San Fernando earthquake, particularly in the realm of understanding the effect of geological site conditions on ground shaking. The late UCLA Professor C. Martin Duke was a pioneer in measuring and disseminating data on seismic site conditions at strong-motion stations that recorded the San Fernando event. Duke's team used geophysical methods to quantify shear-wave velocity (VS), P-wave velocity, and fundamental site period (T0) and disseminated the data in a series of UCLA Engineering reports. Major subsequent efforts by the U.S. Geological Survey, State of California public agencies, the Resolution of Site Response Issues from the Northridge Earthquake (ROSRINE) project, private industry, and numerous individual investigators have rendered the basins and mountainous areas of southern California as among the best characterized for seismic conditions world-wide. This data is instrumental for the development of semi-empirical ground motion models and studies of site response, ground failure, and soil-structure interaction.

In this historical overview of seismic site characterization data collection in the greater Los Angeles region, we describe various geophysical methods that have been deployed over time, and the evolution of data quantity and quality to the present. We also present an ongoing endeavor that has developed the United States Community V_S Profile Database, which provides an open-access platform for the dissemination of seismic site characterization data. Elements of this database in the greater Los Angeles region will be described, and examples will be provided demonstrating how these data are used in both research and industry practice.

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Polymer Injection to Remediate Liquefaction Induced Foundation Settlement: Numerical Simulation of Shake Table Experiments

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ABSTRACT

A series of two large scale shake table tests were performed to investigate the efficacy of the polymer injection technique in remediating liquefaction induced foundation settlement. In these tests, system response was studied initially without, and subsequently with polymer injected into the liquefiable stratum resulting in a set of unique and comprehensive data. Here, a set of preliminary Class C1 numerical simulations of these tests are presented using a set of 3D two phase (solid-fluid) fully coupled finite element models with constitutive model parameters partially calibrated based on earlier studies. The physical and numerical models indicate an extensive reduction in the liquefaction induced foundation deformations due to the injection and associated stiffening of the ground. Comparisons are made between computed and recorded engineering demand parameters (EDPs) including excess pore pressure, acceleration and foundation settlement. A reasonable match is observed to the physical response and the calibrated model is further used to run an additional scenario, with sloping ground conditions and directions for further improvement of the model are suggested.

Tunnel Lining Design for a Strike Slip Fault Rupture on Westside Purple Line Extension Project Section 2

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ABSTRACT

Several underground projects in seismic areas are currently dealing with active fault crossings, in such locations the tunnel lining performance is a key element for the project's success. The Westside Purple Line Extension Project - Section 2 (WPLE2) in Los Angeles is crossing a zone affected by Santa Monica Fault. Advanced three-dimensional numerical models were developed to capture the tunnel lining response to several fault rupture scenarios. A special precast concrete tunnel lining (PCTL) was designed to accommodate the imposed displacements on the tunnels due to the risk of a strike slip fault rupture. The tunnel lining incorporates numerous special seismic provisions to safely accommodate the imposed fault displacements during a Maximum Design Earthquake (MDE) event. Finally, a physical testing program was developed in conjunction with the University of California San Diego (USCD) to physically test all key aspects of the special lining, document actual behavior and allow for refinement of the structural design.

Seismic Reliability Assessment of Water Distribution Networks Accounting for Geotechnical Variability and Liquefaction Potential

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ABSTRACT

Water distribution networks are critical lifelines that must remain operational following a seismic event. Pre-earthquake assessment, management and mitigation of the seismic risk is therefore of paramount importance to the authorities and the water distribution agencies. Existing methodologies put emphasis on the properties of the network (e.g. pipes, connectivity, geometry), and with few exceptions (Adachi and Ellingwood 2008; Hwang et al. 1998; Miller and Baker 2014; Romero et al. 2010) do not consider the role of different soil conditions across the wide area covered by the water network. Most importantly, they typically do not account for the implications of soil and site response on the, inevitably spatially variable, seismic ground motion and pipe demand. This study presents a case study that is based on the water network of the city of Lefkada in Greece, which experienced water pipe damage and liquefaction in a wide area along the port during the Ms 6.4, 2003 earthquake. A methodology for a system-wide analysis utilizing component analysis, network topology and spatial variability assessment due to local soil conditions is presented involving a simple probabilistic model for predicting the spatial variation of the ground motion parameters of interest such as peak ground velocity (PGV) and permanent ground deformations (PGD). Site response, considering liquefaction susceptibility is accounted for by means of a series of one-dimensional, nonlinear analyses of the multi-layered, damped soil profiles within the water network grid. Uncertainty is introduced on the bedrock ground motion and on the properties of the soil materials. The reliability of the network is assessed assuming both uniform and varying geotechnical conditions for comparison. Network analysis demonstrates the importance of realistic consideration of soil profiles particularly in parts of the grid that are affected by liquefaction, while it highlights the need for well documented soil databases (Brandenberg et al. 2020; Gilder et al. 2020). It also shows that improving the water network robustness and/or upgrading the pipes in the above locations can significantly reduce seismic risk and improve the resilience of the system.

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State of the Practice for Mitigating Earthquake-Induced Liquefaction and Instability

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ABSTRACT

Ground improvement methods e.g., deep dynamic compaction, vibratory compaction, sand compaction piles, granular columns, deep mixed columns, jet-grouted columns, rigid inclusions, compaction and permeation grouting, bio-treatment, earthquake drains, and mechanically-stabilized earth walls, have been successfully and increasingly employed in practice to mitigate potential earthquake-induced liquefaction and/or instability. This review provides historical developments and recent advances of these methods. One of these ground improvement methods may be used or combined with other methods to densify liquefiable soil, provide chemical and biological bonding between particles, reduce shear stresses, provide drainage, and decrease saturation in liquefiable soil; as a result, potential earthquake-induced liquefaction is prevented. The ground improvement methods also increase the strengths of foundation soils and earth retaining backfill so that lateral spreading and slope/wall instability due to earthquake events can be prevented. Mechanically stabilized earth walls with metallic or geosynthetic reinforcement behave as flexible structures and have demonstrated better performance during earthquake events than gravity and rigid earth retaining structures. This review will highlight benefits of ground improvement methods for mitigating potential earthquake-induced liquefaction and instability problems, discuss some design concepts and issues related to these methods and applications, and demonstrate improved performance of superstructures and earth structures after ground improvement.

Time Frequency Analysis of Strong Ground Motions from the 2011 Sikkim Earthquake

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ABSTRACT

Earthquakes in the Himalayan region occur due to the continuing collision between the Indian and Eurasian tectonic plates. While typical earthquakes in the Himalayan region are inter-plate in nature, however, the 2011 Sikkim earthquake was triggered from an intraplate source on the over-riding Eurasian Plate. This major earthquake had a moment magnitude of 6.9 and caused enormous damage to the building stock in the Himalayan region. Several unreinforced masonry buildings, heritage structures and framed structures collapsed due to the strong ground motions caused by the earthquake. The response of structures is influenced primarily by the amplitude and frequency content of the ground motions. Typically, the amplitude and frequency content of ground motions are obtained separately using the time-acceleration and Frequency-Fourier representations, respectively. However, both descriptions carry incomplete information and do not enable the proper correlation of ground motion characteristics to structural damage. In this work, the wavelet analysis technique is used to perform time-frequency analyses of strong ground motions recorded in the 2011 Sikkim earthquake. The response spectra of the strong ground motions exhibit sharp peaks at low periods, thus indicating the presence of extremely high-frequency content. Further, the continuous wavelet transforms of these ground motions show that these high frequencies were also sustained in time, thus causing enormous damage to low-rise structures. Further, the earthquake induced physical damage to infrastructure, at various locations in Sikkim, was obtained from multiple reconnaissance-based damage surveys. The results from the time frequency analyses of strong ground motions are consistent with the damage data from the post-earthquake reconnaissance studies.

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Unlined Spillway Erodibility Assessment, from Emergency Response and Recovery to Evaluating Future Risk at Oroville Dam, CA

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ABSTRACT

Scour of rock and soil from unlined spillways during spill events can contribute to a range of unintended environmental, safety, and reliability consequences. In February 2017, headcutting erosion in the Oroville Emergency Spillway threatened to undermine concrete monoliths of the weir, and prompted the evacuation of nearly 200,000 downstream residents. To recover functionality of the emergency spillway, DWR and their contractors constructed several erosion protection measures, including a roller compacted concrete (RCC) apron, and a new secant pile cut-off wall approximately 700 feet downstream of the weir. Below the secant pile wall, the emergency spillway remains unlined.

This work was a screening-level study to evaluate potential erosion of the unlined hillslope after repairs, as part of a broad, “Comprehensive Needs Assessment” of the Oroville Dam facilities. The study relied on iterating between geologic and hydrologic analyses to estimate the volume of materials that could be eroded from the unlined hillside during a range of potential hydrologic events. We integrated data from geologic mapping, boreholes, and exposed soil profiles to develop a 3-dimensional geologic model of the emergency spillway in GIS. Geologists combined field data and geotechnical laboratory tests to develop erodibility characteristics for each geologic unit. To capture changes in geologic and hydraulic conditions during hydrologic events, we modeled a series of flows that incrementally increased to the probable maximum flood (PMF), using HEC-RAS software from the U.S. Army Corps of Engineers. At each step, the locations and depths of scour and deposition were used to modify the site DEM prior to running the next HEC-RAS iteration, a process that has not been used before in an erodibility study. The resultant estimated volumes of eroded material for the range of modeled flows were used in a semi quantitative risk assessment to inform the consequences of hydrologic loads and evaluate additional needs for the facility going forward. This risk-evaluation technique can be adapted for many facilities with unlined spillways, and can be used to predict the evolution of a scour channel in future spill events and evaluate the specific vulnerabilities of a site.

A Data-centric Analysis of Flood Propagation in Urban Regions

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ABSTRACT

Flood in urban areas put a great threat to assets and lives. Understanding how flood propagates and conducting near real-time flood propagation prediction is of great importance for emergency response during major floods. However, using advanced hydrodynamic flood propagation models for near real-time flood prediction is highly computational demanding and requires vast hydrological input for model development. To overcome the limitations, a data-centric framework is used for prediction of flood propagation in urban scale using deep learning techniques such as fully convolutional neural network. The proposed framework takes advantage of the big data generated by the sensors in place for recording rainfall and flow data as well as social media and crowdsourcing platforms and presents a highly accurate and efficient flood prediction in near real-time. In specific, the proposed model employs flood recording sensors and human-generated flood reports and constructs multivariate time series of flood status for different units of the urban region. The flood prediction is then treated as a time series classification problem using the proposed deep learning model to predict the inundation status of different urban units over the flood event period. The framework is tested in Harris County, Taxes based on the recent flood events. The results show that the framework can yield excellent performance for urban flood prediction. This framework enables a decision-making tool for emergency managers to inform the evacuation and distribute the emergency resources.

A New Landslide Runout Model and Implications for Understanding Post Wildfire and Earthquake Threats to Communities in California

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ABSTRACT

Wildfires and earthquakes contribute to a nearly ever-present cycle of hazards that are managed by coastal California communities every year. Worse still, fires and earthquakes drive slope instability, primarily in the form of debris flows, debris avalanches, and debris floods whose runout can impact environment, infrastructure, and threaten lives along the landslide path. A better understanding of future landslide runout paths, travel distance, and potential landslide depth along the path, will improve our ability to manage future hazards, however, predictive models can be difficult to implement, hard to calibrate, and/or expensive to acquire. Landslides: an Agent Based Simulation (LABS) is an agent-based runout model that predicts runout of debris flows and debris avalanches based on aggregate behavior of flow-type landslides as measured along hundreds of landslide reaches over several years. By relying on the self-similar behavior of flow-type landslides the model is able to ignore important, but secondary (or tertiary) effects of the actual initiating conditions including, for example, specific landslide rheology or moisture content, and focus instead on easily acquired data from a digital surface. The user easily defines landslide initiation zones in a specific area of interest (e.g. a recent burn, or high hazard zone), populating a number of agents, or subroutines, onto a 5 m digital elevation model. Once initiated, each agent runs through a program that estimates scour and deposition, path selection, and agent spawning, at each time step until it has a zero mass balance and the agent is terminated. Behavior estimates are probabilistic, and results vary somewhat from run to run. LABS therefore allows the user to conduct multiple runs and report average results. Landslide behavior is credible and easily verified using several built-in features such as exporting model runs to a GeoTIFF to visually compare to existing landslides. LABS is intended to be used as a predictive model to better inform and constrain land management decisions where debris flow and debris avalanche hazards exist.

Case Study: A Moving Mud Spring Threatens Critical Infrastructure, Imperial County, California

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ABSTRACT

Due to the tectonic environment, mud pots and mud volcanoes are common at the southern end of San Andreas Fault near the Salton Sea. These features are generated from carbon dioxide gas at depth and while their level of activity may fluctuate, they are generally stationary. In 2016, a mud pot (referred to as a mound mud spring) began moving southwest. Critical infrastructure, including the Union Pacific Railroad (UPRR) dual tracks, utility and petroleum pipelines, and a state highway were in the path of the moving mud spring. The mud spring impacted the UPRR tracks in late 2018, which carries freight from the Ports of Los Angeles/Long Beach to the eastern part of the country. To accommodate the mud spring movement, we utilized sheet piles, shoofly tracks, and rip rap to keep the trains operational.

Kinder Morgan evaluated the moving mud spring impact on their critical petroleum pipeline that provided fuel to civilian and military facilities in the desert southwest. After considering a temporary bridge to support the pipeline, Kinder Morgan elected to reroute their pipeline around the mud spring's path. As of August 2020, the mud spring has moved over 100 m (300 feet), cutting a path through the UPRR main line tracks and beginning to impact the state highway. Shoofly (detour) tracks were constructed to allow train traffic to go around the mud spring. The spring's rate of movement is variable, but averages about 3 meters (10 feet) per month. The UPRR has largely restored services on the main line tracks by backfilling the erosion area left in the mud spring's wake.

Scientific studies to understand the mechanism behind the unique mud spring movement are continuing as the mudspring continues its journey across the desert.

Selection of Multihazard-Based Damage Scenarios for the Los Angeles Water Supply Network

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ABSTRACT

Earthquake damage scenarios are required to support design and analysis of spatially distributed infrastructure systems. We develop a computationally efficient set of damage scenarios for the Los Angeles water supply system that considers multiple hazards (ground motion, liquefaction, and surface fault rupture). Each damage scenario describes one possible realization of damage to the pipe network and includes the corresponding multihazard scenario and an associated weight. Each damage scenario, which specifies the damage state of each pipe in the network, is defined to be physically realistic and consistent with the associated multihazard scenario. Together, when probabilistically combined, the set of damage scenarios with their weights match the probabilistic hazard and system functioning (e.g., percentage of demand satisfied) exceedance curves. The scenarios are selected to be small in number so that subsequent analysis is efficient. We combine ideas from recently developed methods to generate sets of multihazard scenarios and damage scenarios for analysis of spatially distributed infrastructure systems. The method applied involves simulating multihazard scenarios, simulating a number of damage scenarios for each, and using an optimization to select a subset of damage scenarios and assign weights.

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Regional Hazard Assessment for Multihazard Analysis of Spatially Distributed Infrastructure

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ABSTRACT

Seismic risk assessment of spatially-distributed lifeline infrastructure systems ideally (1) captures spatial correlation, (2) is probabilistic, (3) is computationally efficient, and (4) addresses the multiple hazards that co-occur in an earthquake. We introduce a Multihazard Optimization-based Probabilistic Scenario (Multihazard OPS) method that addresses these four issues. The method includes five main steps: (1) generate a candidate set of earthquake scenarios, (2) reduce the set of earthquake scenarios based on their contribution to the ground motion and liquefaction hazards, (3) reduce it and assign hazard-consistent annual occurrence probabilities using a mixed integer linear program (MILP), (4) generate multihazard scenarios for each earthquake scenario in the reduced set in a way that minimizes sampling variability, and (5) reduce the multihazard scenarios using the same MILP from Step 3. The result is a relatively small set of probabilistic multihazard scenarios (tens to hundreds), each with an associated hazard-consistent annual occurrence probability. A multihazard scenario is a map and associated narrative, both depicting a possible realization of the multiple hazard effects associated with a single earthquake, including ground motion intensity contours, liquefaction potential contours, and permanent ground deformation due to surface fault rupture. We share results of a case study application for the City of Los Angeles, including, a sensitivity analysis to examine the effects of multiple hazards and an analysis of their effects using the reduced set to estimate regional water pipeline damage. The results suggest 350 multihazard scenarios together capture the probabilistic hazards and damage with error small enough for most practical applications. The tradeoff between minimizing the number of multihazard scenarios and the error can be described explicitly.

Dynamic Automated Seismic Hazard (DASH): Rapid Damage Estimates for PG&E Gas Transmission Infrastructure

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ABSTRACT

The Pacific Gas & Electric Company (PG&E) Dynamic Automated Seismic Hazard (DASH) system provides consistent earthquake information for the company's lines of business and is used to prioritize post-earthquake inspections of PG&E's electric and natural gas transmission and distribution systems. Utilizing asset, geohazards, and near-real time ground shaking geospatial data, DASH rapidly produces facility-specific damage estimates following significant earthquakes affecting the PG&E service territory within a 15- to 20-minute timeframe after the event. For example, the PG&E gas transmission system consists of approximately 6,800 miles of gas transmission pipelines exposed to multiple seismic hazards including surface fault rupture, liquefaction, and landslides. Earthquake-related ground movement can result in increased pipeline strain which in turn can lead to permanent pipe deformation and possible operational impacts. Immediately after an earthquake, DASH pulls in ShakeMap data from the USGS and runs algorithms incorporating predictive damage models to develop customized reports that help prioritize where to dispatch damage assessment and repair crews. In addition, interactive map-based earthquake information is accessible within PG&E's intranet via the DASH website for use by earthquake responders. Following the 2014 Mw 6.0 Napa earthquake, DASH was used to quickly check gas leaks and immediately deploy employees to restore electrical service to about 70,000 customers in a little more than 24 hours. Although some ShakeMap data feed issues occurred initially for the 2019 Ridgecrest earthquakes, DASH contributed to PG&E's response for pipeline damage assessment and repair in this recent large earthquake. DASH development includes a continual improvement and development process that incorporates feedback and lessons learned from earthquake emergency response and restoration events. These include improvement of system reliability and data feed redundancy, and performance-based infrastructure damage models.

Lessons Learned from Two Earthquakes that Afflicted Mexico City-- After a Pause of 32 Years

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ABSTRACT

As history would have it, the recent Mw7.1 Puebla-Morelos intraplate event occurred on September 19, 2017, coincidental to the 32nd anniversary of the 1985 Mw8.0 Michoacan interplate event. The former had less impact both in affected areas and in severity than the latter which had profound impacts on the nation. The roles played by the ground motion input, site setting of the Mexico City with its thick lake sediment deposits, and structural types of affected building stocks on earthquake damage in the two events shared general similarities with subtle nuances. The author participated in the Canadian reconnaissance teams after both events. This work discusses the vulnerability of Mexico City to the two events that are representative of two types of source mechanisms: the recent event being moderate yet closer, while the earlier one being major but further away. In addition to the difference in earthquake magnitude and epicentral distance, they also generate ground motions of different frequency contents. The earthquake and damage data for this pair of events are compared in a summary table. Moreover, the earthquake early warning system, having its origin because of the 1985 event, has been fully operative since 1993, including in the 2017 event.

The NHERI RAPID Facility and Applications in Lifeline Performance Reconnaissance in Natural Hazards

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ABSTRACT

The Natural Hazards Reconnaissance Facility, known as the RAPID, is part of the National Science Foundations' Natural Hazards Engineering Research Infrastructure network. Housed at the University of Washington (UW), the RAPID is a collaboration between UW, Oregon State University, Virginia Tech, and the University of Florida. The RAPID facility enables natural hazard and disaster researchers to conduct next-generation quick response research through reliable acquisition and community sharing of high-quality, post-disaster data sets. These data allow researchers to characterize civil infrastructure performance under natural hazard loads, evaluate the effectiveness of current and previous design methodologies, understand socio-economic dynamics, calibrate computational models used to predict civil infrastructure component and system response, and develop solutions for resilient communities.

The RAPID facility provides investigators with the hardware, software, and support services needed to collect, process, and assess perishable interdisciplinary data following extreme natural hazard events. Support to the natural hazards research community is provided through training and educational activities, field deployment services, and by promoting public engagement with science and engineering. Specifically, the RAPID facility has the following strategic activities: (1) acquiring, maintaining, and operating state-of-the-art data collection equipment; (2) developing and supporting mobile applications to support interdisciplinary field reconnaissance; (3) providing advisory services and basic logistics support for research missions; (4) facilitating the systematic archiving, processing and visualization of acquired data in DesignSafe-CI; (5) training a broad user base through workshops and other activities; and (6) engaging the public by enabling citizen science research in natural hazards, as well as through community outreach and education.

The work highlights RAPID's capabilities and example data from deployments, emphasizing data collection applications on lifeline performance.

Implications of Earthquake-Triggered Bedrock Landslides for Post-Earthquake Power Supply Reliability, Hokkaido, Japan

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ABSTRACT

The September 2018 Mw6.6 Hokkaido Eastern Iburi earthquake in southern Hokkaido, Japan was associated with numerous shallow landslides that resulted in local loss of life and damage to lifelines, especially electric distribution networks. In contrast to ubiquitous surficial landslides in the epicentral area, the Pacific Gas and Electric-Southern California Edison--InfraTerra-Hiroshima University reconnaissance team observed two deep-seated translational landslides in shallow dipping Miocene age marine bedrock that damaged key electric transmission towers, resulting in significant disruption to regional power delivery. These failures were surprising as the transmission towers were sited on ridges, the typical practice for avoiding slope failure in Japan and internationally. The largest observed landslide translated a 1000-meter-long bedrock ridge approximately 350 meters, based on geologic and remote imagery reconstructions developed, in part, from unmanned aerial vehicle (UAV) surveys. Geotechnical drilling within the toe of the slide, ongoing at the time of field observations by the reconnaissance field team, identified a likely slide plane at a depth of approximately 50 meters. The plane consists of a weak, one-foot-thick clay layer that separates fractured rock above from competent rock below. Blocks of similar clayey material were found along the base of lateral scarps bounding the translated ridge. Comparisons of pre-earthquake aerial imagery and landslide mapping with post-earthquake field observations document geomorphic evidence of large coalescing older (pre-existing) deep seated landslides that were similar in scale and mechanics to those triggered by the 2018 earthquake. Geomorphic features indicative of pre-existing deep landslides include incipient headscarp grabens, deflected streams, and bedrock exposures of basal slide planes. This study supports the efficacy of using pre-earthquake mapping to help identify potential large-scale ridge-involved landslides for avoidance or mitigative rerouting, or in the case of existing tower alignments that cannot be moved to perform risk evaluations. It also serves as a case history to illustrate that the assumption of ridge stability is not always reliable.

Four Decades of Lifeline Damage, Recovery and Lessons Learned

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ABSTRACT

Since the 1971 San Fernando Earthquake, ASCE's Technical Council on Lifeline Earthquake Engineering (TCLEE) was formed and has sent post-earthquake lifeline investigation teams to 20 international and 10 domestic earthquakes. Much knowledge was collected and presented in various publications including ASCE, the Earthquake Engineering Research Institute, Engineering News Record and numerous presentation summaries at professional meetings and conferences.

This work summarizes prevalent forms of lifeline damage, the resilience and/or lack of resilience of the various lifelines, lessons learned and performance of updated standards/technologies. Significant damage is commonly associated with fires, tsunamis, landslides and liquefaction.

Due to the importance of lifeline services on society's well-being and the complexity of lifeline systems' dependencies, we have learned that taking preventative and proactive actions before earthquakes can greatly minimize disruptions. Seismically designed emergency generator systems with reliable fuel supplies can ensure continuous post-disaster power. The audience will learn practical and efficient methods to reduce damage to lifelines and improve restoration and recovery times.

Damage Analysis of Drinking Water Supply System in the 2018 Hokkaido Iburi-tobu Earthquake in Japan

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ABSTRACT

This work focuses on the damage to drinking water supply system in the 2018 Hokkaido Iburi-tobu earthquake in Japan. An earthquake of about 35 km in depth and magnitude MJMA=6.7 occurred at east of Iburi region in Hokkaido, Japan at 3:07 local time on September 6th, 2018. The human damage of this earthquake were 41 deaths, 18 seriously injured and 731 minor injured. There were 409 completely destroyed, 1,262 partially destroyed and 8,463 slightly damaged houses. 2,249 non-residential buildings were also damaged. The main cause of these damages was landslides occurred at Atsuma town near the epicenter. The drinking water supply system in the stricken areas was also severely damaged. Water stoppage was occurred at about 68,000 houses in 43 waterworks bureaus just after the earthquake. Water supply was recovery in few days in the most waterworks bureaus, however 34 days were required for recovery from the water stoppage at Atsuma town. Tomisato purification plant and reservoir in Atsuma town suffered severe damage by a large scale landslide. This work introduces an outline of damage to the drinking water supply system in the stricken areas of this earthquake and result of damage analysis of the distribution pipeline. Furthermore, lessons learnt from the damage by this earthquake are discussed.

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Lessons Learned from Recent Post-Earthquake Investigations in Alaska and Puerto Rico Focusing on the Performance of Power Generating and Industrial Facilities

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ABSTRACT

The Electric Power Research Institute (EPRI) has sponsored and maintained a database of seismic experience data developed from worldwide earthquakes in the last forty years. The database focuses on the performance of large mechanical and electrical equipment installed at power generating stations and other industrial facilities such as gas-plants, hydro-plants, substations, water treatment plants, hospitals, schools, ports, manufacturing facilities, etc. The database will be expanded with data collected from two recent EPRI post-earthquake investigations in Alaska and Puerto Rico following the M7.1 November 30, 2018 Anchorage and M6.4 Guanica January 7, 2020 earthquakes, respectively. This study will summarize the lessons learned from these events that may be used to increase seismic infrastructure resilience, including for example:

- Typical failure modes that could be prevented with proper design and quality installation/maintenance procedures
- Situations where an extra "resilience margin" may be wisely included
- Opportunities to operationalize infrastructure resilience by reducing the likelihood of losing station power

Telecommunication Performance Puebla Earthquake M=7.1 19 September 2017

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ABSTRACT

The 2017 earthquake in Central Mexico (epicenter East of Ayutla, Mexico Earthquake) that terrorized Mexico City and Puebla occurred on the same month and day as the 1985 Michoacan, Mexico earthquake, which caused significant damage to lifelines in Mexico City. The official name of this earthquake is Puebla Earthquake. The differences between these two earthquakes are locations of the epicenter, the duration of strong shaking, and most importantly the magnitude. The 2017 earthquake epicenter is located about 150 km south-east of Mexico City, it happened at 13:14 local time and the magnitude is 7.1 with a duration of about 60 seconds of strong motion. The 1985 earthquake epicenter is located about 330 km south of Mexico City, it happened at 07:17 local time and the magnitude is 8.0 with duration of 90 seconds of strong motion.

All lifelines in Mexico City and areas around Puebla sustained various degrees of damage and service interruption. Electric power system experienced the most disruptions due to both substation damage and distribution system failures. Although the telecommunication system did not sustain much damage, the power system failures did cause some telecom service interruptions in areas with long duration power outages. Cellular messaging applications on smart phone reportedly were performing well when the voice call lines were saturated during the first day after the earthquake. There were scattered roads and bridges failures and also broken underground water pipelines. There was a report of liquid fuel tank failure but there was no report of cascade damage due to the tank failure. The airport was close for a short time and there was a short section of the road around the airport terminal cracked due to ground failure. Very minor damage was observed in the international airport terminal.

There were building failures and collapses including part of a school building. There were incidents of fire with one fire caused by gas tank explosion. Emergency services performed well.

Lessons learned from the 1985 earthquake probably have resulted in overall better telecommunication lifeline performance. There was no report of Central Office failures.

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Rapid Post-Earthquake Reconnaissance and Paleoseismic Trenching Results for the Mw 6.4 And Mw 7.1 Ridgecrest Earthquake Sequence, Southern California

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ABSTRACT

Rapid documentation of surface rupturing large magnitude earthquakes affecting infrastructure provide opportunity to further our understanding of the hazard and design approach. Specifically, fault rupture parameters such as location, width, style of deformation and slip variability are key factors affecting infrastructure performance. This study presents the observations from 2019 Ridgecrest Earthquake Sequence initiated with the July 4th, 2019 M_w 6.4 earthquake near Ridgecrest, California which later progressed into the July 5th M_w 7.1 earthquake. The coseismic deformation associated with this sequence included an approximately 22-km-long east-west oriented rupture with up to approximately 1 m of left-lateral surface displacement from the M_w 6.4 event, and 55-km-long northwest-southeast oriented right lateral surface rupture with up to 5 m of surface displacement associated with the M_w 7.1 event. These conjugate ruptures are within the Little Lake fault zone; however, not all structures involved in surface ruptures were previously mapped. Our field reconnaissance within 18 hours of the M_w 6.4 event concentrated mostly south of Highway 178 near a gas pipeline that was crossed by the surface rupture and locally revealed a complex and relatively wide deformation zone up to a few kilometers wide. The subsequent M_w 7.1 event resulted in similarly broad surface deformation that crossed a second gas pipeline south of Highway 178. Comparison of site-specific field measurements and subsequent aerial photography-based offset measurements revealed the variability of fault slip especially across complex sections of the fault rupture. Furthermore, three fault normal pipeline inspection trenches across the surface ruptures documented previous activity and subsurface width and deformation of the primary and secondary fault zones.

Spatial Distribution of Damage Potential of the 2019 Ridgecrest Earthquake Sequence Based on Inelastic-Response Spectra of Recorded Ground Motions

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ABSTRACT

The objective of this study was to quantify the spatial distribution of the damage-potential of the ground motions recorded in the 2019 Ridgecrest Earthquake and to visualize it in a geographic map in a manner similar to a Shake Map, which is produced immediately after an earthquake. While ShakeMaps display the geographic distribution of the response of elastic systems to ground shaking, a Damage-Potential Maps also quantify, along with the level of shaking, the fact that structures are designed to different strength levels depending on the type of lateral system they employ, the local seismicity at their site and on their age. Structural yielding is expected for systems subjected to moderate-to-strong ground-shaking intensities. Performing nonlinear response-history analyses of representative structures using the recorded ground motions provides an opportunity to draw different insights into the geographic distribution of damage potential by taking account the strength of the structural system, as well as its mass and stiffness. The main feature of an inelastic model is its ability to capture strength reduction due to yielding as well hysteretic energy dissipation due to cyclic loading and ductility. Using the dense set of recordings from the three main events in the 2019 Ridgecrest Earthquake Sequence, it is possible to compute the inelastic response of different structural types at each site. The damage potential is then computed as the ratio of the maximum inelastic response to site-specific design strength, obtained from the USGS Design-Maps WebServices tools. This process takes into account the spatial variation of both ground shaking and design strength (i.e., capacity). Plotting the damage potential for a geographic region can highlight unexpected regions of high risk even when ground-motions are moderate. Structures are expected to go to the inelastic range under moderate-to-severe earthquake ground shaking. Because it can be automated, the process developed in this study is one step more realistic than presenting the traditional distribution of linear elastic response spectral ordinates.

Segmented Water Pipelines and Fault Crossings from the 2019 Ridgecrest Earthquakes

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ABSTRACT

The 2019 Ridgecrest earthquake sequence, including the July 4th M6.4 foreshock and the July 5th M7.1 mainshock, occurred on faults within the Salt Wells Valley Fault Zone (SWVFZ) and the Paxton Ranch Fault Zone (PRFZ), respectively. Both fault zones produced extensive surface rupture (GEER, 2019; Dawson et al. 2020) that affected the Naval Air Weapons Station, China Lake (NAWSCL) and multiple water and gas pipelines that service the towns of Trona and Argus.

The Geotechnical Extreme Events Reconnaissance (GEER) association mobilized after the foreshock and before the mainshock to document the earthquake effects to the natural environment and to infrastructure (GEER 2019). Here we present observations of the surface fault rupture (SFR) effects on water pipelines. There are at least two water pipelines that cross the surface ruptures from both events. This includes water supply pipelines owned by the Searles Domestic Water Company (SDWC) that run roughly parallel to highway 178 between Ridgecrest and Trona, and also within the NAWSCL. Notably, where the M6.4 event damaged the SDWC pipelines there was approximately 0.5 meters of offset. These water pipes are made of multiple pipe materials, including steel, ductile iron, and concrete being approximately 30.5 to 40.5 cm in diameter. We describe the SFR mechanisms that led to the damage observed on the water pipelines. In addition, we provide detailed measurements of SFR spacing within the rupture zones, the distribution of the associated ground offsets, and their impacts to the water supply pipelines. Finally, we compare observed ground offsets at the locations of the water pipelines to estimates of ground offsets based on local tectonic activity (slip quantity estimates of adjacent faults or average movement in the fault zone) and site characteristics. It is anticipated that these data, observations, and findings will serve as a resource for subsequent efforts such as the validation of numerical pipe-fault crossing models, and the improvement of analytical solutions for rapid assessment of pipeline damage.

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Image-Based Modeling of Bridges and Buildings for Regional Scale Physical Damage Predictions for Natural Hazards

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ABSTRACT

Over the past decades, despite the steady advancements in the procedures that accurately simulate the behavior of engineering structures, the capabilities to estimate the effects of natural hazards at the regional level saw limited improvements. This research focuses on addressing one of the key factors behind this shortcoming: the inability to capture the response of individual elements of the built environment in regional studies. In specific, the study demonstrates how street-level imagery can be fused with public-domain maintenance and cadastral records, as well as class statistics available in the civil engineering literature to establish structure-specific models of bridges and buildings. The use of camera auto-calibration algorithms for geometric reconstruction of structures and augmentation of this data with machine learning classification and segmentation methods are discussed. The approach's effectiveness is evaluated from both geometric and structural perspectives for a number of case studies. Subsequently, simulation procedures required to develop fragility functions for the models that can be generated using the presented approach are discussed for earthquake, tsunami, and flood hazards. Lastly, several bridge and building structures are modeled using the developed procedure, and a comparison between their expected and observed performances is performed for several recent earthquake and flood incidents. With its explicit use of high-performance computing and public-domain datasets in a semi-automated manner, this study presents unique ways civil engineers can benefit from modern computational resources. Thus, it provides the audience with a vision of the future directions in Hazards Engineering.

Investigation of Water Pipeline Failures at Balboa Blvd. during the 1994 Northridge Earthquake

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ABSTRACT

Hazard estimation of earthquake-induced ground failure is an essential element to minimize the risk of urban infrastructure from natural disasters. Ground failure hazard, however, remains difficult to understand, quantify, and incorporate into infrastructure loss estimation, and emergency planning and response efforts. For geographically distributed systems, developing the ability to make rational decisions regarding their design and resilience estimation ideally requires: (a) an understanding of the regional geological background, (b) simulations of the spatial variability of soil properties incorporating the geological knowledge, (c) reexamining well-documented case histories and using them as a validation basis for both the ground and the pipeline performance, and (d) developing an improved understanding of when and when not to expect failures, such that design criteria for pipelines can be formulated.

By using state-of-the-art but commercially available tools and all pertinent data, this investigation revisits the well-documented Balboa Blvd. case history of the 1994 Northridge earthquake, which underwent extensive ground- and pipeline failures. Prior work by the authors focused on nonlinear deformation analyses (NDAs) that provided insights into the failure mechanism, patterns of ground deformation, and the magnitude of permanent displacements. Transitional probability geostatistics were used to develop stratigraphic models that capture the heterogeneity and the spatial variability patterns of sand-like and clay-like soils present at this site. Results from these NDAs suggested that a compounded effect of both liquefaction of sand-like soils and cyclic softening of clay-like soils led to the excessive ground deformations at Balboa Blvd. In addition, observed strains extended beyond the boundaries of the lateral spreading mass (head and toe scarps).

This work aims to better understand the correlations between Peak Ground Displacements and the welded steel water pipeline damage observed during post-earthquake repairs. The investigation focuses on the Granada and Rinaldi trunk lines of Balboa Blvd. such that the soil deformation patterns and the associated imposed demands are compared to the damage patterns observed. The ranges of the ground deformation patterns obtained from the NDAs are compared to the pipeline failure data and conclusions are drawn with regards to the degree to which the pipeline failures can be justified by the ground failure. Conclusions are drawn with regards to the ability of this study to provide a resolution to this historical failure, as well as inform future efforts and the development of design criteria for pipelines in liquefaction-prone areas.

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Influencing Resilience During Reconstruction

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ABSTRACT

The manner in which society responds to the consequences of a natural or man-made disaster has a direct impact on the resilience of the reconstructed infrastructure including lifelines. A review of reconstruction efforts following a number of recent large earthquake events and associated cascading events such as landslides, tsunami and debris flows reveals a range of approaches. These solutions that might be described by the following broad categories: (a) Stay and rebuild; (b) Relocate and build new; (c) Confront nature; (d) Work with nature; and (e) Build bigger and stronger. Each of these approaches has merits and demerits that embed an inherent resilience into the post-disaster reconstructed infrastructure. Despite this, little intentional effort is given to evaluating these various approaches in many cases. This may be in part due to the range of drivers involved in reconstruction decisions and the balance that is placed between these competing factors and externalities. This research illustrates these various approaches against the backdrop of several recent events. Specifically, examples following the 2008 Wenchuan earthquake and subsequent debris flows, the 2011 Tohoku earthquake and associated tsunami and the 2017 Hurricane Maria – 2020 Puerto Rico earthquake sequence are presented. A preliminary framework for evaluating the merits of the different reconstruction approaches is proposed.

Planning Road Reconstruction Activities after a Disaster - A Case Study Based on the Northridge Earthquake

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ABSTRACT

This study has developed a quantitative methodology for the optimal scheduling of reconstruction activities following a disaster. When roads are damaged or blocked by debris after a disaster, the resulting situation represents a threat for the population affected by the disaster because it could severely limit their accessibility to vital locations such as hospitals, police stations, and fire stations. It is essential to develop a restoration schedule for fixing the roads damaged that prioritizes access to essential public facilities, while considering interdependencies arising from locations of equipment/crew and road network connectivity issues. To this end, this study developed a new sequential methodology employing quantitative models based on the Steiner Tree and production scheduling algorithms that incorporate the principal characteristics of the real-world situation. An optimal schedule for restoring the roads, including the crews' assignment is provided. Maximizing the "comfort" of the people affected by the disaster was the main goal. We defined comfort as returning victims' lives "back to normal" as soon as it is possible. Because of this, the objective was to minimize the total completion time to fix the road infrastructure. Hazus, a software tool developed by the Federal Emergency Management Agency (FEMA) was used to generate data related to the impact of a disaster on facilities and the transportation network in the affected area. Using Hazus, a scenario that replicated the 1994 Northridge earthquake was created to generate the data needed for the case study.

Restoration Functions for Quantifying the Resilience of Bridges Exposed to Scour

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ABSTRACT

Bridges are the most vulnerable components of our transport networks. They are disproportionately exposed to natural hazards, with floods being the main cause of bridge failures across the world. Their performance is continuously challenged by the combined effects of natural hazard stressors, e.g. flash floods, exacerbated by climate change, aggravated by structural ageing and increasing traffic volume and loads. The most frequent mode of failure is under flash floods related actions, such as scour, hydraulic forces and debris accumulation. For assessing the resilience of flood critical bridges, it is essential to have realistic and reliable fragility and restoration models, which are the two main components of resilience and their convolution will lead to the generation of reliable resilience models for given hazard stressors. Hence, it is surprising that despite the importance of bridges and their high vulnerability to hydraulic actions, there is no available integrated framework for quantifying their risk and resilience to hydraulic hazards, for facilitating well-informed decision making, toward reliable prioritization and efficient allocation of resources. The international literature completely lacks in restoration models for scour critical bridges despite the fact that the literature has addressed extensively the actions due to floods on bridges, the assessment of their risk or vulnerability. This study is the first effort in the international literature that aims at generating reliable restoration models on the basis of an extended detailed questionnaire that was filled in by a number of experts coming from academia, consultants, decision makers and scientists from research institutions. The result of this study is a set of restoration models accounting for variable damage levels for each bridge component, sequences of restoration tasks and lag times. Correlations of damage with functionality levels and repair costs are also discussed. These models are expected to contribute in more reliable resilience assessment of scour critical bridges and inform decision-making by transport network operators.

Predicting Post-Earthquake Casualty Arrival Rates at Hospitals

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ABSTRACT

A healthcare system is an organization of people, institutions, and resources that deliver healthcare services to a target community. In this system, hospitals are the pillars and main providers of acute care. Hospitals' emergency departments (EDs) are the points of entry for all patients with emergencies. Over the past decades, EDs have been suffering from a frequent crowding crisis under normal conditions. The Institute of Medicine has described the problem as being "at the breaking point." Nonetheless, extreme events can significantly exacerbate the situation through an extraordinary surge in casualties. In particular, earthquakes are among the most injurious and deadly natural events. However, there has been limited research on ED performance after earthquakes. More specifically, there has been limited research on ED arrival rates. Current arrival rate models have three main limitations. Firstly, they do not capture the physics of the problem in terms of hazard, damage, casualties, and response. Secondly, they do not accurately model the time dimension of arrivals at EDs that is essential in determining arrival rates. Thirdly, they do not capture the inherent aleatory variability and epistemic uncertainty since they determine a single estimate of arrivals. To address these limitations, we propose a novel and general mathematical formulation that transforms the spatial random field of the earthquake intensity measure into a temporal stochastic process of casualty arrivals at the ED. The formulation captures the spatially varying intensity of the hazard, the building characteristics and damage, the distribution of casualty severities, the search-and-rescue process, the damage to the transportation infrastructure, and multi-modal transportation to the ED. As such, the formulation leverages physics-based models informed by real-life data, it models the time dimension of arrival rates, and it offers an appropriate approach that can capture the aleatory variability and epistemic uncertainty. Lastly, we illustrate the proposed formulation considering an example community. Consequently, the resulting stochastic casualty arrival rate at the ED (i.e., demand) can considerably assist hospitals in their disaster planning and preparedness and can be coupled with an ED service rate model (i.e., capacity) to predict the ED's ability to avoid excessive wait times by conducting a comprehensive reliability analysis.

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A Probabilistic Socioeconomic Impact Model for Critical Infrastructure Node Identification

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ABSTRACT

When disasters strike, the lifeline infrastructure of entire cities is impacted. It is known that post-disaster lifeline service interruptions can exacerbate the community's disaster impact and suffering [1]. FEMA's mitigation planning guidelines emphasize accurate risk assessment of a community's assets (e.g., built environment and people) in order to best identify the assets with high vulnerability and community impact [2]. Therefore, lifeline infrastructure risk mitigation planning should be based on a proper risk assessment considering the further impact of lifeline service interruptions on the community. This investigation proposes a probabilistic model to estimate the impact of lifeline service interruptions in order to identify critical nodes of high impact and risk. The model is developed by integrating a lifeline infrastructure system model and a socioeconomic impact model. The model assumes that socioeconomic impact is assessed by considering the physical dependencies on lifeline infrastructure services (i.e., water, electric, sewage, and transportation) as well as demographic characteristics (e.g., single-family home status, percent Hispanic, etc.). The dependency of the impact on lifeline outage is modeled through a conditional impact probability stemming at the household-level. Individual household impacts given outage are associated with base lifeline nodes and aggregated to form conditional impact probability density functions (PDFs) to characterize socioeconomic impact of individual base nodes. Utilizing the infrastructure system model, the impact PDFs are propagated upwards to all upstream lifeline nodes. Monte Carlo simulation is utilized to account for randomness in (1) household demographic characteristics stemming from census data, (2) the lifeline's nodal vulnerability through fragility curves, and (3) the hazard. This work is demonstrated with a case study for the power and water systems of Galveston, Texas, U.S.A., with the social impact of household dislocation during a hurricane event.

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Optimal Seismic Risk Mitigation Planning for Evolving Urban Civil Systems

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ABSTRACT

Rise in urban population and deterioration of built environment lead to higher seismic risks. Quantification of this increase in risk requires models of urban growth and of infrastructure deterioration. Furthermore, promoting the recovery of the functioning of infrastructure serving a community requires undertaking mitigation measures ranging from periodic maintenance to retrofit actions. Planning such risk mitigation measures to promote resilience level needs capturing the uncertainty of the number and magnitude of seismic events. We propose a stochastic optimization formulation that yields a risk mitigation plan by minimizing the total cost of implementation of the plan and averted consequences of inaction over many earthquake scenarios. The formulation is based on a network representation of interdependent urban systems. The time dependence of demand and capacity of nodes and edges mimics the evolution of the nodal demand and capacity. The time dependence of the demand is due to changes in topology of the networks due to urban growth and sprawl. The time dependence of the capacity is due to the deterioration or replacement of infrastructure components. The formulation is illustrated on the simplified water, power and gas network of Shelby County, Tennessee considering the change in population, network capacity and topology from 1990 to 2010. The generality of this method allows its application for obtaining optimal decision-based mitigation plans to a system evolving due to external and internal factors to promote resilience.

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Seismic Resilience of Intermodal Freight Transportation Networks with Ties to Economic Impact Modeling

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ABSTRACT

Intermodal freight transportation networks play a major role in the US economy, yet the majority are exposed to a wide range of natural hazards including earthquakes, tsunamis, floods, hurricanes and severe storms. Seaport-roadway-railway intermodal networks have suffered significant damage in past earthquake events, with the potential for significant physical, social, and economic impacts on communities. Resilience assessment of intermodal transportation networks exposed to such hazards as earthquakes poses unique challenges with respect to complex systems modelling at the individual mode (e.g. port); lacking input tools for the damage, restoration and operation of these modes; coupled systems analysis of the intermodal freight flow; and potential for model analysis across scales. Furthermore, physical system damage and disruption of freight flow can have direct and indirect economic impacts on a community over time.

This study presents a baseline framework to quantify the resilience of intermodal freight transportation networks disrupted by seismic events. The framework integrates available seismic fragility and restoration models for infrastructure components, and poses a port operation model along with network model that couples seaports with highway and railway to evaluate freight flow through intermodal transfer nodes, integration which is currently lacking in existing literature. Emphasis is placed on assessing the damage to intermodal systems, functionality evolution for the individual modes, and intermodal freight throughput metrics such as TEUs (twenty-foot equivalent unit). The proposed framework enables loss assessment considering physical and operational disruptions. A preliminary loss estimation model is presented based on estimates of direct repair costs and indirect business disruptions. Furthermore, this work lays a foundation for future integration of the infrastructure resilience model with community scale economic impact models by tracking the time evolution of the class and volume of goods disrupted across the affected region. A case study illustrates application of the proposed framework and opportunities for future work leveraging a hypothetical intermodal network located on the West Coast of US, constituent of a container seaport connected to roadway and railway networks, exposed to varying levels of scenario seismic hazard events.

Assessment of Protective Actions and Adjustments Taken by Shelter-in-Place Households Facing Disruptions in Critical Lifeline Services

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ABSTRACT

Natural hazards place tremendous pressure on critical lifelines and inevitably cause service disruptions which pose serious risks to community residents. Though previous research has studied the culture of preparedness in communities to mitigate the impact of natural hazards, few have examined the direct relationship between preparedness and disaster-induced service disruptions. Thus, there is little empirical understanding about the protective actions and adjustments available to and taken by affected residents to mitigate service disruptions. For instance, residents may respond to a power outage by purchasing supplies (generator, batteries), deciding to do nothing and tolerate the disruption, or leaving the residence until the service returns. Using descriptive and statistical analysis on survey data collected from individual households, the research aims to establish a framework on the protective actions and adjustments related to infrastructure service disruptions. The research will examine the disruptions in the power, water, communication, and medical services caused by Hurricane Harvey (2017), Hurricane Florence (2018), and Hurricane Michael (2018). It also investigates whether other influencing characteristics, such demographic information, perceived expectation of service disruption, and length of forewarning of the impending disaster, will influence the ability and inclination to use certain substitutes and responses. The research will assist invested stakeholders such as community leaders, emergency planners, and utility companies in understanding which households are most prepared and which are most vulnerable for potential service disruptions. Such findings will also reveal the underlying social impacts in order to prioritize the investment and restoration of infrastructure services affected by natural hazards.

Households' Protective Actions in Response to a Nighttime Earthquake: The 2018 Eastern Taiwan Earthquake

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ABSTRACT

The belief that individuals are more vulnerable to earthquakes that onset during nighttime hours is a common preconception. One reason for this belief may be a presumed limited capacity for individuals to react and to protect themselves appropriately in darkness. To better understand this issue, this study surveyed the experiences of households during the 2018 Eastern Taiwan Earthquake, a magnitude 6.4 event that struck Taiwan at 11:50 PM local time. Data were collected with regard to structural, environmental, social, and household contexts, as well as perceived shaking intensity, risk perceptions, individual preparedness, earthquake experience, and demographic characteristics, and compared against reported immediate individual protective actions taken. The results, then analyzed against two comparable daytime earthquakes (the 2011 Christchurch Earthquake and the 2011 Great East Japan Earthquake), indicate that approximately half of the respondents who experienced the 2018 Eastern Taiwan nighttime earthquake (49.7%) did not take any protective actions, which was slightly higher than both the 2011 Christchurch Earthquake (43.1%) and the more severe 2011 Great East Japan Earthquake (37.5%). Eastern Taiwan Earthquake respondents were more likely to have been in a familiar environment at the onset of the event (97.7% compared to the daytime earthquakes studied, 85.0% and 84.0%, respectively) and less likely to have had family members absent who's safety was unknown (15.6% vs. 49.3% and 55.2%, respectively). In addition, respondents to the Eastern Taiwan Earthquake survey reported lower levels of apprehensive emotions (M = 3.18 vs. 3.54 and 4.44, respectively). Regression analysis revealed that respondents' social and environmental contexts, directly associated with the earthquake occurring at night, affected the individuals' emotional response, and, in turn, their adoption of protective actions. The ability to form accurate expectations with regard to the rate of public recommended protective action response compliance based on earthquake intensity, population demographics, and contextual factors, is of particular practical importance during disaster preparedness and response operations. The results of this study are intended to highlight possible differences under diverse scenarios, and, in turn, encourage researchers and practitioners to design preparedness and response exercises that account for varying protective action responses to earthquakes under different circumstances, such as darkness. This study also provides clear intelligence regarding the response of individuals during earthquake events that can better inform policy decisions and structural regulations in earthquake-prone areas, reducing injury and promoting household and community resilience.

Household-level Impacts of Disruptions in Food-Water-Energy Systems Nexus in Disasters

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ABSTRACT

Water, energy and food systems are essential for the wellbeing of households sheltering-in-place during disasters. However, the highly integrated nature of these systems makes them susceptible to physical disruptions that have the potential to transform a natural hazard into a disaster of cascading events. In order to protect the wellbeing of the maximum number of households during a disaster, understanding differential household behaviors during food, energy, and water (FEW) infrastructure failures is critical. Within current disaster and infrastructure resilience literature, linkages between infrastructure and social systems in infrastructure interdependency studies are seldomly included. When they are included, the analysis is generally limited to impact assessments of physical infrastructure loss on economic sectors. As a result, a systems understanding of household-level processes related to demand and access to FEW resources during disasters with respect to differential household experiences remains limited. Combining disaster risk theory and Food Energy Water (FEW) Nexus systems thinking, this study develops a new framework to analyze the collective influence of integrated infrastructure disruptions and socioeconomic factors on household vulnerability during Hurricane Harvey. ANOVA one-way tests are used to determine the disparity in disaster risk measures across non-vulnerable and highly vulnerable households. Structural Equation Modeling (SEM) is employed to test the proposed associative pathways between infrastructure disruptions, urban attributes, household preparation behaviors. The results of the model intend to specify the effects of infrastructure disruptions on households' access and consumption of FEW resources and inform about the household-level attributes and behaviors that shape the demand and access to FEW resources in the context of natural hazards. In doing so, the model can address existing gaps in our understanding of FEW nexus system interactions and vulnerabilities at the household level regarding the: (1) urban attributes and disaster characteristics influence the sensitivity of vulnerable populations to FEW system disruptions, (2) nature and extent to which interdependencies among urban food, energy, and water systems influence a households' demand and access to these critical resources during extreme weather events, (3) cascading effects of disruptions in one system of FEW nexus on households' demand and access to resources from other systems, and (4) the behaviors that influence the extent of impact experience by FEW disruptions.

Modeling and Quantifying School Recovery for a Community Subjected to Tornado Loads

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ABSTRACT

This study focuses on modeling the recovery of schools after major disruptions using agent-based modeling. First, a model for the recovery trajectory of schools during the aftermath depending on their initial damage state is proposed. Afterwards, recovery of a network of schools in a community is simulated using agent-based modeling approach accounting for uncertainties in the models. A class of models in addition to the proposed school recovery model are developed in here in order to model the recovery of the school network. This class includes models to predict the tornado intensity and estimate the affected area, fragility models to predict the physical damage of each school depending on their location relative to the tornado path, models to simulate the response of other sectors of the community (e.g., households and lifelines), as well as models to simulate the response of school district decision makers and construction companies available in the community. Using agent-based modeling approach, these models are connected together considering their interactions to simulate the complex behavior of the community during the cumbersome circumstances after a tornado. The outcomes of this study are evaluation of the resilience of the school network in the target community subject to potential hazards as well as the effect of various decisions on the recovery response of schools within an affected community. As the application of this study, these models are implemented and tested on the Centerville testbed and results will be presented. The potential audience of this study would be researchers studying the community resilience as well as decision/policy makers dealing with decisions affecting the robustness and resilience of the education systems in the communities.

Integration of Housing and Social Vulnerability into an Optimization Model for Community Resilience Planning

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ABSTRACT

Hurricanes in 2017 caused a combined $265 billion in damage and resulted in widespread displacement of survivors (FEMA After-Action 2017 Report). The Community Resilience research program at NIST provides guidance on planning to reduce the severity of impacts from hazards. Here, the integration of housing and social vulnerability into a community-scale resilience planning tool, NIST Alternatives for Resilient Communities (NIST ARC) model, is described. NIST ARC is designed to facilitate stakeholder exploration of alternative sets of actions to take across the community with the aim of improving resilience. Underlying NIST ARC is a mathematical programming model, consisting of two decision stages (mitigation and recovery), and addressing key community resilience concepts, including hazard loading and resistance, system dependencies, redundancy, and recovery scheduling. Here, extensions of the model are described that capture aspects of social vulnerability as it relates to housing. Equations are introduced based on research linking variables such as race-ethnicity, financial resources (e.g., insurance), income, and tenure, to housing recovery. Results for a case study, one based on the experience of Lumberton, NC that endured Hurricanes Matthew (2016) and Florence (2018) will be presented. Limitations of the approach and future directions for development of the tool will also be discussed.

Firm-Level Resilience Indicators: The Relationship Between Profitability, Staffing, Capacity, And Operational Continuity

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ABSTRACT

Several measures of business recovery have been used in the literature as dependent variables in regressions or as proposed resilience metrics. Examples include change in revenue, perceived capacity, change in number of employees, self-reported recovery, and length of interruption. To the authors' knowledge, however, no study has empirically tested the relationship among these various measures. To fill this gap, this study analyzes survey data from a multidisciplinary, longitudinal field study in Lumberton, North Carolina after 2016 Hurricane Matthew to explore the various measures of business recovery, how they relate to each other, and how they behave when controlling for different business characteristics. We then discuss how the interpretation and use of these indicators may change through time and how researchers and practitioners might more efficiently collect data and design surveys to capture business outcomes after a disaster event.

A Review of Resilience Indicator Frameworks

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ABSTRACT

This work discusses the results of an analysis of a variety of resilience indicator frameworks. It details the process by which the frameworks were analyzed and discuss the results including what focal areas are common across the frameworks; the spatial and temporal scales at which they have been applied; and, the major differences of the frameworks studied. The target audience are community resilience practitioners, resilience researchers, and those interested in discovering new insights in the field of community resilience metrology. The audience will walk away with a better understanding of the variety of resilience indicator frameworks; assess the potential application of specific frameworks to their resilience metrological goals (e.g., evaluation of potential actions and investments, monitoring progress in reaching resilience goals); and for researchers, it will assist in the development of new resilience indicators frameworks. The field of resilience indicator frameworks can be overwhelming to those new to it. By laying out the components of a variety of resilience indicator frameworks, the review and results delivered will better position practitioner-oriented audience members to implement a resilience framework that suits their needs. Researchers can apply the findings presented to their own work to develop a resilience framework that addresses gaps in existing frameworks or to test an existing framework to move toward validation. Practical solutions to understanding the mechanics, inner workings, and application of resilience frameworks by unraveling the web of existing indicator frameworks will be the benefit of this work.

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Probabilistic Metrics and Decision Support Framework for Infrastructure Resilience Planning

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ABSTRACT

This study presents probabilistic infrastructure resilience metrics and a decision support framework that can assess and improve the resilience of community level infrastructure systems following planning guidelines such as the Community Resilience Planning Guideline by National Institute of Standards and Technology. The probabilistic resilience metrics incorporate community's expectations on the performance of infrastructure systems and their actual performance. These expectations are expressed in terms of robustness and rapidity based infrastructure performance objectives, which relate to the immediate post event performance and restoration time of infrastructure systems, respectively. These resilience metrics are used in the decision support framework for quantifying the resilience of several interdependent infrastructure systems under multiple hazards. For this purpose, the framework combines information on the built environment with hazard data for probabilistic simulations to determine damage, performance, restoration time, and losses while propagating uncertainties in capacity and restoration time estimates of infrastructure components. To bridge the gap between the current and expected infrastructure performance, the framework also incorporates mitigation and response strategies. For all combinations of hazard, infrastructure interdependences, mitigation, and response strategies, Bayesian networks are used to quantify the resilience of infrastructure systems based on the probabilistic resilience metrics. The framework and the resilience metrics are demonstrated for Seaside, Oregon, considering building, transportation, water, and electric power infrastructure subjected to seismic and tsunami hazards emanating from the Cascadia Subduction Zone. The results highlight the effects of community's expectations, interdependence between different systems, hazard intensities, resilience metrics, and response and mitigation measures on the overall performance and resilience of the infrastructure systems.

Quantifying the Relationship Between Interdependent Infrastructure Data Availability and Estimation Accuracy of Community Resilience Metrics

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ABSTRACT

The data and information available at the community-scale directly affects the ability of a community to make a resilience-informed decision; however, the relationship is quite complex to quantify because of the presence of distributed interdependent networks. The objective of this study is to quantify the relationship between interdependent infrastructure data availability and estimation accuracy of resilience metrics for informed decision-making across key engineering, economic and sociological dimensions at the community level. The method of approach is to generate a series of increasingly diminished data quality cases, i.e., increasing the apparent lack of knowledge in a community to assign fragility functions to their infrastructure systems within computational models developed for each data availability case by accounting for interdependency between infrastructure systems. The component-level estimates for each case are subsequently used for community-scale damage and functionality assessment, and in turn, to provide resilience information at the community level that informs a key decision based on the physical damage, the level and distribution of economic activity and social disruption metrics. The estimated metrics are employed to quantify the effects of diminishing data availability in estimating physical and socio-economic metrics within the community. The present study does not account for modeling resolution and uncertainty, which will be forthcoming in future work.

This study considers the case study of the Memphis Metropolitan Statistical Area (MMSA) in Tennessee, USA. The NIST Center of Excellence for Risk-Based Community Resilience Planning (CoE) has selected this case study as one of its five testbeds to test algorithms developed for community resilience assessment. MMSA represents a large urban area with a diverse population and economy. This study considers interdependent buildings, the electric power network, and water network, under simulated earthquake hazards for the network area, and seeks to inform a) a computable general equilibrium (CGE) model for the MMSA to simulate changes in a series of economic stability metrics, and b) changes in a sociological component, which in the present case is the estimate of population dislocation as a function of building damage and socio-demographics.

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Illustrating a Probabilistic Framework for the Estimation of Lifeline Recovery Time after Seismic Events and its Influence on Functional Recovery of Buildings

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ABSTRACT

Assessment of how to reach the pre-event normal operability of buildings after an earthquake event within an acceptable time, known as "functional recovery", has become the focus of earthquake engineering and associated policy making in the last few years. Functional recovery of lifelines is a key component to achieve this goal. In particular, the estimation of the recovery time of lifeline networks, such as electric power, water, natural gas, and telecommunication, affects the availability of these services at each building and, therefore, how and when a building can be used. The existing literature has focused on the lifeline network recovery at the lifeline component level. These component models are then integrated into network-topology dependent and location-specific models that can be used to estimate lifeline recovery.

This study develops a generic probabilistic framework for the estimation of lifeline network recovery time at the network level that is useful for incorporation into the building functional recovery simulations, accounting for the interdependency among the lifeline systems, lifeline system network damage and restoration information. Four fundamental lifeline systems in a community – electric power, water, natural gas, and telecommunication (including public switched telephone networks, mobile telephone network, and data transmission network) – are considered. The proposed framework uses lifeline network damage models for Shelby County, Tennessee, available in the literature, in terms of interdependent seismic fragility curves, and estimates network restoration time, within a Monte Carlo simulation platform. The interdependency between different lifeline systems has been accounted for by incorporating the concept of primary-secondary relationships among critical network infrastructure components in the different lifeline systems. The proposed framework can also be applied to the lifeline networks at various locations and seismic hazard levels based on the assumption of using the probabilistic lifeline network damage and restoration models of Shelby County as a basis to identify the mean values of a set of randomized variables required for the framework (e.g., a network damage state, network-based restoration times, etc.) with an associated standard deviation to account for the inherent uncertainty in the process. Lifeline restoration is quantified in terms of the percent of buildings served such that the outcome can be used for and linked to the building functional recovery. Its application does not require that the building engineer have any specialized knowledge in lifeline systems or their typology.

Predicting Pipeline Damage from a Seismic Event for Catastrophic Reserve Budgeting

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ABSTRACT

The cost of restoring basic utility services following a seismic event depends on the magnitude of the event, and the level of repairs and associated costs required to restore basic service. Costs to repair pipeline breaks and restore basic water and sewer service was the primary factor of interest to the City of Santa Rosa, the client who commissioned this study. The repair estimates developed in this study are used to establish a catastrophic reserve fund for the purpose of restoring basic utility service and allowing life and commerce to resume unhindered by these essential services. The methodology requires a utility GIS with pipeline size and material attributes, and it can be applied to any seismically active fault for which GIS earthquake ground motion data is available. For purposes of this study, the planning scenario considers the damage caused by the maximum probable earthquake along the Rodgers Creek Fault, and earth shaking data was obtained from the USGS. This fault bisects the City of Santa Rosa, and has a high probability of causing an earthquake with a magnitude greater than 6.7 on the Richter scale within the next 30 years.

Pipeline damage resulting from an earthquake is grouped into two general categories: wave propagation damage and damage resulting from permanent ground deformation. Liquefaction and landslides were not specifically considered. Earthquake liquefaction susceptibility throughout Santa Rosa is very low to moderate, and liquefaction related pipeline damage is inherent in the wave propagation damage assessment. Santa Rosa's terrain is generally flat, with few areas where landslides pose a risk to underground utility. Research conducted over the past several decades correlates pipeline failures resulting from wave propagation damage and Peak Ground Velocity (PGV). The PGV parameter is correlated most to pipeline damage because it is related to ground strain, the main cause of pipeline damage from seismic waves. Similar research correlates pipeline failures from PGD. These material-specific fragility formulae have been developed empirically from historical seismic events correlating repair rates for various pipeline materials against PGV and PGD. A proximity based damage assessment using GIS spatial analysis is used to identify the utilities subject PGD. Overlaying the spatial fault maps onto GIS utility maps identifies these utilities. Unit repair costs are then developed from historic construction pricing and applied to develop repair estimates. The cost of loss of service can also be quantified based on estimated repair time.

The empirically-based methodology used in this study differs from probabilistic models, like the FEMA HAZUS Earthquake Model, in that the mathematical functions used to estimate damage are derived from regression analysis of data correlating measured earth shaking with actual repair rates for specific pipeline materials from past seismic events. This micro-scale analysis allows utility owners of any size to develop data-driven system-wide pipeline damage and repair estimates. Conversely, HAZUS is a macro-scale model which provides results at a city or regional scale, usually in conjunction with potential damage to other infrastructure assets such as building and transportation facilities. HAZUS utilizes probabilistic functions to qualitatively assign exceedance probabilities for various levels of peak ground acceleration (PGA) and permanent ground deformation (PGD). HAZUS users have limited pipe material options, and analysis results are not correlated to documented damage likelihoods.

Modeling Temporal Inter-event Dependencies using Series of Semi-Markov Processes in the Context of Multihazard Infrastructure Recovery

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ABSTRACT

Modeling infrastructure recovery after hazard events is the central aspect of infrastructure resilience assessment. Much progress has been made on modeling infrastructure recovery after single hazard events, with approaches ranging from single degree of freedom system analogies to agent-based recovery models. However, models accounting for temporal inter-event dependencies between multihazards during the infrastructure recovery process are lacking. This work uses a series of semi-Markov processes approach to model the inter-event dependencies during infrastructure recovery [1]. Recovery between successive hazard events is represented by a unique semi Markov process that models the reduced recovery rates and increased recovery times due to incomplete recovery from a prior hazard event. Two formulations for inter-event dependencies are presented: maximal effects dependency (worst effects of two successive hazard events influences subsequent recovery) and cumulative effects dependency (cumulative effects of two successive hazard events influences subsequent recovery). The case study of recovery of a community in Charleston, SC, subjected to earthquake and hurricane hazards at random inter-arrival times is presented. Results indicate that accounting for inter-event dependencies can lead to lesser community resilience; however, the hazard intensities and their arrival times also govern the extent of inter-event dependencies. A proposal is given for converting recovery curves to a performance-based engineering decision variable, supporting decision-making for resilient designs.

[1] Dhulipala, S.L. and Flint, M.M., 2020. Series of semi-Markov processes to model infrastructure resilience under multihazards. Reliability Engineering & System Safety, 193, p.106659.

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Applying Consequence Driven Scenario Selection to Lifelines

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ABSTRACT

We present a new consequence-driven framework for earthquake scenario selection. For emergency managers, utility operators, policy makers, and other stakeholders, a scenario-based seismic risk assessment is often necessary for the purpose of emergency management and planning. In developing a scientifically defensible scenario, stakeholders can simulate a realistic event in order to pre-identify vulnerabilities in the system, and support action to address these vulnerabilities. Methods for identifying characteristics of a scenario earthquake include expert elicitation, duplication of a past event, application of the maximum considered earthquake, or matching a probabilistic seismic hazard event. For both probabilistic methods and deterministic risk assessment methods, current state-of-practice methods for scenario selection often rely on knowledge of recurrence intervals of mapped active faults. This can result in inadvertently discarding relevant hazard scenarios too early in the analysis and potentially overrepresent presumed culprit events. Selecting scenarios is particularly challenging for important population centers or remote critical infrastructure in stable tectonic environments, such as in the Central and Eastern US, where uncertain long-term seismicity and unknown faults offer inadequate constraint. Notably, events in these so-called stable regions do occur (e.g., Nahanni, Canada, 1985; Tennant Creek, Australia, 1998). In regions of low seismicity, even moderate events can be consequential due to higher vulnerability of buildings typical of such regions. Furthermore, communicating seismic risk to stakeholders and the general public in these regions can be especially challenging due to characterization of the hazard level. In this new approach, the analysis begins instead with the explicit definition of a consequence of concern to the specific stakeholder. This can range from a definition of loss (in lives, dollars, or other), or a performance metric for lifeline infrastructure. The framework leverages USGS software (ShakeMap, PAGER, and ShakeCast) to run the hazard and consequence analysis. Driven by this stakeholder-defined consequence, an inversion analysis generates a complete event set of candidate scenarios that could breach this consequence. The final selection of a scenario, or family of scenarios, is then informed by characterization of the hazard but not limited by it.

Exploring the Concept of Emergency Levels of Service for Critical Infrastructure

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ABSTRACT

Without defined levels of service, planning and mitigation actions for disaster response may have good, but vague goals. The creation of a recommended set of levels of service across the lifeline utilities would therefore be of value for their asset managers and for emergency planners. Such levels of service should be phrased in simple terms that can be understood by both lifeline utility operators and community members. The levels of service should be outcome-focused (i.e. the delivery of services such as liters of water per person per day) rather than input-based (i.e. the likelihood of a particular watermain being operational) to increase the community understanding of any recommended level of service.

This study outlines the concept of 'emergency levels of service'. Recommended levels of service are anticipated to be detailed in a conceptual framework that will be created by practitioners and researchers and will subsequently be operationalized. The operationalized framework could then be used to measure existing levels of resilience at suburb level. This would indicate to both the lifeline utilities and communities where there are potential or likely gaps in delivery of those levels of service. This differs from other frameworks and scorecards as the aim is to identify outcome-focused indicators and is directly applicable to community members.

While not directly focused on buildings or supply chains, the proposed emergency levels of service could be used by those sectors to inform their own potential response and mitigation actions. The defined emergency levels of service will not be prescriptive in how they are to be achieved, as water can, for example, be provided by reticulated supply or through other means such as movement by tanker trucks.

It is anticipated that emergency levels of service will be unique to each context/setting. This study will use the Wellington Region, Aotearoa New Zealand, as a test-case. The selected levels of service developed in this study are aligned to infrastructure types, including access, energy and water. They are split into timeframes (the first week, the rest of the first month, the second and third month, and for the fourth month onwards.

Survival Functions of the Shelter-in-place Households for Disruptions in Infrastructure Services

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ABSTRACT

This work provides a necessary analysis of community tolerance for the prolonged disruptions of the infrastructure services due to natural hazards based on empirical data. Currently, little is known about how households are affected by prolonged disruptions. As identified by the National Institute of Standards and Technology (NIST) reports on the assessment of lifeline systems' performance, the measures for assessing the performance of the infrastructure systems are based on the physical attributes and neglect the heterogeneity of households' ability to tolerate such prolonged outages. In this work, we develop a series of survival models for various infrastructure systems using empirical data collected in the aftermath of three major hurricanes, namely Hurricane Harvey, Hurricane Florence, and Hurricane Michael. Survival analysis was conducted on the empirical data to determine the household's tolerance level for the disruption of infrastructure services. Various factors, including the households' sociodemographic characteristics, risk perception, previous experience, resources, and sensitivity of households to the disruptions, were considered in determining the households' tolerance for the service losses. In addition, survival curves were developed, showing the proportion of households experiencing hardship when the disruptions exceed certain levels. These graphs are analogous to empirical fragility curves, which are widely used in the risk and reliability assessment of infrastructure systems. The results show that survival curves are similar in different locations (especially the median level), albeit the differences in disruptions of power systems and transportation closures. Additionally, there is a higher uncertainty in developing the survival curves for the transportation network in comparison to other infrastructure services. Moreover, previous experience of the affected households with the common disruptions affects the survival probability of the community. The presented survival models could be adapted in various locations for different infrastructure services to assist the utility companies and the involved stakeholders for developing metrics considering the societal expectation of the infrastructure services. The introduced measures facilitate decision-making by considering the service needs of the community, setting priority for the restoration, and better communicating the risks with service users.

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Emergency Construction Services: Early Contractor Design Involvement

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ABSTRACT

Early Contractor Design Involvement (ECDI) enables public agencies to rapidly move through the design phase to construction for emergency procurements by developing expedited procurement procedures before emergencies occur. ECDI provides information regarding the immediately available means, methods, and materials allowing a higher quality, schedule-centric design that can be executed rapidly with a lower probability for delays due to design changes from errors and omissions. ECDI was a crucial feature employed in accelerating complex critical infrastructure reconstruction efforts following both devastating earthquakes in Christchurch, New Zealand. ECDI is an established practice employed multiple DOTs using various types of solicitations and payment provisions. Public agencies such as DOTs, county transportation departments, and municipalities can utilize ECDI to improve their ability to responsively deliver quality emergency construction projects for their stakeholders.

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A Framework to Incorporate Disaster Preparedness on Water Infrastructure Recovery Planning

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ABSTRACT

In the aftermath of earthquakes, damage to water distribution infrastructure may lead to interruptions of service. The impact of these interruptions is not evenly distributed among the population. Households with higher socioeconomic status are more likely to possess the necessary resources to cope with an emergency, and not rely on the distribution system exclusively. Conversely, for households at lower socioeconomic status, access to potable water may be directly dependent on the public water system. Restoration plans for water infrastructure developed without considering these aspects may lead to strategies that do not minimize the number of persons without water. This study addresses the development of restoration plans for water infrastructure that account for the household's access to alternative water sources. An agent-based object-oriented approach is used to simulate the damage to water distribution system in San Francisco and estimate the duration of shortages to different areas in the city. Each facility in the water system is modeled as an individual agent. Their structural characteristics of the facilities is obtained from reports by the local water authority and used to select appropriate fragility functions to estimate damage. The model is used to identify a prioritization plan for the restoration of the water system that is based solely on the extent of damage and the number of persons affected. In the sequence, a logistic regression model is developed using data from the 2016 American Housing Survey and used to estimate the disaster preparedness of households based on their demographics. The disaster preparedness of the households is used as a proxy to their access to alternative sources of water, e.g. bottled water. Thus, the areas of San Francisco with the least capacity to cope with interruptions in the water service are identified. A prioritization plan for the restoration of the water system that accounts for disaster preparedness is identified. The results indicate that the prioritization plans are significantly different if the disaster preparedness of households is accounted for. That is, it is identified that restoring water supply to certain regions with low capacity to cope with water shortages should be a priority even when they have not experienced extensive damage. The framework developed in this study can be used by system operators to develop informed post-earthquake restoration plans for water infrastructure.

Emergency Restoration Strategy for Water Distribution System from the Viewpoint of Disaster Resilience Curves

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ABSTRACT

Earthquake resistance of the water distribution system has been recently required for earthquake disaster resilience especially in Japan. The objectives of this study are to develop an estimation procedure for pipeline damage sites after an earthquake disaster in formulating an emergency restoration plan in the water sector, and to investigate the emergency restoration strategy for smart recovery of economical and industrial activities. In this study, each pipe is classified according to the pipe, ground, damage, and hazard attributes in the pipe damage database, that covers the following earthquake disasters in Japan: Kobe City's urban area during the Great Hanshin-Awaji Earthquake in 1995; Ojiya City and Nagaoka City during the Niigata-Chuetsu Earthquake in 2004; Kashiwazaki City during the Niigata-Chuetsuoki Earthquake in 2007; Sendai City during the Easte Japan Earthquake in 2011; Kumamoto City during the Kumamoto Earthquake in 2016. A standard fragility function model on the peak ground velocity (PGV) and the damage rate is developed by applying the Weibul distribution. In this study, PGV provided in "Quake Map", an earthquake motion map instant estimation system by Advanced Industrial Science and Technology, is used. While considering the damage rate deviations caused by uncertainty factors, damage determination is presented using the Poisson distribution. In addition, the disaster resilience curves were calculated in the case study of Nishi-Mikawa region after the presumed Nankai trough earthquake disaster in Japan using a numerical simulation model on emergency restoration. We calculated an opportunity loss as an integration value of the economic activities rate of decline by the suspension of water supply with the pipeline damage in the emergency restoration period. As a result, it was pointed out that disaster resilience in water sector would require not only earthquake-resistant pipe technology but also emergency restoration strategy for mitigation of opportunity loss.

Planning for Post-Earthquake Fires Considering Performance OfTransportation and Water Networks

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ABSTRACT

Fire following earthquake, as a potential cascading event after an earthquake, can lead to major losses in a community. Historical events, such as the 1994 Northridge earthquake, confirm the risk of fire spread within communities if ignitions are not controlled by emergency responders. An earthquake amplifies the likelihood of multiple fires across a region, while disruptions in lifeline infrastructure, such as water and transportation networks, cause delays in response of firefighters. This research aims at improving existing modeling techniques for fire following earthquake by integrating layers of information on fire ignition, fire spread, response time of fire department considering performance of transportation network, and suppression actions based on water availability after an earthquake.

Therefore, the study incorporates inputs from two lifeline systems (transportation and water) while capturing the behavior of fire spread inside and between buildings of a community. The community layout is represented by three-dimensional 10m x 10m x 10m cells, where fire spread within and between buildings are simulated based on a combination of physics-based and data-driven models. Performance of the transportation network is captured by inclusion of damage to bridges as well as potential debris accumulation on roadways in dense urban areas. Bridges are classified based on a developed taxonomy to capture the level of damage and the likelihood of passability by fire engines, accordingly. Moreover, the structural system of buildings is considered as an input to quantify the generated debris from buildings.

Damage to components of the water network are included to assess the changes in water flow and pressure within the network. The suppression action is driven by a decision-making algorithm for fire engine mobilization to minimize losses. Fire engine assignments consider appraised value of the buildings in danger of fire, response time of the fire department, and water pressure in the region. The framework is applied to a case study. Sensitivity analysis is conducted to predict vulnerable areas of the community with possible pre-positioning of resources to minimize losses. The results of this research can be used by decision makers for preparedness and mitigation as part of community resilience planning.

Understanding the Consequences of Wellington's Infrastructure Vulnerability to Earthquake

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ABSTRACT

The Wellington Lifelines Group (WeLG) is comprised of the lifeline utilities serving the Wellington region of New Zealand. They share a collective understanding that Wellington's infrastructure is vulnerable to natural hazards, which was gained from previous studies based on a variety of modelling and expert opinion approaches. These initial studies provided a foundation for deeper analysis to be undertaken around the vulnerability of the region's infrastructure to earthquakes. The focus was on the likely damage states, interdependencies, and direct and wider economic consequences of a potential major earthquake in the region. The in-depth study used computer modelling and focused stakeholder engagement to quantify the improved resilience and economic benefit of the construction of a package of infrastructure upgrades. The study informs consideration of the mitigations that could be applied to address the core issues – short-term (emergency planning works), medium term (policy change at central government level) and long-term (the potential construction of new, resilient, infrastructure). The project outcomes are informing key decision makers in the region on the benefits of investing in resilience.

Actor Collaboration Networks for Resilience Planning of Urban Systems: A Hurricane Harvey Study

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ABSTRACT

The objective of this study is to examine the properties of the actor collaboration network and to analyze how they influence resilience planning in Harris County, Texas. Effective resilience planning can only be achieved through the collective actions of various actors and the network structures on which the collaboration among the actors unfold. Understanding the structural properties of actor collaboration networks for hazard mitigation may hold the key to understanding and improving the resilience planning process. To this end, we conduct a stakeholder survey after Hurricane Harvey in order to report actor collaboration networks in Harris County, Texas prior to the event, and to study the extent of collaboration in hazard mitigation across various sectors (e.g., flood control, transportation, and emergency response) before hurricane Harvey. We examine three network structural properties: degree centrality, boundary spanners, and core-periphery structure. The results show the following: 1) governmental actors involved in different infrastructure sectors have a greater potential influence on coordination improvement and information dissemination in hazard mitigation due to their high degree centrality; 2) actors with high degree centrality tend to be potential boundary spanners, which means that these actors have an increased influence on information dissemination and coordination improvement; and 3) fewer flood control and non-governmental actors were at the core of the actor collaboration networks, which reduced the extent of hazard mitigation coordination. The results identify potential influential actors (such as City of Houston, Harris County, and Houston-Galveston Area Council) in hazard mitigation integration across diverse sectors in resilience planning. Also, the results yield recommendations for increased actor networks cohesion for better coordination for hazard mitigation integration in resilience planning.

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The Importance of Enhancing the Dynamics of Lifeline Infrastructure Damage Assessment

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ABSTRACT

After an earthquake or a hurricane, performing comprehensive and detailed damage assessment of lifeline infrastructure across a community is a labor-intensive and challenging process. Tasks include determining which buildings need to be evacuated and identifying the roads, pipes, or cables that need to be fixed. Engineers and disaster managers responsible for infrastructure recovery look to provide solutions to optimize recovery tasks in order to maximize resilience. However, there is still a lack of critical understanding of the process of collecting data about the performance of lifeline infrastructure after a disaster, essential to facilitate response and recovery decisions. For that reason, and with limited resources to deploy inspection teams and technologies, the damage extent of infrastructure systems is often uncertain and expensive to measure. These challenges are exacerbated in developing countries, where the lack of implemented technologies makes it difficult to effectively assess damage after a disaster. In addition, the uncertainties associated with damage assessment make the evaluation of the economic impact of damage imprecise, resulting in a potential improper allocation of resources for the community.

In recent years, there has been rapid increase in the implementation of tools and metrics to assess the performance of lifelines after a disaster. These tools include: satellite data, drone imagery, LIDAR, sea level sensors, structural strain gages, expert opinion, etc. Each of these tools has a different precision, capability, and purpose. In practice, these technologies are often deployed in an uncoordinated and ad hoc manner. Therefore, there is an opportunity to provide more detailed, accurate, and comprehensive lifeline damage assessment through coordinated and mutually beneficial data collection efforts, particularly in capturing the dynamics of lifeline performance after a disaster. To achieve this requires a critical analysis of the tools and metrics available for post-disaster assessment. This work presents the tools and metrics used for lifeline damage assessment, and critically compares them to provide qualitative strategies to enhance the dynamics of damage assessment. Included are tools and metrics across lifeline networks, including transportation, water distribution, electrical supply, and building infrastructure; as well as across hazard types, including earthquakes and inundations resulting from hurricanes or extensive rain.

New York City's Use of Mapping Technology for Post-Disaster Assessment

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ABSTRACT

Advancements in mapping technologies have allowed New York City's Department of Buildings to significantly improve its recovery efforts for natural disasters. Following such events, the Department's mission is to provide emergency response, mainly in the form of building damage assessments. Since September 2001, the Department has performed inspections utilizing standardized Applied Technology Council (ATC) format. Such forms were implemented locally, for example, for building assessments after Hurricane Sandy, however, the collection of results required significant back office work as they were done manually and thus were time consuming, expensive, and resource intensive.

In the last 5 years, the Department has since evolved from traditional paper-based tracking of disaster assessments to using web-based mapping applications to track inspection work in real-time from across the globe. Utilizing Geographic Information Systems (GIS) software, the Department has developed mobile applications that produce both rapid and detailed electronic damage assessments that follow the ATC system. This enables inspectors and engineers to assess damaged buildings while making the information readily available to all stakeholders regardless of location. The evaluation, entered by an inspector at the site, is automatically linked to GIS mapping and indicates the building address with high accuracy, along with any photos taken at the site.

Receiving assessments in real time enables necessary information for the reconstruction of structures to be quickly obtained in these post-event investigations, thus resulting in an overall faster recovery effort. Specifically, GIS software significantly aided in the efficient and timely safety evaluations of buildings when deployed after Hurricane Maria. Using the mobile application for the inspection process, NYC Buildings' Inspection Team was able to collect field-level information for 84.45% of the identified damaged structures within just 5 days (~730 assessments). More recently, the Department provided personnel certified in structural damage assessments to aid in Puerto Rico after the January 2020 earthquakes. Over 16,000 post disaster assessments were completed in 27 days using the electronic damage assessments developed for use in ArcGIS. The implementation of ArcGIS software has proven to increase the Department of Building's ability for timely disaster response, which has had profound impacts on recovery efforts for the reconstruction and reestablishment of villages heavily impacted by disasters.

Analyzing Flows and Hierarchy of Human Movements using Aggregated Data in Disasters

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ABSTRACT

The objective of this study is to quantify and analyze the flow structure and hierarchy in human movement networks in response to natural disasters and man-made crises. Disasters cause large perturbations on human lives including commuting movements in urban areas. These perturbations make it difficult for relief organizations to efficiently reach people in need. Understanding the structure of human movement network such as flows and hierarchies in disasters is key to predicting the locations of affected people and operating effective humanitarian relief actions. Recent advances have been examining quantitative features of movement networks in stationary situations. Little is known, however, about the movement patterns when the population encounters emergencies. To explore the movement networks in disasters, we partnered Facebook Data for Good team and analyzed the aggregated movement data of Facebook users with location services enabled on their mobile devices. Six cases across different types of disasters including hurricane, earthquake, wildfire and flooding were selected for this study. We created the movement network in which nodes represent locations (tiles) and the count of users on a movement link represents the weight of a link. Based on these movement networks, we examined the degree distribution of the nodes in the networks and identified the hotspots using Lorenz Curve method. The results suggest that the power-law distribution can describe human movement networks in all disaster cases. In addition, the adjacency movement matrix is symmetric, indicating the presence of commuting patterns during disasters. To further explore the geometric feature of the movement networks, we calculated the flow hierarchy among different levels of hotspots. By comparing to the results from the gravity model and null model, we can find significant flow hierarchy in the human movement networks. The findings deepen our fundamental understanding of urban mobility structures under extreme conditions, which contribute to predicting the spatial distribution of affected people. The movement patterns uncovered in this study could help first responders and decision makers to better target their interventions and distribute available resources more effectively.

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A Deep Learning Approach to Rapid Regional Post-event Seismic Damage Assessment

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ABSTRACT

Earthquakes have caused severe economic losses and casualties around the world. Once an earthquake occurs, timely and accurate evaluation of the seismic damage in a disaster area is of great importance for organizing effective post- event relief. However, conventional in-situ inspection methods are time-consuming and labor intensive. Thus, they are unlikely to meet the requirements of proper emergency response when deployed alone. Although post-event damage/loss prediction methods that are based on fragility analyses are efficient, their accuracies are insufficient because limited information (e.g., amplitude) of the ground motions is used. A more accurate, yet less computationally efficient, approach is to use recorded ground motions in nonlinear time-history analyses (NLTHA) of structure-specific predictive models. However, carrying out such complicated NLTHA on structure-by-structure basis across an entire urban region is not yet quite possible to meet the granular demands of emergency response efforts, especially for urban areas with thousands of buildings. Given this perspective, a rapid regional post-event seismic damage assessment method based on a widely used deep learning method - convolutional neural network (CNN), is proposed in this study, which offers fair accuracy and can render predictions in near real-time. In this approach, an inventory building of a given region, the definitions of their damage/performance levels, and a suite of anticipated ground motions for the region are established. Numerical models like multi-degree of freedom models or finite element models can be established for buildings. These data and models are then used in NLTHA to establish a training and testing set for CNN that will estimate the damage state of a building or selected region, given the time- frequency distribution (TFD) graphs acquired by wavelet transform of ground motions. This CNN estimate can be made nearly instantaneously—i.e., it is suitable for rapid post-event assessment—and can result in high accuracy. CNN is particularly well suited for this task because TFDs are essentially visual representations of both the frequency- domain features, and instantaneous as well as cumulative time-domain features of ground motions. The proposed methodology is verified with a numerical case study on a typical reinforced concrete frame and the buildings of the Tsinghua University campus in Beijing. Detailed settings of networks are discussed, and the accuracy and efficiency of the proposed method are compared with traditional methods.

Beyond the Code: Practical Steps Toward Earthquake Resilience

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ABSTRACT

Many people think that modern building codes are sufficient to keep the doors open following an earthquake. People who have experienced any large earthquakes that have struck the west coast in the last forty years feel those events represent the worst damage an earthquake can do. The result to both of these lines of reasoning yields an environment that is a mixture of apathy (No worries-- we've survived the worst) and ignorance (The building codes will keep us open!).

This work attacks these misguided notions head on. Beginning with an attention-grabbing earthquake scenario where outcomes vary widely based on taking just a few easy steps, the discussion proceeds into a brief overview of building codes and how and why policy makers respond to disasters. This work dispels the myths about the nature of large earthquakes and the codes enacted to keep people safe during them. Once the code process and its intent is revealed, the vulnerabilities to communities post-earthquake become quite clear. The best practices currently in place in the field of earthquake damage mitigation are revealed. What are the best practices in surviving the actual shaking, tracking employees, limiting damage and keeping the doors open following an earthquake?

One of the most common questions, regardless of the specific earthquake-related issue at hand, is "What Should I Put In My Earthquake Kit?" It seems folks really like checklists. FEMA introduced a new business resiliency program, which is in a nutshell a checklist approach to post-earthquake business continuity. An introduction to this free program, it’s categories, the back-to-business assessment toolkit, and the recommended methods of addressing vulnerabilities in structure, systems and space are described. A budgeting exercise where attendees can begin the process of doing actual earthquake mitigation is useful. An overview is provided on “What’s New!” in the world of earthquake retrofit, including new pallet restraint bars that fall into place during shaking, earthquake-activated cabinet door latches, and shaking-activated emergency lighting. Additionally, this work covers:

1) How many building codes historically have been enacted to prevent the disaster that just happened from happening like that again. This will feature multiple examples related to California earthquakes, thesubsequent action taken, and the intent of the building code.
2) How the San Fernando earthquake changed things in relation to California hospitals and how the Northridge earthquake changed things even more. Why people should care about what California hospitals do and don’t do to prepare for earthquakes.
3) How the 2019 CBC has changed in the way it mandates the anchorage of non-structural building components. How OSHPD responded to those changes with a policy intent notification that clarifies everything.
4) How to properly classify and categorize equipment and furniture and how to determine the best way to secure non-structural elements. Why all businesses should do what California hospitals must do.

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Novel Framework for Resilience Assessment of Tall Buildings

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ABSTRACT

Big cities are currently witnessing a rapid increase in the construction of tall buildings, where reinforced concrete (RC) core walls are the most commonly used as a lateral-load resisting system. The tall building design is currently performed according to the Performance-Based Seismic Design methodology that focuses only on the performance of building structural components to ensure life safety and collapse prevention, whereas the level of damage-impaired losses and building recovery is not being considered. Therefore, tall buildings are not designed to be resilient at moderate and high magnitudes of ground shaking, which may have a devastating impact on communities given a large number of building occupants. Previous studies that attempted to assess the seismic performance of tall buildings used crude recovery models that consider post-earthquake recovery in a simplified manner. Recently developed framework for modeling functional recovery of tall buildings provides an opportunity to analyze the seismic performance of tall buildings from a new perspective resulting in a more accurate estimation of building post-earthquake recovery, and consequently its resiliency. As such, the presented framework can be used to conduct a series of studies to establish new design criteria for improved seismic performance of tall buildings. This study presents the novel framework for resilience assessment of tall buildings and demonstrates its application on a 42- story PEER TBI RC core wall building. A nonlinear model of the building is created in OpenSees using a newly developed three-dimensional model for RC walls. Building seismic response is obtained for three seismic hazard levels corresponding to SLE, DBE, and MCE-level events. Based on the results of nonlinear analyses, damage- impaired losses are calculated using FEMA P-58 tools, while the duration and speed of the building's functional recovery and associated resiliency index are evaluated using the recently developed recovery model. Moreover, recovery analysis results are used to identify building components that dominate the recovery process and to propose the earthquake mitigation strategy to improve seismic performance.

Seismic Resilience Analysis of Metro Tunnels in Shanghai

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ABSTRACT

The seismic resilient infrastructure should have the capability to reduce the damage induced by earthquakes and minimize subsequent losses with an effective recovery. This study presents a probabilistic approach to evaluate the seismic resilience of the metro tunnels in Shanghai. The seismic loss and resilience demand of metro tunnels subjected to transverse seismic excitations are quantified. Typical circular tunnels in Shanghai are adopted as a case study, and the corresponding numerical models are established by ABAQUS. A series of ground motions are selected and scaled from 0.1g to 1.0g to perform non-linear incremental dynamic analysis (IDA), aiming to obtain the tunnel responses under increasing levels of ground shaking intensity. Fragility curves are generated at the free-field ground surface, considering the main sources of uncertainties. Furthermore, vulnerability curves are derived from the above fragility curves, so as to estimate the seismic loss of metro tunnels under various ground shaking intensities. Finally, the resilience analysis of metro tunnels based on numerical approach is conducted. The results show that this type tunnels are good of seismic resilience.

Seismic Risk and Resilience Modeling of Water Distribution Systems

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ABSTRACT

The water distribution system is a critical component for community operation as it contributes to the functionality of all other infrastructure and lifeline systems. Earthquakes and other natural hazards can cause damage to the components of a water distribution system, causing far-reaching consequences to the socioeconomic and overall well- being of a community. This study contributes to the body of research on seismic risk and resilience modeling of water distribution system. First, an end-to-end simulation framework to simulate post-earthquake functional loss and restoration of a water system is developed, which encompasses seismic hazard characterization, component damage, hydraulic performance, and network restoration modeling. The modeling framework is validated using data from the 2014 South Napa Earthquake and extended to a hypothetical scenario. To deal with the temporal complexities that are embedded in the post-earthquake restoration process, a general dynamic updating framework is developed to reduce uncertainties in the outcomes of post-event recovery forecasts using Bayesian Inferencing, by exploiting real- time data. The specific example of updating predictions (post-earthquake functional recovery forecasts including total recovery time and complete recovery trajectory) is presented and validated on a real pipe network (Napa water system) and event (2014 earthquake and recovery). The end-to-end framework is then extended to enable stochastic event set assessments of the water network using the UCERF2 (Uniform California Earthquake Rupture Forecast, Version 2) earthquake rupture forecast model. Given that evaluating a large set of events with end-to-end simulation modeling is computationally expensive, a framework that uses Bayesian optimization to select a subset of ground motion maps and associated occurrence rates that reasonably estimates the water network risk is also developed. Ultimately, this study contributes to the large body of research on risk and resilience assessment of distributed infrastructure systems exposed to natural hazards.

Probabilistic Framework for Evaluating Community Resilience

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ABSTRACT

This study puts forward a probabilistic framework to quantify and evaluate the resilience of communities, consisting of a portfolio of building and interdependent infrastructure systems. This is achieved through a seamless integration of risk models and agent-based simulation in a Monte Carlo sampling scheme. In each sample, the proposed framework starts with risk models to probabilistically simulate the hazard event and evaluate the post-hazard state of the community. This includes the response, the damage, and the performance of buildings and infrastructure systems, and the ensuing consequences and their cascading effect due to interdependencies. The output is then integrated into a novel agent-based simulation module to model the recovery of the community from those consequences. This entails decentralized, autonomous, and interactive decision-making entities called "agents." Agents carry out recovery operations by continually making decision on allocating resources to damaged buildings and infrastructure components. This results in agents repeatedly scheduling discrete events with uncertain duration and cost, each corresponding to the end of a recovery operation and possibly, the start of newly scheduled operations. Monte-Carlo sampling yields the probability distribution of the total cost incurred by the community and the total recovery time. A resilience measure is then proposed that integrates the total community cost, representing the demand, and the gross regional product of the community, representing the coping capacity to tackle that demand. The framework serves as a decision support tool for policymakers to evaluate the effectiveness of their policies to enhance the resilience of their communities. The proposed framework is showcased through an application to a community including residential and commercial buildings, electric power system, water distribution system, and healthcare system subject to seismic hazard.

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Empirical Examination of Societal Risks of Disaster-Induced Infrastructure Service Disruptions

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ABSTRACT

The objective of this work is to systematically assess and identify factors affecting risk disparity due to infrastructure service disruptions in extreme weather events. We propose a household service gap model that characterizes societal risks at the household level by examining service disruptions as threats, level of tolerance of households to disruptions as susceptibility, and experienced hardship as an indicator for risk impacts. The concept of "zone of tolerance" for the service disruptions was encapsulated to account for different capabilities of the households to endure the risks. The model was tested and validated through survey data from the residents of Harris County in the aftermath of Hurricane Harvey in 2017. The results reveal that population subgroups show variations in the hardship level for service disruptions. However, the disparity in the experienced hardship is not due to the unequal exposure to a higher duration of service outages. Instead, the lower zone of tolerance of the socially vulnerable population causes their higher hardship. The results show that certain sociodemographic groups, such as racial minorities, lower-income households, and those who do not own their properties have a lower zone of tolerance, and hence experience a higher level of hardship from the service disruptions. The results show that households' need for utility service, preparedness level, the existence of substitutes, possession of social capital, previous experience with disasters, and risk communication affect the zone of tolerance within which households cope with service outages. The findings highlight the importance of integrating social dimensions into the resilience planning of infrastructure systems. The proposed model and results enable human-centric hazards mitigation and resilience planning to effectively reduce the risk disparity of vulnerable populations to service disruptions in disasters.

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Benefit-Cost Optimization of Resilient Lifeline Networks

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ABSTRACT

Society needs to be resilient in the face of disasters. A key contributor to resilience is resilient critical infrastructure, or lifelines, that at worst are only damaged to acceptable levels and that quickly restore lost function given a disaster. Measurement of a lifeline's resilience and determining how to configure and design a lifeline to achieve acceptable resilience, is a complex and challenging task. To examine these questions, urban water and electric power distribution resilient grid concepts are investigated using an idealized region typical of a mid-sized US city. The system is stressed by earthquakes of increasing intensity which affect lifeline networks by causing increased demands due to damage.

The damaged water network is hydraulically analyzed for the demands due to leaks, breaks and post-earthquake fires in a pressure driven analysis (PDA) mode using EPANET to determine the network capacity vis-à-vis these demands. We use Modified Mercalli Intensity (MMI) to summarize seismic intensity for presentation purposes only, because MMI tends to be easier for readers to understand and relate to than either PGV or PGD (peak ground velocity and peak ground displacement, respectively). It is found that resilient water grids have a benefit-cost ratio (BCR) of about 6 to 8 for seismic environments typical of Los Angeles and San Francisco, with lower values for Seattle and Portland. Similarly, electric networks are examined using as an exemplar seismic retrofitting of high voltage electric substations stressed by earthquakes of increasing intensity.

In summary, the project team finds that (1) The resilient grid concept has a BCR significantly greater than for high seismic hazard environments. (2) A major benefit of a resilient water grid is improved supply of firefighting water. (3) The benefit of the resilient grid is constrained by the capacity of the fire service. If the fire service can increase its capacity by for example having a greater capacity to move water by tanker trunks or portable water supply systems, then the resilient grid is much more beneficial. (4) These findings reinforce the point that the resilient grid concept is not solely a water department initiative but would need to be pursued in close cooperation with the fire service. (5) Irrespective of the fire aspect, the resilient grid is quite likely to result in significantly reduced time to restore water supply to customers. (6) there is an optimum spacing for a resilient grid, with closer spacings not significantly increasing the grid's BCR.

Resilient Cities / Resilient Lifelines: Past, Present and Future

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ABSTRACT

The national infrastructure of utilities and transportation lifelines is varied, complexly interconnected, and critical to life safety and the nation's economic welfare. Community resilience depends on resilient lifelines. Despite such interdependence, risk governance varies by lifeline sector and is often virtually self-regulated.

Where federal agencies or public utility commissions have regulatory responsibility, risk often goes unaddressed because of a lack of technical and monetary resources. Responsibility for risk management often falls to individual utilities (many investor-owned) that lack the capacity and broader perspective necessary to ensure a nationally resilient infrastructure. When developing design requirements, lifelines commonly externalize societal economic risks and account only for life safety and short-term internal costs. The result is an uncoordinated and wide variation in risk management, often with catastrophically poor disaster preparedness as evidenced by numerous infrastructure failures in disasters reaching as far back as 1971 SanFernando, 1989 Loma Prieta, and 1994 Northridge earthquakes, as well as recent disasters such as Hurricane Katrina, Superstorm Sandy, and the COVID-19 pandemic. Siloed risk management has produced under-design and poor maintenance. It has left operators unable to express a value proposition to the rest of society on how raising rates, fees, construction costs, and maintenance expenses can reduce society's long-term ownership costs and risk of catastrophic future losses. Recent studies by the National Institute of Building Sciences (NIBS) for several federal agencies and nonprofit sponsors demonstrate how we can optimize seismic design of lifeline infrastructure using well accepted engineering economic principles to minimize societal long-term cost of ownership. The studies, entitled Natural Hazard Mitigation Saves, deal both with retrofitting existing infrastructure and designing new infrastructure. They account for first costs and future losses to property, safety, and functionality ("dollars, deaths, and downtime"). Such accounting could be used in future design to better align the interests of lifeline operators with those of therest of society.

An organization is needed to provide leadership in how to establish design requirements that account for all those costs—first costs and future losses. Congress established NIBS to serve as the nation's convener of building sciences, bringing together experts in industry, academia, and government. It can serve a similar role to help America develop consistent reliability standards across its lifeline infrastructure.

Practical Seismic Resilience Modeling of Water Supply Systems

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ABSTRACT

Water districts in earthquake country must be able to assess their resilience under as-is and what-if conditions if they want to manage the risk they externalize on society and assure a reasonable degree of resilience. But existing tools to do so are either proprietary black-box models or are dispersed among numberless unfamiliar scholarly articles and studies. Recent studies for the United States Geological Survey and Water Research Foundation have attempted to solve that problem. In open, peer-reviewed publications, the authors developed, documented, tested, and implemented a model that encodes a small number of equations and parameter values to allow water district engineers to estimate earthquake damage and restoration of their buried pipeline network. The calculation can be coded in a spreadsheet. The model starts with a system map in GIS format. It characterizes lifeline interaction and repair-resource limits. It estimates physical damage to pipes and restoration over time, accounting for an entire earthquake sequence (mainshock and aftershocks), spatially correlated random ground motion and ground failure. The final output includes time series of number of repairs and degree of service restoration. The model treats most major sources of uncertainty and allows the user to perform stochastic simulation of damage and restoration. With information about the economic consequences of lost water service, one can estimate much of the societal cost of earthquake damage to a water supply system. The model, called CUWNet, goes a long way toward enabling a water utility to measure and manage its resilience in terms that matter most to the community it serves. Doing so could better align the interests of the water district and the rest of society, producing a resilient water system to support a resilient community.

Optimum Bridge Retrofit Based on Highway Network Resilience Analysis

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ABSTRACT

In cases of seismic events in regions with highly developed and complex highway networks, the inter-dependency between structural damage and system functionality is key for assessing social impact and financial cost (Cavalieri et al. 2012). One of the challenges associated with informed disaster risk mitigation and management of such networks is the quantification of resilience in a feasible, meaningful, and pragmatic manner. This study builds upon a recently developed, multi-dimensional (i.e., structural, geotechnical, transportational and financial) framework that permits consideration of bridge damage, repair rates and downtime in the decision-making process for pre-earthquake retrofit (Kilanitis and Sextos 2019). Bridge fragility is assessed based on rigorous, frequency- and intensity dependent models for soil-pier (Lesgidis et al. 2017) and deck-abutment-embankment interaction (Zhang and Makris 2002), while regional seismic hazard is represented in the form of scenario-based spatially variable intensity measures. A set of novel, time-variant, resilience-based indicators which consider financial, environmental and social consequences are then used to identify the bridges that would have the maximum beneficial impact at a network level if strengthened prior to an earthquake event. This probabilistic risk management framework, as well as the corresponding GIS-based software, are deemed a useful tool for local/state or national stakeholders in prioritizing the pre-disaster strengthening schemes and accelerating the post-earthquake inspection and recovery measures, respectively.

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Estimating the Duration of Business Interruption using a System Reliability Formulation

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ABSTRACT

Critical infrastructure and their provision of goods and services to communities determine the well-being and economic prosperity of modern society. Critical infrastructure are generally interdependent, and they jointly operate to support the production and distribution of goods and services. Buildings, bridges, and other structures and components of the infrastructure are exposed to low-probability, high-consequence events, which may lead to a reduction or loss of functionality of critical infrastructure. Business interruption may occur because of (i) direct damage to the business properties and facilities, (ii) reduction or loss of functionality of the supporting critical infrastructure, or (iii) impact on social systems affecting the availability of the workforce at a specific business and supporting businesses. Business interruption might lead to reduced or loss of production and sales, reduced income for shareholders and employees, as well as temporary or permanent closure. Current approaches do not estimate the duration of business operations while modeling the functionality of business properties, supporting infrastructure, and the impact on social systems, obtaining primarily qualitative estimates of business interruption losses. As a result, current approaches mainly serve to better understand past events, yet they might not apply to predict the duration of business interruption of different businesses, supporting infrastructure, social systems, locations, and hazards. Also, such predictions would, in general, not reflect possible changes in the built environment due to mitigation and adaptation strategies. To overcome the limitations in the current approaches, a mathematical formulation is proposed to model and quantify the duration of business interruption by incorporating the dependency of business operations on physical structures, infrastructure, and social systems. The proposed mathematical formulation integrates the predictive models of each cause of business interruption to estimate the time-dependent probability that the state of a business is fully or partially operational, or nonoperational. Importance measures are also defined to quantify the relative effects of each cause of business interruption to the operational state of a business. The information from the importance measures can help in efficiently allocating resources for mitigation and adaptation strategies.

Coupling Social, Economic, and Lifeline Systems to Predict Hazard Impacts

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ABSTRACT

Natural hazards often have far-reaching impacts on communities. These impacts go beyond the physical damage to infrastructure and often affect the social and economic dimensions of well-being. As a result, we need to define hazard impacts which go beyond infrastructure damage and downtime. Additionally, accurate quantification metrics which can represent these impacts must be a function of both the physical infrastructure and the characteristics of society. Much work has been done to create accurate prediction models for infrastructure damage and downtime, however, less work has been done to define the necessary societal characteristics. Moreover, coupling societal characteristics with infrastructure characteristics has been neglected in the literature. Existing quantification metrics often rely on aggregate information about societal characteristics which could lead to an underestimation of hazard impacts. This underestimation is especially salient when examining smaller case study areas where societal characteristics are often at a very coarse resolution. We propose a disaggregation method for defining relevant societal characteristics such as age and occupation on the household level. We then couple this information with physics-based models of infrastructure damage and recovery times for a given hazard to create realistic quantification metrics to measure the effect of a hazard on dimensions of well-being including Being Educated and Earning Income. We illustrate our results by studying the impacts of a hypothetical earthquake on the real community of Seaside, Oregon.

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GRIP: Global Risk Index for Power A Global Index to Identify Critical Infrastructure And Industrial Production Subject To Cascading Economic Impact From Natural Disasters

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ABSTRACT

Business-interruption, or how efficiently and quickly economies recover from disasters, is a key factor in resilience. When essential infrastructure, such as power generation or industrial sectors, are damaged in disasters, affected businesses quickly deplete capital and can no longer employ workers. The cascading effects of damage to key systems can have far-reaching impacts that, when quantified, greatly exceed the cost of rebuilding the physical infrastructure itself. Hurricanes Maria and Katrina and the Tōhoku earthquake and tsunami provide additional examples where damage to critical infrastructure resulted in cascading effects that severely impeded recovery and crippled regional economies.

It is not easy to assess regions where business interruption is likely to be problematic. The standard methods of modeling economies and critical infrastructure can be thorough to a fault. In supply chain analysis, for example, suppliers and alternate suppliers must be identified, a process that for complex products in a dynamic marketplace is akin to fingerprinting the metaphorical invisible hand. The analysis is robust, but the data is very difficult and expensive to develop, can take years to characterize, and the data is out of date as soon as it has been collected and properly georeferenced. Likewise, assessing the vulnerability of critical "lifeline" infrastructure requires gauging not just vulnerability, but a networks physical connectivity. Reluctance to share data can also be an obstacle to assessment. The more critical a network, the more likely access to data will be held in confidence due to security concerns. Even with access to data, the interoperability of critical infrastructure systems and industry combined with economies and global hazards has not proved feasible to model. Simpler methods are needed to prioritize and drive the process.

This work discusses GRIP, a global risk index for power, to identify pockets of critical infrastructure and industrial production subject to natural hazards and cascading economic impact. EO-based technologies were used to extract high-production regions from satellite imagery and hazards datasets and combine these results with global hazard datasets and economic indicators to establish an index. This index can in turn be used to prioritize in-depth studies that rely on more detailed economic analysis combined with a vulnerability assessment.

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The Psychology of Disasters and the Implications on Critical Infrastructure Systems

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ABSTRACT

Effects of disasters including earthquakes on our built environment are unique and complex. It requires a multi-dimensional and multi-disciplinary approach (including policy, design and construction, and operation) to improve resilience of critical infrastructure systems. Fundamental to this approach are people, including those managing and operating the infrastructure systems as well as the broader communities they serve. By understanding people and how they respond during disasters, insight can be gained into how to better address their needs in times of a disaster. This work describes the psychology of disasters, how people react, and implications to improve resilience of infrastructure systems to better serve our communities. It also considers the interdependent nature of our infrastructure systems. Experiences and lessons from disasters including the 1964 Alaska Earthquake, the 2011 Tohoku Earthquake and Tsunamic Crisis, the Coronavirus pandemic as well as recent wildfires in the Pacific Northwest Region serve as a basis for this work. Engineers, operators, leadership, and policy makers involved in making decisions about how to improve resilience of critical infrastructure systems will benefit from this work.

The goal of this work is to understand better the psychology of people in times of a disaster and infrastructure interdependencies to enhance the resilience of critical infrastructure systems within our communities. This provides the opportunity for those involved with infrastructure systems to better target how and when to delivertheir services to their communities. It will also provide insight into the broader interdependent nature of infrastructure systems serving communities and highlights potential areas requiring further coordination.

Societal Impact Evaluation of Infrastructure Disruption due to Disaster: in the Case of Water Analysis

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ABSTRACT

Compared with the physical and economic impact assessment of disaster, people rarely know about the societal impact of disaster, especially the impacts on daily activities or well-being of individuals. Critical infrastructure, which plays an important role in providing essential products and services to people, is vulnerable to disaster and its disruption would lead to huge societal impacts. This study established a theoretical framework and an integrated model to evaluate societal impacts considering disruptions and the interdependency of various infrastructures in disaster scenario. The integrated model incorporated social and engineering dimension analysis, and expanded from water analysis perspective. In societal impact estimation, this study firstly defined the societal impact as the percentages of population in different need satisfaction levels, and built the quantitative relationship between need satisfaction level and water quantity, which is provided by water related infrastructure. As for the engineering dimension analysis, an integrated water quantity estimation model is proposed considering the availability of tap water, bottled water, and emergency water, which are provided by water system, commercial facilities, and emergency service, respectively. While the availability of tap water from water system can be evaluated by hydraulic simulation in EPANET-EMITTER considering different direct damage of components. Besides, the access to bottled water was measured by the availability analysis of commercial facilities considering the situation of electricity, transportation, and direct damages. Additionally, the quantity of emergency water provided by shelter was estimated by equal distribution optimization model, which equally maximizing the water quantity that each person can get in shelter given limited resources and disrupted transportation. Finally, the proposed model is applied into Osaka city to validate the applicability and effectiveness.

Vulnerability of Cities to Disaster: Case of 2003 Earthquake in Boumerdes (Algeria)

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ABSTRACT

The concept of risk has become increasingly complex, and has been used not only in relation to the natural features of a region, but also to its socio-economic context. In this conceptualization, the latter directly influences the capacity of a community to cope with, recover from, and preparedness to disaster. Vulnerability is defined as the long-term factors that affect ability to respond to events or make it vulnerable to disasters, vulnerability has thus two sides: an external side of risks, shocks, and stress to which an individual or household is subject; and an internal side, which is defenselessness, meaning a lack of means to cope without damaging loss. Loss can take many forms becoming or being physically weaker, economically impoverished, socially dependent, humiliated or psychologically harmed. This study attempts to explain, through the analysis of the 2003 earthquake in the province of Boumerdes (Algeria). A unequal distribution of damages between one city and another by testing the risk management model according to which social and physical vulnerabilities are directly linked to places. To assess physical and social vulnerabilities before and after this disaster, we selected a set of indices based on a deductive approach, and adopted GIS to spatialize these vulnerabilities. The results highlight the importance of using social vulnerability study as the point of departure for defining seismic-risk mitigation policies, emergency management, and territorial planning in order to reduce the impacts of disasters.

Resilience of Two California State University Communities During the COVID-19 Pandemic

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ABSTRACT

The College of Engineering, Computer Science, and Technology (ECST) at Cal State Los Angeles (Cal State LA) and the College of Engineering (CENG) at California Polytechnic State University, San Luis Obispo (Cal Poly, SLO) are investigating the impact to the educational mission of the disruption caused by the COVID-19 pandemic within a framework of resilience. This study contributes to the knowledge of the resilience of communities to this unprecedented disaster. The results will be of interest to both researchers and practitioners in community resilience, particularly those who are interested in understanding the needs, vulnerabilities, and capabilities of the represented demographic groups. The location of the conference makes the Cal State LA results of particular interest to local community resilience practitioners. This study works across the following four dimensions to inform understanding of resilience in higher education with an equity lens:

- Temporal: Measure resilience over time through a longitudinal survey.
- Stories: Perform in-depth interviews and focus groups to investigate details of the university community response during the initial shock and ongoing recovery.
- Inclusive: Include a variety of groups in the college environment: students, staff, and faculty.
- Institutional comparisons: Data at Cal State LA, a Hispanic Serving Institution (HSI) and Cal Poly, SLO, a Predominately White Institution (PWI), will allow comparisons between populations with different ethnic and socioeconomic demographics.

The project is based on theories of resilience from both educational and community perspectives. The data collected will allow for an in-depth exploration of response and adaptation over time. Previous work on resilience in students at institutions of higher education does not explicitly compare diverse populations, and little is known about the institutional resilience of universities in these settings. The conditions imposed by the pandemic create different challenges across student populations. The knowledge gained in this study will inform future explorations of resilience among a variety of populations, particularly those served by Hispanic Serving Institutions and the communities to which they belong. Audience Takeaways: (1) strengths and vulnerabilities of the represented demographic groups, (2) longitudinal (time-series) data informing robustness, recovery, and thereby resilience, (3) proposed resilience metrics for these groups in a higher education setting, (4) conclusions generalized to the communities in which these students and universities are situated. These results will inform efforts to build resilience in similar communities.

Power Outages and Public Health: Developing a Metric for Assessing Communities' Disparate Health-Related Vulnerability to Power-Service Disruptions

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ABSTRACT

Power outages due to extreme-weather events (e.g., hurricanes and snowstorms) can cause severe health impacts on human communities. Increasing empirical evidence shows that the disruption of power services can increase the occurrence of health-related hardship, including cold- or heat-related illness, foodborne illness, exacerbation of chronic conditions, and even mortality within human communities. However, human communities experience different levels of health-related hardship during power outages due to their disparate vulnerability to power losses. Such disparate vulnerability of communities can derive from their unequal needs for the continuity of power services to support home appliances or medical equipment, as well as their different capacities to respond, cope with, and recover from the harm due to power losses. Therefore, recognizing communities' disparate health-related vulnerability to power outages can help inform the prioritization of pre-event resource allocation (e.g., back-up generators) and post-event power-service restoration for those most vulnerable communities with the aim of minimizing the adverse health impacts on human communities during power outages.

Vulnerability index is a prevalence decision-making tool for quantifying communities' disparate levels of vulnerability to external stressors through aggregating a set of indicators in multiple dimensions. Most of existing vulnerability indices focus on quantifying communities' vulnerability to natural disasters such as hurricanes and earthquakes, little attention has been paid on communities' vulnerability to infrastructure-service disruptions, especially on communities' health-related vulnerability to power-service disruptions. Therefore, the present study aims to develop a power-service vulnerability index (PowerVI) for gauging the disparate health-related vulnerability of communities to power-service disruptions. Based on a conceptual framework and theoretical justification from the literature, PowerVI aggregates the indicators to determine communities' health-related risk and need for the continuity of power services during power outages. The empirical validity of PowerVI is examined by correlating the PowerVI scores of communities with the increased emergency-medical-services calls, emergency-department visits, hospitalizations, and mortality rates during major power outages after extreme-weather disasters in the U.S. urban areas. It is hoped that the PowerVI can serve as a promising decision-making tool for the policymakers to identify the most medically vulnerable communities to power outages and support their prioritization decisions on adaptation planning and resource allocation in response to future power outages.

Simulation-Based Examination of Societal Risks of Disaster-induced Power Outages

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ABSTRACT

The objective of this study is to propose an agent-based simulation framework for examining the societal risks of the prolonged power outages caused by severe weather events. The existing models of infrastructure failures (such as power outages) in disasters fail to consider the societal risks of the service disruptions. Current models mainly focus on the physical performance of the systems and do not account for the disparities that exist in the susceptibility of the households to the service outages. This limitation is mainly due to the lack of empirical information about the anatomy of susceptibility to the infrastructure services and the underlying factors influencing the unequal household' susceptibility to the service outages. In addressing this critical gap, this study develops a framework for modeling the household' tolerance for facing prolonged power outages. The household' tolerance for the infrastructure services is determined by the combination of households' need for the service and their protective actions. Sociodemographic characteristics, information-seeking behavior, and the households' social influences affect their decision on the protective actions. This study examines the effect of proper risk communication and social networks in mitigating the societal risks of the prolonged power outages during the disaster. In this study, empirical data from household surveys collected from three hurricane events, namely, Hurricane Harvey, Hurricane Florence, and Hurricane Michael are used in determining the underlying mechanisms affecting households' tolerance for the power outages. The agent- based simulation model was then developed by integrating the households' susceptibility to the outages with best- practice models for simulating the power outages and restorations of power networks. The model was used to examine the effects of different public warnings, information treatment, and restoration resource allocation strategies to reduce the societal risks of service disruptions. The results show the capability of the proposed model for integrating the household's susceptibility in societal risks to prolonged power outages. Hence, the model enables integrating human- centric aspects in resilience planning and assessment of infrastructure systems in disasters.

Considerations for Low-Income and Underserved Communities when Developing Guidance for Earthquake Preparedness

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ABSTRACT

People who live in "earthquake country" should be aware of the risks associated with this natural hazard and be prepared for the effects an earthquake might have on their house and community. State agencies and local organizations typically provide guidance on those risks as well as mitigation techniques for residents to apply to their living situation. However, people who live in low-income or underserved communities may not have access to the resources and mitigation methods suggested by the guidelines. This work reviews publicly available earthquake safety and preparedness guidelines from several jurisdictions across the United States and examine them through the lens of low-income or underserved communities. The analysis will begin with the development of two user personas based upon evidence-based characteristics (education level, access to internet, etc.) Then, empathy mapping will be developed for each persona in three geographically-distinct areas prone to earthquakes. It will share observations and put forth suggestions that could make the guidance more sensitive and inclusive to the needs of these communities. This work provides a chance for feedback on guidelines based on the challenges that different demographic groups face, such as not having access to a car and not speaking or reading English. The outcome is a robust discussion that will lead to ideas that can be implemented in future versions of guidelines to positively impact the outcomes of earthquake events in low-income and underserved communities.
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Preliminary Seismic Vulnerability Assessment of Historical Urban Centers: Case Study of the Yungay Neighborhood, Santiago, Chile

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ABSTRACT

The 2010 Chile earthquake (Mw 8.8) caused considerable physical and socio-economic losses with severe and extensive structural damage in historical masonry buildings which are generally part of important civic neighborhoods. A fundamental step for the reduction and mitigation of seismic vulnerability of these historical urban centers with high population density is the seismic assessment of representative clusters of their constructions.

In this work, the urban area selected as a case study is the so-called Yungay neighborhood, a limited urban area of the Historic Downtown of Santiago City. It should be noted that in the area of influence of this neighborhood there is critical infrastructure, such as two hospitals, one fire department's station and sixteen schools. Therefore, a scenario of great seismic damage in URM constructions of this neighborhood could affect the connectivity of this critical infrastructure, as has occurred in past earthquakes in different parts of the world (e.g. 1971 US earthquake, among others).

The work provides an assessment of the seismic damage and fragility of historical urban centers employing the results of a field survey of 268 old unreinforced masonry (URM) dwellings located in the Yungay neighborhood, after the 2010 Maule earthquake. The observed damage was correlated with recurrent failure modes of aggregate URM structures, by considering 14 local mechanisms, both in-plane and out-of-plane, involving macro-elements on these buildings. The average damage level suffered by each structural unit was calculated through a new damage index, Id, computed as a weighted mean of the levels of damage observed for each mechanism. Considering variables related to geometrical, architectonic and stylistic features, as well as damage levels for the 2010 Maule earthquake, this building sample was classified into two homogenous groups: Colonial style derivations, such as Republican and Popular Classicism buildings [CD], and Classicist style and variant [CL&Va]. Moreover, a preliminary qualitative assessment of the seismic capacity of these structures is provided herein using a vulnerability-index-based-methodology (VI).

The results, obtained by the application of Id and VI methodologies, were analyzed and the expected damages have been estimated in terms of Probability Mass Functions (PMFs). As a novelty, the PMFs developed herein are the first publicly available functions for Chilean URM ordinary buildings. They can be directly usable by stakeholders involved in risk assessment aimed at the strategies prioritization of possible future damage mitigation, and for a rapid recovery of lifeline systems present in the Yungay neighborhood. Moreover, the procedure could be applied to other historical centers of Chilean central valley and other Latin American cities with similar characteristics.

Extraction of Bridge Damage in the 2016 Kumamoto Earthquake using Airborne SAR Data

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ABSTRACT

Synthetic aperture radar (SAR), which can observe the ground surface in all whether conditions and in 24 hours, is useful to grasp the situation of affected areas due to natural disasters. Modern airborne SAR is especially suitable for grasping damage situations since it is possible to perform emergency observation with very high-resolution (about 30 cm) and by the full-polarization (HH/HV/VH/VV) mode. In this study, we tried to extract landslides and damaged bridges using airborne SAR data in Minami-Aso Village, Kumamoto Prefecture, Japan, due to the 16 April 2016 Kumamote earthquake. The pre- and post-event Pi-SAR-X2 (X-band air SAR) taken in the similar heading angles were introduced to obtain the differences of the backscatter in the different polarizations and scattering components. According to the results, the HH polarization and the surface scattering (Ps) component were found to be most suitable to observe landslides, where the difference in the Ps component was larger than that in the HH polarization. The bridge outlines were created for four damaged bridges in the target area. The average value of the scattering powers within the outlines were obtained. In order to compare the scattering powers of those bridges in an equal manner, the contribution ratio of each scattering component was calculated. Regardless the illumination angles, the surface scattering dominates the backscatter of the bridge deck. However, the ratio of the double-bounce scattering increased as the illumination angle went larger. Although the increase of the Ps ratio was observed from three damages bridges, it was still difficult to grasp the backscattering characteristics of damaged bridges from those limited samples. More cases will be introduced in the future to identify the damage situation of bridges only from post-event SAR backscattering profile.

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Genius Gas System for Integrated Intelligent Pipeline Safety Supervision Platform

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ABSTRACT

As the lifeline infrastructure, the gas pipeline network is becoming more large-scale and complexity with the growth of modern city. However, the events that impact the safe operating of the city gas system happens from time to time, including leakage accidents caused by aging and corrosion, explosion, and third-party damage. If the running safety of the gas pipeline cannot be guaranteed, it will cause environmental pollution, waste of resources and casualties. Therefore, it is suggested to establish the pipeline safety monitoring system by sensing the deformation of the pipeline, the working state of the cathodic protection system, and the intruding by third-party. Although the gas company has established a variety of visualization and information systems, but each system is independently established in different periods, resulting in the data cannot be shared, not to mention the intelligent analysis of data. The Genius Gas safety supervision Platform (GGP) was developed in this study based on the artificial intelligent technology, Internet of Things and the powerful pipeline simulation cloud. The GGP consists of five sub-systems: 1 GIS and SCADA system, 2 Pipeline safety monitoring and appraisal system, 3 Gas pipeline network hydraulic simulation system, 4 Gas pipeline network risk assessment system, 5 Gas pipeline network safety maintenance system. All data about the safe control was stored in one virtual database to avoid data silos. The GGP was applied to two gas pipelines in Suzhou and Zhengzhou. In the case studies, MEMS sensors, electric potential monitoring, and optical fiber sensing technology were used to monitor the deformation of the pipeline, cathodic protection system and the intruding by the third-party. The results show that the GGP can connect the data of monitoring, evaluation, simulation and operation and maintenance in an effective and efficient way.

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Developing a Building Inventory for Low Probability-High Consequence Seismic Events in Urban Areas

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ABSTRACT

Cites with a low-probability of seismic events, but high seismic vulnerability and potential consequences often have little to no building feature data tailored for seismic risk performance analysis. In this study, we present an inexpensive building inventory development methodology with the capability of being replicated in cities where existing building data is lacking. The city of El Paso, TX is used as a case study because of the presence of the East Franklin Mountains Fault and the city's proximity to the increasing seismic activity in the Permian Basin region. El Paso's lack of earthquake history and data has left a research gap in its seismic infrastructure effects and its community resilience. Despite the occurrence of a M5.0 earthquake in Mentone, TX (175 miles to the East) in March 2020, residents of the city still do not consider earthquake as a hazard of concern, and subsequently do not plan for that eventuality. Earthquake engineering has continually improved over the past several decades as we collectively learn more from each domestic seismic event. Today, researchers have access to affordable seismic building performance tools such as SimCenter's Regional Workflow for Hazard and Loss Estimation (rWHALE) and FEMA's Hazards US (HAZUS). We created a building inventory for El Paso using publically accessible LiDAR data, cadastral data, and building footprints in ArcGIS. We performed risk performance assessments using the updated building inventory and standard tools. The building inventory was leveraged in rWHALE and compared to assessment results of the existing integrated building inventory in HAZUS. In order to make the process as scalable and transferable as possible, the entire approach to developing the inventory is presented with numerous data options as all cities will not have the same data. The case study on El Paso, TX focuses on the data available to the researchers.

Fiber Seismic Sensing Along Lifelines: Seismic Hazard and Health Monitoring

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ABSTRACT

Widespread use of fiber optic cables forms the backbone of modern telecom networks. Many of the fiber optic cables are along lifelines, such as highways and pipelines. Now these fibers can be turned into dense sensor networks to detect ubiquitous ground vibrations caused by earthquakes, traffic, wind, and humans. We are exploring a new technology, Distributed Acoustic Sensing (DAS), that can convert every few meters of a fiber optic cable into a seismometer. By shining laser pulses into a strand of dark fiber and interrogating the backscattered energy, we're able to measure miniscule length changes of the fiber during vibrations. This will allow high- resolution mapping of seismic hazard on a block-by-block basis. Furthermore, fibers along bridges, gas/water pipelines, and other distributed infrastructures can be used to monitor their health conditions, for example by detecting land subsidence or drift in their resonance frequencies. We believe fiber seismic sensing is an emerging technology that can greatly enhance safety of lifelines. This work reveals the technology and explores how it can apply to the lifeline system assisting the day-to-day monitoring and the seismic evaluation of the spatially distributed infrastructure system.

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DesignSafe: How Cloud-Based Data and Tools are Being Used to Enhance Research in Natural Hazards Engineering

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ABSTRACT

The DesignSafe cyberinfrastructure (www.designsafe-ci.org) is part of the NSF-funded Natural Hazard Engineering Research Infrastructure (NHERI) and provides cloud-based tools to manage, analyze, understand, and publish critical data for research in natural hazards engineering. The DesignSafe Data Depot provides private and public disk space to support research collaboration and data publishing through a web interface. The DesignSafe Reconnaissance Portal uses a map interface to provide easy access to data collected to investigate the effects of natural hazards on the built environment. The DesignSafe Discovery Workspace provides cloud-based tools for simulation, data analytics, and visualization; as well as access to high performance computing (HPC). This paper provides an overview of the DesignSafe cyberinfrastructure and describes specific examples of the use of DesignSafe in research for natural hazards engineering. These examples include: (1) integration of computational simulation, data analysis, and data publishing, (2) electronic data reports that use Jupyter notebooks that allow researchers to interrogate data interactively within the web portal, and (3) the publication of reconnaissance data using the DesignSafe Reconnaissance Portal and HazMapper App. These examples demonstrate how DesignSafe is enhancing research in natural hazards engineering and research related to infrastructure resilience.

Seismic Behavior of Masonry Building with Spread Base Isolation using Natural Rubber

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ABSTRACT

Masonry is one of the most widely used materials due to its availability and ease of construction in various rural parts of the world. For a developing country like India, 85% of buildings are constructed using masonry as per the 2011 housing census. Brittle nature of the masonry makes the buildings more vulnerable during an earthquake. Significant damages to masonry buildings were observed during 2005 Bhuj earthquake and 2015 Nepal earthquake. There are several existing techniques to control the damage of masonry building like reinforced masonry, confined masonry, and isolation systems. With global increase in the use of base isolation systems like high damping rubber bearing, fiber reinforced elastomeric bearing, lead rubber bearing, etc., rubber plays an important role in dissipating seismic energy. These techniques require specialized manufacturing process, skilled labor and are uneconomical for middle to low cost income people in seismic regions. To overcome these challenges, this study is focused on novel isolation technique with locally available low cost rubber as a cost effective emerging solution for masonry buildings. A numerical study is carried out on an experimentally validated one-story masonry building. This building has been modeled using a commercially available finite element tool ABAQUS. Displacement at the roof level and cracking of masonry in tension are chosen as output parameters to assess the behavior of building and to validate with the existing experimental results. The building is then modeled with the locally available natural rubber, which is spread throughout the wall above the plinth beam. Experimentally obtained properties of the natural rubber are given as input for numerical simulation. The building is subjected to 1986 Indian Earthquake ground motion, and the responses are recorded. The obtained responses are compared with those of existing fixed base building in terms of displacement, acceleration and failure stress. The wall-top displacement of the base-isolated building was reduced to 68%, and wall top acceleration has reduced to 64% compared to building with the fixed base. Results indicated that there is a significant improvement in the seismic performance of masonry building with the proposed isolation technique using locally available natural rubber.

Depth Completion from Sparse 3D Maps for Automated Defect Quantification

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ABSTRACT

For lifeline systems, routine visual inspections play a vital role in gathering structure-level data for maintenance strategies. Current research has shown that data repeatability and objectivity may be enhanced with computer vision and robotics, whereby manual collection, cataloguing, and quantification of defects is automated. We demonstrate the efficacy of automating fine-scale defect quantification in 3D maps built from lidar measurements. While mobile lidar scanners provide a fast and inexpensive way of obtaining defect measurements, they lack the density required for precise contours. To remedy this, we combine depth completion enhanced point cloud data from a lidar, and labelled image data to extract a more complete surface estimate in physical scale. Given a 3D map and linked image data with known poses, our approach first implements a point cloud to depth map transformation utilizing ray casting and intrinsic calibrations. Depth maps are then densified using a depth completion algorithm that employs traditional image processing techniques tuned for sparse lidar map data. Lastly, the combination of labeled defect images and dense depth maps is exploited to extract high-resolution area and linear measurements for defects such as spalls, delaminations, and cracks. The accuracy of our method has been assessed by comparing results to those obtained from non-depth completed data and to ground truth measurements obtained using a high-resolution monocular camera with scale input. Our results show that performing depth completion on lidar maps improves area quantification accuracy by ~12%, resulting in a total error of <2%. Similarly, crack length estimates were improved by 5% with a total error of <3%. Crack widths were calculated with an error of 8% from ground truth whereas these measurements were unattainable without depth completion. The data suggest depth completion of sparse 3D maps to be effective in fine-scale defect quantification, providing a more complete assessment of lifeline systems when more affordable scanning technology is used.

Deep Learning Models for Post-disaster Damage Assessment from Aerial Imagery

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ABSTRACT

Accurate and timely damage assessment after a natural disaster is essential to successful hazard mitigation, response, and recovery. In large-scale disasters such as floods or earthquakes, preliminary damage assessment (PDA) is commonly performed using flyover footage captured by satellites, helicopters, or unmanned aerial vehicles (UAVs). PDA is often followed by deploying field inspectors and engineers to the disaster-affected areas who will use guidelines and metrics established by local or federal governments to evaluate the functionality and integrity of structures. While removing expert judgment from this human-in-the-loop scheme is still considered a computationally hard problem, new advancements in remote sensing and artificial intelligence (AI) have paved the way for carrying out faster and equally accurate PDA to provide insights to first responders such as paramedics, firefighter, search and rescue (SAR) teams, and other critical players for successful disaster response operations.

The goal of this research is to assess and enhance the performance of AI-based post-disaster damage assessment using aerial imagery. Specifically, we use deep learning in the form of convolutional neural networks (CNNs), to predict the severity of damage experienced by dwellings on the ground using standard damage scales for residential buildings established by the Federal Emergency Management Agency (FEMA). In particular, we train, validate, and test Mask R-CNN (region-based CNN) and MobileNet (multi-classification CNN) on two datasets, an in-house, fully-annotated UAV-captured video dataset, and a satellite imagery dataset from NASA. For faster training, transfer learning is used to adapt pre-trained CNN architectures. Additionally, to achieve better multi-classification CNN training, the Earth mover’s distance (EMD) is adopted as the loss function. We evaluate the performance of these fully-trained CNN models using footage from several disasters. Furthermore, we group the content of the in-house dataset into three difficulty levels of easy, moderate, and hard, which represent different levels of labeling effort and human annotator’s personal judgment used to label the image content based on FEMA damage scales. Beyond practical applications in disaster mitigation, the outcome of this study seeks to shed light on how the reliability of class labels affects the overall confidence in utilizing CNN models for post-disaster PDA, which in turn, will lead to more informed AI-assisted disaster management practices.

Target-Tracking Digital Image Correlation for Advancing Infrastructure Assessment and Structural Health Monitoring

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ABSTRACT

Retrofitting or rebuilding the nation's infrastructure calls for more efforts and advanced solutions for continuous assessment and monitoring of such systems. Innovative applications of vision-based video monitoring and digital image correlation (DIC) concepts is given for structural health monitoring (SHM) and infrastructure performance assessment. The first part of the work provides several applications from field and laboratory monitoring of full bridge systems under ambient excitations and earthquake loading using target-tracking DIC. The laboratory monitoring involved several bridge shake table tests at the University of Nevada, Reno Earthquake Engineering Laboratory. The second part is concerned with newly developed image compression and signal processing tools that use compressive sensing techniques with application to footbridge monitoring. The last part will discuss a mixed image and signal processing and enhancement approach that is validated using dedicated displacement measurement accuracy tests, then applied to post-processing data from a unique monitoring application of a full-scale reinforced concrete building tested under seismic excitations at the E- Defense testing facility in Japan.

Deep Metric Learning for Disaster Mapping and Damage Identification in Remote Sensing Images

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ABSTRACT

Using space-borne images and their time series for disaster-induced damage detection and mapping has been a classic topic since the advent of remote sensing (RS) technology. The traditional methods usually start with a change detection step that extracts features of structural changes followed by a pattern classification model (e.g., a support vector machine as a classifier). We review these traditional methods in a mathematical workflow and further identify the ensuing technical challenges, including inter- and intra-class variances, scene complexities, high-dimensionality, and small training data sizes. By exploiting recent advances in deep learning (DL) and the availability of big and semantic remote-sensing data, the authors developed a set of deep metric learning frameworks for identifying damage in bitemporal or post-event for extracting damage in low- to high-resolution RS images. These frameworks construct an integrated workflow for dealing with practical challenges in disaster-response practice, wherein low- to moderate-resolution RS data are usually available first, and the high-resolution ones come later. We will demonstrate these networks using real images from disaster events (including satellite images for flooding and images captured by unmanned aerial vehicles for a tornado event). Last, we will argue that how deep-learning and RS-based damage mapping contributes to resourcefulness, response, and rapid recovery during the life-cycle resilience cycles for both civil lifeline systems and communities.

Two technical innovations are recognized. Firstly, a new feature extraction model based on a Triplet-network is proposed. Based on the combination of the ternary input, it also merges the pre- and post-event images together as input. Secondly, we show an improved triplet loss function method, which enhances the model in dealing with intra- and inter-damage class variances. We describe the performance of the DL network in the context of a number of disaster types. For example, for wind-induced damage classification, we gain about 91.0% precision, 91.08% recall, and an F1-score of 0.92. Last, we share our vision towards developing a global remote sensing-based disaster mapping platform with a focus on flooding related disasters, which are the most frequent hazard globally.

Experimental Investigation of 3D-Printed Elastomeric Dampers

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ABSTRACT

The increasing use of tall buildings worldwide has led to rising demand for strategies to control lateral displacements in these buildings. Viscoelastic Damper (VED) devices are passive systems that depend on energy dissipation through a constrained viscoelastic material. As opposed to the conventional casting methods used in manufacturing VEDs, in this study, additive manufacturing (AM) is used to 3D-print Thermoplastic Polyurethane (TPU) to act as a VED. This study aims to investigate the significance of interior infill patterns, made possible by AM technology, on the energy dissipation of 3D-printed TPU VED. The mechanical characteristics, including hyperelastic and time-dependent viscoelastic properties of 3D-printed TPU, were determined in the laboratory using cyclic uniaxial tension and stress relaxation tests. The 3D-printed VEDs, with different infill patterns, were adhered to steel plates and subjected to sinusoidal signals with varying frequencies and strain amplitudes to examine its energy dissipation capabilities. The tests showed that the 3D-printed VED is capable of dissipating energy with good efficiency. Infill patterns, however, did not seem to have a significant effect on the energy dissipation. It is demonstrated that energy dissipation highly depends on the mass of the constrained damping layer.

A New Method to Determine Young's Modulus for Concrete Cylinder: Electromechanical Resonance Method

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ABSTRACT

Electromechanical impedance (EMI) testing has been used as an in-situ nondestructive testing (NDT) method for concrete material property testing, e.g. strength and Young's modulus, for decades. However, current EMI methods for determining Young's modulus require establishing a large database of conventional compressive testing results to correlate EMI spectrum. Although they can track the development of Young's modulus of concrete using statistical metrics the EMI method cannot quantitively determine the Young's modulus of concrete without referring to a reference state in the baseline database. EMI physical models usually consider the contribution of the host structure as mechanical impedance which is more localized than global mechanical properties of the structure. However, very few studies have investigated the physical relation between mechanical impedance and Young's modulus. Furthermore, the EMI spectrum is highly sensitive to the boundary condition of sensors which results in poor repeatability due to sensor variability. This talk will discuss a novel testing method "EMI Resonance (EMI-R)" that enables quantitatively determining Young's modulus of concrete cylinders by both the theoretical and experimental study. First, the eigen frequencies of a cylinder were tested using the EMI spectrum of a single Lead Zirconide Titanite (PZT) sensor. Then the Young's modulus was calculated based on eigen frequencies. Finite element (FE) analysis and impact resonance (IR) tests were implemented for validation. Results showed good agreement between the newly proposed EMI resonance (EMI-R) method and conventional IR test method. The results have confirmed that the newly proposed EMI-R method does not require any correlation of EMI spectrum to compression testing results. The influence of the variation of sensors is also diminished because of the "inertness" of PZT in the low frequency band.

A Path to Quantifying Emerging Technologies' Contributions to Infrastructure Resilience

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ABSTRACT

Recently, ASCE and the civil engineering industry as a whole has placed serious emphasis and investment in improving the resilience of our critical infrastructure systems. Furthermore, many technologies have hit the commercial market claiming to be able to improve the resilience of infrastructure. The exact nature of these improvements has been difficult to identify, but recent studies have been conducted to do just this. In this work, a recently published qualitative framework by the ASCE Infrastructure Resilience Division's Emerging Technology Committee that identifies areas of resilience where emerging technologies can contribute is explained. This framework does not, however, identify how to quantify such contributions. In this study, a path forward to resilience contribution quantification for emerging technologies is identified. This work further sets up a collection of case studies that implement the framework and in turn, present how current emerging technologies can improve the resilience of specific infrastructure systems facing hazard scenarios.

Monitoring Defects in Attention Allocations of Nuclear Power Plant Operators through Eye Tracking and Task Analysis

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ABSTRACT

During nuclear power plant (NPP) operations in control rooms, operators selectively focus their attention on alarms, indicators, and control switches. Failures in allocating attention at the right spots, at the right time, have caused around 35% of the situation assessment errors in the past. Previous studies of the NPP operator's visual attention have been limited due to either the lack of access to quantitative visual attention data or the lack of mathematical models that reveal the mechanisms of visual attention allocations. In many cases, the operators observe objects and events in a given order per needs of their tasks, as well as the salience of the visual features (e.g., colors and sizes of objects). Some studies found that the visual exploration behavior patterns of operators during the NPP monitoring processes (e.g., top-down, goal-directed scanning) could help signify skill levels of operators. These observations led to the following research question: To what extent do NPP operators' sequences of visually exploring a scene and the visual features of the observed objects collectively impact operational performance?

This work utilizes a mobile eye-tracker and computer vision techniques to study the sequential and temporal properties of the NPP control room operators' visual attention patterns. The authors first coded the task features from the perspective of attention drivers, including both top-down (task-driven) and bottom-up (visual-feature-driven) approaches. The authors then examined a mathematical model that captures the operator's visual attention transferring patterns in various task contexts and helps assess the impacts of such patterns on the efficiency and safety of NPP operational processes. A case study allows the authors to compare the task completion time and the number of task execution errors of multiple operators for research validation. In the case study, the authors recruit student volunteers to perform simple, complex, and off-normal operation tasks using a reactor simulator (Rancor). The data collected during the simulator experiments show that the operators who have higher efficiency and lower error rates usually follow specific visual patterns discovered through the mathematical models created in this research. Overall, the proposed mathematical model is comparable to the observed work performance data and could provide quantitative answers to when and why errors occur due to defects in operators' visual attention transferring patterns. This model could also provide insights into the operator's ability to handle tasks of different complexity levels.

Improving Natural Gas Transmission Pipeline Resilience Using Distributed Strain Sensing: A Case Study

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ABSTRACT

Distributed strain sensing (DSS) is a distributed fiber optic sensing (DFOS) technology that is gaining traction within the civil infrastructure monitoring industry. Research over the last two decades has shown that DSS can inform infrastructure management decisions by identifying and measuring localized strain. The literature shows that DSS has been effective for monitoring tunnels, retaining walls, dams, levees, drilled shafts and many other pieces of civil infrastructure. In this study, DSS is examined for how it can contribute to natural gas transmission pipeline resilience. A new resilience model and framework for evaluating emerging technologies is used to examine DSS with respect to a transmission pipeline that traverses a landslide zone. Facets of resilience where DSS contributes or does not contribute are discussed. It is demonstrated that DSS can provide resourcefulness and responsiveness to the pipeline system and therefore improve its resilience.

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Case Study of Resilience Analysis: Piezoelectric Sensors for Concrete Strength Monitoring

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ABSTRACT

The piezoelectric sensor-based electromechanical impedance (EMI) method is one of the most promising methods to monitor the real-time strength gain of concrete. It can be used for assisting the decision making to determine whether the newly poured concrete structure is ready for opening. The trial adoption of the piezoelectric sensing method for interstate concrete pavement projects showed that the sensing results are close to the compressive strength of concrete obtained from destructive tests. The piezoelectric sensing technique is evaluated for how it can contribute to the resilience of concrete structures in this case study. To examine the resilience of this sensing method, a proposed new resilience model and framework for evaluating emerging technologies are adopted on the scenario of premature cracking in concrete as failure mechanisms. The evaluation results show that piezoelectric sensing technology can contribute to the rapidity and resourcefulness to enhance the resilience of the concrete structural system.

Evaluating the Influence of The Internal Curing Aggregate on The Self-Healing Behavior of Fiber-Reinforced Cementitious Composite

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ABSTRACT

The existence of the cracks in concrete would shorten the service life of the structure by generating a pathway for harmful compounds to invade concrete from the external environment. To address this problem, it is desired for concrete equipped with the ability to self-heal the cracks. With self-healing ability, the event of cracks propagation and structural failure may be prevented. The infrastructure resilience can therefore be improved. Previous studies have found that during the self-healing process, water is a critical factor that determines the efficiency of the healing. Therefore, enhancing the ability of the concrete to absorb and store water from the external environment may potentially improve the self-healing performance. In this study, a hypothesis that the incorporation of the porous internal curing aggregates can improve the self-healing behavior of the designed concrete is proposed. In order to verify the hypothesis, two types of internal curing agents, zeolite and lightweight aggregate (LWA) were separately incorporated into the designed concrete by varying content. The pore structure of the internal curing aggregate was firstly examined by the scanning electron microscopy (SEM). Then, the compressive and tensile strength of prepared specimens were measured at the age of 28 days. In the meanwhile, samples were pre-cracked by uniaxial tensile loading. After curing for 7 wet/dry cycles, the self-healing performance was evaluated by resonance frequency measurement and microscopic observation. To further understand the influence of the internal curing on the designed concrete, water retention behavior of the bulk sample and the internal curing aggregates was evaluated. The result of the mechanical tests indicates that the incorporation of porous internal curing aggregates did not compromise the mechanical performance of the concrete. The evaluation of the self-healing performance of cementitious materials shows that the use of the internal curing aggregates increased the self-healing recovery ratio from 12.6% to over 18%. Based on the water retention behavior and SEM image of the internal curing aggregate, it can be found that a smaller size of the pores in zeolite particles makes it capable of storing a larger amount of water under low humidity, which is favorable for the healing of the concrete material. Therefore, a better self-healing performance can be expected when the zeolite is used as internal curing aggregate to improve the sustainability and resilience of concrete structures.

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Improving Infrastructure Resilience Using 3D-Printed Concrete: A Case Study

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ABSTRACT

Concrete 3D-printing is an emerging technology that is experiencing exponential growth in the number of research and field projects. The adoption of concrete 3D printing by the construction industry is rather slow, mainly due to the absence of standardization and the unclear cost savings associated with this technology compared with conventional construction methods. Research has suggested that concrete 3D-printing has the potential to reduce design and construction time through digitization and to narrow the gap between design and construction. In this study, we investigate how 3D-printed concrete can contribute to improving infrastructure resilience. A case study examining the restoration of a bridge that collapsed after an earthquake is considered. We suggest that post-tensioned 3D-printed concrete is used to build the new bridge and to restore system functionality. We examine the ability of 3D-printed concrete to improve resilience using a newly developed framework for assessing the role of emerging technologies on infrastructure resilience. We demonstrate that concrete 3D-printing can significantly enhance the rapidity of infrastructure recovery and thus contributes to improving infrastructure resilience.

A Methodology for High-Resolution Earthquake Damage Simulation and Performance Assessment for Potable Water Networks

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ABSTRACT

The NHERI Computational Modeling and Simulation Center (SimCenter) is developing a framework to integrate data and analysis tools into computational workflows to perform regional-scale simulations of the impact of natural hazards on buildings and infrastructure. These integrated workflows can utilize high-resolution data and multi-fidelity models to describe and simulate earthquakes and their damaging effects and consequences on the built environment. This research combines elements of the assembly-based FEMA P-58 Seismic Performance Assessment method for buildings with the HAZUS-type damage and loss models for water infrastructure to provide a high-resolution approach for seismic performance assessment of potable water networks. The proposed method is illustrated through a case study on an idealized water utility system in Memphis, TN. A scenario earthquake in the New Madrid seismic zone is characterized using spatially-correlated ground motion shaking intensity. Damage is evaluated to individual pipe segments of the primary feeders in the water distribution network to estimate the impacts on water delivery service. The uncertainties in the ground motions and the network characteristics are propagated through the simulations and their influence is quantified. The advantages of the high-resolution damage modeling with quantified uncertainty from the component level to network level are highlighted through a county- scale water network performance assessment using a Bayesian network system modeling approach.

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Using IN-CORE to Develop a Spatially Explicit Decision Support Framework to Increase Community- And Parcel-Level Resilience: An Application to Seismic-Tsunami Hazards and Multiple Infrastructure Sectors

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ABSTRACT

A spatially explicit decision support framework for quantifying and increasing parcel- and community-level resilience against natural hazards is developed using Bayesian networks. Whereas previous work has asked, "how resilient are infrastructure systems in a community", this work reframes that question to ask, "how resilient are parcels in a community given that they rely on these same infrastructure systems". This framework begins with a probabilistic infrastructure damage analysis using IN-CORE, an open-source modeling suite that assesses the impact of natural hazards on communities. These results inform operability curves that define the initial loss in infrastructure performance at each parcel and subsequent time to recover. Statistics are extracted from the operability curves to populate the Bayesian networks, which are then employed as a decision support tool to generate maps of spatial resilience. Seaside, Oregon is used as a testbed community and multi-hazard seismic-tsunami events are considered. The performance of four infrastructure systems are evaluated and dependencies between two of which are captured. By applying this framework to the testbed community, it is first shown that under status quo conditions, the seismic-tsunami hazard associated with the 1,000-yr event results in overall low community resilience and that the seaward most parcels are less resilient compared to their inland counterparts. Second, deaggregated results demonstrate that this low resilience is driven by the electric and water networks' time to recover. Third, by retrofitting and decreasing repair times associated with these infrastructures, the use of decision nodes within the Bayesian network are shown to increase inland parcel resilience. And fourth, resilience across various recurrence intervals shows that the community is least resilient against mid-magnitude events.

Earthquake Damage Prediction of Underground Steel Pipe with Screw Joint Using Machine Learning

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ABSTRACT

In communication network in Japan, buried conduits protects optical or metal cable, and it becomes a highly reliable network against disasters and accidents. However, when a large-scale earthquake occurs, some conduit joints are ruptured, and the cable may be damaged by damaged conduit. Though most damage conduits were old type and constructed from 1960's to 1970's, most conduits can withstand on normal times, and they have to be used without renewing as much as possible. Hence, it is necessary to take measures only for the conduits that will be damaged in the large-scale earthquake. Therefore, it is important to predict the underground conduits damage of telecommunication in advance.

In this study, damages of the old type steel conduits are predicted using machine learning. The used machine-learning algorithm is supervised learning, gradient boosting method. To construct the estimation model, we used inspection data from five past large earthquakes, the 1995 Southern Hyogo Prefecture Earthquake, Mid Niigata Prefecture Earthquake in 2004, The Niigataken Chuetsu-oki Earthquake in 2007, The 2011 off the Pacific coast of Tohoku Earthquake, and the 2016 Kumamoto Earthquake. The damage were checked by pipe camera.

The model was constructed using 80% of the 23833 records results of the inspection, and a test was carried out using the remaining 20% records. A record has label; damaged or no damage, and has 13 variables; seismic intensity, peak ground velocity (PGV), peak ground acceleration (PGA), spectral intensity, displacement converted from PGV and PGA, equivalent dominant period, ground strain, average shear-wave velocity to 30m, average ground level, average inclination, estimated artificial flat terrain, years buried and conduit length. Using this method, a model were constructed which has high prediction accuracy, an area under the receiver operating characteristic curve of 0.88 with the test data. In addition, in this model the converted displacement contributed the most by confirming contribution of the respective variables. The old type steel conduits have screw joint and cannot absorb displacement, and the estimation model may be interpretable.

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A Deep Reinforcement Learning Based Framework to Support Restorative Decision Making for Water Distribution Systems

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ABSTRACT

Repair scheduling is critical for efficient functional restoration of water distribution systems in the aftermath of major earthquakes. A deep reinforcement learning based framework is proposed to improve repair sequence decision making in the post-event environment. Two popular deep reinforcement learning models: Deep Q Network and Deep Actor Critic are first implemented to demonstrate the methodology on a hypothetical water system. Next, an extension of the Deep Actor Critic model, Wolpertinger, is adapted to address the challenge of large action space in the repair decision making for large systems and improve the scalability of the methodology. The modified model is then applied to a water distribution system in North Marin, California. Both case studies demonstrate that the proposed methodology significantly outperforms the base repair policy.

Intelligent Human Technology for Predictive Civil Infrastructure Security

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ABSTRACT

The target audience of this research are researchers and industry leaders who are considering the use of Artificial Intelligence and Data Science (AI&DS) in improving the operational safety and efficiency of civil infrastructure systems (CIS, e.g., bridges, airports, power plants). CIS are critical for supporting the lifelines of communities during daily life and emergencies. Specifically, this work introduces a dynamic human-technology analysis framework that captures, diagnoses, and predicts risks of human-technology interaction and collaboration processes in operation and maintenance of civil infrastructure systems. This framework integrates human behavior tracking and analysis methods, automated sensory data collection and analysis techniques, stochastic models for data-driven human-in-the-loop simulations, and knowledge-based reasoning for vulnerability checking of human-technology systems. The presenter will use case studies to illustrate how this dynamic human-technology analysis framework enables risk assessment of the operation and maintenance processes of airports, transportation infrastructure, and nuclear powerplants.

The outcomes will help the audience identify proper A.I. solutions to practical problems of CIS operation and maintenance with human-in- the-loop. First, the audience will learn that the operation and maintenance of aging civil infrastructures (e.g., bridges, airports, power plants, and water facilities) in the built environments pose various systems security challenges that interweave natural, technical, and human decision and operational processes. Second, the audience will understand how information and communication technologies enable engineers, stakeholders, and the public to collaborate on CIS operation and maintenance while bringing human-systems security challenges. They will see examples demonstrate that while the interactions between people and technology form dynamic human-technology systems that can link people into teams, these interactions sometimes introduce redundancies, confusion, delays, and errors. For example, when thousands of workers and managers are working on a shutdown of an old nuclear power plant for refueling and maintenance, minor cognitive and communication errors in exchanging task status and water levels can cause failures in operating connected water and electronic systems. Third, the audience will learn how A.I. techniques, such as symbolic modeling and reasoning, machine learning, brings potentials of revealing the mechanisms underlying those CIS security issues. Specifically, the presenter will clarify how A.I. techniques could learn from the human-computer-technology interaction histories of experienced infrastructure operators to achieve more robust intelligence in complex infrastructure operation contexts.

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Probabilistic Modeling and Inference for Building Structures under Earthquake Sequences Using Matrix-based Bayesian Network

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ABSTRACT

To ensure the resilience of our society, the performance of essential structures should be evaluated for complex natural hazards such as a strong earthquake followed by aftershocks. Although such sequential earthquake events frequently occur and bring about critical impacts on our living environment, the aleatory uncertainty of real-world systems and the complexity of the problem prevent us from evaluating the exact risk induced by the disaster. Probabilistic modeling enables us to assess the risk, and probabilistic inference can update the risk based on the observed information. The sequence of main- and aftershocks has many uncertain factors correlated to each other, and structural damage under main shock makes the behavior of structural system more unpredictable against upcoming aftershocks. In order to handle this challenge through probabilistic modelling and inference, this study proposes to use Bayesian network (BN), which is one of the advanced machine learning methods and especially powerful for modeling complex phenomena. Selected features regarding the sequence of main- and aftershocks and structural responses under the sequential earthquakes can be represented using a BN. To show the construction of BN model for complex structural systems, a multi-story reinforced concrete (RC) flat slab building, which is a typical structural type in Mid-America, is investigated in this study. The multiple measures of structural responses including maximum inter-story drift ratios and seismic intensities of ground motions are used in the BN model. The probabilistic relationships between these features are estimated while considering complex combinations of main- and aftershocks. In addition, the BN model can exploit information regarding the physical properties of ground motions for updating the estimated relationships, which consequently helps to assess the risk of upcoming aftershocks more accurately. Even though BN facilitates many advantages in dealing with the complex event, conventional BN methods may suffer from computational memory and efficiency issues. To address this difficulty, the recently proposed, Matrix-based Bayesian network (MBN; Byun et al., 2019) is employed in this study. The proposed MBN-based framework is expected to contribute to maintain a resilient community from hazardous events by evaluating the risk of sequential earthquakes and making optimal risk-informed decisions.

Reference:
Byun, J.E., K. Zwirglmaier, D. Straub, and J. Song (2019). Matrix-based Bayesian Network for Efficient Memory Storage and Flexible Inference, *Reliability Engineering and System Safety*, Vol. 185, 533-545

Correlation and Neural Network Modeling of Shear Wave Velocity of Macau Soils using SPT and CPT Data

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ABSTRACT

Shear wave velocity of soil is an important parameter for earthquake analysis and civil engineering designs. Correlations between shear wave velocity and SPT-N value based on the simple power-law regression model were provided by previous studies. However, due to the inherent uncertainties the SPT, estimation of shear wave velocity may be improved by incorporating other site investigation data in addition to SPT-N values.

In this study, nonlinear multivariable regression and artificial neural networks were used for the correlation analysis between the shear wave velocity with SPT and CPT data, based on recent field tests data obtained from the site investigation program of a major transportation project at Macau. Due to the significance of this project as a major lifeline system at Macau, seismic hazard analysis was carried out for the design of the project. Consequently, the shear wave velocity of the subsoils was measured for assessing the site condition.

The results of this study indicated that incorporating the additional soil parameters in the correlation models would improve the prediction performance. When combined with SPT and CPT to form nonlinear multivariable regression and neural network model, the better prediction would be obtained than that using SPT or CPT alone. This newly established correlation may be applied to the design of future lifeline systems in Macau.

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Cepstrum Features for Earthquake Damage Assessment of Bridges Leveraging Deep Learning

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ABSTRACT

Bridges are indispensable elements in resilient communities as essential parts of the lifeline transportation systems. Knowledge about the functionality of bridge structures is crucial, especially after a major earthquake event. While conventional methods of structural inspections have been mainly human-based, recent advances in artificial intelligence portray great potential for rapid structural assessments. Among various approaches, vibration-based damage diagnosis can be performed by uploading the accelerometer records of hundreds of instrumented bridges into a remote location for post-processing. Given the complexities of ground motion and structural response, machine learning algorithms can be used to translate vibration into damage in near real-time. However, the accuracy of such methods, especially in predicting damage severity, will highly depend on the quality of input features and the architecture of the data-driven model.

In this study, we propose cepstrum coefficients as a preprocessing step of the acceleration data. These features model the temporal variations of a signal by overlapping time frames. The cepstrum coefficients are obtained from a series of filter banks that indicate how much energy exists in different frequency ranges for each frame. After processing the accelerometer records into a mask of cepstrum features, the time-variant input is fed into a hybrid deep learning structure for damage diagnosis. A long short-term memory autoencoder will be used to extract a compressed representation of cepstrum masks. We will show that these representations can be combined with a variety of machine learning algorithms to predict structural damage. The proposed framework has been validated on an reinforced concrete bridge structure in California. The bridge is subjected to 99 bi-directional ground motion excitations with different scale factors and intercept angles. The testing accuracy of the proposed framework indicates the superiority of cepstrum coefficients as damage sensitive features compared with other metrics such as cumulative absolute velocity. The developed strategy for spatio-temporal analysis of signals enhances the capabilities of damage diagnosis modules that use machine learning to monitor lifeline structures.

Estimating Peak Floor Acceleration Using Hybrid Traditional Neural Network and Convolutional Neural Network

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ABSTRACT

Peak floor acceleration (PFA) is one of the structural responses that are not commonly used in structural analysis besides to estimate design forces for non-structural elements. The equations included in the ASCE7 provisions for estimating the PFA demands are based on the design spectrum. Consequently, to predict PFA for a building subjected to a specific ground motion (GM), a time-history analysis (THA) must be performed, which can be time-consuming. Researchers have tried to estimate PFA using a simplified continuum model, however, such solutions can be cumbersome when used in some real-life situations such as applying such models that involve reduction of the complexity of the structure into a simple beam. There is a need to provide PFA immediately after an earthquake to optimize the inspection and allocate recovery resources, especially those with no visible damage but with sustained nonstructural damage that can inhibit their function or pose a hazard to their occupants. On a large-scale application, and in the case of a seismic event, optimizing rescue and inspection resources can be detrimental for life safety and essential lifelines. A machine learning (ML) approach using Neural Networks (NN) and Convolutional Neural Networks (CNN) will be investigated to predict PFA using energy-based intensity measures (i.e. Arias intensity), GM and structural properties. Such an approach is aimed to handle variability, discover hidden data patterns and generate results quickly. In addition, ML models are continuously learning taking advantage of the abundance of data published every day plus it can be tailored to a specific area or type of structures. Many do not prefer replacing physics-based models with ML. However, in this study, the data from THA will be utilized initially to train the model, which in turn, will be tuned to adapt the data from monitored structures. This study is expected to present a model that can predict PFA immediately after the seismic event using primary information such as the GM record, number of floors and structural properties. The study will also provide an evaluation for performance of such an approach in seismic related problems.

Enhancing Seismic Resilience of Buildings through Deep Learning-based Visual Data Analytics for Rapid Post-Disaster Reconnaissance

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ABSTRACT

Quick recovery from natural disasters is an important pillar of community resilience and calls for a rapid post-event assessment of buildings in an affected region. Timely assessment of damages induced to buildings due to an earthquake is essential for ensuring life-safety, mitigating financial losses and expediting the rehabilitation process. As manual inspection is expensive, time consuming and risky, low-cost unmanned aerial vehicles (UAVs) or robots can be leveraged as a viable alternative for quick reconnaissance. Visual data captured by the sensors mounted on the robots can be analyzed and the damages can be detected and classified autonomously. The present study proposes a deep learning-based approach to this end. Region based convolutional neural network (Faster RCNN) is exploited to detect four different damage types, namely, surface crack, spalling (which includes façade spalling and concrete spalling), severe damage with exposed rebars and severely buckled rebars. The performance of the proposed algorithm is evaluated on manually annotated image data collected from reinforced concrete buildings damaged under several past earthquakes such as Nepal (2015), Taiwan (2016), Ecuador (2016), Erzincan (1992), Duzce (1999), Bingol (2003), Peru (2007), Wenchuan (2008), and Haiti (2010) earthquake. The detection algorithm could predict the class levels and locations of the damaged areas with reasonable accuracy. A mean average precision (MAP) of 60.8% was achieved by the best architecture considered in this study. The proposed technique can be potentially integrated with UAVs or inspection robots to autonomously survey buildings damaged by earthquake, which will help plan retrofit operations quickly, minimize the damage cost and restore the essential services in no time.

Artificial Intelligence-Enabled Decision Support for Flood Risk Mitigation Using Google Street View Images

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ABSTRACT

Floods are the most damaging natural disaster that cause economic losses and human casualties. With the expected sea level rise, flood risk resiliency become a crucial concern for coastal area residents and governments to make effective decisions about risk mitigation. Louisiana state in the U.S. has produced its Comprehensive Master Plan for a Sustainable Coast and laid out $50 billion USD for coastal protection and restoration. However, most data for assessing flood vulnerability are from expensive street-level surveys in 1991 that are incomplete and obsolete. In this study, an online decision support system is developed to tackle the grand challenge of flood risk mitigation. An artificial intelligence (AI) framework is proposed that can collect comprehensive data without human-involved street surveys where the framework analyzes Google street view (GSV) images and estimates multiple attributes of buildings simultaneously, including foundation height, foundation type, building type, and number of stories, that are necessary for assessing flood risks. The proposed framework achieves 0.58-feet mean absolute error (MAE) for foundation height prediction and prediction accuracies of 82.1% for foundation type, 93.7% for building type, and 98.3% for building stories while requiring 0.405 seconds for building detection and 0.038 seconds for attribute prediction. This information can be used for risk mitigation analysis.

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Real-Time Crack Detection in Inspection Videos Using Fully Convolutional Network and Parametric Data Fusion

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ABSTRACT

For the safe operations of nuclear power plants, it is important to inspect the reactor internal components frequently. However, current practice involves human technicians who review the inspection videos and identify cracks on metallic surfaces of underwater components, which is costly, time-consuming, and subjective. Detecting cracks on metallic surfaces from the inspection videos is challenging since the cracks are tiny and surrounded by noisy patterns in the background. While other crack detection approaches require longer processing time, this study proposes a new approach called naïve Bayes- fully convolutional network (NB-FCN) that detects cracks from inspection videos in real-time with high precision. An architecture design principle is introduced for fully convolutional network (FCN) where the FCN can take image patches for training without pixel-level labels. Based on naïve Bayes (NB) probability, a parametric data fusion scheme called pNB-Fusion is proposed to fuse crack score maps from multiple video frames and outperforms other fusion schemes. The proposed NB-FCN achieves 98.6% detection average precision (AP) and requires only 0.017 seconds for a 720□540 frame and 0.1 seconds for a 1920□1080 frame. Based on its capability and efficiency, the proposed NB-FCN is a significant step toward real-time video processing for autonomous nuclear power plant inspection. The fusion of information extracted from different video frames significantly enhances the performance of the proposed approach with respect to state-of-the-art crack detection algorithms.

Innovative Coupled BIPV Cladding and Battery Systems for Building Energy Resilience

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ABSTRACT

Energy-generating cladding systems for buildings are gaining in popularity. In this work, we provide an overview of solar panel systems that also serve as the building facade. These systems include thin film glass cladding as well as more standard monocrystalline photovoltaic (PV) modules. When incorporating these new systems into commercial structures with curtain wall systems, designers typically must weigh the energy savings and cladding costs to compare the costs of the solar systems versus more traditional cladding systems. That is, a complete building life cycle cost analysis is required with an in-depth analysis of the cost of the cladding materials, installation and connection to the building electrical system, energy savings due to the on-site generation and reduction of GHG. A comparison of these systems for the Life Sciences Building on the University of Washington campus, which has Onyx thin film fins along its southern façade, will be presented. In situ energy data for the existing Onyx fins are available, as is the total energy usage in the building. This comparison provides the starting point for our innovative design for photovoltaic (PV) cladding systems that will greatly contribute to meeting renewable energy goals.

The proposed cladding design couples a tilted building-integrated photovoltaic (BIPV) panel with one or more storage batteries at each building placement. Each cladding panel plus storage battery bank is designed as a stand-alone module, which is useful for installation, operation, and maintenance in a typical building. That is, the unit does not need to connect to the building electrical system as it provides interior AC plugs and DC ports. A typical building facade for a curtain wall system would be designed to contain multiple cladding BPPL systems along with glazing in an aesthetically pleasing format. A prototype system with a solar module at a 45o tilt, and two 200 W batteries, embedded in a wooden frame has been built and tested on the University of Washington campus. The greatest improvement over the standard BIPV is that the window sized BPPL is tilted for better irradiance and the storage batteries allow for improved energy resilience. A numerical comparison will be made to show the feasibility of the proposed building perma-power link panel (BPPL) implemented as cladding on the southern façade of the UW Life Sciences Building.

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Meeting Future Renewable Power Goals for Buildings

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ABSTRACT

In the US, it is estimated that people spend 90% of their time in buildings. Inhabitant quality of life is strongly connected to the indoor experience. The ability of occupants to go about their daily activities within buildings relies upon support services such as lighting and heating and cooling. Buildings comprise about 40% of the entire US energy budget. A breakdown of this energy budget shows that 65-70% of the electricity consumed in the US is in buildings. Reductions in fossil fuel consumption as a means of influencing climate change will have a major impact on energy usage. To reduce the carbon footprint, use of renewable energy sources will be increased while reductions in energy consumption will be sought. Energy management specialists have developed procedures to reduce energy consumption.

Energy management practices in buildings have been and continue to be a major focus in building design and retrofit; however, they tend to focus more on the use of so-called “active” systems, which require energy input to function properly. For example, appliances and lighting fixtures have been made more efficient in their usage of electricity. Low-tech “passive” systems have not received much attention until recently. “Passive” systems make use of building form, orientation, fenestration, glazing, natural ventilation, and other non-energy means.

The link between occupant demand and energy consumption has been widely documented. Behavioral methods have been developed by social psychologists to provide occupants with tools and techniques to reduce consumption, such as shutting off lights when leaving a room. The acceptance of behavior modification is influenced by the attitudes of the individuals within a community. Some are very supportive of lifestyle changes to create greener communities and see the reduction of the carbon footprint as a social good. Others do not. In sum, the ability of a building to support occupants in their activities is dependent upon the active and passive means available to provide needed services. At present, the design of the support services in an engineered structure is conducted in a top-down multi-disciplinary manner under the general supervision of an architect. We propose a new framework that is human-centric and incorporates energy demand with occupant comfort and safety. We demonstrate this concept's applicability through a case study approach using the Bullitt Center in Seattle, Washington. This framework is called a “bottom-up” approach as opposed to the existing top-down one.

Aerodynamic Mitigation and Power Generation Systems (AMPS) for Resiliency and Sustainability

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ABSTRACT

Roofing components suffer from great damage during extreme wind events. Moreover, such events often result in extensive power outages. This study investigates the application of an emerging mitigation strategy, in the form of an Aerodynamics Mitigation and Power System (AMPS), designed to reduce wind damage and provide power to residences. The system components include horizontal axis wind turbines that are integrated to the roof edges. Full-scale tests were carried out at the Wall of Wind Experimental Facility at Florida International University to study the efficacy of this system. The test protocol varied the relative location of AMPS with respect to the parent roof structure and considered several wind directions. The findings showed that area-averaged mean and peak roof pressure coefficients were reduced for certain cases when the AMPS system was present. Flow visualization studies showed that the turbines helped to disrupt the conical vortices caused by cornering winds, thereby reducing the wind uplift forces on the roof. The previous research results encourage the team to do further testing on other types of roofs and integrate with other renewable energy devices (such as, PV arrays). The work focuses on future direction of the research work.

Deploying Computer Vision to Create High-Resolution Risk Data from Satellite Imagery

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ABSTRACT

Regional disaster risk analysis has been the cornerstone that supports disaster risk mitigation efforts such as the development of insurance products for catastrophic events or the development of disaster preparedness plans for response and recovery. However, regional disaster risk analysis requires large exposure datasets covering the infrastructure of entire cities or countries. Such datasets are often unavailable, have insufficient quality, and are costly to collect. Recently, remote sensing and computer vision technologies have shown promise in exposure identification for risk analysis. However, existing studies have not fully integrated the exposure evaluation into the regional risk analysis workflow. This work shows the results from extending TernausV2 deep learning model focused on extracting building footprints from satellite imagery to jointly predict buildings' structural vulnerability features for earthquake risk analysis. The TernausV2 model is initially trained on the SpaceNet building footprint dataset. Then, the extended model is customized to predict building height, age, structural type, and occupancy using a recently developed building exposure dataset in the Bay Area, California. We observed that in successful predictions, visual cues in satellite imagery can be indicative of relevant building features. For example, size and location of air conditioning units on rooftops can indicate commercial use, and architectural style and building size can correlate with the structural type. We integrated the exposure predictions into a regional earthquake risk workflow and show that the resulting annual loss exceedance rates match well the rates obtained with ground truth data. While the validity of the TernausV2 model needs to be tested in other regions of the world, these results in San Francisco are promising and encourage wider testing of computer vision techniques for less cost-prohibitive collection of exposure data and use of disaster risk analysis worldwide.

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Experimental Methods to Identify Modal Parameters of Bridges, Viaducts, and Other Civil Structures

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ABSTRACT

Identification of modal parameters of a structure is useful for verification of finite element analysis models, identifying structural degradation and damping appropriate to anticipated structural response levels. Accurate identification of actual modal properties consequently leads to more accurate structural analysis and response prediction. Modal properties are defined as resonant frequencies, mode shapes and modal damping. The effective values of these modal properties may vary depending on the excitation levels. The effective modal property variations with amplitude are gradual but in fact shed interesting light on the nature of these non-linearities and their relation to structural damage. These experimental studies focus on various experimental techniques to identify modal properties of bridges, viaducts, and other civil structures. These techniques include ambient vibration surveys, impulse excitors, eccentric mass vibrators producing sinusoidal forcing, and servo hydraulic vibrators producing impulsive, random, or sinusoidal forcing. Example results and applications are presented with emphasis on railway bridges and viaducts, but also dams and nuclear power plant structures. Many of the test and structural model identification techniques were developed at the University of California Los Angeles following the 1971 San Fernando Earthquake.

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Rapid Post-Earthquake Damage Assessment of Veteran Affairs Medical Centers

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ABSTRACT

Following the 1971 San Fernando Earthquake, which resulted in several hospitals collapses, the US Geological Survey (USGS) installed ground-level sensors on 60 Veteran Affairs (VA) medical centers in collaboration with the US Department of VA to measure ground shaking during an earthquake. In 2008, the USGS National Strong Motion Project (NSMP) initiated a campaign for instrumenting VA hospitals with denser sensor arrays to record every floor's response during an earthquake, which provides an opportunity to carry out near real-time Structural Health Monitoring (SHM). There are currently 28 hospitals in the earthquake-prone regions of the US equipped with such dense sensor arrays, and the recorded data are processed and analyzed through an SHM system developed by the USGS. Specifically, the Inter-story Drift Ratio (IDR) is one of the most essential structural/non-structural damage indices, which can be calculated directly using measured acceleration data. This work discusses the history, details, and challenges for carrying out this task along with the benefits that the aforementioned SHM system provides for making rapid and crucial decisions after a destructive earthquake.

Uncertainty Handling in Structural Damage Detection using Non-Probabilistic Meta-Model and Interval Mathematics

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ABSTRACT

Rapid progress in the field of sensor technology has led to acquisition of massive amounts of measured data from structures being monitored. The data, however, contains inevitable measurement errors which often cause quantitative damage assessment to be ill conditioned. Attempts to incorporate a probabilistic method into a model have provided promising solutions to this problem by treating the uncertainties as random variables usually modeled with Gaussian distribution. However, the success enjoyed by the probabilistic method is limited by the lack of adequate information to obtain an unbiased probabilistic distribution of uncertainties. In addition, the probabilistic surrogate models involve complex and expensive computations, especially when generating output data. In this study, a non-probabilistic surrogate model based on wavelet weighted least squares support vector machine (WWLS-SVM) is proposed to address the problem of uncertainty in vibration based damage detection. The input data for WWLS-SVM consists of selected wavelet packet decomposition (WPD) features of the structural response signals, and the output is the Young's modulus of structural elements. This method calculates the lower and upper boundaries of the changes in the Young's modulus based on an interval analysis method. Considering the uncertainties in the input parameters, the surrogate model is used to predict the output of this interval bound. The proposed approach is applied to detect simulated damage in the four-story benchmark structure of IASC-ASCE SHM group. The results show that the proposed method can perform well in uncertainty-based damage detection of structures with less computational efforts compared to direct finite element model.

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Use of Geoelectrical Techniques to Detect Hydrocarbon Plume in the Leaking Pipeline

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ABSTRACT

Soil contamination due to pipeline leakage has an adverse effect on the environment. Geoelectrical methods play a vital role in assessing the hydrocarbon contamination within soil medium. This study experimentally investigated the Electrical Resistivity (ER) and Induced Polarizations (IP) effectiveness in detecting and monitoring hydrocarbon soil contamination due to buried pipeline leakage into clayey backfill material. Localized areas within the soil layer were injected with a 10% non-aqueous phase liquid (NAPL) contaminant (motor oil) concentration. The Electrical Resistivity Tomography (ERT) and IP surveys were conducted in 2D, 3D, and 4D format to verify the contamination's location and size and its progress with time. The one-layer soil profile results are presented and show how the ERT and IP techniques can be implemented to delineate the hydrocarbon plume and the density of anomaly in the subsoil. It is discussed how NAPL detection using these methods could help in designing sampling strategies to save cost and time.

Wavelet Parameter Selection for Non-Parametric Analysis of Big Data in Structural Health Monitoring- A Comparative Study

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ABSTRACT

A critical issue facing structural health monitoring (SHM) in civil engineering is how to analyze the collected massive amounts of non-stationary data (NSD) and how to best correlate the information to important structural characteristics. Wavelet transform (WT) is an effective tool for analyzing NSD due to its unique characteristics. However, the challenge to ensure the WT effectiveness, in analyzing NSD from civil engineering structures (CES) and health diagnosis, is the selection of right wavelet. The question which wavelet is best suited for the analysis of NSD, in CES, has remained open and no clear guidelines have been reported to describe how to select the best suited wavelet. Therefore, this study aims to address an important question in this regard by proposing a new framework for selecting a proper wavelet that can be customized for NSD analysis and for the purpose of separating disturbances and extracting damage features. Our method takes into account data type and its characteristics, application purposes, wavelet properties, similarity, sharing information, and reconstruction quality. The novelty of this study lies in integrating multi-measures including common measures such as linear correlation index, mean square error, and signal to noise ratio and energy / entropy ratio. In addition, it introduces and considers new proposed measures such as nonlinear correlation, information quality ratio, energy moment, retained energy and others to evaluate various base wavelets capabilities in proper decomposition of structural dynamic responses (SDR). The accuracy of the technique is evaluated using both simulated and excremental data. The results show that the db3 and sym3 exhibit a better performance in terms of all quantitative parameters compared to others. Our suggested strategy can be applied to other applications beyond CES.

Real-life Investigations of Inverse Filtering for Frequency Identification of Bridges Using Smartphones in Passing Vehicles

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ABSTRACT

This work puts forward a real-life assessment of a novel inverse filtering methodology to extract bridge features from acceleration signals recorded on smartphones in the passing vehicles. The vibration of a moving vehicle is affected by various features, such as suspension and speed. This study focuses on filtering out these effects from the signals to extract bridge frequencies as the vehicle crosses the bridge. Hence, the spectrum of the vibration data recorded on the vehicle when moving off the bridge is employed to form an inverse filter which removes the vehicle-related frequency content. Since the speed of the vehicle is found to be one of the most effective factors in the filter design in our previous studies, a database of the off-bridge vibrations is built for different speeds. Later, when the same vehicle is moving on the bridge, the corresponding inverse filter is applied to the recorded on-bridge data to suppress the vehicle frequencies and amplify the bridge frequencies. The effectiveness of the proposed methodology in real-life conditions will be evaluated considering different vehicle types and bridge systems. All the required data are recorded using the built-in accelerometer and GPS sensor of the smartphone, eliminating the need for any extra instruments. In addition, this approach considers each data source separately and designs a unique filter for each data collection device within each vehicle, which makes it robust against device and vehicle features. As a result of the proposed methodology, it would be possible to monitor a large number of bridges using crowdsourced data collected from the smartphones in the vehicles. Such methodologies are expected to improve the sustainability and resiliency of our future infrastructure systems and future cities.

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Critical ShakeCast Lifeline Users and Their Response Protocols

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ABSTRACT

ShakeCast® is a U.S. Geological Survey (USGS) software application that automatically retrieves ShakeMap shaking estimates and performs analyses using fragility functions for buildings and lifelines. The ShakeCast system aims to identify which facilities or lifeline segments are most likely impacted by an earthquake—and thus which ones should be prioritized for inspection and response—and sends notifications to responders in the minutes after an event. By focusing inspection efforts on the most damage-susceptible facilities in the severely shaken areas, ShakeCast can reduce critical lifeline inspection prioritization and response time in the aftermath of a significant earthquake. Overviews and technical specifications of the ShakeCast software have been presented at earlier conferences; here we discuss ShakeCast users and their response protocols to provide further insight into the use of the ShakeCast system. We focus on users responsible for monitoring and response for critical infrastructure, and we emphasize inventory, fragility, and notification issues pertinent to the lifeline engineering audience, as well as issues tied to developing protocols for prioritizing post-earthquake inspections and response. DOTs are a critical lifeline that are uniquely able to take advantage of the ShakeCast technology since bridge fragilities can be readily derived from the National Bridge Inventory (NBI). DOTs also share the need for prioritized response strategies given their very large numbers of facilities with varying vulnerabilities over wide areas, many of which could potentially be affected by earthquake shaking. In order to describe how a variety of fragility functions are employed in ShakeCast, we also discuss new system users, including pipeline (the Trans-Alaska Pipeline Company, Alyeska) and dam (the Federal Energy Regulatory Commission, FERC) infrastructure, providing details on their strategies for deploying and utilizing ShakeCast for earthquake situational awareness on potential impact to their critical facilities.

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Development of Piezoelectric Sensor for Real-Time Concrete Strength Measurement: From Laboratory Experiments to Field Implementations

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ABSTRACT

The compressive strength of concrete is an important factor in quality assurance (QA) and quality control (QC). The conventional method to determine the concrete strength is conducting compressive testing on cylindrical concrete samples according to ASTM C31/C39. However, the current methods are not able to provide real-time information on concrete strength for field engineers to determine the construction schedule. Moreover, it is hard to monitor the development of concrete properties after the construction completed. Thus, it is critically needed to develop a reliable in-situ method to evaluate real-time strength development of concrete.

To fill the critical need, we have developed a piezoelectric sensing technique that enables tracking of concrete strength development through measuring the dynamic electromechanical impedance (EMI) between the piezoelectric sensor and the host concrete structure. A series of experiments was conducted with samples contain various types of cement, different supplementary materials (SCMs), the aggregate amount, and water-to-cement ratio to prove the concept. It has found that the compressive strength gain of concrete can be reflected in the admittance spectrum obtained from the impedance analyzer overtime. The correlation coefficient (R2) between the cylinder test and sensing results are all higher than 0.9 for a total of 300 cylindrical samples. Built on the success of the laboratory experiments, the team has implemented the sensing technology on interstate highway 70 (Plainfield), I-74 (Batesville), and I-465 (Indianapolis) in Indiana, USA. The measurements were collected at the age from the first hour after concrete casting until the 8th hour, and at 24th hour to 72nd hour. The results indicated that the sensor can provide satisfactory results for monitoring the in-situ strength of concrete and life-cycle performance to achieve the resilience and sustainability of our nation's infrastructure systems.

Comparison of Traditional and Emerging Technologies for Assessing Slope Stability in an Urban Environment

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ABSTRACT

Quarrying operations between the late 19th and early 20th century transformed the once moderately rolling, stable eastern slope of San Francisco's Telegraph Hill to a slope with near-vertical rock faces prone to rockslides. One such failure occurred following an intense rain event in December 2019 on a portion of slope directly beneath the Filbert Steps, a popular tourist attraction leading to the iconic Coit Tower. Geological mapping using three independent methods, manual measurements using a Brunton Pocket Transit (Brunton Compass), unmanned aerial system (UAS) data capture, and terrestrial Light Detection and Ranging (LiDAR) data capture was carried out as part of the emergency response. The results of this study showed structure from motion (SfM) models derived from UAS photogrammetry to be an effective method for characterizing a rock mass, capable of obtaining similar results to more expensive pieces of equipment (i.e. LiDAR) and eliminating the safety concerns associated with mapping unstable slopes using a Brunton Compass. The comprehensive dataset of structural measurements obtained from the UAS imagery-based SfM model facilitated relatively robust analyses at an early stage in the project, which were used to inform slope stabilization recommendations both for emergency response and permanent restoration. This work presents a comparison of the three methods used for geological mapping and provides commentary on the effectiveness of UAS mapping for provision of efficient slope stabilization recommendations at the slope.

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Designing a Socioeconomic Equity Analysis Framework to Support the Development of a Robust and Equitable URM Retrofit Policy in Portland, Oregon

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ABSTRACT

With an increased effort to improve public safety during an earthquake event, several cities have developed and/or are developing unreinforced masonry (URM) retrofit policies. The implementation of these policies has the potential to both positively impact as well as burden the residents of the cities. For example, California passed a URM law in 1986 that required local governments to develop a loss reduction program to reduce the potential loss in the event of an earthquake. In the City of Seattle, various entities set out to analyze the impact of implementing a URM policy by examining the potential earthquake damage on un-retrofitted buildings in its low-income communities.

Another city that has made establishing a URM policy a priority is Portland, Oregon. In October 2019, the City Council of Portland began the process towards developing a voluntary seismic retrofit policy. Due to demonstrations and protests associated with police violence, fires, the COVID-19 pandemic, and other issues that require more immediate resources and attention, the Portland City Council voted to dissolve the URM building workgroup. Despite the uncertainty in the City's next steps regarding the policy, this work reviews the work that Portland has already done and develops a socio-economic equity analysis framework that can complement its work. Such a framework will synthesize socioeconomic data and Portland's URM Building Database to assess the role of socio-economic status on the spatial distribution of existing URM buildings. In turn, the findings would help inform Portland in developing robust and equitable policies to mitigate the severity of earthquake damage. The research begins with an in-depth review of URM related efforts in Portland, as well as infrastructure-related equity analyses that have been developed and used in other cities. After the equity analysis framework is designed and applied to Portland, results from the analysis will be used to establish three URM policies - related not only to buildings but other lifelines as well, including water and transportation systems. Lastly, the research examines the potential impact that these policies would have in low-income areas in Portland. The work will result in the development of an equity analysis framework, demonstrate its potential to enhance the quality of Portland's process, and provide a starting place for a general URM equity analysis framework that other cities can easily adapt and apply.

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The Need for Utility Data Governance Policies for Improving Lifeline Recovery

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ABSTRACT

Our existing utility network is a system of systems, whereby a service disruption to any portion of one utility network has the probability of a cascading effect not only on other utility systems but also other lifelines such as transportation. A majority of our utility networks are accommodated within public right-of-way and under streets. A significant percentage of existing utility structures within the streets are abandoned and have no recoverable records. Active utility systems may have records, but the quality of those records are uncertain in regards to accurate location and attribute information. After utility system damage, finding those utilities becomes more difficult since most geophysical imaging techniques rely upon continuous conductivity of pipes, wires, and tracer tapes; and uniform gradient soils in the case of Ground Penetrating Radar. The Christchurch recovery efforts in 2011 were hampered by the inability to locate existing utility systems quickly and repair them without damage to nearby known and unknown utility structures. Having access to better comprehensive data on the location and attributes of existing utilities will help recovery efforts.

The American Society of Civil Engineers put together two standards to assist in solving this problem. ASCE 38, Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data, prescribes a series of actions that result in affixing a value judgment of utility location uncertainty to buried utility segments. A second standard in balloting now, Standard Guideline for the Recording and Exchanging of Utility Infrastructure Data, prescribes a series of actions that result in the documentation of the accuracy and measurable attributes of above and below ground observable utility segments. Taken together, these two standards document utilities at known accuracies and judged uncertainty, facilitating restoration of damaged utility lifelines after an event. Placing these data into a central secure database for access by utility owner and emergency personnel is challenging in the U.S. due to proprietary and security concerns, and public officials need to weigh the risks versus rewards for keeping an up-to-date comprehensive central repository of our underground lifelines.

Risk-Targeted Loads for Seismic Design of Lifelines: Opportunities and Challenges

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ABSTRACT

In 2010, the American Society of Civil Engineers *Minimum Design Loads and Associated Criteria for Buildings and Other Structures (ASCE 7-10 Standard)* adopted "Risk-Targeted" Maximum Considered Earthquake ground motion maps. Whereas the prior three editions back to 1998 used "uniform-hazard" maps for a chosen return period, *ASCE 7-10* instead back-calculated ground motions for a targeted risk of building collapse. Analogous risk-targeted design loads had previously been adopted by the ASCE *Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities (ASCE 43-05 Standard)* and were subsequently adopted for snow loads in *ASCE 7-16*. Now risk-targeted loads are also being considered for the seismic design specifications of the AmericanAssociation of State Highway Transportation Officials and countries outside of the United States. Risk-targeted design loads correspond to return periods of hazard impacts (e.g., deaths), whereas uniform- hazard design loads correspond to return periods of the hazard itself (e.g., earthquake ground motions). The seminal1978 Applied Technology Council *Tentative Provisions for the Development of Seismic Regulations for Buildings (ATC 3-06)* recognized that "it really is the probability of structural failure with resultant casualties that is of concern, and the geographic distribution of that probability is not necessarily the same as the distribution of the probability of exceeding some ground motion." In other words, the concern is risk of impacts rather than hazard, and uniformity of risk is not addressed with uniform hazard, nor is quantification of risk. Whether across geographic locations, types of construction (e.g., buildings vs. lifelines), design goals (e.g., life safety vs. functionality), or hazards (e.g., ground motions vs. fault offsets), comparisons of risk quantities are more informative than those of hazard return periods. Such comparisons can inform decisions on tolerable risk levels, in part by facilitating communication with stakeholders outside of civil engineering. In these and other ways, risk- targeted design loads are an improvement over uniform-hazard loads like those adopted in the American Lifelines Alliance *Seismic Guidelines for Water Pipelines*, as one of many examples.

We discuss the opportunities and challenges in risk-targeted loads for seismic design of lifelines by demonstrating the back-calculation of such loads for water pipelines. The demonstration uses new peak ground velocity hazard curves from the U.S. Geological Survey (USGS) and repurposed pipeline fragility curves gathered for a pilot national-scale USGS risk assessment, both of which are presented by other authors.

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Assessment of Resilience in Design Criteria, Codes, and Regulations for Buildings and Infrastructure Systems

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ABSTRACT

Effective implementation of community resilience planning efforts requires that, over time, communities adopt and implement codes and standards to improve the performance of its built environment for natural hazards. While compatible performance between infrastructure system (e.g., buildings, electric power, water and wastewater, transportation) is expected, these systems have separate design practices, codes, standards, and/or regulations, leading to differences in performance during the same hazard event.

Design criteria, codes, standards, and/or regulations are reviewed with regards to community resilience impacts and consequences, and to identify areas to improve understanding of current infrastructure design criteria and performance, limitations in addressing system interdependency issues, and methods to address the impact of changing environmental conditions on infrastructure.

The review addresses national US codes, standards, and best practice for buildings and water, electrical power, and transportation systems for flood, wind, and seismic hazards from a community resilience perspective. The topics reviewed include design hazard characterization, expected performance, recovery of function, interdependency issues, and emerging methods to address the impact of changing environmental conditions on infrastructure design and performance.

A better understanding of how the built environment performs and recovers over a range of hazard levels along with technical gaps for resilient systems will help inform stakeholders (industry associations, design professionals, community building code officials, community and city planners, and researchers) with resilience planning and research. The following findings will be presented:

- Overview of hazard criteria and relative performance expectations for buildings and infrastructure systems,
- The degree to which concepts of resilience (e.g. ability to adapt to changing conditions, rapid recovery, interdependencies) are incorporated, and
- Areas where improvements are needed to increase the resilience of these systems at a community-scale.

Performance-Based Specifications for the Enhancement of Service-Life and Durability of Concrete Infrastructures

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ABSTRACT

Concrete materials in lifeline infrastructures sustain substantial damage throughout their service-life. The cost, time, energy, emissions, and waste associated with the repair, replacement, and strengthening concrete components has an adverse impact on the resilience of these infrastructures. The performance-based specifications aim to promote the durability and service-life of concrete and address the gap in current approaches to design and construction of concrete infrastructures. This work provides a review of current challenges for practitioners in management, design, construction, and quality control and assurance fields. The overview includes the state of practice and regulations for durable concrete and introduces best practices in performance-based specifications of concrete in respect to materials and methods. The methodology incorporates a service-life prediction model, simulated by Life365TM and using transport properties of selected concrete materials. Results include the assessment of these materials for application in major climate zones including dry-wet and cold-warm regions and four levels of maximum concentration of sulfates per building code requirements and specifications. The conclusions link the outcomes of these specifications with the resilience performance measures.

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Recommendations Toward Functional Recovery Performance of Lifeline Infrastructure Systems

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ABSTRACT

Lifeline infrastructure systems are vital in the day-to-day operations of our communities, and their functionality becomes a decisive factor in recovery after earthquakes and other extreme events. Lifelines include electric power, gas and liquid fuel, water and wastewater, telecommunication, and multi-modal transportation systems. These systems are not only spatially distributed, with some large systems covering multiple states, but also interconnected and interdependent to function. The operation of a given infrastructure system depends on numerous components, designed and built over time, using a variety of standards, procedures, and material types. Failure of a single critical component can result in cascading failures within a system and to other systems. However, lifeline infrastructure system organizations tend to operate in silos, without deliberate coordination with others. All of these factors have created challenges and barriers in achieving orderly and timely post-earthquake functional recovery.

The late-2018 reauthorization of the National Earthquake Hazards Reduction Program (NEHRP) includes a heightened focus on achieving community resilience. The reauthorization required NIST and FEMA to "convene a committee of experts … to assess and recommend options for improving the built environment and critical infrastructure to reflect performance goals stated in terms of post-earthquake re-occupancy and functional recovery time" and submit a report to Congress by June 30, 2020. The report includes an overarching recommendation for developing a framework for functional recovery, and six additional supporting recommendations for improving the performance of buildings, improving the performance of lifeline infrastructure systems, expediting recovery through pre-disaster planning, and enabling action with education and financial resources.

This reporting examines the recommendations, tasks, and alternatives associated with functional recovery performance objectives for lifeline infrastructure systems. It includes key recommended activities drawing from case studies, national frameworks, and best practice applications to emphasize the needs of: (i) establishment of a consistent national performance framework across all lifeline systems that can evolve into provisions adopted by state-level regulatory authorities, adjusted for local hazard exposure and infrastructure asset types and conditions; (ii) assessment of existing lifeline infrastructure systems to evaluate their expected performance and identify and prioritize required future upgrades; (iii) development of national standards to support orderly recovery across all systems at component, system, and system-of-systems levels; and (iv) creation of regional councils to identify and manage dependencies and interdependencies within and among lifelines, and address the coordination among agencies both in regular operations and post-event emergency response and recovery.

Indicator-Based Approach for Predictions of the Future Built Environment

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ABSTRACT

Having land-use plans that limit how the built environment evolves in time may be a great instrument to increase resilience. However, basing the land use plans on the current built environment without understanding the possible changes in the built environment may result in ineffective plans. One of the main reasons is that the regional risk analyses, which are one of the tools needed to devise effective plans, may underestimate the risk and consequent losses. Furthermore, it is necessary to have urban planning capable of recording these land-use changes. Despite the large uncertainty involved in the future variation of the built environment, providing a range of possible scenarios based on the future distributions of specific indicators may improve the regional risk analyses and, consequently, the effectiveness of the land use planning.

This research focuses on the use of indicators that describe the built environment for forecasting models related to urban growth. Such indicators describe not only variations in infrastructure presence and land use but also socioeconomic factors. The indicators are defined on a County scale through a grid of uniform hexagonal cells. Each cell has uniform values that are derived from publicly available databases or satellite images. An initial indication of the urban growth can be obtained by modeling the time evolution of such indicators separately for each cell. A further step is to model the correlation among the indicators of different cells. Initial results related to a case study of the Houston metropolitan area are presented.

Community Resiliency Infrastructure and Sustainability Protocol (CRISP)

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ABSTRACT

Engineers must hold paramount the safety, health, and welfare of society when they design or maintain infrastructure. It is impossible to separate the technological issues from the political and sociological ones. In particular, decisions about investment in infrastructure, both existing and planned, should be informed by an assessment of the risks that a community faces and is willing to assume. Individuals within society generally have a clear desire to maximize the utility of infrastructure. The oversight and limitation of consequent activities are entrusted to elected officials, and the laws and policies they create. Professional societies are ultimately responsible for codes and standards that guide development of the built environment to serve the needs of society while respecting natural resources and the rights of individuals (e.g., ASCE/SEI 7 and ASCE 24). Elected officials are, ultimately, responsible for the allocation of public funding to ensure the resilience and overall performance of new and existing infrastructure for community sustainability. This is the intersection of public policy and engineering, and a place where engineers can and should take a more active role. For society to use concepts of lifetime, sustainability, and resilience in its decisions about the built environment, it must find a way to harmonize these fundamentally long-term issues with the realities of our political process, which tend to be based on relatively short-term planning horizons. This study outlines a process for public accounting of the above-described principles using value analysis of the regional infrastructure, including benefit-cost analysis for new structures as well as any increase in value to existing infrastructure resulting from retrofit measures that increase hazard resilience. CRISP, Community Resiliency Infrastructure Protocol, is founded on robust probabilistic estimates, stochastic analysis, and accepted discounting assumptions. Through CRISP, infrastructure accounting statements could become part of a total public trust report card, integral to the political process for all government authorities having jurisdiction over public infrastructure.

In addition to outlining a process for public accounting, this investigation provides ideas on how to develop the process and implement it into action. The ASCE Infrastructure Resilience Division has initiated a project to further develop this concept. The goal is to create methodologies that can be utilized as common practice for decision-making, improving the resilience and sustainability for infrastructure systems and communities. ASCE could one day utilize these concepts in engaging policy leaders and the general public on the importance and return on investments in infrastructure.

Structural and Functionality Monitoring for Building Resilience in Transport Infrastructure

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ABSTRACT

The societal importance, value and cost of transport infrastructure, justifies an urgent need in building resilience in transport assets and networks. Today, even more important investment is required to combat climate change and multiple-hazard stressors, which can cause abrupt and/or cumulative damages on transport infrastructure. The control of such hazards by monitoring both the structural integrity and functionality enables efficient means for extending the life cycle of such structures with increased accuracy. Monitoring can assist in reducing uncertainties during the life cycle and therefore mitigate risk levels and losses. Early-warning systems, triggered by actionable performance indicators, can help toward preventing failures and losses and they permit a rapid recovery, by indicating effective mitigation measures. The monitoring of the performance locally e.g. the structural members and globally e.g. the whole transport network, can shift the management of existing decaying or new transport networks to a holistic approach increasing the resilience, by taking into account all the parameters and interdependencies of the network and the natural environment. The work describes this approach and gives examples on how monitoring can build resilience into transport networks.

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