Chapter 1
Multi-hazard Approaches to Civil Infrastructure Engineering: Mitigating Risks and Promoting Resilence

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Abstract Natural and anthropogenic hazards cause billions of dollars of damage every year around the world, as well as several thousand fatalities or injuries and other societal impacts. While the frequency of damaging natural events is expected to increase due to climate change, new engineering solutions can help mitigate their impact and accelerate the recovery process. This volume is dedicated to the critical issue of creating successful solutions to multiple hazards. It examines a range of specific topics, including methodologies for vulnerability assessment of structures; new techniques to reduce structural demands through control systems; instrumentation, monitoring, and condition assessment of structures and foundations; new techniques for repairing structures that have suffered damage during past events, or for structures that have been found in need of strengthening; development of new design and construction provisions that consider multiple hazards; novel considerations toward resilient infrastructure; as well as questions from law and the humanities pertaining to successful management of natural and anthropogenic hazards. This book contains contributions from some of the world's leading experts in each of the fields covered by the edited volume.

The volume is organized into six main parts, after the introduction (Part I). Part II focuses on probabilistic methods and formulations needed for risk analysis. Part III starts the discussion on multiple hazards, by presenting recent advancements in earthquake engineering and then introducing concepts on disaster resilience and optimization. Part IV begins with a discussion of fires following earthquakes and then continues with other contributions specific to fire and blast, including both modeling and testing. Part V summarizes recent advances related to wind hazards, specifically considering tornadoes and hurricanes. Part VI focuses on geo-hazards, including the modeling of physical phenomena, condition assessment, and treatment of uncertainties. Finally, Part VII looks more generally at the impact of

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extreme events on society by discussing risk management, strategies for resilient communities, and new policy approaches. While each of Parts III–VI is primarily focused on a particular hazard, many of the parts include at least one chapter that looks beyond the specific hazard by bringing in considerations from a multi-hazard perspective and related to overall infrastructure resilience.

1.1 Introduction

Natural and anthropogenic hazards cause billions of dollars of damage every year, as well as several thousand fatalities or injuries and other societal impacts (Gardoni et al. 2016). While the frequency of damaging natural events is expected to increase due to climate change, new engineering solutions can help mitigate their impact and accelerate the recovery process. This edited volume focuses on the development of novel approaches and the interdisciplinary considerations needed to improve mitigation of natural and anthropogenic hazards. Work to date has focused on, and made considerable progress toward, the mitigation of individual hazards (earthquakes, wind, and so forth). The current volume addresses concerns related to overall safety, sustainability, and resilience of the built environment when subject to multiple hazards.

Multi-hazards can be classified as *concurrent* (e.g., wind and surge), *cascading* (e.g., fire following earthquake), or independent and likely to occur at different times (e.g., wind and earthquake). Two of the deadliest disasters due to *concurrent hazards* occurred in the Bay of Bengal in 1970 and Myanmar in 2008. A cyclone hit the coast of the Bay of Bengal and the storm surge killed approximately 500,000 people. In Myanmar, a storm surge killed more than 138,000 people. In 2005, the USA experienced one of the greatest recorded storm surges when Hurricane Katrina hit the coastline of the Gulf of Mexico. Another high storm surge hit the east coast of the USA when Hurricane Sandy landed in 2012. Fires following earthquakes are an example of *cascading hazards*. A number of seismic events around the world (including in Chile, Japan, and the USA) have been characterized by significant damage and loss of lives caused by fires following earthquakes. Finally, while some regions around the world might be at risk for a single hazard type, many parts of the world are likely to face multiple hazard types for which the occurrences are independent (*independent hazards*), and as a result they typically occur at different times.

When considering the annual probability of failure or of reaching a specified damage state for a structure/infrastructure, accounting for the most relevant hazards and their possible dependency is essential, instead of simply considering a single hazard type. Within the USA, for example, seismic, wind (tornado), and flood hazards have been among the most damaging. A number of regions in the Midwest are vulnerable to both seismic and wind hazards, and other regions to both wind and flood. Similarly, much of the coastline of Japan is at risk for both earthquakes and tropical storms.

1.2 Overall Goal and Contributions

The goal of this edited volume is to promote mitigation of the impact of natural and anthropogenic hazards on society. The volume has a strong interdisciplinary emphasis, focusing on issues related to reliability analysis, risk determination, risk evaluation, and risk management for various hazards, as well as on disaster response and recovery. While the primary attention is on engineering aspects of the problem, consideration is also given to relevant interdisciplinary aspects related to public policy, sociology, and law.

There has been a considerable amount of research on assessment of the seismic vulnerability of structures, development of new methods to control earthquake forces transmitted to a structure (through base isolation or energy dissipation devices), incorporation of newly acquired knowledge into design provisions, assessment of the condition of existing structures, and planning of retrofit and repair strategies using both conventional and new materials. However, there is now a need to put all these developments into proper perspective, to critically examine the many methodologies and techniques available, to recommend the most appropriate ones for each case, and to identify remaining research needs.

Furthermore, while the seismic hazard has in past years received significant attention, many other hazards (like those related to water and wind) have caused substantial damage and had a significant societal impact. Therefore, there is a clear need to make progress toward mitigation of multiple hazards and, when appropriate, to expand the methodologies developed for the seismic hazard to other hazards. In addition, while work has been done considering one hazard at a time, there has only been limited work toward a uniform reliability for infrastructure considering multiple hazards.

This volume is the first book fully dedicated to the critical issue of multi-hazards. It examines a range of specific topics, including methodologies for vulnerability assessment of structures; new techniques to reduce structural demands through control systems; instrumentation, monitoring, and condition assessment of structures and foundations; new techniques for repairing structures that have suffered damage during past events, or for structures that have been found in need of strengthening; development of new design and construction provisions that consider multiple hazards; novel considerations toward resilient infrastructure; as well as questions from law and the humanities pertaining to successful management of natural and anthropogenic hazards. The edited volume collects contributions from some of the world's leading experts in each of the various fields covered.

1.3 Structure and Overview of the Volume

This volume is organized into six main parts, after the introduciton (Part I). Because of the underlying uncertainties associated with natural hazards and their impact, Part II focuses on probabilistic methods and formulations needed for risk analysis. Part

III starts the discussion on multiple hazards, by presenting recent advancements in earthquake engineering and then introducing concepts on disaster resilience and optimization. An earthquake might be followed by fire, and so Part IV begins with a discussion of fires following earthquakes and then continues with other contributions specific to fire and blast, including both modeling and testing. Part V summarizes recent advances related to wind hazards, specifically considering tornadoes and hurricanes. Part VI focuses on geo-hazards, including the modeling of physical phenomena, condition assessment, and treatment of uncertainties. Finally, Part VII looks more generally at the impact of extreme events on society by discussing risk management, strategies for resilient communities, and new policy approaches. While each of Parts III–VI is primarily focused on a particular hazard, many of the parts include at least one chapter that looks beyond the specific hazard, bringing in considerations from a multi-hazard perspective and related to overall infrastructure resilience.

Part II focuses on probabilistic methods for risk analysis. Hazard maps are often used in risk analysis to express spatial variability in the likelihood of occurrence of hazards, but such maps have only been developed to provide the probability that an intensity measure of interest at a given location on the map will exceed a specified threshold (typically in 1 year). However, as Paolo Bocchini, Vasileios Christou, and Manuel Miranda, authors of the first chapter in this part (Chap. 2) titled "Correlated Maps for Regional Multi-Hazard Analysis: Ideas for a Novel Approach," point out, lifeline and regional risk assessment require knowledge of the spatial correlation between any two points in space. The chapter discusses a random field formulation to capture the spatial correlation between intensities of interest at any two points. The presented formulation is general and applicable to any hazard, and so it is therefore particularly well suited for multi-hazard analysis.

Aging and deterioration of structures and infrastructure can play an important role in their reliability and on the risk faced by communities. Chapter 3 titled "Supporting Life-Cycle Management of Bridges Through Multi-Hazard Reliability and Risk Assessment," by Jamie Padgett and Sabarethinam Kameshwar, studies the impact of multiple hazards on deteriorated structures (bridges in particular). The chapter uses meta-models to develop parameterized time-dependent bridge fragility estimates considering multiple hazards, including earthquakes and hurricanes. The chapter ends with applications showing the relative importance of earthquake and hurricane hazards when considering different bridge characteristics and states of deterioration.

Risk assessment often has high computational costs. Chapter 4 titled "Natural Hazard Probabilistic Risk Assessment Through Surrogate Modeling," by Alexandros Taflanidis, Gaofeng Jia, and Ioannis Gidaris, focuses on modeling techniques that can be used to alleviate such computational costs. Specifically, the authors discuss the use of kriging surrogate modeling, including its advantages over other approaches as well as implementation details. The effectiveness of the proposed kriging surrogate modeling is illustrated considering two hazards—in seismic risk assessment and hurricane risk assessment.

There is often a distinction between natural hazards (e.g., earthquakes, hurricanes, and tornadoes) and anthropogenic hazards (human errors and malevolent acts). However, some of the methods for risk analysis and decision-making can be common between the two types of hazard. Mark Stewart, in Chap. 5 titled "Risk and Decision-Making for Extreme Events: Climate Change and Terrorism," discusses how optimal decisions can be reached using risk-based approaches where not only the likelihood of the threat, the vulnerability to the threat, and the exposure to the threat are modeled probabilistically, but the effectiveness of protective strategies and their costs are also modeled accounting for their uncertainties. The chapter illustrates the presented methodology by considering risk-based assessment of counterterrorism and climate adaptation strategies.

Part III starts the discussion on multiple hazards by presenting recent advances in earthquake engineering and then introducing concepts on disaster resilience and optimization. Once hazard maps are defined (e.g., by using the procedure described in Chap. 2), there is a need to quantify the vulnerability of structures and infrastructure. In the case of seismic hazards, buildings that lack earthquake-resistant details and therefore are characterized by non-ductile behavior are particularly vulnerable. As a result, in case of a seismic event there is a high probability of partial or global collapse of such buildings. Khalid Mosalam and Selim Günay, in their chapter (Chap. 6) titled "Progressive Collapse Simulation of Vulnerable Reinforced Concrete Buildings," note that two of the current challenges are the identification of such vulnerable buildings and definition of the most effective and economical retrofitting strategies. The chapter discusses methods to model gravity load failure as well as the underlying uncertainties and research needs in this field.

Still on the subject of seismic assessment of existing buildings, Paolo Pinto and Paolo Franchin, in Chap. 7 titled "Probabilistic Seismic Assessment of Existing Buildings: The CNR-DT212 Italian Provisions," describe an overview of a probabilistic approach for seismic assessment of buildings developed by the Italian National Research Council (CNR). The approach is intended to provide a more rigorous theoretical base for revising the European code (Eurocode 8, Part 3) and is of particular value in cases where a more rigorous analysis is required. The chapter also focuses on the definition and modeling of the states of damage for both structural and nonstructural components.

Design optimization strategies have traditionally focused on considerations toward a single hazard, while Hussam Mahmoud and Akshat Chulahwat, in Chap. 8 titled "Multi-Hazard Multi-Objective Optimization of Building Systems with Isolated Floors Under Seismic and Wind Demands," extend concepts of optimization for design variables considering multiple hazards. The chapter optimizes a sliding slab system considering both seismic and wind hazards, indicating the effectiveness of the proposed sliding slab system to withstand seismic and wind loads, and of the optimization scheme in identifying the most suitable configuration of the system.

In addition to multi-hazards, consideration can also be given to other factors that might influence the design or retrofit of a structure. In their chapter (Chap. 9 titled "Energy Efficiency and Seismic Resilience: A Common Approach"), Gian Michele Calvi, Luis Sousa, and Cristiana Ruggeri note that seismic retrofit and enhancement for energy efficiency of buildings are currently subject to separate considerations as to their benefits and costs. This chapter presents a formulation for the assessment of integrated investment strategies targeted at improving both the seismic resilience and energy efficiency of buildings. The chapter shows how an optimal solution can be achieved through the proposed integrated approach, instead of considering seismic resilience and energy efficiency as separate individual aspects.

Part IV begins by shifting the focus of the discussion to fires following earthquakes and then continues with other treatment on fire and blast, including both modeling and testing. Chapter 10, by Negar Khorasani, Maria Garlock, and Paolo Gardoni, is titled "Probabilistic Evaluation Framework for Fire and Fire Following Earthquake," and it provides a probabilistic framework to evaluate the performance of a structure under fire and fire following earthquake, by studying the response of the structure considering several limit states and incorporating uncertainties in demand and capacity parameters. The multi-hazard framework is applied to a steel moment-resisting frame in order to evaluate structural performance under post-earthquake fires.

Recent events have shown that local damage to building frames is often followed by fire igniting near the location of damage, but in current practice little consideration is given to fire as a cascading hazard for progressive collapse-resistant design. With that in mind, Spencer Quiel, in his chapter (Chap. 11) titled "Progressive Collapse Resistance for Steel Building Frames: A Cascading Multi-Hazard Approach with Subsequent Fire," explores the effects of fire following an extreme event that causes failure of a column on the perimeter of a steel building frame, which is a representative damage scenario in the typical design case for assessing progressive collapse resistance. Results include estimates of time to collapse initiation and correlation between the level of remaining passive fire protection and collapse time, with overall guidance also provided in the chapter for the assessment of these hazards.

Still on the topic of fire performance of structures, Venkatesh Kodur, in Chap. 12 titled "Strategies for Enhancing Fire Performance of NSM FRP-Strengthened Reinforced Concrete Beams," discusses approaches for achieving required fire resistance in reinforced concrete (RC) beams that have been strengthened by the application of near-surface-mounted (NSM) fiber-reinforced polymers (FRP). NSM FRP strengthening is a common approach used for structural retrofit of RC members to enhance their flexure and/or shear capacity. Results from numerical and experimental studies are used to quantify the influence of various parameters on fire resistance of NSM FRP-strengthened RC beams, and guidelines are provided in the chapter for achieving optimum fire resistance in such cases.

Moving along to the blast hazard, Lauren Stewart and Bradley Durant note, in Chap. 13 titled "Experimental and Analysis Methods for Blast Mitigating Designs in Civil Infrastructure," that incorporation of blast and shock loading into a multi-hazard framework requires consideration of the mechanical/structural behavior of a component or system in the impulsive loading regime. For such high-rate loading, material and structural response must often be evaluated experimentally in order to produce basic mechanical properties, initial design validation, and final design acceptance for construction implementation into new or existing infrastructure. Using a case study of a curtain wall system for blast response, the chapter utilizes various analysis and experimental procedures to highlight the process of designing and validating systems for blast mitigation.

Part V includes recent advances related to wind hazards, specifically considering tornadoes and hurricanes. For example, in Chap. 14, titled "Woodframe Residential Buildings in Windstorms: Past Performance and New Directions," John van de Lindt and Thang Dao demonstrate that residential buildings in coastal areas are often at risk to hurricanes, which can result in both wind and storm surge damage, while tornadoes are one of the most devastating natural hazards that can occur all across the USA, both in terms of high wind loading and debris impact. Based in part on an examination of collected damage data, this chapter proposes a general procedure for performance-based wind engineering, as well as related research needs for its specific development and application to wood frame structures.

Typical tornado risk assessment methodologies currently used by various agencies utilize empirically derived loss models that rely on historical claim data for predicting future effects of tornadoes. Xinlai Peng, David Roueche, David Prevatt, and Kurtis Gurley, in their chapter (Chap. 15) titled "An Engineering-Based Approach to Predict Tornado-Induced Damage," note the potential limitations of this current approach and that a more rigorous strategy may be the development of engineering-based tornado damage assessment (ETDA) models, which can be made applicable to construction in any region and to any tornado size and strength. The chapter presents a framework for an ETDA of low-rise buildings, which is then shown to predict damage in good agreement with post-tornado damage observations for vulnerable non-engineered residential buildings.

As alluded to above, the landfall of a hurricane can involve different hazard sources (wind, wind-borne debris, flood, and rain) that interact to generate the overall hazard scenario for a given structure, and so hurricanes ought to be viewed as multi-hazard scenarios. With that in mind, Vipin Unnikrishnan and Michele Barbato, in Chap. 16 titled "Performance-Based Hurricane Engineering: A Multi-Hazard Approach," use a probabilistic performance-based hurricane engineering (PBHE) framework for risk assessment of pre-engineered and non-engineered residential structures subject to hurricane hazard. Results include annual probability of exceedance of various repair costs for the target residential buildings due to each hazard, as well as their combined effect, which highlights the importance of considering the interaction between different hazard sources.

Arindam Chowdhury, Mohammadtaghi Moravej, and Filmon Habte continue the treatment on hurricanes, in their chapter (Chap. 17) titled "Wall of Wind Research and Testing to Enhance Resilience of Civil Infrastructure to Hurricane Multi-Hazards." They report on two large-scale experimental wind studies, performed on low-rise building roof coverings, which included wind-induced roof surface pressure and roof panel deflection measurements. Observed failure modes under realistic wind loading conditions were different from what is typically observed using standard uniform pressure testing methods, and so the experiments reported in the chapter reveal new aspects of roof response to high wind speeds and highlight the importance of large-scale modeling of structures that can incorporate realistic component and connection details, as well as architectural features.

Part VI focuses on geo-hazards, including modeling of physical phenomena and condition assessment, as well as some related treatment of uncertainties. On that latter point, Robert Gilbert, Mahdi Habibi, and Farrokh Nadim, in their chapter (Chap. 18) titled “Accounting for Unknown Unknowns in Managing Multi-Hazard Risks,” note that a significant challenge in managing multi-hazard risk pertains to accounting for the possibility of events beyond our range of experience. In such cases, classical statistical approaches and subjective assessments are of limited value, respectively, because there are no data to analyze and they are derived from within our range of experience. The chapter therefore proposes a new framework, called decision entropy theory, to assess probabilities and manage risks for possibilities in the face of limited information. From a practical perspective, the theory highlights the importance of considering how possibilities for natural hazards could impact the preferred alternatives for managing risks, underscoring the significance of developing adaptable approaches to manage multi-hazard risks.

In Chap. 19, titled “Bayesian Risk Assessment of a Tsunamigenic Rockslide at Åknes,” Zenon Medina-Cetina, Unni Eidsvig, Vidar Kveldsvik, Sylfest Glimsdal, Carl Harbitz, and Frode Sandersen introduce the application of two methods for estimating the risk due to a potential tsunamigenic rockslide. The first method follows a classical approach for empirical relations between the risk components, while the second method follows a more recent approach based on Bayesian networks, which introduces the notion of causal effects. A key component in both approaches is the evidence assimilation of experts, who provide technical information and also their beliefs in terms of probability measures, which is a strategy that introduces a unique approach for incorporating fine engineering judgment into risk measures in a transparent and systematic manner. The chapter shows that rockslide risk estimates obtained from the methods yield significant qualitative differences in terms of inference capabilities, but their orders of magnitude for overall expected risk are relatively similar.

The next chapter (Chap. 20) investigates the relevant hydrologic and geotechnical processes triggering failure of steep hillside slopes under rainfall infiltration. This chapter, by Ronaldo Borja, Jinhyun Choo, and Joshua White, is titled “Rock Moisture Dynamics, Preferential Flow, and the Stability of Hillside Slopes.” The work focuses on the triggering mechanisms of slope failure induced by rainfall events and highlights the multi-physical nature of the problem. Nonlinear finite element simulations of the failure of hypothetical hillside slopes, similar in configuration to two well-documented test slopes, are presented in the chapter, revealing the impacts of slope/bedrock topography, rainfall history, rock moisture dynamics, and preferential flow pattern on the failure of hillside slopes.

In Chap. 21, titled “Innovation in Instrumentation, Monitoring and Condition Assessment of Infrastructure,” Kenichi Soga argues that the design, construction, maintenance, and upgrading of civil engineering infrastructure requires fresh thinking to minimize the use of materials, energy, and labor, which can only be achieved by understanding the performance of the infrastructure (both during its construction and throughout its design life) through innovative monitoring. It is hypothesized that the future of infrastructure relies on smarter information, such as the rich data obtained from embedded sensors, to act as a catalyst for new design, construction, operation, and maintenance processes for integrated infrastructure systems linked directly with user behavior patterns. The chapter also presents some examples of emerging sensor technologies.

Part VII focuses on the societal impact of extreme events—the four chapters in this part look more generally at the impact of extreme events on society by discussing risk management, strategies for resilient communities, and new policies. In the first chapter of the part (Chap. 22, titled “Theories of Risk Management and Multiple Hazards: Thoughts for Engineers from Regulatory Policy”), Arden Rowell looks at regulatory policy for managing multiple risks. After a discussion of the core challenges to multi-risk management faced by policymakers, the chapter then discusses three approaches for regulatory risk management: the precautionary principle, cost-benefit analysis, and the capabilities approach.

Chapter 23, titled “Disaster Risk Reduction Strategies in Earthquake-Prone Cities,” by Lori Peek, Stacia Ryder, Justin Moresco, and Brian Tucker, describes specific risk reduction activities currently implemented in 11 earthquake-prone cities around the world. Understanding the tools and actual resources that practitioners and organizations have available can help in developing more effective strategies. The chapter is based on both survey results and in-depth interview data obtained from a variety of professionals in government, business, health care, and education, as well as from grassroots groups. The chapter ends with practical advice on how to develop effective hazard mitigation strategies.

A recent concept in risk reduction and recovery from extreme events is resilience. Chapter 24, titled “Community Resilience: The Role of the Built Environment,” by Therese McAllister, brings in the notion of community resilience, namely, the ability of communities to prepare for a recovery from the occurrence of extreme events. Specifically, it looks at the roles of buildings and infrastructure systems in defining community resilience and argues that the dependencies/interdependencies between buildings and infrastructure systems are currently not properly modeled and accounted for. The chapter illustrates this limitation by considering the performance of the built environment in the cases of Hurricane Katrina and Superstorm Sandy. This chapter ends by putting forward recommendations to improve community resilience.

New technologies play an important role in mitigating risk and promoting resilience. In the final chapter of this volume (Chap. 25, titled “Digital Technologies, Complex Systems, and Extreme Events: Measuring Change in Policy Networks”), Louise Comfort examines methods of digital data collection and how data are analyzed, plus she describes models developed to evaluate the complex, dynamic interactions between extreme events and affected communities. The chapter presents specific applications considering three different types of hazard: a superstorm, an airport fuel leak, and a wildland fire. As a conclusion, the chapter presents a proposal to operationalize the monitoring and modeling of interactions between extreme events and the affected communities.

If only one point could be taken away from this volume, it would be that to promote mitigation of the impact of natural and anthropogenic hazards on society, there is a need to go beyond the traditional boundaries of hazard-specific research. Optimal strategies for the mitigation of risk and promotion of resilience should be developed in consideration of all the multiple, relevant hazards. Such strategies should consider the life cycle of a building or infrastructure (accounting for aging and deterioration.) Furthermore, technical engineering strategies can be successful only if they are well integrated with policymaking. This volume helps make a step toward the development of successful *multi-hazard approaches to civil engineering infrastructure*.

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Reference

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