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Performance-Based Engineering of Transportation Infrastructure Considering Multiple Hazards

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16. Abstract

A framework is developed for performance-based engineering of transportation infrastructure considering multiple hazards. The framework builds upon the FEMA P-58 methodology for seismic performance evaluation of buildings, but utilizes an event-based approach in a multi-hazard context and considers both structural and downtime losses.

The framework is exercised to explore the financial implications of selecting retrofit strategies for an interdependent civil infrastructure system subjected to multiple hazards. A bridge-roadway-levee system, subjected to earthquake and high-water (storm surge) hazards, is analyzed and retrofit strategies for the levee and bridges of the system are evaluated in terms of risk metrics commonly used in the field of financial engineering for portfolio optimization. The risk metrics include the average annual losses, value at risk or probable maximum losses, conditional value at risk, and worst-case losses. It is shown that an optimal retrofit strategy depends upon the metric(s) being used for risk evaluation. It is also quantitatively argued that various stakeholders, including the owners, policy makers, and insurance companies may perceive risks differently, use different metrics for risk evaluation, and come up with different retrofit strategies for risk mitigation of the same system. Moreover, scenarios are discussed where privately held capital could potentially be invested in retrofitting civil infrastructure systems.

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Transportation infrastructure, interdependent system, multihazard, earthquake, flood, performance-based engineering, risk metrics, financial engineering, retrofit

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Chapter 1

Description of the Problem

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Nikellis, A., "Risk-informed decision making for civil infrastructure subjected to single and multiple hazards", Ph.D. Dissertation, University at Buffalo, The State University of New York, Buffalo, NY, September 2019.

1.1 Introduction

In the field of earthquake engineering, resilience was defined by Bruneau et al. [9] as the ability of a structure to reduce the probability of failure due to a shock, absorb efficiently the shock once it occurs and recover as quickly as possible. They introduced a measure for resilience, which is related to the quality of infrastructure that varies over time. They also provided examples of complementary measures of resilience for critical systems, in terms of global, technical, organizational, social and economic performance measures. The civil engineering community is still exploring different aspects of resilience and tries to promote it both in the design of new structures but also in the analysis and retrofitting of the existing ones. Whether civil infrastructure is resilient or not against natural and man-made hazards remains a complicated question to be answered. The difficulty in answering this question relies upon the fact that resiliency can be examined from many different perspectives, some of which are difficult to quantify. For example, in order to conclude whether a transportation system is resilient against the seismic hazard, information should be collected regarding the structural response of the systems (i.e. roads, bridges), and the societal and economic effects of traffic disruption and bridge reconstruction, if needed.

The idea of designing structures that reach different performance levels under seismic events was introduced through the performance-based (PBD) design framework [14]. These performance levels are mainly related to and expressed in terms of structural demand parameters (i.e., drift and acceleration). In a resiliency-based framework such performance levels could be expressed through many other parameters that can capture the societal and financial impacts of the hazard to the system. Furthermore, since resiliency is a much more holistic approach to quantify the effects of a hazard to society, the analysis can be extended from a single structure to a portfolio of structures or an infrastructure system with many different constituents.

Making our communities resilient against catastrophic events, decisions should be made prior to the event for better preparedness (Community resilience was a Presidential directive (PPD8) in 2011, and underpinned the 2011 National Academies report [31]: ”National Earthquake Resilience: Research, Implementation, and Outreach”). Amid inevitable uncertainties in dealing with extreme events these decisions should be risk-informed. To this end, information should be collected for the hazards, vulnerability of the structures against these hazards and time needed to recover from a catastrophic event. Then, the societal and financial impact of the catastrophe has to be quantified and properly communicated to various stakeholders including the owners, policy makers, and insurance companies.

Quantifying the potential financial losses after a catastrophe can help prepare for risk mitigation, inform for risk financing and plan for emergency management. In a nutshell, risk-informed decision making prior and after a catastrophic event can enhance community resilience only if the risk is properly quantified.

A first step towards making decisions that could lead to more sustainable and resilient communities is the proper quantification of the risk associated with the occurrence of potential natural hazards. Although, civil engineering has progressed and evolved throughout the years, natural hazards still pose a threat to the infrastructure and extreme events can lead to great economic losses. The direct losses from Hurricane Andrew in 1992

($25 billion), the Northridge earthquake in 1994 ($45 billion), Hurricane Katrina in 2005 ($161 billion), Hurricane Sandy in 2012 ($71 billion) and Hurricane Harvey in 2017 ($125 billion) are the costliest natural disasters in the history of the United States of America.

Current practices evaluate the risk imposed by each hazard independently. The performance-based design and engineering [14, 15, 16, 29] were pioneered by the Pacific Earthquake Engineering Research (PEER) Center at UC Berkeley and focused on individual buildings subjected to earthquake shaking. This framework is the cornerstone for conducting performance-based earthquake engineering (PBEE) and is expressed as a triple integral, based on the total probability theorem [4]. This framework convolves the hazard, with the vulnerability of a structure and expresses the result in terms of a decision variable (e.g., financial losses). Based on this framework a recent study by Nikellis et al. [33] showed that during the performance-based cost-benefit analysis of buildings with special moment-resisting frames both wind and earthquake hazards should be taken into account, otherwise large errors in the predicted life-cycle losses could be expected.

A number of recent review articles also summarized progresses and challenges associated with risk assessment and mitigation of civil infrastructure systems subjected to multiple hazards. Koliou et al. [23] conducted an extensive literature review of community resilience studies and suggested future directions for better modeling and understanding of resilience. They concluded that to develop policies on risk-informed decision-making and optimization and prioritization of sustainable retrofit solutions, more research was needed on a varieties of infrastructure systems under various combinations of hazards. Bruneau et al. [8] described the state-of-the-art in the field of multi-hazard design of structures and interdependent infrastructure systems. They underlined that the existing approach of designing infrastructure systems while evaluating the performance of their constituents under various hazards independently may not be appropriate. With an example of a transportation system where the design of the bridges did not reflect the objectives at the system level, they qualitatively argued that a retrofit strategy that is not evaluated through a system-wide, multi-hazard analysis may not be the optimum risk mitigation strategy in terms of enhancing resilience of a system.

Furthermore, the financial aspects of decision making introduce to many challenges. Quantifying the financial losses of a potential catastrophe is a crucial piece of the puzzle for decision making. Providing such information can help various stakeholders allocate funds. Decisions can be made based on the available funding resources in conjunction with the quantification of financial risk related to the exposure of a system to catastrophes. For example, insurance companies are very much interested in quantifying their exposure to risk associated with natural disasters. Some calculate the probability of becoming insolvent due to a natural hazard and on this basis select whether to hedge their exposure through reinsurance and insurance-linked securities such as catastrophe bonds. Such financial products are mainly used for hedging the risk related to privately held civil infrastructure and used infrequently for public infrastructure since policy makers usually rely on federal disaster relief after a catastrophic event [36]. Nevertheless, another possible way for hedging the risk related to catastrophic events is through retrofit of structures prior to the events. Thus, if the financial losses related to a catastrophic event are properly evaluated through a cost-benefit analysis, insurance companies might considering investing in retrofit strategies to reduce their exposure, instead of doing so through the financial markets. If such a decision is made, then privately held capital could be infused into public projects and have a positive social impact as well [36, 37].

Finally, during the decision-making process, stakeholders with different backgrounds and potentially competing goals perceive risk differently. Thus, great care should be given to risk communication. To this end, since the financial aspects of decision making are of great importance, risk metrics that have been extensively used in the insurance sector and the financial engineering field for portfolio optimization could serve as a common language between stakeholders to communicate risk and potential financial losses. Based on these metrics, risk-informed decisions could be made, enabling more resilient communities.

1.2 Objectives

This report provides insight to the risk of civil infrastructure subjected to multiple hazards and seeks to improve communication between different stakeholders for better risk-informed decisions and efficient risk mitigation. The primary objectives of this research are:

(i) To formulate a multi-hazard framework for the risk assessment of civil infrastructure. This framework is based on the assembly of the works of other researchers, primarily in the field of earthquake engineering.

(ii) To quantify life-cycle losses of structures subjected to multiple hazards.

(iii) To explore financial aspects of selecting retrofit strategies for interdependent civil infrastructure systems subjected to multiple hazards.

(iv) To utilize risk metrics commonly used in the field of financial engineering for portfolio optimization for better risk evaluation of civil infrastructure and risk communication between various stakeholders.

1.3 Organization of the Report

This report is organized into four chapters with contents described below:

- Chapter 1 presents an introduction to risk assessment of civil infrastructure and briefly highlights the challenges for decision making for risk mitigation, risk financing and resilient community planning. It also summarizes the main objectives of this report.

- Chapter 2 presents a brief literature review for the risk assessment of civil infrastructure through an event-based approach. Based on this literature review, it presents a framework for multi-hazard risk assessment of civil infrastructure, considering independent and cascading hazards.

- Chapter 3 explores financial aspects of selecting retrofit strategies for an interdependent civil infrastructure system subjected to multiple hazards. A hypothetical bridge-roadway-levee system, subjected to seismic and high-water (storm surge) hazards, is analyzed and retrofit strategies for the levee and bridges of the system are evaluated in terms of risk metrics commonly used in the field of financial engineering for portfolio optimization. It is also quantitatively argued that various stakeholders, including the owners, policy makers, and insurance companies may perceive risks differently, use different metrics for risk evaluation, and come up with different retrofit strategies for risk mitigation of the same system.

- Chapter 4 summarizes the overarching conclusions of this report. The original contributions of this report are highlighted, recommendations and directions for future work are presented.

A list of references follows Chapter 4.

Chapter 2

Methodology

2.1 Framework for Multi-hazard Risk Assessment of Civil Infrastructure

> This chapter is part of the Ph.D. dissertation of Alexandros Nikellis [32]. The complete citation information is as below:
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> Nikellis, A., “Risk-informed decision making for civil infrastructure subjected to single and multiple hazards“, Ph.D. Dissertation, University at Buffalo, The State University of New York, Buffalo, NY, September 2019.

The Pacific Earthquake Engineering Research (PEER) Center, during the late 1990s, presented a probabilistic framework for the seismic performance assessment of structures [14]. This framework, which has its roots in work completed for the US nuclear industry [35] in the late 1970s and early 1980s, is the cornerstone for conducting performance-based earthquake engineering (PBEE) and is expressed as a triple integral, based on the total probability theorem [4]:

$$\lambda(DV) = \int_{DM}\int_{EDP}\int_{IM} G(DV|DM)dG(DM|EDP)dG(EDP|IM)|d\lambda(IM)| \tag{2.1}$$

where $\lambda(DV)$ is the annual frequency of the decision variable DV, DM is a vector of discrete damage states for each component of the network, EDP is a vector of engineering demand parameters (e.g. displacement, drift, acceleration), IM is a vector of intensity measures of the hazard (e.g. spectral acceleration, peak ground acceleration, peak ground velocity, peak ground displacement) and $\lambda(IM)$ is the annual rate of occurrence of events (e.g. ground motions, hurricanes) associated with each hazard. $G(|)$ is a complementary distribution function and $dG(|)$ is its derivative.

This framework, was originally proposed for the assessment of the performance of individual facilities (e.g. single buildings, bridges) subjected to seismic hazard. For a single structure subjected to a single hazard, the DM and EDP are vectors, whereas the IM is a scalar. Thus, for the evaluation of Eq. (2.1), a Monte Carlo type simulation technique can be utilized for the DM and EDP integrals, whereas the IM integral can be directly evaluated [3].

This methodology is a powerful tool for the assessment of the performance of civil infrastructure and it can be extended to any other type of hazard, considering single or multi-hazard scenarios. In addition, it can be applied to spatially distributed systems even though there are many challenges with doing so. The main challenge in evaluating the triple integral presented in Eq. (2.1) for a spatially distributed infrastructure system is that both the intensity measures and damage states are correlated vectors [3]. An event-based approach has been utilized in the literature to partly overcome such a challenge [28]. An event-based approach, although can be computationally very expensive for large-scale systems, has the advantage that it can be implemented for any type of single or multi-hazard conditions. FIG. 2.1 shows a flowchart for an event based analysis of spatially distributed systems subjected to multiple independent hazards.

For the event-based analysis of a spatially distributed system the following steps are followed: (i) all the hazards that could affect the system are identified, (ii) for each hazard, scenarios with different annual rates of occurrence are generated, (iii) for each scenario, hazard intensity maps are constructed, (iv) for each hazard map, multiple damage maps are generated, and each damage map, contains information regarding the damage states of the constituents of the system, and (iv) as a final step, each damage map is translated to a performance metric (e.g., financial loss) of the system with a weight that is related to the annual rate of occurrence of the scenario.

It should be noted that even though event-based analysis of an infrastructure system is not new, this chapter summarizes the steps that are needed to conduct such an analysis for infrastructure systems subjected to multiple independent hazards, while considering their simultaneous occurrence, and multiple cascading hazards.

2.1.1 Multiple Independent Hazards

A spatially distributed system can be subjected to multiple hazards during its lifetime. These hazards can affect the system individually or coincidentally, even if they are independent of each other. For example, in the case of seismic and wind events, even though the probability of occurrence of an earthquake and a hurricane at the exact same location and time is extremely low, both these hazards can affect the civil infrastructure of an area multiple times during its lifetime. FIG. 2.1 illustrates the steps that are needed in order to evaluate the triple integral presented in Eq. (2.1) through an event-based analysis of an infrastructure system subjected to multiple independent hazards.

2.1.1.1 Hazard Analysis

Following the multi-hazard flowchart presented in FIG. 2.1, the first step for the event-based analysis of a spatially distributed system is the hazard characterization. Initially all the hazards that could potentially affect the system, during its lifetime, should be identified. Multiple scenarios, with different annual rates of occurrence, can then be generated for each hazard. For example, for the seismic analysis of a distributed system in

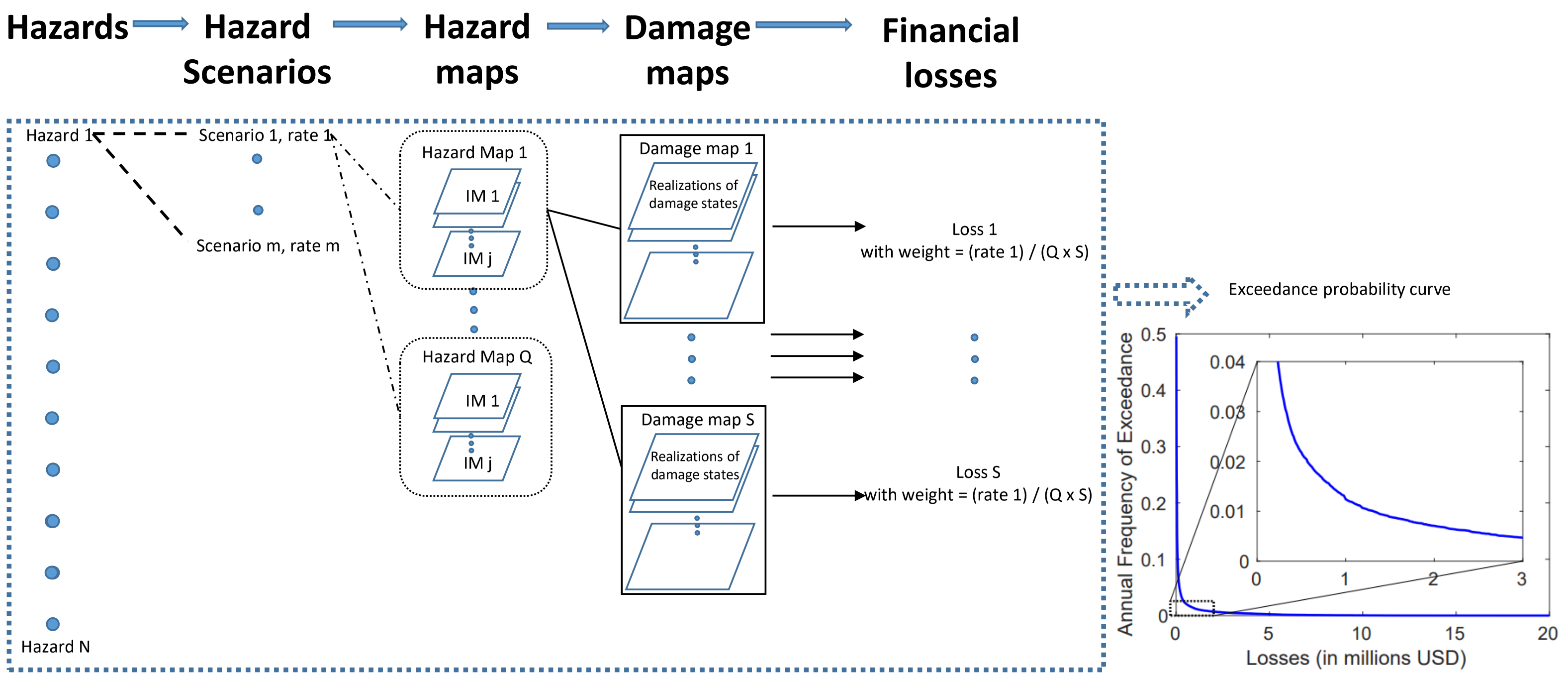

Figure 2.1: Visualization of an event-based decision-making framework for spatially distributed systems subjected to multiple independent hazards

California, the UCERF2 [17] source model could be utilized during the probabilistic seismic hazard analysis. This model provides information for the annual rate of occurrence of earthquake scenarios.

For each scenario, hazard maps can then be generated. These maps contain information related to the intensity measures that the scenario can produce at different locations of the infrastructure system. For example, if a system is analyzed under a seismic scenario, then the hazard maps of the system for this scenario contain information regarding the ground motion intensity measures (IMs) at different locations of the system. A single hazard map can contain information of many different intensity measures. For example, a hazard map can contain information for both the peak ground acceleration and the peak ground velocity at all the locations of the system. For the generation of seismic intensity hazard maps, the median IM at the sites of the structures of the system can be quantified through ground motion prediction equations (attenuation relationships). Then, realizations of an IM are sampled by adding within-event (intra-event) and between-event (inter-event) residuals to the median IMs, following [1, 6, 12, 13]:

$$ln(IM_{ij}) = ln(\overline{IM}_{ij}) + \sigma_{ij}\epsilon_{ij} + \tau_i\eta_i \tag{2.2}$$

where i refers to the site, j refers to the earthquake, ϵ_{ij} is the intra-event residual, η_i is the inter-event residual, and σ_{ij} and τ_i are standard deviations calculated by the ground motion prediction equation.

The within-event residuals capture the variability of the IM around its median value from location-to-location of the system for one earthquake event. The between-event residuals capture the variability of the IM around its median value from earthquake-to-earthquake at all locations of the system [26]. Cross correlation between different IMs is observed at both within and between-event residuals, whereas spatial correlation is observed only for within-event residuals. For example, Jayaram and Baker [20] formulated a model that captures the correlation of ground motion intensities on a spatially distributed system and they showed that the intra-event residuals, around the predicted median ground-motion intensity measure, follow a multivariate normal distribution. Thus, during the sampling process of the hazard maps for a system subjected to earthquake scenarios, the intensity measures of the ground motions will be spatially correlated and the correlation between them will be addressed by this model. The spatial correlation should always be incorporated in the sampling process of intensity measures for any type of hazard considered in the risk assessment of a system.

2.1.1.2 Vulnerability Analysis

Following the multi-hazard flowchart presented in FIG. 2.1, multiple damage maps are generated for each hazard map, since the damage states of the components of the system are directly associated to the *IMs* of each hazard map. Each damage map contains information regarding the damage states of the components of the system at different locations. Since there is uncertainty related to the damage state that a component of the system will be at or exceed, given an intensity measure, realizations of damage states for each component of the system should be sampled. Thus, multiple damage maps are sampled for each hazard map.

The realizations of the damage states of each component of the system are sampled based on the probability of the component at being or exceeding a damage state at a certain value of an intensity measure (which is provided by the hazard map). Thus, fragility curves of the components of the system are generated for each hazard that is taken into account during the event-based analysis of the system and that are related to different intensity measures. For example, for the seismic hazard, the fragility curve of a bridge is related to the spectral acceleration at the period of the bridge, whereas for the flood hazard, due to internal erosion of a levee, the fragility curves of the levee segments are related to the water elevation of the river.

For the calculation of the probability of a component of the system of being or exceeding a damage state, due to a hazard, the following form of the fragility function can be used (e.g., [27]):

$$F(DS_{ik}|IM_i) = \Phi\left(\frac{lny - \lambda_{k,i}}{\xi}\right) \tag{2.3}$$

where $F(DS_{ik}|IM_i)$ is the fragility curve of the i^{th} component being or exceeding the k^{th} damage state conditioned on the IM_i, and Φ is the standard normal cumulative distribution function with mean $\lambda_{k,i}$ and standard deviation ξ. It should be noted that, if the simultaneous occurrence of two hazards (e.g. storm surge and waves) is taken into account then instead of fragility curves, fragility surfaces are generated [22].

Once the fragility curves of the components of the system are generated, damage states are sampled based on the following:

$$P(DS_{ik}|IM_{ij}=y) = \begin{cases} 1 - F(DS_{ik}|IM_{ij}=y) & \text{if } k=0 \text{ (no damage)} \\ F(DS_{ik}|IM_{ij}=y) - F(DS_{i(k+1)}|IM_{ij}=y) & \text{if } 1 \leq k < n \\ F(DS_{ik}|IM_{ij}=y) & \text{if } k=n \end{cases} \tag{2.4}$$

where $P(DS_{ik}|IM_{ij}=y)$ is the probability the i^{th} component being or exceeding the k^{th} damage state conditioned on a realization y of the IM_{ij} at the j^{th} hazard map. During the sampling process of damage states, the damage correlation, between similar components of a system, should be taken into account. For example, if there is damage at a location of a levee then it is more probable that damage will occur at another location of the levee at a distance of 1m, whereas is less probable that damage will occur at another location of the levee at a distance of 100m [24]. In the same fashion, bridges in a system with similar characteristics will have similar damage [25], when subjected to the same hazard.

2.1.1.3 Decision Analysis

Once the damage maps of the system are sampled for each scenario, each damage map is translated to a single value of a performance metric. For example, each damage map of the system contains information for the damage states of the components of the system and the damage states of the components are directly associated to potential economic losses. Thus, each damage map of a system can be translated to an economic loss, through the summation of the losses of all the components of the system.

Each scenario produces losses with same weight. This weight is related to the annual frequency of occurrence of the scenario, based on which the damage maps are generated. For example, if Q hazard maps are generated for a scenario with an annual rate of occurrence equal to ν_1, and for each hazard map S damage maps are generated, then the weight of the losses per damage map is equal to $\nu_1/(Q \times S)$. It should be noted that, the same number of hazard maps should be sampled for all the scenarios of a hazard and the same number of damage maps should be sampled for each hazard map, while the number of hazard and damage maps per scenario can be different.

Once all the performance metrics, along with their weights, are calculated for all the scenarios then the final step of an event-based analysis of an infrastructure system is the calculation of an exceedance probability (EP) curve. This curve contains information regarding the annual frequency of exceeding a threshold value of a performance metric. If the financial losses is the selected metric, then the EP curve provides information regarding the annual frequency of being or exceeding a given loss threshold. Once the losses, along with their weights, are calculated for all the scenarios of all the hazards considered in the analysis of the system, then the annual frequencies of exceedance of given loss thresholds are calculated and the EP curve is constructed.

If the hazards that affect a system are independent, without considering the simultaneous occurrence of these hazards, then the annual frequency of exceedance of a loss threshold value of the system is equal to the summation of the weights of the losses that are equal to or exceed this threshold value, while considering all the scenarios. For example, if a system is analyzed under two hazards, while considering one scenario per hazard with annual rates of occurrence equal to ν_1 and ν_2, respectively, then if these losses exceed a given loss threshold value the annual frequency of exceedance of this loss threshold value due to these hazards is equal to [21]:

$$\nu_{multihazard} = \nu_1 + \nu_2 \tag{2.5}$$

If the simultaneous occurrence of the scenarios is taken into account Eq. (2.5) takes the following form:

$$\nu_{multihazard} = \nu_1 + \nu_2 + \nu_{1,2} \tag{2.6}$$

where $\nu 1, 2$ is the annual rate of the simultaneous occurrence of those two scenarios and is calculated following [21]:

$$\nu_{1,2} = \nu_1 \nu_2 (\mu D1 + \mu D2) \tag{2.7}$$

where μD_1 and $\mu D2$ are the average durations of the scenarios.

In the case of three scenarios, Eq. (2.7) transforms to [21]:

$$\nu_{1,2,3} = \nu_1 \nu_2 \nu_3 (\mu D1 + \mu D2 + \mu D3) \tag{2.8}$$

2.1.2 Multiple Cascading Hazards

Each hazard scenario presented in FIG. 2.1 could contain information for both a main and a cascading hazard. This case is presented in this section and shown graphically in FIG. 2.2.

2.1.2.1 Hazard Analysis

For each scenario hazard maps for the main hazard (e.g., earthquake) are generated. For each such hazard map, multiple cascading hazard (e.g., fire following earthquake) maps are generated. The intensity measures of the cascading hazard maps may be dependent on the intensity measures of the hazard map generated from the main hazard.

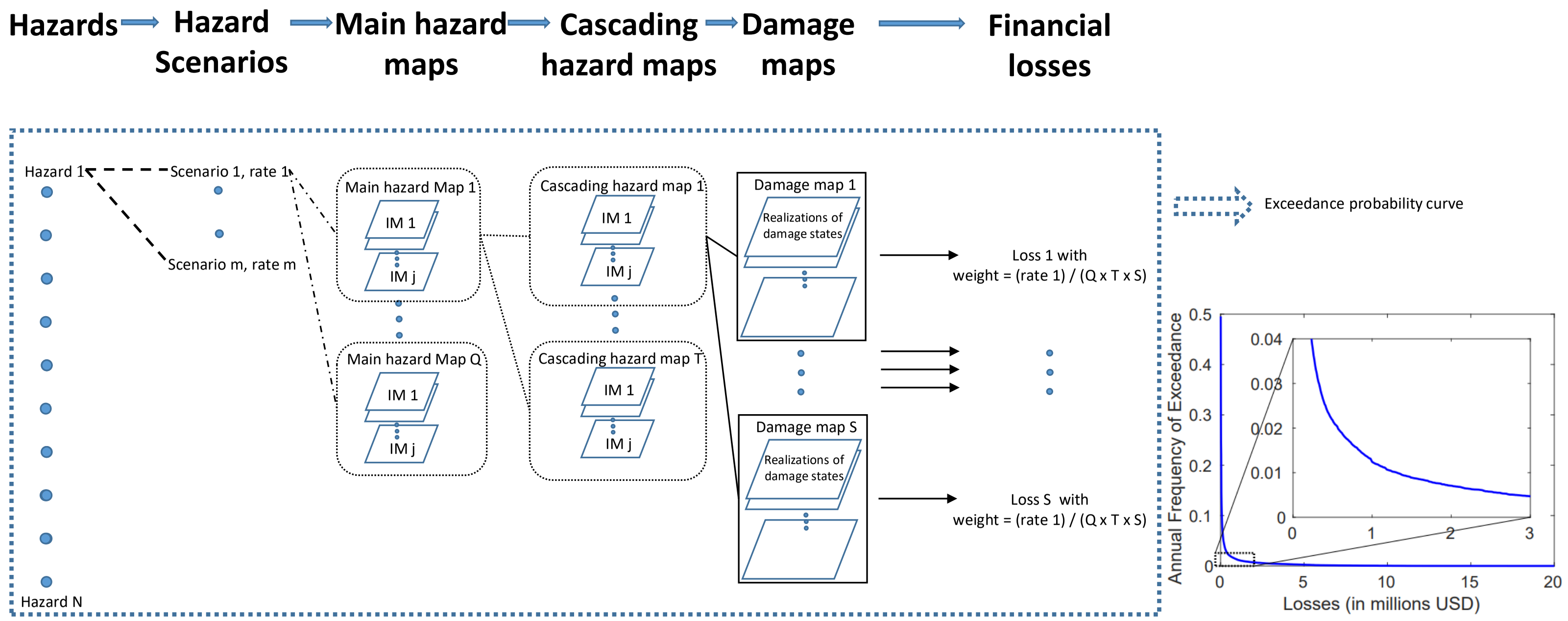

Figure 2.2: Visualization of an event-based decision-making framework for spatially distributed systems subjected to multiple cascading hazards

2.1.2.2 Vulnerability Analysis

Damage states of the components of the system are sampled for each cascading hazard map. The damage states of the components of the system are sampled based on their fragility curves. In order to generate fragility curves for the components of the system under cascading hazards, both the main and the cascading hazards should be taken into account. For example, if incremented dynamic analysis (IDA) [38] is utilized to generate fragility curves for components under a mainshock-aftershock seismic scenario then ”back-to-back” IDAs of mainshocks and aftershocks should be conducted [39].

2.1.2.3 Decision Analysis

Each scenario produces losses with same weights. These weights are related to the annual rate of occurrence of the scenario, based on which the damage maps are generated. For each scenario, both main and cascading hazard maps are generated and then damage maps are sampled. Thus, the annual rate of occurrence of a cascading hazard map contains information for both the main and the cascading scenarios and can be calculated as follows:

$$\nu_{total} = \nu_{main} + \nu_{cascading|main} \tag{2.9}$$

where $\nu_{cascading|main}$ is the annual rate of occurrence of the cascading hazard map given that the main hazard map has occurred.

For example, Yeo and Cornell [39] proposed a framework for aftershock probabilistic seismic hazard analysis. They proposed an equation for the calculation of the mean number of aftershocks in a period of time after the mainshock, which is a function of the magnitude of the mainshock and the period of time after the mainshock during which the aftershock can occur.

If for a scenario with an annual rate of occurrence equal to ν_{main} are sampled Q main hazard maps, and for each main hazard map are sampled T cascading hazard maps, with an annual rate of occurrence equal to $\nu_{cascading|main}$, then there will be $Q \times T$ main-cascading hazard maps, with an annual rate of occurrence equal to $\nu_{total}/(Q \times T)$. If for each main-cascading hazard map are sampled S damage maps then the weights of the losses will be equal to $\nu_{total}/(Q \times S \times T)$.

These losses, with their weights can be combined with losses related to other independent hazards and a multi-hazard EP curve can be constructed in a similar way presented in the previous sections.

Chapter 3

Multi-hazard Risk Assessment and Cost-Benefit Analysis of a Bridge-Roadway-Levee System

This chapter is published in the proceedings of the 10th New York City Bridge conference. The complete citation information is as below:

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3.1 Introduction

Risk assessment and performance evaluation of individual structures subjected to seismic hazard were pioneered by the Pacific Earthquake Engineering Research (PEER) Center [14]. A few recent studies (Bocchini and Frangopol [5]; Guidotti et al. [19]; Alipour and Shafei [2]; Gardoni et al. [18]; Sharma et al. [34]) have also explored the performance of civil infrastructure systems subjected to multiple hazards. These studies have mainly discussed the quantification of resiliency through the resilience metric defined by Bruneau et al. [9] or indirectly through other metrics (e.g., financial losses). A few recent review articles presented progresses and challenges regarding the risk assessment of civil infrastructure systems under multi-hazard conditions. An extensive literature review of community resilience studies was recently conducted by Koliou et al. [23], concluding that more research is needed for the development of policies on risk-informed decision-making and optimization, prioritization of efficient retrofit solutions. Bruneau et al. [8] qualitatively argued that retrofit strategies for the constituents of a system should be evaluated through a system-wide, multi-hazard analysis. Otherwise, these strategies might not be optimum for the maximization of the resilience of the system. This paper quantitatively evaluates retrofit strategies for an interdependent civil infrastructure system subjected to multiple hazards, in terms of risk metrics commonly used in the field of financial engineering for portfolio optimization. A hypothetical, interdependent civil infrastructure system consisting of bridges, roadway stretches and a levee is subjected to seismic and high-water (storm surge) hazards. For this system different retrofit strategies are evaluated in terms of risk mitigation and financial loss reduction. To this end, risk metrics, including the annual frequency of exceedance of losses, average annual losses, value at risk, conditional value at risk, and worst case losses are utilized. Direct financial losses related to the potential damage of the constituents of the system, as well as indirect economic losses due to traffic disruption to the system are considered in this study. Cost-benefit analyses, utilizing the risk metrics, for the retrofit strategies of the bridges and the levee are also conducted and an optimum risk mitigation strategy is presented. The importance of conducting risk assessment at the system level and in a multi-hazard context, is underlined. Otherwise, the risk and the potential financial losses can be significantly underestimated. Different conclusions, regarding the cost-benefit evaluation of the optimum retrofit strategy, are drawn for different risk metrics.

3.2 The Testbed System

The testbed is a hypothetical system, assumed to be part of the Bayshore Freeway, near the San Jose International Airport in California. It is shown schematically in FIG. 3.1. The system consists of 6 bridges, 2 freeway stretches and part of a levee along the Guadalupe river. The bridges are located at 3 sites: (37.382 N, 121.964 W), (37.377 105 N, 121.942 W), and (37.375 N, 121.933 W). At each site there are 2 bridges (one bridge each for the southbound and northbound freeways). Between the bridges there are

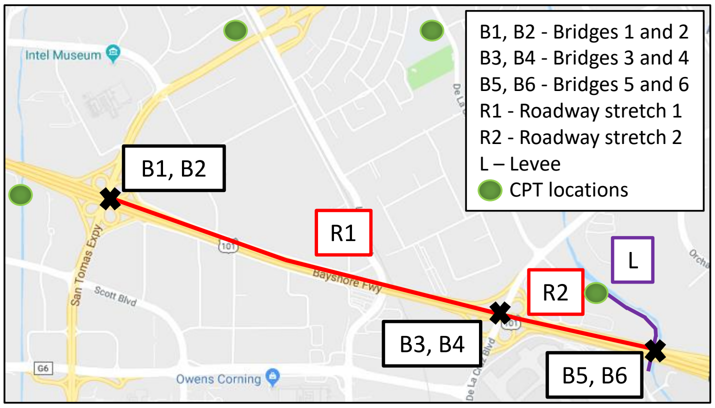

Figure 3.1: The testbed system.

freeway stretches with four lanes and a shoulder at each directional carriageway. The length of the levee considered in this study is 0.65 km. The structural characteristics of the constituents of the system are assumed. Two-span reinforced concrete box-girder bridges supported on single circular piers and diaphragm abutments are selected. The details of the bridges selected for this study are presented in TABLE 3.1. The levee cross section and structural properties are assumed to be the same as those analyzed by Zimmaro et al. [40].

Steel jacketing of the pier of the bridges and improvement of the foundation of the levee through jet grouting are the selected retrofit strategies for the constituents of this system.

Table 3.1: Details of the bridges in the system.

	Bridges 1 and 2	Bridges 3 and 4	Bridges 5 and 6
Span length (L; m)	25	30.48	36.58
Pier height (H; m)	5.49	7.62	10.36
Pier diameter (D; m)	1.53	1.83	2.74
Pier foundation type	pile	pile	pile
Deck width (W; m)	10	10.67	12.19
Box-girder height (m)	1.38	1.68	2.01
Abutment backwall height (m)	3.35	2.97	4.50
Number of piles per abutment	7	8	9

3.3 Risk Assessment

The risk assessment of the system and the risk-informed evaluation of its retrofit strategies are conducted through an event-based approach and consider both structural and downtime losses. This approach relies on the performance-based earthquake engineering framework [29], extended here in a multi-hazard context. The hazards considered during the analysis of this system are: (i) high-water (storm surge) hazard and (ii) seismic hazard and its triggering effects. The high water hazard can cause internal erosion of the levee. The seismic hazard can cause structural damages to the bridges and levee, and liquefaction-induced damages to the roadway stretches. Analysis of historical gage height (water elevation) measurements available for the river and probabilistic seismic hazard analysis for the entire system are performed for the quantification of the high-water and seismic hazards, respectively. For the vulnerability analysis of the bridges under seismic excitation, the technique of incremented dynamic analysis (Vamvatsikos and Cornell [38]) is employed. Fragility curves for both an original and retrofitted bridge are presented in FIG. 3.2. The vulnerability of the roadway stretches against liquefaction is evaluated following HAZUS [30]. For the estimation of the probability of liquefaction, site-specific cone penetration test (CPT) data are analyzed according to Boulanger and Idriss [7]. The vulnerability of the levee against both hazards is quantified with fragility curves provided by by Zimmaro et al. [40].

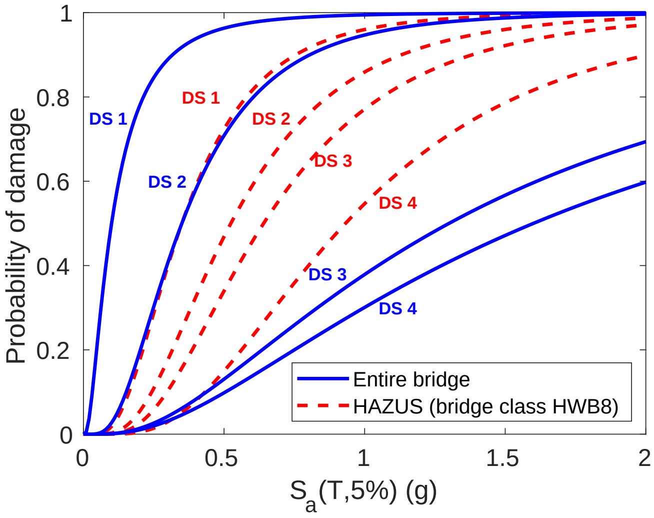

Figure 3.2: Damage fragility curves for Bridge 1.

Exceedance probability (EP) curves are utilized in the field of earthquake engineering to express annualized losses. This curve describes the probability that a level of loss will be exceeded annually (e.g., Miller and Baker [27]). The EP curves for the selected system with and without the mitigation (retrofit) and for both the seismic and flood hazards, are presented in FIG. 3.3[1]. The bridges produce lower losses than the roadway stretches for higher annual frequencies of exceedance, whereas the levee produces higher losses for lower frequencies of exceedance, which are related to extreme, rare seismic events. These observations underline the importance of analyzing all three interdependent constituents of the system. Furthermore, through a comparison of the EP curves of the original system while considering the seismic and the flood hazard independently, it is observed that even though the flood hazard is less than the seismic hazard, it is not negligible. This observation corroborates the importance of conducting risk assessment at the system level and in a multi-hazard framework.

3.3.1 Risk Metrics

The risk related to extreme events is quantitatively assessed with different risk metrics. The selected metrics for this study are the Value at Risk (Var), the Conditional Value at Risk (CVaR), the Annual Average Loss (AAL) and the Worst Case Loss (WCL). These metrics are extensively used in the insurance and reinsurance sectors for assessing catastrophe risk and in financial engineering for conducting portfolio optimization.

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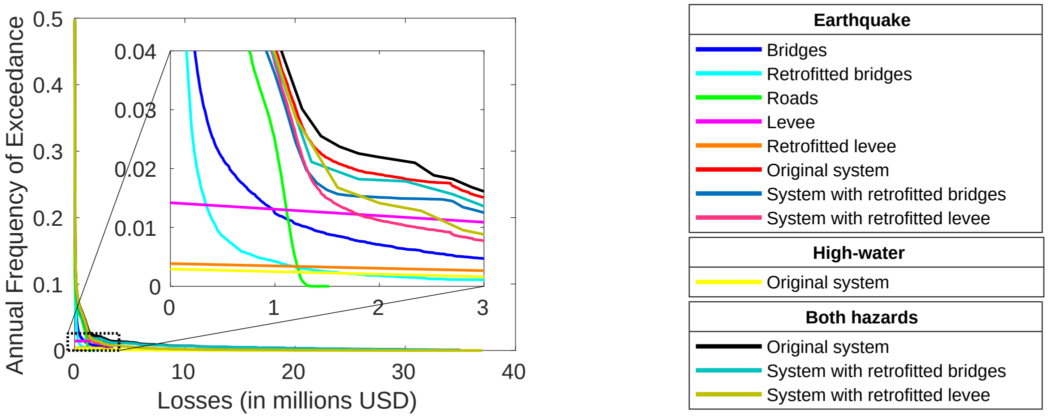
[1] Best viewed in color.



Total losses

Figure 3.3: Exceedance probability curves for the original and retrofitted systems along with their constituents.

3.3.1.1 Average Annual Losses

The Average Annual Loss (AAL) represents the expected loss per year and is equal to the area under the EP curve. In the insurance sector, the pricing of insurance premiums is based on AAL. As shown in FIG. 3.4(a), at the constituent level, the retrofit of the bridges leads to a reduction of the total AAL of 57%, whereas the retrofit of the levee reduces the total AAL due to seismic events by 82%. At the system level, the total AAL for the seismic, the flood and both hazards are \$0.26 million, \$0.015 million and \$0.27 million, respectively. Considering only the seismic or the flood hazard would lead to a misrepresented, lower total AAL of the system by 4% and 94%, respectively. Furthermore, while considering only the seismic hazard, the total AAL reduces by 9% and 47% when the bridges and the levee are retrofitted. When both hazards are considered, the retrofit of the bridges reduces the total AAL of the system by 9%, whereas the retrofit of the levee reduces the total AAL of the system by 44%. These observations underline the importance of conducting risk assessment at the system level for all hazards. Based on the total AAL of the selected system, retrofitting the levee for the seismic hazard leads to the greatest reduction in the total AAL, both at the constituent and the system level, while considering only the seismic or both hazards. Thus, such a retrofit strategy could be of the benefit of the owner of the system in order to negotiate better insurance premiums.

3.3.1.2 Value at Risk

Value at Risk (VaR) is a risk metric that indicates the minimum loss that will be reached or exceeded annually with a given probability. The selected annual probability of exceedance for the calculation of VaR is equal to 0.4% corresponding to events with a return period equal to 250 years. The VaRs of the system and its constituents, for both hazards are presented in FIG. 3.4(b). Insurance companies utilize VaR to decide whether to hedge their risk through reinsurance and financial instruments such as insurance linked securities (e.g., catastrophe bonds). Furthermore, VaR could be utilized by a policy maker or the owner of a system, to quantify the exposure of the system to a certain amount of risk related to a certain value of financial losses. Regarding the seismic hazard, the total VaR of the levee contributes most to the total VaR of the system, followed by the total VaR of the bridges and the roadway stretches. The total VaR of the bridges and of the roadway stretches are 22% and 8% of that of the levee, respectively. The total VaR of the original system, considering only the seismic or the flood hazard, is 1% and 100% less than that considering both hazards. At the system level, considering only the seismic hazard, the retrofit of the levee reduces the total VaR of the original system by 67%, but only 1% for the retrofit of the bridges. If the same comparison is made, considering both hazards, then the retrofit of the levee reduces the total VaR of the original system by 65% and the retrofit of the bridges by 1%. These observations confirm that retrofit of the levee is a better strategy for mitigating risk at events with a return period equal to 250 years.

3.3.1.3 Conditional Value at Risk

Even though the VaR is a simple risk metric to calculate, once the EP curve is constructed, it only provides information regarding a single loss related to an annual frequency of exceedance. Further information can be extracted from the EP curve and better conclusions can be made for the exposure of the system to catastrophe and financial risk. The Conditional Value at Risk (CVaR) is a measure that quantifies the average value of losses that exceed a specific VAR. This is a better risk metric than the VaR for making conclusions regarding the tail risk of the EP curve as it considers all losses at the tail of the EP curve under the condition that they exceed a certain

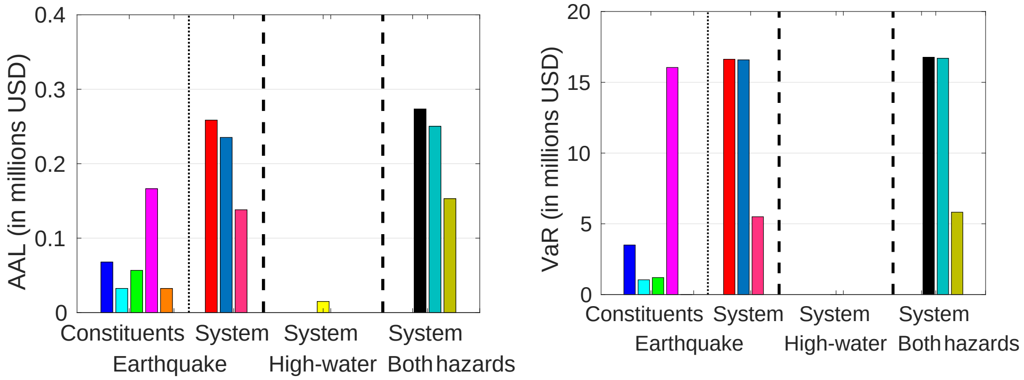
VaR value. FIG. 3.4(c) shows the CVaR values of the system conditioned at the selected VaR value for this study (related to an annual probability of exceedance of 0.4%). For the original system the total CVaR related to flood hazard is 25% of that related to the seismic hazard. This observation confirms that these two hazards compete with each other in terms of potential financial losses that are related to the tail of the risk curve and corroborates the importance of conducting multi-hazard risk assessment. Furthermore, the difference of the total CVaR between the original and retrofitted bridges at the system level is negligible, which is not the case for the total CVaR related to the retrofit of the levee. Thus, retrofitting the levee is a better management strategy for mitigating risk related to extreme events with low probability of occurrence, but high financial consequences.

3.3.1.4 Worst Case Losses

This risk measure is defined in this study as the maximum loss that a system or its constituents could experience. These losses are related to the most extreme case hazard scenarios. It is related to the value of losses at the point where the EP has an annual probability of exceedance equal to zero. For the owner of a system or a policy maker, the Worst Case Loss (WCL) could be of great interest since such losses are related with the absolute failure of some constituents or the system. The WCL of the constituents of the system are presented in FIG. 3.4(d). Regarding the roadway stretches of the system, the total WCL is 95% lower than the total WCL of the bridges and the levee. This large difference between the total WCL of the roadway stretches and the other constituents of the system is attributed to the probability of liquefaction of the soil at the selected location. After the retrofit of the bridges of the system, the earthquake-related total WCL is reduced by 24%. On the contrary, the retrofit of the levee does not affect the seismic related total WCL. This means that there are potential extreme seismic events that can cause the total collapse of the levee even after its retrofit is implemented. The retrofit of the bridges reduces the total WCL of the system, due to both hazards, by 3% whereas the retrofit of the levee does not affect it. This observation leads to the conclusion that retrofitting the bridges is a better option for mitigating risk associated with extreme case seismic events with very large return periods.

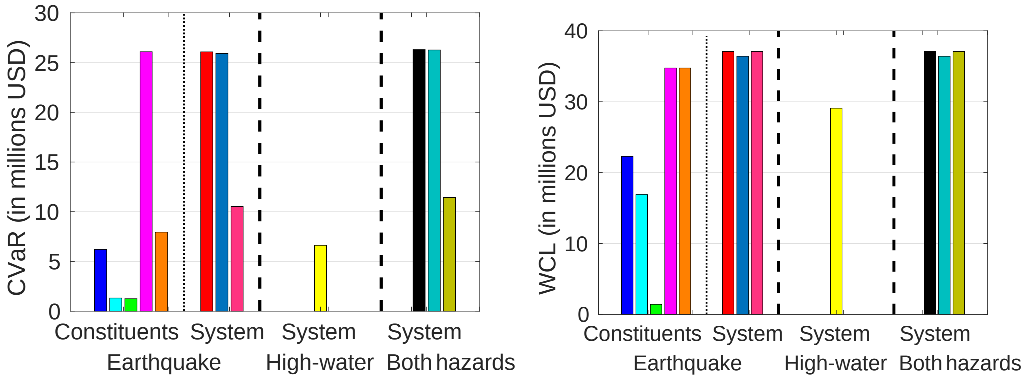
3.4 Cost-Benefit Analysis

The risk measures presented in the previous sections characterize the EP curve. Based on these metrics, conclusions are made regarding the assessment of the catastrophe risk of the system and its constituents. Reducing the risk of a system has social impact and could be of great interest for both an owner and a policy maker. At the same time, for an owner, it is important to identify whether reducing the catastrophe risk of the system, by retrofitting certain constituents, would lead to an economically



(a) Average annual losses (AAL)

(b) Value at risk (VaR)



(c) Conditional value at risk (CVaR)

(d) Worst case losses (WCL)

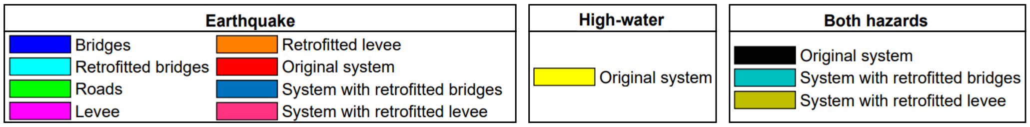


Figure 3.4: Various risk metrics for the original and retrofitted systems along with their constituents.

beneficial investment strategy. To this end, a cost-benefit analysis for each retrofit strategy is conducted utilizing each risk metric. The capital cost of the retrofit strategies is compared with the losses related to each risk metric prior and after the mitigation of the retrofit strategy. Conclusions regarding an optimum retrofit strategy are based on the results of these cost-benefit analyses. A retrofit strategy is economically viable if it produces a reduction in the losses of the system greater than the capital cost of the implementation of the strategy. The retrofit strategy for the bridges (steel jacketing of the pier) is related to the cost of the structural steel used for it. The cost related to the steel jacketing of the pier of the bridge is estimated to be \$39.7/kg (\$18/lb) based on bidding prices provided by Caltrans [11]. The retrofit strategy for the levee is related to the improvement of its foundation through jet grouting. The jet grout price is estimated to be \$130.8 per cubic meter of levee foundation [10]. Based on this price the cost for retrofitting the levee is estimated to be \$12,204 per meter. The capital costs of the retrofit strategies are presented in TABLE 3.2.

Table 3.2: Capital costs for retrofitting the constituents of the system.

Constituent	Capital cost (\$)
All bridges	2,171,432
Levee	7,932,600

3.4.1 Value at Risk

If losses associated with a specific annual frequency of exceedance are of primary interest, then the VaR could be selected as the appropriate risk metric for conducting a cost-benefit analysis for the retrofit strategies of the system. Thus, if the purpose of retrofitting constituents of the system is reduction of risk and potential financial losses with an annual frequency of exceedance equal to 0.4% then the following observations are made by comparing the VaR, shown in FIG. 3.4(b), and the capital cost of the retrofit strategies, presented in TABLE 3.2. While considering the earthquake-induced total VaR of the levee before and after the implementation of the retrofit strategy, it is evident that by investing $7.93 million for retrofitting the levee, the losses whose annual frequency to be exceeded is 0.4%, are reduced by $16.05 million. In addition, losses equal to $16.05 million for the retrofitted levee have an annual frequency of exceedance equal to 0.06%. Thus, there is a reduction of 85% of the annual frequency of seismic-induced losses of the levee to exceed $16.05 million. The reduction of the total VaR of the system under multi-hazard conditions due to the retrofit of the levee is equal to $10.95 million. Thus, investing $7.93 million for this retrofit strategy would lead to an economically beneficial strategy for mitigating financial losses related to events with a return period equal to 250 years. The reduction of the total VaR of the bridges at the constituent level is $0.29 million higher than the capital cost of the retrofit strategy, whereas at the system level, both under single and multi-hazard conditions, it is negligible.

3.4.2 Conditional Value at Risk

If the purpose of retrofitting systems of the system is the reduction of potential average financial losses beyond a 0.4% VaR, then a comparison between the CVaR shown in FIG. 3.4(c), and the capital cost of the retrofit strategies, presented in TABLE 3.2 makes sense. At the system level, under seismic events, the total CVaR related to the retrofit of the levee system is reduced by $15.56 million and outweighs the capital cost of this retrofit strategy. If both hazards are included in the cost-benefit analysis then the difference of the total CVAR between the retrofitted and original system is $14.88 million and is 100% greater than the capital cost of the retrofit of the levee. The reduction in the total CVaR, due to retrofitting the bridges, is negligible at the system level, both under seismic and multi-hazard conditions, even though at the constituent level, considering the seismic hazard only, the total CVAR of the original bridges is reduced by 80%.

3.4.3 Worst Case Losses

If retrofitting the constituents of the system is undertaken to minimize the potential worst-case losses of a system and its constituents, then cost-benefit analysis should be based on the comparison of the total WCL shown in FIG. 3.4(d), and the capital cost of the retrofit strategies, presented in the TABLE 3.2. By investing in the retrofit of the levee, the total WCL is not affected at the constituent and system level, both under seismic-only and multi-hazard conditions. At the constituent level, the total WCL of the bridges is reduced by $5.4 million, which is approximately 2.5 times higher than the capital cost of the retrofit of the bridges. This reduction is 7.9 times larger than the reduction of the total WCL, associated with the retrofit of the bridges, at the system level under multi-hazard conditions. This observation underlines that by neglecting the flood hazard and considering only one constituent of the system, the error in the analysis would be 790%.

3.5 Summary

This study explores the use of risk metrics, broadly used in the field of financial engineering, for risk assessment of a spatially distributed civil infrastructure system subjected to multiple hazards.

The results of this study are presented in terms of direct economic losses due to structural damage of the constituents of the system and indirect economic losses due to traffic disruption of the transportation network. The results presented in this study underline the importance of conducting risk assessment and cost-benefit analysis at the system level and under multi-hazard conditions. Otherwise, the error in the risk and loss estimation can be very high.

Furthermore, it is also shown that the retrofit strategies for a system should always be evaluated using a multi-hazard framework while considering all the interdependent constituents. Otherwise, a risk-informed decision-making process could result in erroneous conclusions.

Finally, the optimum decision depends upon the individual making it. An insurance company and a policy maker could potentially perceive risk from different perspectives. Thus, different risk metrics should be utilized for better risk communication, in an attempt to provide more resilient civil infrastructure systems.

Chapter 4

Conclusions, Recommendations, and Outreach

4.1 Summary and Key Conclusions

This section provides a summary and key conclusions of this report:

(i) **Framework for multi-hazard risk assessment of civil infrastructure:** The steps needed to conduct risk assessment of infrastructure systems subjected to multiple independent hazards and multiple cascading hazards are presented. The presented framework is an assembly of research works conducted in the past from many other researchers mainly in the fields of earthquake engineering and multi-hazard risk assessment of civil infrastructure. The main modules of this framework: (i) hazard analysis, (ii) vulnerability analysis, (iii) decision analysis, are presented both graphically and through equations.

(ii) **Financial aspects of selecting retrofit strategies:** The financial aspects of selecting retrofit strategies for an interdependent civil infrastructure system subjected to multiple hazards are explored. The system is analyzed using the performance-based earthquake engineering framework, but in a multi-hazard context, through an event-based approach of constructing hazard and damage maps. The risk to the original system and its possible mitigation through retrofitting the bridges and levee are evaluated by utilizing risk metrics commonly used in the insurance and reinsurance industry for assessing catastrophe risks and in the field of financial engineering for portfolio optimization. These risk metrics capture various aspects of the risk to the original and retrofitted systems. Cost-benefit analyses of the retrofit strategies, utilizing the risk metrics, are also performed in exploring a financially optimum retrofit strategy. The results presented in this study underline the importance of assessing risks and making decisions on any civil infrastructure systems only at the system level and only under multi-hazard conditions.

(iii) **Risk metrics and risk perception:** An optimum retrofit strategy for any civil infrastructure systems depends upon the the risk metric(s) being used for the evaluation and the person who is making the decision: policy makers, owners, and insurance companies often perceive risk from different perspectives and decide on different strategies for the same system.

(iv) **Risk metrics for better risk communication:** Amid inevitable uncertainties in dealing with extreme events, risk metrics allow for proper communication of risks to various stakeholders, including owners, policy makers, and insurance companies.

4.2 Recommendations for Future Work

This section provides recommendations for future work:

(i) For the multi-hazard risk assessment of the bridge-roadway-levee system the characteristics of the structures are assumed and do not correspond to actual structures and a system. Similar analysis of interdependent civil infrastructure systems subjected to multiple hazards should be conducted for real, large-scale systems.

(ii) More retrofit strategies should be included in future analyses of interdependent civil infrastructure systems for the proper evaluation of the optimum one.

(iii) More hazards should be included in future analyses of interdependent civil infrastructure systems.

(iv) Further research is needed to generate vulnerability curves for levees due to internal erosion, overtopping and earthquake-induced damage.

(v) Further research is needed to generate vulnerability curves for roadway segments related to the liquefaction-induced damage.

(vi) Realizations of ground motion intensity measures are sampled while considering their spatial and cross correlation of their residuals. Further models are needed that will capture the spatial and cross correlation of various ground motion intensity measures. For example, a model is needed that will capture the spatial and cross correlation of peak ground acceleration and peak ground velocity.

(vii) Formulation of damage correlation functions are needed during the sampling process of the damage maps of a spatially distributed interconnected civil infrastructure system. Otherwise, reduced-order models could be developed for the analysis of large systems and/or portfolios of structures (e.g., bridges). To this end the analysis will become tractable, while the fidelity of the predicted results will be preserved.

(viii) Further metrics for the quantification of the resilience of systems against hazards should be developed. These metrics will be used for better communication between different stakeholders, who might perceive risk differently and have competing goals.

(ix) Cost-benefit analysis of retrofit investment strategies of civil infrastructure systems should be compared with investment strategies including financial products such as insurance-linked securities.

4.3 Outreach

This research project has led to the following publications and presentations:

Book Chapter

1. Nikellis, A., Sett, K., Wu, T., and Whittaker, A. S., "Multi-Hazard Financial Risk Assessment of a Bridge-Roadway-Levee System", in Risk-Based Bridge Engineering, Khaled M. Mahmoud (ed.), pp. 299-307, CRC Press, London, United Kingdom, 2019

Journal Article

1. Nikellis, A. and Sett, K. "Multi-Hazard Risk Assessment and Cost-Benefit Analysis of a Bridge-Roadway-Levee System", *Journal of Structural Engineering*, 2019, in print, doi: 10.1061/(ASCE)ST.1943-541X.0002579

Conference Paper

1. Nikellis, A. and Sett, K., "Risk Assessment of a Bridge-Roadway-Levee System Subjected to Multiple Hazards", *Proceedings of the 2nd International Conference on Natural Hazards & Infrastructure*, Chania, Greece, June 23-26, 2019

Technical Presentations

1. “Multi-Hazard Risk Assessment of a Bridge-Roadway-Levee System considering Downtime Losses”, EMI 2019, Caltech, Pasadena, CA, June 18-21, 2019

2. “Risk Assessment of a Bridge-Roadway-Levee System subjected to Multiple Hazards”, ICONHIC 2019: 2nd International Conference on Natural Hazards & Infrastructure, Chania, Greece, June 23-26, 2019

3. “Multi-Hazard Financial Risk Assessment of a Bridge-Roadway-Levee System”, 10th New York City Bridge Conference, New York, NY, August 26-27, 2019

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