2015

Measuring the Resilience of Transportation Networks Subject to Seismic Risk

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MEASURING THE RESILIENCE OF TRANSPORTATION NETWORKS
SUBJECT TO SEISMIC RISK

A Thesis Presented

by

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Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

February 2015

Civil Engineering

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ABSTRACT

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SUBJECT TO SEISMIC RISK**

FEBRUARY 2015

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Infrastructure systems are essential for day-to-day life but when subject to seismic hazards, these critical systems can experience disruptions that severely impact the communities that are so heavily reliant upon them. After a seismic event, a resilient society should be able to minimize disruption and recover in a timely fashion. In this thesis, a framework to quantify resilience of highway networks to seismic events is presented. A resilient system should have the ability to absorb the initial impact of the event, provide alternatives for damaged infrastructure, prioritize goals and provide additional resources where needed, and restore functionality to an acceptable level quickly. This study details the development of a model that combines structural fragility analysis and complex network flow analysis to determine the impacts of a seismic event on the network functionality. The highway network of the San Francisco Bay area and the Oakland area are selected as the test bed for the developed methodologies. To account for the effect of different improvement strategies before and after earthquake, an original highway network is compared with several scenario-based models with retrofits and improved repair conditions. The costs associated with each event is calculated including costs from the actual repair of the bridge and costs experienced by network users due to decreased traffic performance is estimated. Using the probability of each event, the seismic risk can also be calculated. Post-event scenarios are compared and include planning activities that contribute to effective and rapid recovery strategies. For this case, a series of repair acceleration techniques are applied in order to shorten the repair time and restore the network to an acceptable level of functionality with minimum

resources. This thesis provides network stakeholders with a means to determine the resilience of their network which will provide appropriate decision making tools that will limit disruptions due to earthquakes in a cost effective manner.

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CHAPTER 1

INTRODUCTION AND MOTIVATION

1.1. Introduction

It is crucial for a modern society that critical infrastructure systems such as water distribution, power gridlines, transportation networks, and communication services run smoothly. Critical infrastructure systems are required to maintain a healthy economy, allow reliable transportation and to provide the day-to-day needs for communities. After a natural disaster however, these infrastructure systems can experience damage that can severely decrease their performance. This problem is exacerbated by the fact that the performance of these systems is of greater importance during and directly after the disaster for emergency response and recovery actions.

Transportation networks are one of the most important types of civil infrastructure systems. Transportation networks let users commute to conduct their everyday activities, allow for emergency vehicles to perform time critical duties, and provide businesses with a means to transport goods among other important functions. When a transportation network is damaged, the local community can suffer costs. In some cases, when the network is an important part of a larger network, the losses even propagate to communities further away. After a network is damaged, until different segments are repaired, the indirect costs associated with its normal functionality accumulate over time.

In seismically prone regions, performance of transportation networks could be substantially disrupted due to failures to its components such as roadways, tunnels, bridges, and culverts. Bridges in particular are susceptible to the effects of seismic events as they can be damaged by ground shaking, liquefaction and landslides. Also, the repair

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time for bridges can be expensive and lengthy. Furthermore, bridges normally act as "bottlenecks" in case of damage and can hinder the emergency responses after disruptive events. In the United States, the Loma Prieta (1989) and Northridge (1994) earthquakes damaged important highway bridges which brought on heavy repair costs and large traffic delays.

Performance of transportation networks under seismic hazards highlights the need to study the concept of risk and resilience. *Risk* is a function of the possible seismic events, the probability of occurrence each event, and the outcomes of the events. *Resilience* is the ability of a system to absorb the impact of an event then recover afterwards. Resilience is a complex measure which can be seen as the aggregate of its components. These components include the expected level of physical damage after an event, the topographical reliability of the network layout, the prioritization important goals and the speed of which the network recovers to an acceptable level. While the concept of resilience has existed for decades, the applicability to complex systems such as transportation networks is a recent and understudied topic. This thesis will concentrate on applying the concepts of resilience to transportation networks under seismic risk. It aims to provide efficient methods of evaluating the resilience of transportation networks so that the owners of the network can gauge its vulnerability, discover weaknesses in the network, and increase preparedness in order to limit the potentially large direct and indirect costs that an earthquake can carry.

1.2. Overview of the Thesis

The goal of this thesis is to quantitatively assess the risk and resilience of transportation networks subjected to seismic hazard and to develop methods that provide decision

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makers with the required tools to make pre-event decisions that can improve the resilience of the network. First in this thesis, an overview on the topics of risk and resilience will be provided. Following this, the methods used to quantify said risk and resilience will be detailed and a case study demonstrating these methods will be detailed. To help decision makers make pre-event decisions, a method of prioritizing bridge retrofits will be detailed and demonstrated in another case study.

Chapter 2 concentrates on the topics of risk and resilience and provides methods to quantify each. A comprehensive literature review on the resilience of civil infrastructure systems is given to provide an overview on the topic. For this purpose, first the historical disruptions to infrastructure networks under natural hazards have been reviewed. The chapter continues with a look at the vulnerability of bridges and explains the integration of the traffic demand model to the damaged network. For a system wide analysis, modeling the damage to each bridge in detail would be prohibitively expensive. For this purpose, the damage state limit state are defined for a set of 28 bridge classes and then the fragility curves are utilized to determine the probability of each damage state for a given bridge. This is done using the characteristics of the bridge and the level of shaking at the bridge site or the amount of displacement from liquefaction. The level of damage is tied into the ability for the bridge to carry traffic. With that, the traffic model is updated using a four step model to estimate the changes in the capacity of the network before and after the earthquake. Furthermore, the concept of resilience and its historical applications is introduced. An in-depth interpretation of the different components of resilience is presented each with its own quantitative measure. Resilience is then linked to the costs associated with a given earthquake scenario. Costs come from both the actual

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repair costs of the bridge and the costs from the change in network performance after the earthquake.

In Chapter 3, the available methodologies to analyze the seismic risk of the spatially distributed systems have been discussed and a review of the effects of prioritization and alternative repair techniques on restoration of the functionality of the network after extreme events has been conducted. The chapter ends with a case study that takes place in the San Francisco Bay area. The San Francisco Bay area is a populous region subject to very high seismic hazard making it an ideal location for a test bed. The highway network in the study area will be subjected to a series of earthquakes in order to evaluate the post-earthquake behavior of the network. A risk assessment is presented for the given area utilizing a range of earthquakes from nearby faults. Then, the resilience of the network is studied. Lastly, the effects of prioritizing bridges for repair are explored in greater depth.

Chapter 4 will analyze the options available for retrofitting against seismic hazards and provides a method to select bridges for retrofit based on their importance in the network. A history of bridge retrofitting will be collected and a list of common retrofit techniques will be given that includes advantages and disadvantages to each technique. Next, some optimization methods considered for the study are detailed and the technique used in this thesis will be justified and explained. A case study in the Oakland area will be conducted that selects retrofits based on the risk in the area. Also shown in the study will be sensitivity of the costs to factors such as cost of retrofitting and risk.

The last chapter reviews the conclusions for the thesis and discusses possible future developments. A summary of the thesis will be collected and the possible uses and potential impact of the study will be given.

RISK AND RESILIENCE ASSESSMENT

2.1. Impact of Earthquake on Infrastructure Systems

The economy of the modern societies and the well-being of its citizens depend on the uninterrupted and reliable functionality of its infrastructure systems. According to the report of the U.S. President's Commission on Critical Infrastructure Protection (PCCIP-1997), the nation's critical infrastructure systems provide a reliable flow of products and services essential to the defense and economic security of the society. Transportation networks are categorized as one of the critical infrastructure systems as their physical damage and functionality loss not only hinder every day residential and commercial activities but also impair post disaster evacuation, response, and recovery. Furthermore, considering the interdependent nature of the critical infrastructure systems (Rinaldi et al. 2001), the loss of functionality in transportation network can also adversely affect interdependent networks such as telecommunication and health networks (Chang et al. 2013). Highway bridges are one of the most critical components of the transportation network acting as "bottlenecks" in case of any disruption or failure in their service. Seismic events impose a large hazard to highway transportation network as they can adversely affect a large portion of this spatially distributed system. Earthquake prone areas bear the risk of very large losses due to seismic events. The estimated annualized earthquake loss in the United States has been determined by FEMA to be 5.3 billion in 2005. A large portion of the annualized cost is concentrated along the west coast with nearly 40% of the cost in the Los Angeles and San Francisco Bay area alone (FEMA 2008).

Historically, seismic events have caused major disturbances to transportation networks. After the 1995 Great Hanshin earthquake, the Port of Kobe in Japan suffered damage that severely limited its ability to move cargo for two years causing severe and possibly long-lasting impact to the area (Chang 2000). The 1989 Loma Prieta earthquake stressed the public transit systems as the highway bridges were damaged and users began using public transit as an alternative (SPUR 2010). Los Angeles saw major disruptions to the highway network after the 1994 Northridge earthquake. Most notably, portions of the Santa Monica Freeway, an extremely busy highway with average daily traffic being about 261,000 around the time of the earthquake, were shut down until bridge repair could be done (US DOT 2002).

Predicting the effects of earthquakes on transportation networks can be difficult. Post-earthquake traffic flows are more difficult to predict than in other emergencies such as hurricane or nuclear hazards as earthquakes offer no prior warning and are coupled with immediate damage to infrastructure (Chang et al. 2010). Bridges are especially important when considering earthquakes because the supports of bridges are often located near bodies of water or steep slopes which means particular susceptibility to landslides and liquefaction. The repair cost that is associated with liquefaction is generally high since liquefaction can lead to high damage states (Kiremidjian et al. 2007).

Substantial research has been focused on evaluating the impact of seismic events on the transportation networks. These studies include the post-earthquake flow models to estimate the functionality of the network (Nojima and Sugoito 2000, Lee et al. 2011, Chang et al. 2012), development of annual risk curves using probabilistic scenario based models (Shiraki et al. 2007, Stergiou and Kirmidjian 2010, Alipour 2010), integrating

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transportation network and regional economic models to estimate the direct and indirect costs associated with failure of bridges in transportation networks (Cho et al. 2000, Tatano and Tsuchiya 2008, Danielle and Love 2010, Rose et al. 2011 and Furtado and Alipour 2014a), and proposing prioritization methods for bridge retrofit to enhance the functionality of the networks (Zhou et al. 2010, Chang et al. 2012, Bocchini et al. 2012, Rokneddin et al. 2013, Venkittaraman and Banerjee 2013, and Furtado and Alipour 2014b). Most of these studies have suggested strategies for asset protection and vulnerability reduction; however, recently there is an increasing emphasis on the resilience of the transportation networks, which is defined as the ability of the system to withstand, adapt, and rapidly recover from the effect of disruptive events (Turnquist and Vurgin 2013). The recognition of the importance of this issue has caused national security communities seek for alternatives to ensure the infrastructure resilience. The examples of policy shift include the U.S. Department of Homeland Security National Infrastructure Protection Plan (NIPP: DHS, 2009) and Presidential Policy Directive 8 (PPD-8 2011), which contain explicit language calling for increasing the resilience of the nation's critical infrastructure against the threats that pose the greatest risk to the security of the nation, including acts of terrorism, cyber-attacks, pandemics and catastrophic natural disasters. Fragility Analysis of Bridges

2.2. Risk Analysis and Resilience Assessment

The resilience of networks and communities has been a topic of interest in the past few years where it complimented seismic risk assessment and risk management studies. However, resilience is a concept that is difficult to describe quantitatively. The ability to quantify resilience could be useful to management agencies to better understand which

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aspects of a network should be improved in order to better deal with the consequences of earthquakes. The novelty of the current research is to develop a holistic framework to quantitatively measure different dimensions of seismic resilience in a large transportation network.

The term resilience has been used in many fields and, though the core concept remains the same, no singular definition has been universally accepted. The Oxford English Dictionary (2010) defines resilience as the action or an act of rebounding or springing back; rebound, recoil. Holling (1973) was the first to define resilience is a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables. Pimm (1984) introduced a definition of resilience as a speed measure for the system to return to its stability after a disturbance. This definition although initially applied to ecological systems, made a significant impact on other fields. Later the definition of resilience was also applied to the actual speed of recovery. The latter definition has been found useful to investigate both short-term disruptions due to extreme events (e.g., Tierney, 1997, Bruneau et al., 2003, and Rose, 2004) and long-term changes (Dovers and Handmer, 1992, and ASCE, 2013). This highlights the importance of time as a factor in recovery which primarily distinguishes resilience from risk. The PPD-8 (2011) calls resilience as the ability of a system to adapt to changing conditions, withstand disruptions, and rapidly recover from them. This definition is very close to the one proposed by Rose (2009), which divides the resilience into two levels: i) static resilience as the ability of a system to maintain function after a catastrophic event, and ii) dynamic

resilience as the speed by which the system recovers from a severe shock to achieve a desired state of functionality.

Recently there has been an exponential increase in the topic of resilience across many different fields following a string of disasters such as the Loma Prieta earthquake (1989), hurricane Katrina (2005), the recent financial crisis (2008), and the Tohoku earthquake (2011) (Park et al. 2013). Disaster resilience has been the topic discussed by the disaster roundtable under the topic of grand challenges in science and technology and put emphasis on pre-emergency recovery planning (2005). A workshop funded by the National Science Foundation and conducted by the National Research Council labeled community resilience framework as one of five grand challenges in earthquake engineering, stating that such a framework also could advance our understanding of both the direct and indirect impacts of earthquakes so that community-level interactions and impacts can better characterized (2011).

A system's resilience is largely dependent on i) the state of its components also called their vulnerability, ii) the hazards that it may be exposed to, and iii) the consequences of such hazards given the state of the system. Another concept very close to resilience is the risk which could be characterized as a function of three main factors: i) nature and probability of occurrence of a destructive event, ii) state of the system in terms of resilience, and iii) probability of different outcomes or consequences of the events under consideration. Upon identification of the most important components of the system, the risk associated to them can be quantified by a series of predictive models that express the probability and severity of damage due to destructive events. As it relates to seismic risk analysis, the hazards include the probability and the intensity of ground

motion, liquefaction, landslides and other hazards. The vulnerability would relate to the expected level of damage that will occur in components of the system for a given set of seismic events. How exactly resilience ties into risk analysis has been a subject of debate. The resilience of a system is sometimes viewed as an outcome of vulnerability; a system has a certain amount of vulnerability and resilience is the reaction to the events the system is vulnerable to. Other times, resilience is viewed as a process which at least partially bears the responsibility of damage mitigation (Cutter et al. 2008). In this study, risk analysis and resilience will be looked at as interconnected ideas. Risk analysis is useful for estimating how much damage is expected to occur while resilience can help define which aspects of a system are most critical to recovery. Time for recovery is also an aspect which is often more important in resilience than in risk as the characteristics of resilience are often defined using time as a dimension. While still a fairly new topic, there have been studies in the resilience assessment of networks across a range of disciplines. Rose (2004) used the concept of economic resilience and applied it to damage due to earthquakes in water distribution network in the Portland Metro area. Chang and Shinozuka (2004) discussed a quantitative measure for resilience and applied it to the Memphis water system. Improving on the Chang and Shinozuka (2004) model, Chang et al. (2008) measured the resilience of the Los Angeles lifeline network. Cimellaro et al. (2010), following similar framework, evaluated the resilience of a hospital network using the change in healthy population as a measure of resilience. Omer et al. (2009) examined the global internet infrastructure system using the ratio of information flow before and after a disturbance. Bocchini and Frangopol (2012) used resilience and cost as objectives in deciding scheduling for interventions for bridges on a simple highway network.

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According to Haimes (2009), the vulnerability assessment mainly contributes to a system's protection, whereas the resilience assessment goes beyond the system's protection and additionally includes system's recovery following extreme events. As a case in point, hardening of a system against region-specific hazards (i.e., pre-event investment) may reduce the vulnerability of the system, but if the recovery needs are not properly addressed, the resilience of the system in terms of recovery time and cost will not always be improved. Understanding of the needs of broad use of resilience ranging from the bridge structure to other structures to infrastructures to networks to communities, an operational definition of resilience should enable its measurement by meeting the following requirements for which metrics are either available or needed: i) building on national priorities and presidential policy directives (PPD-8 2011, PPD-21 2013), ii) modeling the disturbing events considering their uncertainties as stochastic processes, iii) knowledge of initial capacity or capacity after event of structure/system, iv) accounting for the changes in time due to aging or improvements that will be considered in the system, v) considering the abilities to prepare and plan for, absorb, or adapt to the hazard (NRC 2013), v) including the performances of different entities in the infrastructure system such as the physical assets, people, economy, and community (MCEER 2010), vi) define the system performance in terms of objectives and outputs, vii) integrating models to account for the rate of recovery over time, and viii) being able to connect to other relevant topics such as reliability and risk analysis

Bruneu et al (2003) describes a resilient community as one which has reduced failure probabilities, reduced consequences from failures and reduced time to recovery. These characteristics are ensured if the system has four "R's" for resilience: robustness,

redundancy, resourcefulness and rapidity. According to this definition, robustness is the ability the system or elements to withstand stress without the loss of functionality, redundancy is the ability to provide alternatives and make substitutions for damaged elements in a system, resourcefulness is the ability to prioritize actions and supply resources (human, monetary and otherwise) to achieve goals and rapidity is a measure of how quickly these goals can be achieved. Also laid out are four dimensions aspects of resilience: technical, organizational, social and economic. The technical aspect measures the performance of physical systems after an earthquake event. The organizational aspect is the ability for organizations to react appropriately to earthquakes and perform critical functions. The social aspect refers to the ability to minimize harm done to society itself. The Economic aspect is the ability to minimize economic losses due to earthquakes. Figure 2.1 depicts the components of resilience on a system performance curve. Assuming the system is 100% functional before the event, the severity of the initial drop is dependent on both the robustness and redundancy of the network. Depending on the ability of the system to absorb the shock and find alternatives to accommodate the traffic demand, the percent drop in functionality will be affected. Being interlinked concepts, no discrete portion of the drop can be applied to only robustness or redundancy by itself. Shown in the graph are two separate curves, the one on top is where goals are prioritized and additional resources are allocated and one without these properties. The former shows a more resourceful repair process which prioritizes goal. t_f occurs when the repair curve meets the rapidity performance criteria. At this point, the network reaches an acceptable level of performance. What exactly qualifies as an acceptable level of performance depends on the standards of the managerial bodies responsible. The

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performance of the bridge network can eventually return to the pre-event state if everything is repaired, remain below pre-event levels if some aspects are beyond repair, or even rise above the pre-event levels if improvements are made to the network (Ayyub 2013). For this thesis, it will be assumed that the performance will return to the pre-event level. The area between the two curves is an indicator of the system resourcefulness.
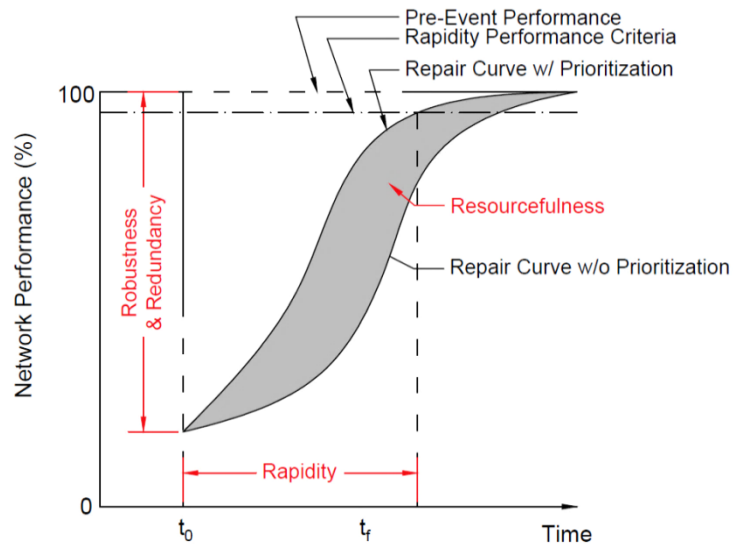
Figure 2.1: Contributions of resilience components on the resilience curve

CHAPTER 3

SEISMIC RISK ANALYSIS

3.1. Introduction

For a long time, risk has been measured as the product of hazard and vulnerability. As it relates to seismic risk analysis, the hazards include the probability and the intensity of ground motion, liquefaction, landslides and other hazards. The vulnerability would relate to the expected level of damage in structures that will occur for a given set of hazards (Musson 2000).

Because of the nearly limitless possible hazard scenarios and network configurations, measuring vulnerability balances accuracy and breadth against complexity and resource intensiveness. Murray et al. (2008) defines four main classifications of approaches for evaluating the vulnerability of the network: scenario-specific, strategy-specific, simulation-based and mathematical modeling methodologies. The scenario-specific assessment looks at a small set of specific disruption scenarios. Strategy-specific assessment looks at scenarios where a structured loss of facilities is expected. The simulation-based approach works under the assumption that if enough simulations are run, a good representation of the vulnerability can be presented. Mathematical assessment seeks out extreme scenarios (worst-case and best-case scenarios). This paper will use a simulation based approach to estimate the seismic risk in the case study.

Analyzing seismic hazards and vulnerability can provide useful and varied insight for network owners. Currently available research explores a range of different performance criteria, geographical locations, seismic sources and general methodologies.

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Shiraki et al. (2007) created risk curves to estimate the annual probability of network delay due to earthquakes affecting the Los Angeles area. Alipour and colleagues (2010, 2011, and 2013) developed a multiple hazard framework to estimate the functionality of the Los Angeles and Orange County areas after earthquakes. Rossi et al. (2012), using a test network in north-east Italy, performed seismic risk analysis to compare different retrofitting scenarios in order to prioritize groups of bridges for retrofit. Mehary and Dusicka (2012) developed a seismic risk assessment model for major trucking routes in Oregon which indicates that an earthquake could disable trading route for extended periods of time and cause other sever economic and social impacts. Chang et al. (2012) demonstrated a model used on the Memphis metropolitan areas road network that looks at the vulnerability of the network in terms of its ability to supply capacity for evacuation. In this study, the seismic risk of the San Francisco Bay area will be analyzed. For this purpose the topology of the network will be created using graph theory and the fundamentals of network science and traffic analysis will be used to measure the performance of the network after the event. Finally, the direct and indirect costs associated with a set of scenario earthquakes will be estimated and the risk curves will be generated.

3.1.1. Test Bed Highway Network

The San Francisco bay area is an ideal location to test of the resilience of a transportation network because of its high seismic risk, bustling urban population, reliance on highway bridges, and the wealth of data available after the Loma Prieta Earthquake. The study area will include five counties in the bay area: San Francisco, Alameda, San Mateo, Marin and Contra Costa. The National Highway Planning Network (NHPN) database is

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used to collect geographic, topographic, and connectivity information for the network under study. Within the study area are 910 traffic analysis zones (TAZs). TAZs aggregate socio-economical information within their borders from which productions (total number of origins) and attractions (total number of destinations) are generated based on this information. The highway network is generalized as a graph which consists of a set of node and links. Nodes are important points in the network such as intersections, trip end locations and ramps. Links are roadways that connect the nodes together. Links should contain information important to the traffic model such as capacity and travel speed. Figure 3.1 presents the location of the links and nodes in the study area.

To determine the effects of bridge damage to the driving public, first a model that can predict driver behavior has to be created. The model should be able to determine the origin and destinations of the trips, the route the drivers take and the frequency of trips. For this purpose, a four step model which consists of trip generation, trip distribution, mode choice, and traffic assignment steps is used.

Trip generation determines how often trips originate and end in different traffic analysis zones (TAZ) across the network. Trip origins and destinations are generalized such that trip ends occur in the geometric center of each traffic analysis zone. TAZs that share common borders are connected by a link with a free flow travel speed of 30 miles per hour. Attraction and production data was taken from the 2009 update to the Regional Transportation Plan (RTP), a transportation project in the San Francisco Bay area that helps define future policy and investment in the area. The tables include predicted trip ends for each of the 910 TAZs in the bay area across 5 time period in the day: AM early (midnight - 6 am), AM peak (6 - 10 am), Midday (10 am - 3 pm), PM peak (3 - 7 pm)

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and PM late (7 pm - midnight). The study area of the RTP is larger than the study area of the model in this paper (containing 4 more of the surrounding counties) so the traffic from the counties that are in the RTP area but not in this study's area will be included as external stations.

After the total number of attractions and productions are determined, the trip distribution step pairs the origins and destinations so that the number of trips between every two TAZs can be determined using the gravity model. In the gravity model, the TAZs that are closest to a production zone will generally attract a large portion of the trips compared to a zone further away. The formula for the gravity model is as follows:

$$T_{ij} = P_i A_j f_{ij} / (\textstyle\sum_{j'} A_{j'} f_{ij'})$$ (3.1)

where T_{ij} is the amount of trips from origin i to destination j, P_i is the number of trips originating from i, A_j is the constant to balance the trips destined to zone j, and f_{ij} is the distance decay factor which is inversely related to the zone separation in a form of gamma, power, or exponential factor.

The mode choice step gives the method of travel for each trip be it by car, train or any other mode of transportation. Since the study is concentrated on highway traffic, the relevant data is the percentage of drivers for each trip purpose. Mode choice is based on the data from the Metropolitan Transportation Commission (MTC) and for the San Francisco Bay area 60% for the total trips are conducted by car.

The traffic assignment predicts the paths that the users on the network will take for each trip. Users on the network will try to select the paths with the least cost so an algorithm has to be used that collects the shortest paths. The algorithm generates all-or-nothing path definition which is a path choice where only one path is used between each

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node pair for every user going between the same O-D pair. In actuality, if every user taking a trip between a specific origin-destination pair took the same path, the roadways on the path may become loaded to the point where congestion increases the travel time. At this point, previously calculated shortest path may not be the shortest path anymore so all-or-nothing assignment is run again utilizing a portion of the previous assignments link flow. This process is repeated until the network reaches user equilibrium: the state where no user can decrease travel costs by changing paths. The travel time of each link after congestion is calculated using the Bureau of Public Roads formula which is:

$$t = t_i \left(1 + 0.15 \left(\frac{v}{c}\right)^4 \right) \tag{3.2}$$

where t is the travel time of the link, t_i is the free flow travel time, v is the volume on the link and c is the capacity of the link.

To identify the shortest path a modified version of the Dijkstra's algorithm has been used. The time it takes to run a basic Dijkstra's algorithm is proportional to the square of the number of nodes in the network. This means that for very large networks or studies that require many simulations, the model can take a prohibitively long time to run. However, the algorithm can be optimized by using sparse matrices. A sparse matrix only considers the non-zero values in the matrix. In a network model of the scale used in this study, the number of links is far fewer than the square of the number of nodes so a sparse matrix is used which offers the ability to ignore some of the updating that the algorithm would have to process.

Traffic demand after an earthquake can be modeled as fixed or variable. In fixed traffic demand assumption, the demand is unchanged from before the event. In variable demand, the demand may increase or decrease after the event. Whether the demand

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increases, decreases or remains the same depends on regional behavior. In the case of decreasing demand, it is possible that the travel time between links also decreases (though not necessarily so). In a fixed scenario, the travel time will increase due to the damaged state of infrastructure. In the case of increasing demand, one could expect an increase in travel time due to both congestion and damaged infrastructure (Kiremidjian et al. 2007). The cost of traffic delay is calculated differently from agency to agency. Overall though, the cost is usually calculated as the product of traffic delay and value of time. The value of time is often based on the average hourly wage in a particular region.

3.1.2. Seismic Hazard and Vulnerability Analysis

The San Andreas Fault is a source of great seismic threat to the San Francisco Bay area. Historically, some of the most important seismic events originate from the San Andreas Fault. The Loma Prieta earthquake, a 7.1 magnitude earthquake that struck south of the San Francisco bay in 1989, severely disrupted the transportation network in the bay area. A span of the San-Francisco-Oakland Bay Bridge collapsed closing the bridge for over a month until the bridge was repaired. Being the busiest bridge in the area, this greatly affected network users who would rely on this bridge for their commute and other purposes (Plakfer and Galloway 1989). For this study the scenario earthquakes on both San Andreas and Hayward faults has been considered. To present the risk from these two faults, four representative earthquake sources were selected: three sites are located on the San Andreas Fault and one on the Hayward fault. Fault lines and rupture locations are shown in Figure 3.2. Six different scenarios with moment magnitudes ranging from 6.0 to 8.5 with 0.5 steps has been considered, which makes for a total of 24 scenario earthquakes. For the purpose of seismic risk analyses, the range of earthquake scenarios

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utilizing all 4 epicenter locations and the magnitudes has been identified. The probabilities of each scenario are then considered to determine the risk. The USGS earthquake probability mapping tool based on the 2008 USGS-National Seismic Hazard Mapping Project update was the source for earthquake probabilities in the area. From there, the probabilities were divided amongst the San Andreas and Hayward fault based on the relative probabilities that each fault will produce an earthquake.

The rupture length for each earthquake is taken as a function of the moment magnitude of the earthquake. The following equations are adapted from Wells and Coopersmith (1994) for a strike slip fault.

$$\log(SRL) = 0.74 * M - 3.55 \tag{3.3}$$

where *SRL* is the median rupture length in km, *M* is the moment magnitude, the standard deviation of the logarithm of the rupture length is equal to 0.23.

The Campbell (1997) attenuation relationship is used here to evaluate the level of ground motion intensity at the location of each bridge.

$$\ln PHA = -3.512 + 0.904M - 1.328 \ln\sqrt{R^2 + (0.149\exp(0.647M))^2}$$
$$+[1.125 - 0.112\ln R - 0.0957M]F + [0.440 - 0.171\ln R]S_{SR}$$
$$+[0.405 - 0.222\ln R]S_{HR} \tag{3.4a}$$

$$Ln(SA_H) = Ln(PHA) + c_1 + c_2\tanh[c_3(M - 4.7)] + (c_4 + c_5M)R$$
$$+0.5\,c_6S_{SR} + c_6S_{HR} + c_7\tanh(c_8D)\,(1 - S_{HR}) + f_{SA}(D) \tag{3.5b}$$

where *PHA* is the peak horizontal acceleration in *g, M* in the moment magnitude, *R* is the site-to-source distance, *F* is 0 for strike slip faulting and 1 otherwise, S_{SR} is 1 for soft rock sites and 0 otherwise, S_{HR} is 1 for hard rock sites and 0 otherwise, SA_H is the median

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value of horizontal spectral ordinates, D is the depth to the basement rock, c_x are coefficients based on period and $f_{SA}(D)$ is a function based on the depth of the basement rock. Figure 3.3 shows the distribution of PHA values for a 7.5 magnitude earthquake occurring at site 2.

In addition to the ground motion, liquefaction can pose a serious threat to transportation networks. San Francisco is particularly affected by liquefaction as a very large portion of the area has soil conditions that make for high liquefaction susceptibility. The HAZUS-MH (2012) methodology will be used to determine the expected peak ground deformation and damage associated with these deformations. The methodology considers the soil conditions at the site and the peak ground acceleration (PGA) that the site is subjected to. Each site has a relative susceptibility rating based on soil conditions. The ratings are broken up into the following categories: none, very low, low, medium, high and very high. Two types of peak ground displacements are considered: lateral spreading and settlement. Lateral spreading is dependent on the susceptibility, PGA and water depth at a site. Settlement is based on the susceptibility and the probability of liquefaction for each susceptibility class. Using the greater of the two displacements, fragility curves similar to those based on shaking are used which instead give the probability of failure for PGD. Figure 3.4 presents the liquefaction susceptibility map for the study area (USGS 2000).This combined with the damage from ground shaking will be used to determine the overall damage in the network.

Bridge information is taken from the National Bridge inventory (NBI). After parsing the NBI for bridges near highway links, there are 2424 bridges in the network. Figure 3.5 presents the location and distribution of all the bridges on the study area. Since

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the developed network contains thousands of bridges, it would be impractical to conduct individual finite element analysis on each individual bridge to measure the response to every possible earthquake scenario. For this purpose bridges which share common characteristics are separated into categories following the 28 categories provided by HAZUS-MH (2012), a loss estimation software package developed by the Federal Emergency Management Agency (FEMA). The characteristics are based on bridge geometry, construction materials and whether or not the bridge was designed with seismic hazard as a major concern. To estimate the likelihood of the bridges damaged under specific earthquake scenarios, the concept of fragility curves has been used. The fragility curves describe the probability of a given level of damage for a given ground motion intensity measure. The fragility function is defined as follows:

$$F_k(a|\zeta_k, c_k) = \Phi\left[\frac{\ln\left(\frac{a}{c_k}\right)}{\zeta_k}\right] \tag{3.6}$$

where $F_k(a)$ is the probability of exceeding damage state of k, $\Phi[\cdot]$ is the standardized normal distribution function and c and ζ are the median and standard deviation, respectively which are estimated using the maximum likelihood function (Shinozuka et al. 2001). Damage states are descriptions of the level of damage that the bridge experiences. Four damage states: minor, moderate, extensive and complete have been considered in this study. The minor damage state corresponds to a situation where the bridge is fully functional and only minor repairs are needed and each state increases in severity until the complete damage state where a complete replacement of a span or bridge has to be conducted. Figure 3.6 shows the envelopes for the fragility curves for each of these bridges types.

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Link damage states will be set equal to the highest damage state of the bridges on the link. In this way, the bridges act like a bottleneck for each link. For each damaged link, the capacity of the road may be reduced based on the damage. For minor damage, it is assumed that the bridge can still carry its full capacity. For moderate damage, it will be assumed that the link can still carry 25% of the original capacity. For extensive and complete damage, it will be assumed that the bridge will be closed for repair so the bridge will have no remaining capacity.

In areas where a single bridge carries all the traffic between an origin-destination (O-D) pair, the capacity of the pair is equal to the capacity of the bridge in its damaged state. If a detour is available, the detour route can carry a portion of the traffic load. To conduct the analysis the concept of residual capacity can be utilized. Residual capacity describes the ability for a link to carry a percentage of its normal capacity even when damaged. For example, there could be a case with high residual capacity where detours allow for 50% of its original capacity when damaged (Bocchini and Frangopol 2011).

3.1.3. Network Performance Measures

To establish a holistic framework that evaluates the functionality of a transportation network, it is essential to identify appropriate performance measures that are capable estimating the state of the network pre- and post-event. Among various measures proposed to date, three measures of connectivity, flow capacity and travel time are proven to be the most appropriate ones. The flow capacity can be used to quantify the extent of damage to the network after an extreme event. This measure represents the largest possible flow between the origin and destination nodes without exceeding the capacity of the connecting links (Ahuja et al., 1993). The connectivity analysis

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determines whether any path remains operational between the given origin and destination nodes and is mostly suitable for immediate post-disaster emergency response (Rojahn et al., 1992). It is especially important in situations where a node with very few links connected to it becomes isolated after a seismic event. Travel time is another measure that has been widely employed to estimate the level of performance of a damaged network (Nojima and Sugito, 2000, Stergiou and Kiremidjian, 2010, and Zhou et al., 2011). The calculation of this measure requires OD data, which can be accessed from surveys or mathematical models. The travel time can be obtained using static or dynamic traffic assignment models. To account for the time-dependent nature of travel time after an extreme event, dynamic traffic assignment models and OD modification factors are introduced to improve the results obtained from the static models (Shinozuka et al., 2005, Shiraki et al., 2007, and Kiremidjian et al., 2007).

While these metrics are useful for looking at each aspect of risk analysis resilience assessment independently, it is useful to have one unit of measure that can be used on multiple aspects of analyses in this study. Monetary cost measures are applicable across various aspects of risk and resilience and can be easily calculated from bridge damage and travel delay. For that reason, the monetary cost will be used in this thesis. Costs will be broken up into two categories: direct and indirect costs.

Direct costs relate to the actual costs of repair of the bridges in the network. The direct cost of an individual bridge is proportional to the level of damage the bridge sustains and the size and complexity of the bridge. Getting a detailed estimate for the cost of each bridge would be prohibitively complicated as it would depend on the bridge type, the extent of damage, the availability of local resources among other factors. In this study

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an efficient method that estimates the repair costs of damaged bridges as a function of the damage state, initial cost and the size of the bridge is used. For each damage state, a damage ratio is given where the damage ratio is the cost of repair divided by the total replacement cost. The total expected bridge cost from the *s*th scenario earthquake can be expressed as:

$$RC_s = \sum_{k=1}^{4} P(Ds_k|IM_s).C_c.r_k \tag{3.7}$$

where RC_s is the expected restoration cost of the bridge due to earthquake event *s*, IM_s is the ground motion at the site of bridge due to *s*th earthquake event, C_c is the replacement value of the bridge, r_k is the damage ratio corresponding to *k*th damage state, and *P* is the probability of bridge in *k*th damage state under ground motion IM_s. The length and area of each bridge comes from the NBI database. Based on California Department of Transportation (2013) data, a value of \$160 per square foot is a reasonable estimate for the replacement value.

The indirect costs associated with delay can be viewed as the product of the delay (hours), the mean vehicle occupancy, and the value of time for the users (dollars/hour). The mean vehicle occupancy and value of time can differ based on local demographics and preferences. The delay is the change in total travel time across the network can be calculated using the following equation:

$$d = \sum_{i=1}^{N}[x_i' t_i'(x_i')] - \sum_{i=1}^{N}[x_i t_i(x_i)] \tag{3.8}$$

where *d* is the delay, *N* is the number of links, x_i is the flow on link *i* before the earthquake, $t_i(x_i)$ is the travel time of the link as a function of the flow before the earthquake, and x_i' and t_i' are post-earthquake flow and travel time, respectively.

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After an earthquake, the demand for travel can also change. As a case in point, the static traffic assignment model used in the Bay area after the 1994 Northridge earthquake overestimated the travel time ten times larger than the travel time obtained from the local traffic reports (Werner et al., 2006). There is a cost associated with the opportunities lost due to the forgone trips. As a lower bound, it can be estimated that the trip would be worth (at the least) the time it would take to travel to the destination. Similarly, if for some reason the travel time decreases after an earthquake, the user gains benefit. The opportunity cost is defined as follows:

$$\phi^p = \sum_i \sum_j \left[\frac{(q_{ij}^p - q_{ij}'^p)(t_{ij}' - t_{ij})}{2} \right] \qquad (3.9)$$

where ϕ^p is the opportunity cost, q_{ij}^p is the number of trips from zone i to zone j before an earthquake, t_{ij} is the travel time between zone i and j before an earthquake and similarly with $q_{ij}^{p\prime}$ and t_{ij}' after an earthquake. As with travel delay, this value can be multiplied by the vehicle occupancy and value of time to get a monetary value. The trip reduction will follow the model used in Shinozuka et al. (2008) where the reduction in trip demand is linked to the reduction of usable floor space in the area.

Unlike direct costs which can be estimated based on the state of the network directly after the earthquake, indirect costs keep piling up day after day until network performance is restored. Because of this, it is important to be able to estimate the time it takes for a bridge to be repaired. In this study, a set of continuous repair curves have been introduced following the HAZUS-MH (2012) strategy. To form these repair curves it is assumed that repair strategies will start right after the earthquake and will increase following a cumulative normal distribution function. The parameters of the normal distribution differ for different damage states indicating the faster repair for minor and

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moderate damage states and more time consuming repair strategies for major and complete damage states (Figure 3.7). To assign a monetary value to the unit time values calculated during this procedure, a probability density function for the value of time for users in the San Francisco Bay area across different income levels proposed by Sall et al. (2009) will be used. Adjusting the value for 2014 dollars, an expected value of $12 an hour can be estimated.

The performance measures mentioned here will be utilized in this and following chapters of this study. This demonstration will show the application of these performance measures to networks of realistic scale, traffic demand and seismic hazard levels and will elevate the topic of resilience beyond a conceptual framework and show the concept of resilience can be used to perform real-world analysis.

3.3. Seismic Risk Analysis

To conduct the seismic risk analyses, the attenuation relationships introduced in section 3.1.2 have been used to estimate level of ground motion intensity measure under each of the scenario earthquakes at the location of the bridges. Figure 3.8 depicts the damage states in network bridges from one of the simulations under the 7.5 magnitude earthquake originated from Site 2 on San Andreas Fault. Considering the high susceptibility of the San Francisco Bay area to liquefaction, the damage states under PGD are controlling in most of the cases. Since Liquefaction results in extensive or complete damage states, the percentage of the failures in these damage states is substantial. Table 3.1 shows the percentages of bridges in each damage state. Most of the damage occurred in the San Francisco and San Mateo County, the two locations closest to the epicenter. Link damage states will be set equal to the highest damage state of the bridges on the link. The

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earthquake is expected to cause very large disruptions to the transportation network. Figure 3.9 shows the link damage states directly after the scenario earthquake depicted in Figure 3.8. As shown, the damage states tend to be higher towards the epicenter of the earthquake. In this scenario, it is especially problematic since the epicenter in proximity of the city of San Francisco which will cause significant travel delays.

The disruption causes network users to change their paths, populating different roads. An example of this shift is seen in Figure 3.10. In this example, the San Mateo Bridge (shown here as the non-operational bridge in the southern part of the bay) is closed. Because of that, there is less activity on either end of the bay, resulting in a shift of demand to other areas. Similarly with the Golden Gate bridge (the non-operational bridge extending north of the city), the bridges nearby to the Golden Gate Bridge experience a substantial increase in traffic. Many of the links in blue experience little change in flow after the earthquake. This is due to fact that the link and surrounding links either didn't have bridges or were far enough from the source that the impact was minimal.

The high potential for structural damage is reflected in large direct damage costs. Figure 3.11 represents the direct losses associated with the scenario earthquakes of all magnitudes in Site 2. It's clear that the direct losses increase with an increase in magnitude of the ground motion at the same site. Figure 3.12 shows the direct losses due to the magnitude of 7.5 across the different sites, highlighting the effect of the location of the source of the ground motion. In this case, the maximum destruction is occurring due to an earthquake in site 4 while the minimum is caused by an earthquake at site 1. This indicates the destructive effects of earthquakes that are originated in proximity of the

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highly populated regions. Comparison of the direct losses over the San Andreas fault shows that they vary based on the location of the rupture and this could be attributed to the fact that some of them are far away from the densely populated regions. On the other hand, the site located on Hayward fault is in the heart of a populated region of the network and as such results in higher losses. For the same magnitudes site 4 on Hayward fault results in losses comparable to that of site 2, the most damaging of the sites located on the San Andreas Fault. Though locations further away from the population zones can also have a strong impact in areas outside the study area.

A study of the simulation results for indirect losses indicates the same trend as those for direct losses. Figure 3.11 shows these results for a range of magnitudes generated in site 2 and for a specific magnitude across the different sites, Figure 3.12. For each of the scenario earthquakes the indirect losses are estimated as a combination of driver's delay and opportunity losses. For very large magnitudes of earthquake (i.e M_w=8.5) there is a diminishing increase in the indirect costs. This may be due to the fact that the network is approaching a state already where many of the vulnerable bridges are already damaged. Also, as the ground motion intensity increases, the number of trips decrease which can offset some of the congestion that would be seen in a more static demand model.

Seismic risk curves for direct damage and daily indirect damage are shown in Figure 3.13. This figure helps put the expected annual cost into perspective; while the very high magnitude earthquakes cause more damage than the lower magnitude earthquakes (in the billions of dollars), they are less likely than the lower magnitude earthquakes. The higher magnitude earthquake are represented in the shallow slopes

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closer to the right side of the figure and the lower magnitude earthquakes have more influence on the left hand side of the figure where the slope is sharper. It is important to note that since the indirect damage is daily, the cost piles up until the network is repaired.

As the network begins to return to normalcy, the daily indirect costs decrease. To simulate the effects of repair progress in the indirect costs endured by the network, the repair curves in Figure 3.7 will be used. For the scenario earthquake generated at site 2 and different magnitudes, Figure 3.14 shows the decrement in the network indirect losses after the earthquake. As shown, scenarios with higher magnitudes, in addition to having higher initial indirect costs, also take longer to return to a state with lower costs. The actual repair time for completely damaged bridges isn't dependent on the magnitude so the final bridges regardless of scenario finishes nearly the same time (assuming every case has a number of bridges in the complete damage state).

Table 3.1: Percentages of bridges in each damage state for one of simulations of the scenario earthquake

Damage State	No damage	Minor	Moderate	Extensive	Complete
Percent of bridges	71.3	6	2.7	5.3	14.7

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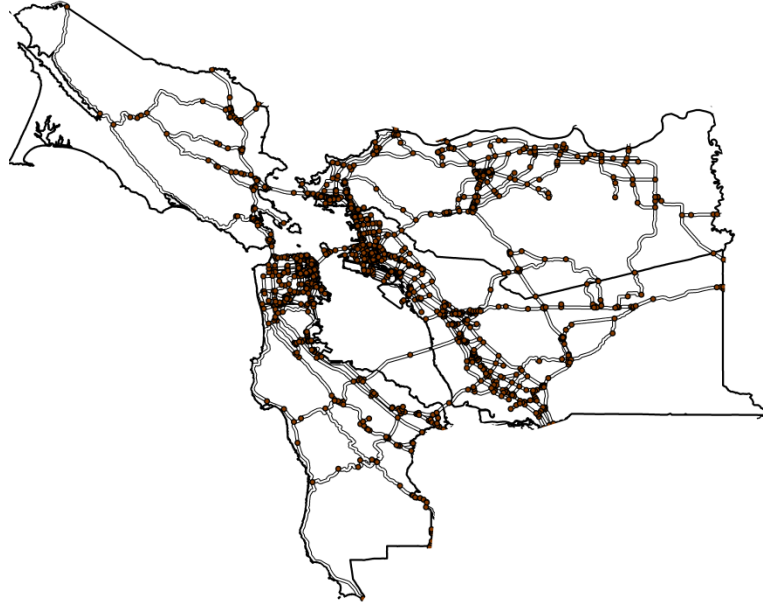
Figure 3.1: Links and nodes representing the highway network of the study area
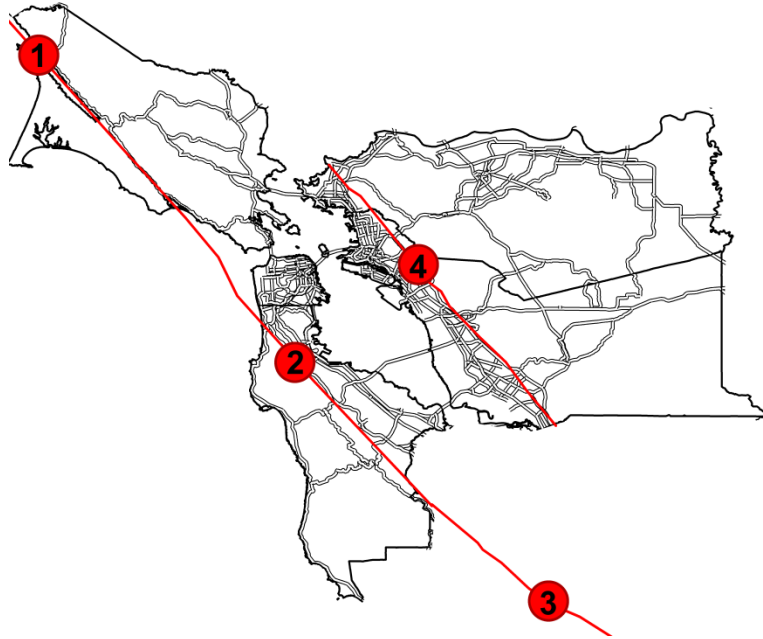
Figure 3.2: Location of four epicenters on San Andreas and Hayward faults

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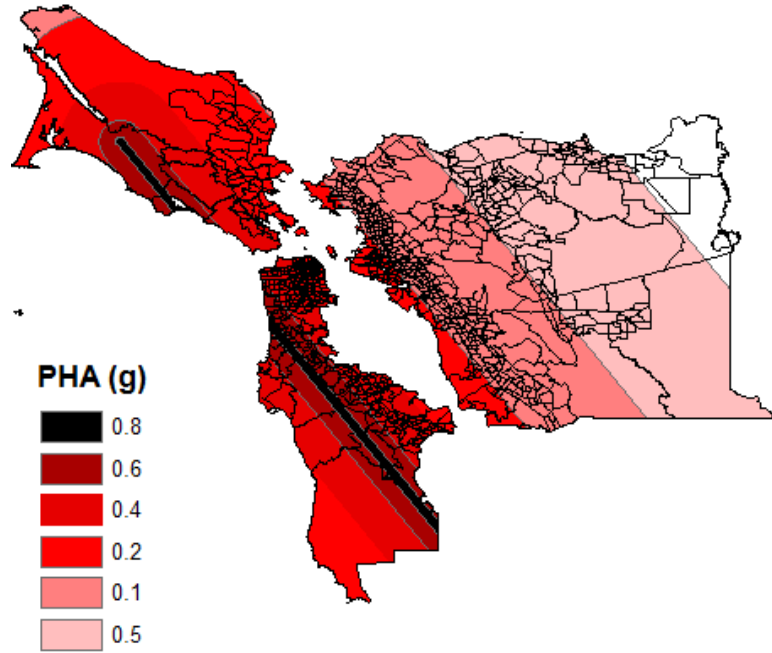
Figure 3.3: Contour of PHA for an earthquake of 7.5 magnitude at Site 2
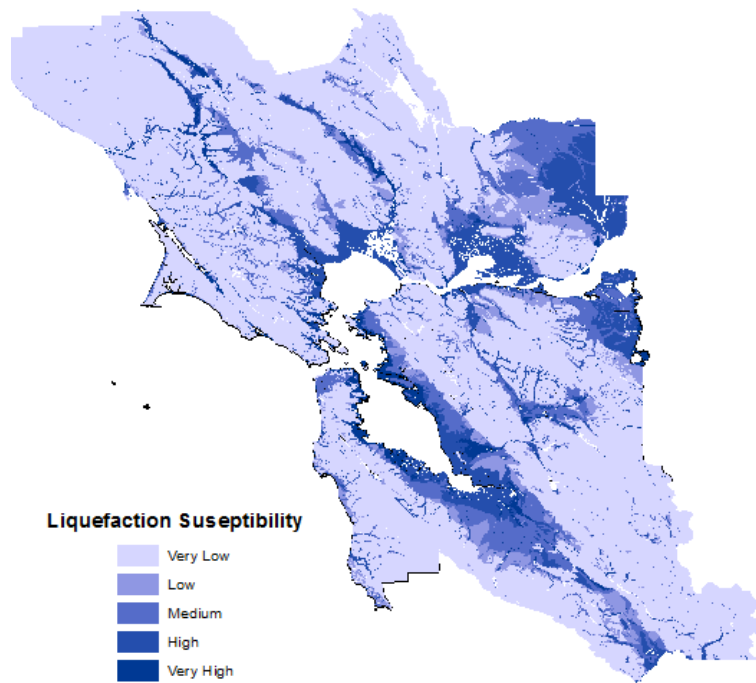
Figure 3.4: Liquefaction susceptibility map of the San Francisco Bay area
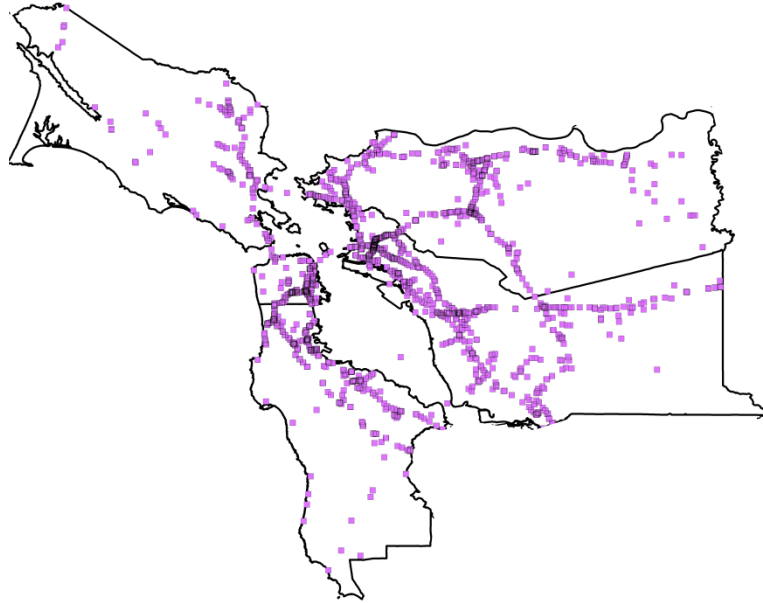
Figure 3.5: Location and distribution of bridges in the study area
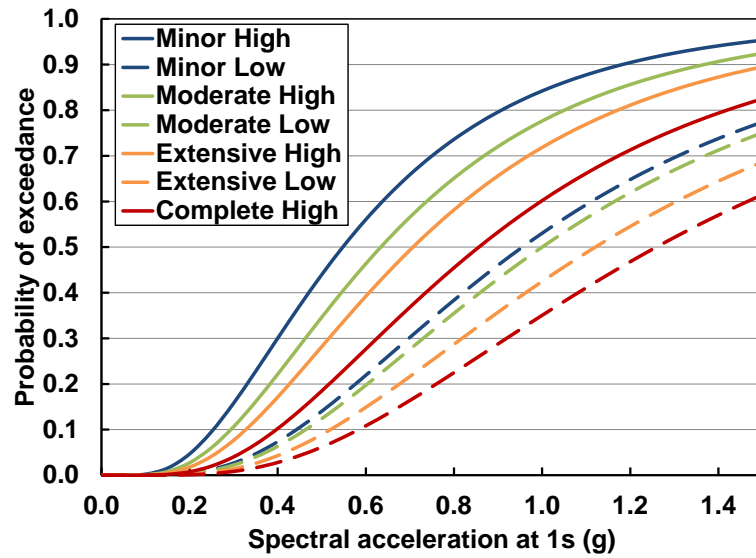
Figure 3.6: Fragility curve envelopes for the 28 category of bridges

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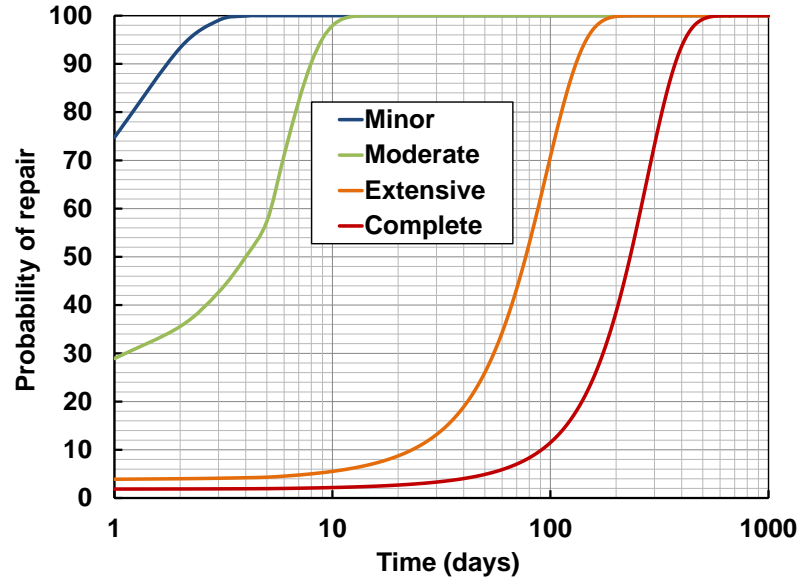
Figure 3.7: HAZUS-MH restoration curves for highway bridges
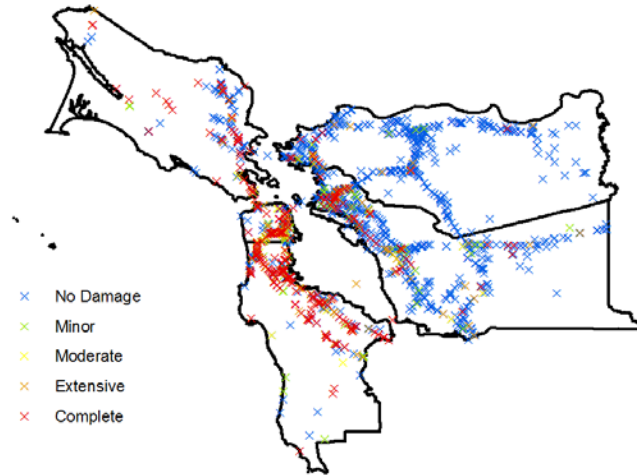
Figure 3.8: A realization of bridge damage states for the scenario earthquake
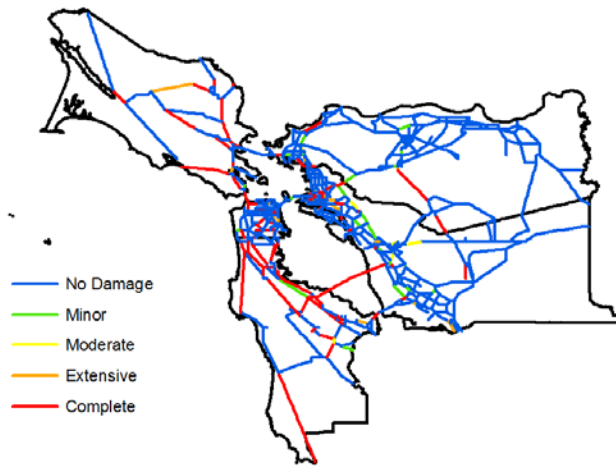
Figure 3.9: A realization of link damage states for the scenario earthquake
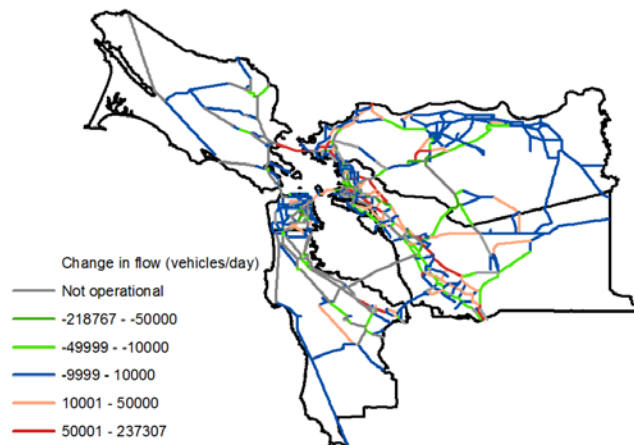
Figure 3.10: A realization of post-event traffic flow for the scenario earthquake

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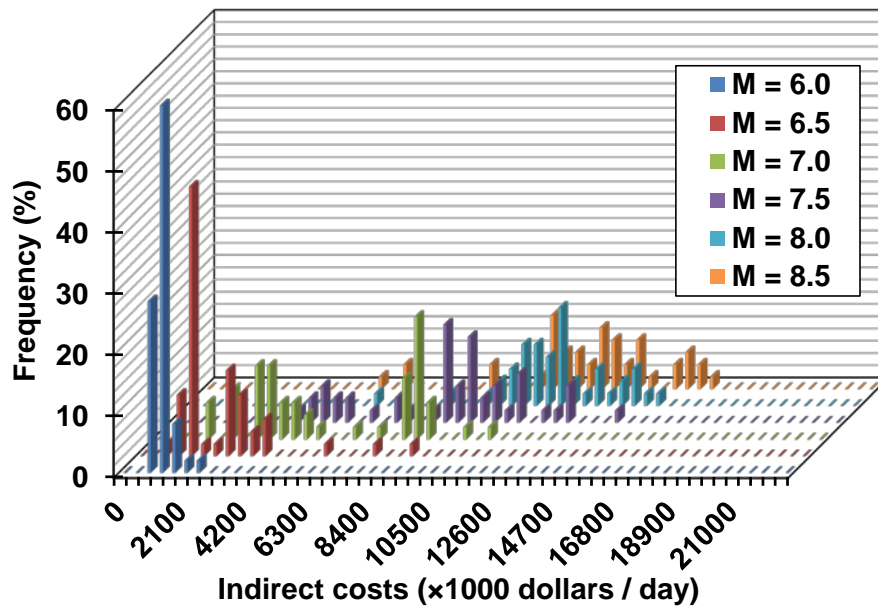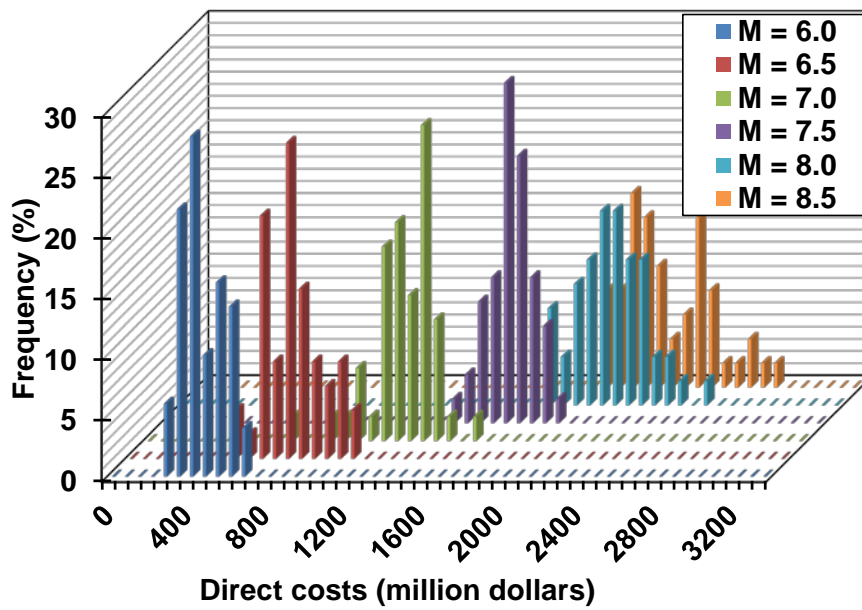
Figure 3.11: Frequency of direct costs (top) and daily indirect costs (bottom) by moment magnitude at site 2
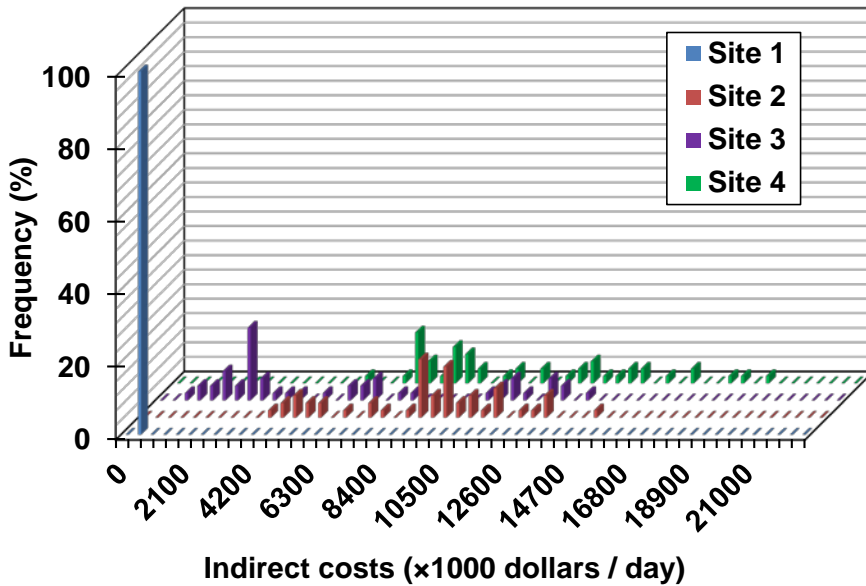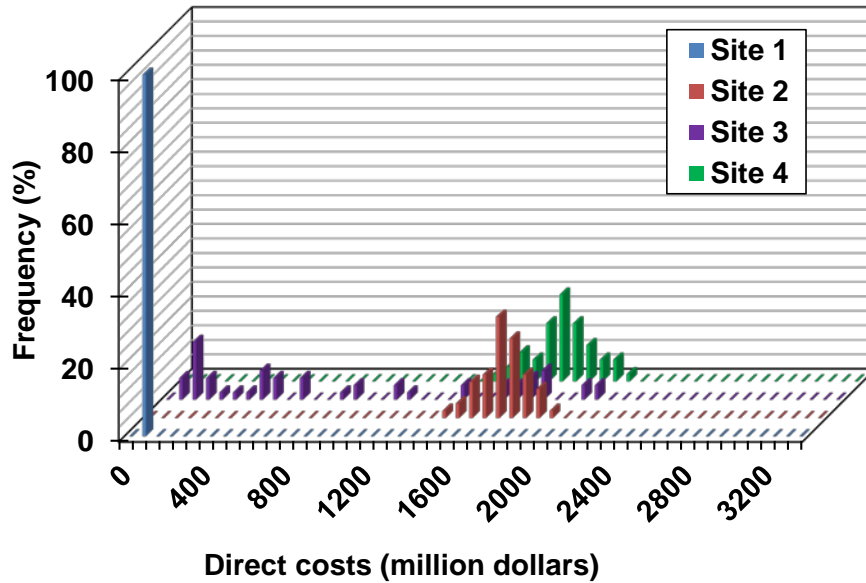
Figure 3.12: Frequency of direct costs (top) and daily indirect costs (bottom) by site location

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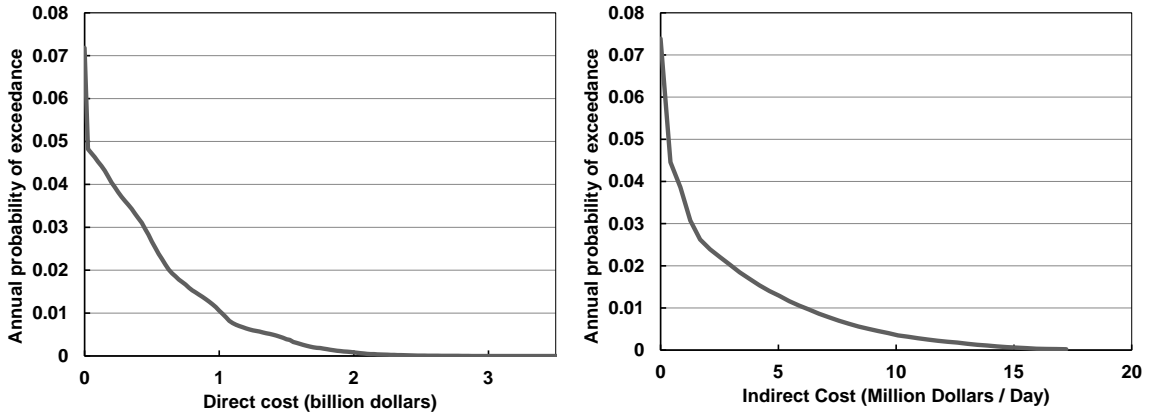
Figure 3.13: Seismic risk curves for the direct (top) and daily indirect costs (bottom)
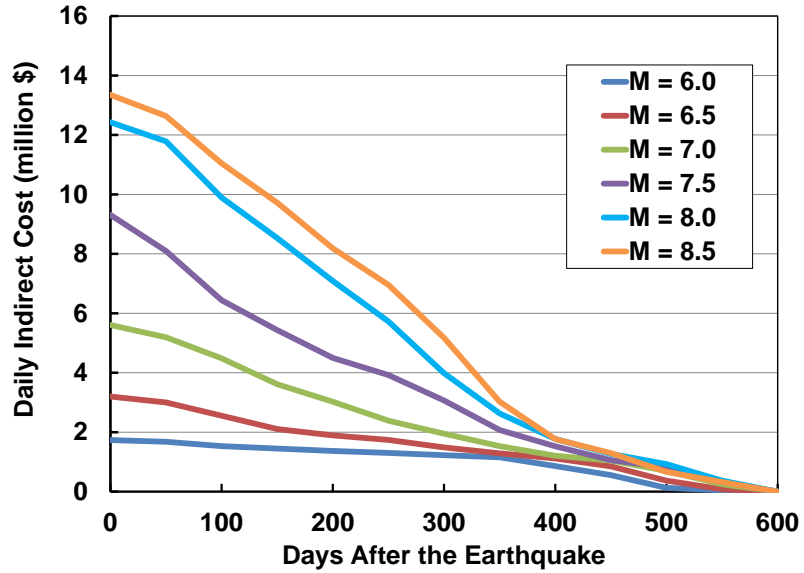
Figure 3.14: Change in indirect costs over time following a scenario earthquake at site 2

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CHAPTER 4

POST-EVENT PERFORMANCE ASSESSMENT

4.1. Seismic Resilience Assessment of Highway Networks

A resilient system is more reliable, faces fewer consequences in face of calamities, and has a faster recovery process. The novelty of the current research is to develop a holistic framework to quantitatively measure different dimensions of seismic resilience in a large transportation network. According to Bruneu et al. (2003) for a system to be resilient, four properties should be provided: robustness, redundancy, resourcefulness, and rapidity. Robustness is an indicator of the level of performance of the system immediately after the earthquake. To define robustness of the systems there is a need to define a suitable system performance metric to evaluate the serviceability of the highway bridge network. As mentioned in Section 3.1.3., the travel time is used as the performance metric for this study. The robustness measure, R^υ, for a transportation network, G, with measure of performance, $\varepsilon(G,d,c)$, the vector of demands, d, the vector of user link functions, c, and the vector of link capacities, u, is defined as the relative performance retained under a given uniform capacity retention ratio, υ, with $\upsilon \in (0, 1]$, so that the new capacities are given by υu. Its mathematical definition is given as follows:

$$R^v(G, c, d, v, u) = 1 - \frac{\epsilon^v}{\epsilon_0} \tag{4.1}$$

Redundancy is a concept which is closely related to robustness. In that way, redundancy can be viewed as a way to describe elements of robustness that don't directly have to do with the vulnerability of the components of the system. In the extreme, a system is completely non-redundant when the failure of a component causes the failure of the entire system (Bertero and Bertero 1999). Redundancy is a complex measure that

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helps quantify the ability of the network to provide alternate routes after a disturbance. In a redundant network, the network will continue to function, although the level of service might be affected due to a decreased capacity of the alternate routes. Redundancy is best defined if aspects of different networks were being compared. Furthermore, redundancy could be categorized as a topological property of the network rather than a flow-based or cost-based indicator. However, it should be noted that even the networks that have same redundancy properties might be different in term of capacity they could handle. Following the network theory the three following indices will be used to measure the connectivity of the network: i) alpha index, α, ii) beta index, β, and iii) gamma index, γ. The alpha index is the ratio of the number of cycles in a network divided by the maximum number of cycles in the network. A cycle is a sequence of links that originate and end at the same node without reusing links. Networks with higher alpha values generally contain more possible paths to take between nodes.

$$\alpha = \frac{u}{2n-5} \qquad , \alpha \in (0, 1] \tag{4.2}$$

The beta index is equal to the number of links in the network divided by the number of nodes in the network. Simple networks have values less than one but more complex networks (such as typical highway networks) should have values greater than one. Networks where every node is connected but only contains one cycle have a value of one.

$$\beta = \frac{l}{n} \tag{4.3}$$

The gamma index measures connectivity by considering the ratio between the number of links and the maximum possible number of links. If every node was directly connected to every other node (without passing through an intermediate node,) the

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gamma index would be equal to one. A value of one is unrealistic but offers an opportunity to compare the current level of connectivity in the network to the theoretical maximum level.

$$\gamma = \frac{l}{3(n-2)} \qquad , \gamma \in (0, 1] \tag{4.4}$$

where n is the number of nodes, l is the number of links (edges), and u is the number of cycles $(l - n + p)$, and p is the number of sub-networks (Rodrigues 2013). With these indices, network owners can compare the level of connectivity in their network to other networks. The indices can also be used in comparing potential additions to the network in terms of their improvement to the networks connectivity.

In this thesis, the most important aspect of resourcefulness is the ability to prioritize goals and to provide additional resources towards goals of particular importance. Specifically, these goals should include the accelerated repair of bridges that have the most impact on the network. The resourcefulness will be relative to a situation where there is no prioritization or additional resources allocated; a situation where every bridge is treated with equal weight and are repaired in the time it would take using conventional repair techniques.

Rapidity is closely related to resourcefulness. Resourcefulness can lead to an increase in network performance partway through the repair process. After the bridges that are being prioritized are repaired, the change in network performance can taper off meaning that, oftentimes, the rapidity as defined in this paper is best suited for situations where the performance criteria establishes an acceptable level of performance that may not necessarily be equal to that of the fully functional state.

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4.2. Robustness and Redundancy

To measure the robustness of the network in terms of direct and indirect costs, the probability distributions of these factors have been generated. The earthquake is expected to result in 1.17 billion dollars in direct costs. Figure 4.1 shows the probability distribution of the direct and indirect costs. Indirect costs were measured against the initial Vehicle Hours of Travel (VHT). For the purpose of the analyses in this study, the performance criteria was set such that the indirect costs directly after the earthquake could not exceed 15% of the initial VHT in the network. The initial VHT was equal to 2.25 million miles per day meaning that an increase of 338,000 hours in cost would cause the network to fail the performance criteria. The mean indirect cost for the earthquake was 760,000 hours daily, a large amount above the criteria. None of the simulations show that, for this scenario, the performance criteria will be met. If a transportation agency had this performance measure, they should consider strengthening the network by measures such as adding more links or retrofitting bridges to decrease vulnerability.

Immediately after the earthquake, there is an average drop in vehicle trips by about 240,000 a day. This drop in trips comes from the expected damage to the floor space of structures in the TAZ affected by the earthquake. Even after the reduction in trips, the average trip length increased significantly. Before the event, the average trip length was equal to about 18.5 minutes. After the earthquake, this value increased to 23.5 minutes, increased by 27.3%. It should be noted that this includes trips whose origins and destinations didn't change after the earthquake. Trips with unchanged trip ends (such as work and school related trips), contributed more to this increase while trips whose ends

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changed after contributed less because these users adapted their trip behavior to suit the change in network performance.

Local agencies may want to consider adding redundancy in order to decrease the effects of the earthquake on the network performance. Values for the connectivity indices that define redundancy are given in Table 4.1. The importance of these indices is more apparent when compared to other networks. For this purpose, the values of connectivity indices from three locations: Los Angeles, CA; Reno, NV; and Boston, MA have been compared to those of the study area. The areas of the networks are clipped such that they are equal in geographic size to the study area and the network data was taken from the NHPN. The highway networks for these cities are shown in Figure 4.2. Los Angeles is similar to San Francisco is some ways; it is a coastal Californian city with high seismic susceptibility. However, Los Angeles is significantly larger in population and the size of the urban area. Reno is less populated and dense then San Francisco and has a simpler highway network. Boston, although located on the opposite side of the country, is similar to San Francisco in population and land area. The connectivity indices for these cities are also in Table 4.1.

As shown, the redundancy of the network is not directly correlated with the complexity of the network. Reno, despite being the simplest network, has similar to values to the San Francisco network. This is because the nodes on the highway network in the Reno network tend to have a higher degree. Boston, despite being a similar city to San Francisco in many respects, has higher connectivity values than San Francisco. This may be intuitive looking at the maps of the two highway networks where Boston looks like a more complicated, interconnected network but the index values confirm this

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mathematically. The Los Angeles network is very densely populated throughout the study area. This plays a part in the need for a complex, deeply connected highway network and it shows in the high index values. Note that these comparisons are made solely on highway links. The bay area is very much dependent on a few bridges that connect highly populated areas. This is one reason why the topology of the network isn't as strong as some of the comparisons. In order to increase the redundancy, more bridges would have to be added across the water. These bridges would be expensive and could be susceptible to earthquake damage themselves so these costs would have to be balanced against the benefit of redundancy.

4.3. Repair Strategies

Repair time itself can be taken into account when considering the cost of repairing a bridge. This is seen in $A + B$ bidding. In this bidding style, bids are awarded to the contractor who can minimize the cost to repair the bridge, A, and minimize the time to repair, B. The total cost of the bridge repair can be seen as $A + B$ multiplied by the daily cost of closure. The competition between contractors to finish early leads to repair times that are shorter than what would be estimated after other bidding processes. The NYSDOT, an early adopter of $A+B$ bidding, started using the process in 1994. The bidding process was to be restricted to critical projects or project phases where traffic inconvenience and delays must be held to a minimum and should not be used as a routine. Under normal circumstances, contractors are expected to work about 40 hours a week. For the projects considered for $A+B$ bidding, the contractor should be allowed to work 60 hours a week with less restrictions on overtime. The NYSDOT found that contractors are bidding at 31% below the engineer's estimated time in $A+B$ contracts. In

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order to make sure that the bridge is repaired in time, incentives and disincentives are placed that reward contractors for finishing ahead of schedule and fine them for finishing behind schedule. Over the course of 133 contracts, the NYSDOT found that 114 earned incentives totaling $57.6 million while securing savings of $305 million in user costs (NYSDOT 1999). In this paper, the *A+B* concept will be further extended by considering the cost of repair and the user costs across an entire network of bridges rather than just individual construction contracts.

Adding incentives increases the possibility of bridges being repaired ahead of the schedule. There have been many documented cases where this has been applied to emergency scenarios. The collision of a barge to bridge pier on I-40 near Webbers Falls, Oklahoma in 2002 resulted in collapse of one of the bridge spans. This bridge was a critical component of the local transportation network and it was imperative that the bridge be restored in a timely manner. For this purpose, the design, demolition and reconstruction phases were all incentivized. The demolition phase was finished by the scheduled time. The design phase was finished 4 days ahead of schedule with a bonus of $5,000 a day. The reconstruction phase was originally expected to take 72 days. Competitive *A+B* bidding helped sign a contract with a 57 day schedule. In addition to these incentives, a $144,000 per day bonus was awarded which lead to the phase completion in 46 days instead. The entire project was finished in 64 days after the collapse, a record for a project of this type (Bai et al. 2006). Table 4.2 demonstrates the details related to different phases of the project and the cost and benefits associated with incentivizing activities.

One of the examples of incentivizing the repair phases was after the 1994 Northridge earthquake when many key components of the transportation network were damaged. For instance, a segment of I-10 was heavily incentivized with an incentive/disincentive of $200,000 for each day deviated from schedule (approximately $315,000 in 2014 dollars adjusted for inflation). This project involved the simultaneous construction of two bridges with work running 24-hours a day, 7 days a week. 228 carpenters and 134 iron workers were assigned to the project which is a large increase from the 65 and 15 respectively for a normal project. As shown in

Table 4.3 , there is a correlation between the incentives and the time percent decrease in repair time (US DOT 2002). In addition to incentivizing the repair process, the recently developed construction techniques could be used to reduce the repair time over conventional construction techniques. One such technique is the accelerated bridge construction (ABC). Under ABC, sections of the bridge are constructed and assembled off-site and then put in place afterwards. This technique has been used extensively in recent years for the construction of new bridges but it can also be used in emergency replacement. Benefits of this technique include a much shorter construction time even with the inclusion of the off-site construction but it can cost more than conventional construction. It is estimated that the direct cost of ABC is about 30% higher than conventional construction (California Department of Transportation 2008). Also, not all bridges are candidates for ABC replacement. In general, simpler bridges are better candidates for this technique.

Combining incentivizing and ABC has been shown to have impressive results. In 2007, a fuel tanker traveling in Oakland, California tipped over and caused an explosion

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which damaged the I-580/990 connector. Two spans were destroyed. The indirect losses of this segment were estimated to tally $6 million a day for the busy San Francisco bay area. Using the ABC techniques and a $200,000 daily incentive resulted in the completion of the project in only 20 days after the accident (California Department of Transportation 2008).

Other techniques have been utilized such as modular bridging which can provide temporary bridges while the original bridge is repaired. The concept from a cost standpoint is similar; an extra direct cost is incurred but there should be a reduction in the indirect cost. In this thesis, the application of the *A+B* and ABC techniques in the rapidity of repairs after earthquakes will be presented considering a decrease in the mean repair time of bridges and an increase in the direct cost of the bridges. Because of the complex interaction between bridges in a network where multiple bridges fail simultaneously, it would be an over simplification to apply an indirect cost per day to each bridge and instead the total indirect cost summed across the entire network will be the focus in this thesis.

4.4. Resourcefulness and Rapidity

To simulate the impact of resourcefulness, three different repair techniques will be tested: i) conventional repair ii) incentivized repair and iii) accelerated construction techniques. Considering the importance of the allocation of resources and the repair strategies, it is required to identify the links that mostly impact the performance metrics of the system. For this purpose, the concept of the betweenness centrality from network theory will be used to rank the most important components of the system. The

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betweenness centrality of a link, *l*, is defined as the number of shortest paths between pair of nodes that pass through a specific link, given by this equation:

$$BC_l = \sum_{i \neq j \neq l} SP_{ij}(l)/SP_{ij} \tag{4.5}$$

where $SP(l)$ is the number of shortest paths between nodes *i* and *j* that pass through *l* and SP is the total number of shortest paths. After each link is ranked, the links with the highest rank will have the additional resources allocated to the bridges on the link. From there, the next highest link is evaluated and the process is repeated until the additional resources are dispensed.

The benefit of resourcefulness is shown in Figures 4.3-4.8. Accelerating the repair of important bridges helps decrease the indirect costs for the users on the network over the baseline case where no accelerations are committed. In order for the accelerations to be worth the investment, the decrease in indirect cost should exceed the additional costs for repair. The decrease in indirect costs is measured as the area between the non-accelerated curve and the curves for other repair scenarios in Figure 4.3. Each curve has been averaged from 100 simulations for each scenario. Data is taken in time steps of 50 days. As shown, there is a reduction in indirect costs with the increase in the number of bridges accelerated and the scenarios with accelerated construction techniques showed an improvement over scenarios with incentivization alone. In every scenario, there is a large decrease in daily cost in the 50 to 100 day time step. This is due to the fact that this is when the majority of the extensively damaged bridges become repaired. In the more accelerated scenarios, the decrease starts earlier and is more pronounced. This is due to the repair time of accelerated extensive and complete damaged bridges being completed during the first 100 days. The scenarios with accelerated construction techniques presents

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an earlier drop than those with incentives only, this is because the accelerated construction techniques have completed quicker. Eventually, the indirect costs per day converge as the last few bridges are repaired. At this point, even though there aren't many bridges remaining, the impact of the damaged bridges is still substantial.

The indirect costs decrease as the physical state of the bridges improves. Figure 4.4 shows the number of bridges at each damage state throughout the repair process. As shown, there are a large number of bridges in the more severe damage states that remain to be repaired even after the less severe bridges are repaired. This is unfortunate as the higher damage states also affect the network performance more than the lower damage states because the more damaged bridges carry less (if any) capacity. Also shown are repair curves with resourceful prioritization for extensive and complete damage state. Similar curves for minor and moderate damage states are coincident with the non-resourceful curves as these damage states are less likely to be prioritized for repair in this scenario. Comparing this figure with Figure 4.3, it can be seen that a period of rapid repair results in a sharp decrease in the indirect costs namely in the 0 to 100 day range. Also shown in a fairly constant rate of repair between the 100 to 350 day range after which the repairs taper off.

For rapidity, let the performance measure be the time it would take to return to 95% of the original performance where the loss of performance is the ratio of the delay to the total VHT. Local agencies will have to be able to set different measures based on the standards they hold. A more resourceful network may meet rapidity goals sooner as shown in Figure 4.5. The expected amount of time it would take to meet the performance measure is less than 200 days for the quickest repair scenario. For comparisons sake,

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without the additional resources, it would take 350 days to meet the criteria. However, if the performance measure was set to a complete restoration of performance, the resourcefulness would not significantly contribute to rapidity.

The total cost accumulated piles up quickly early on in the repair stages and tapers off as the network achieves better performance. Indirect costs accumulate quickly early on in the repair stages and slows down when more bridges are repaired and stops accumulating when the network reaches its pre-earthquake state. The indirect costs end up being the dominant cost after accumulation of all other costs. The additional repair costs and incentives are small in comparison to the indirect costs. This shows that, if even a fairly small percentage of the indirect cost is deterred, the additional repair and incentives will be worth it. As the number of bridges accelerated increases, the indirect cost decreases and the incentives and additional direct costs increase. Even then, the indirect cost still dominates and the additional costs are small in comparison.

Figure 4.6 depicts the costs associated with different rapid repair techniques over time. With incentivization alone, the direct costs are equal early on. After the incentivized bridges are completely repaired, the baseline scenario and the incentivized scenarios deviate in favor of the incentivized scenarios showing that the offset of indirect costs outweigh the incentivization costs. Similar behavior is seen in the ABC with incentivization with the exception of the increased direct costs early on due to the increased construction costs associated with the ABC.

Table 4.4 shows the change in total costs using incentivization alone and ABC with incentivization over the baseline cost. As shown, both techniques offer improvements over baseline scenario. While there is a continual decrease in the costs as

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more bridge repairs are accelerated, there is a decrease in efficiency. For example, there is a decrease in cost of over 14% after 10% of the bridges are incentivized. To decrease the cost by an additional 5%, another 20% of the severely damaged bridges must be accelerated. This shows the importance of being resourceful enough to at least accelerate the repair on the most important links. This can include making a list of contractors for invitational bidding and providing the resources needed for ABC among other means of preparation. In this study, there is an improvement with each of the acceleration regimes but it this can be different depending on the study area. These characteristics may include the costs of the bridges damaged, the redundancy of the network (availability of detours with similar costs) and the travel behavior and volume of the users on the network.

Next is the comparison between a prioritized and the non-prioritized repair processes. Figure 4.7 demonstrates this for the 10% incentivized scenario as an example. In this case, even without targeted prioritization, there is still a benefit from improving the network. However, the benefit is significantly less than in the prioritized scenario. The difference between the two prioritization scenarios is about $390 million dollars; a cost that can be easily avoided by determining the importance of the links before the seismic event.

Table 4.1: Connectivity indices for the highway networks of San Francisco, Los Angeles, Reno and Boston

	San Francisco	Los Angeles	Reno	Boston
α	0.269	0.373	0.272	0.303
β	1.536	1.745	1.526	1.605
γ	0.513	0.582	0.523	0.536
N	707	2264	76	1015
L	1086	3950	116	1629

Table 4.2: Oklahoma I-40 Bridge repair acceleration using ABC techniques

Project	Reconstruction	Demolition	Design	Total
Scheduled completion time	72 days expected, 57 days as bid	16 days	16 days	89-104 days
Completion time	46 days	16 days	12 days	64 days
Decreased Time (%)	19.3 over bid	0	25%	28.1 to 38.4
Bonus/day	$144,000	$50,000	$5,000	-
Total Bonus (est.)	$1,488,000	$0	$20,000	$1,508,000
Cost of project (no bonus)	$10,900,000	$850,000	$137,000	$11,887,000
Bonus / Cost of project	13.65%	0.00%	14.60%	12.69%

Table 4.3: Example of bridge repair acceleration after the Northridge earthquake using incentives

Project	I-10	SR-14/I-5	I-5 Gavin	SR-118
Scheduled completion time	158 days	207 days	154 days	124 days
Completion time	84 days	172 days	121 days	116 days
Decreased Time (%)	46.8	16.9	21.9	7.3
Bonus/day	$200,000	$100,000	$150,000	$50,000
Total Bonus (est.)	$14,800,000	$3,500,000	$4,950,000	$400,000

Table 4.4: Improvement over baseline for total costs at the end of the repair process

Repair Strategy	Improvement	
	Percent	**Million dollars**
Incentive (5%)	11.5	393
Incentive (10%)	14.10	481
Incentive (30%)	19.10	652
ABC+ Incentive (5%)	15.90	542
ABC+ Incentive (10%)	19.20	655
ABC+ Incentive (30%)	26.90	917
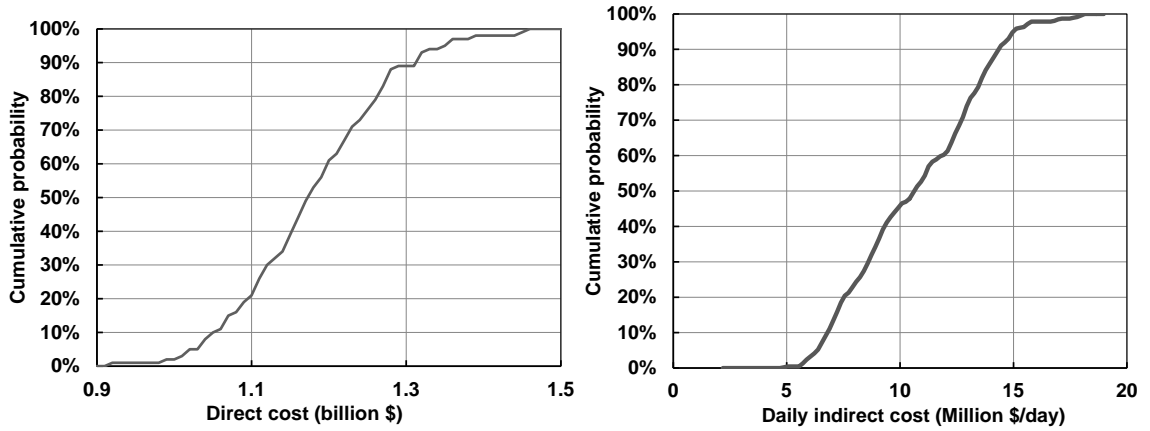
Figure 4.1: Cumulative probabilities for direct (left) and indirect cost (right)
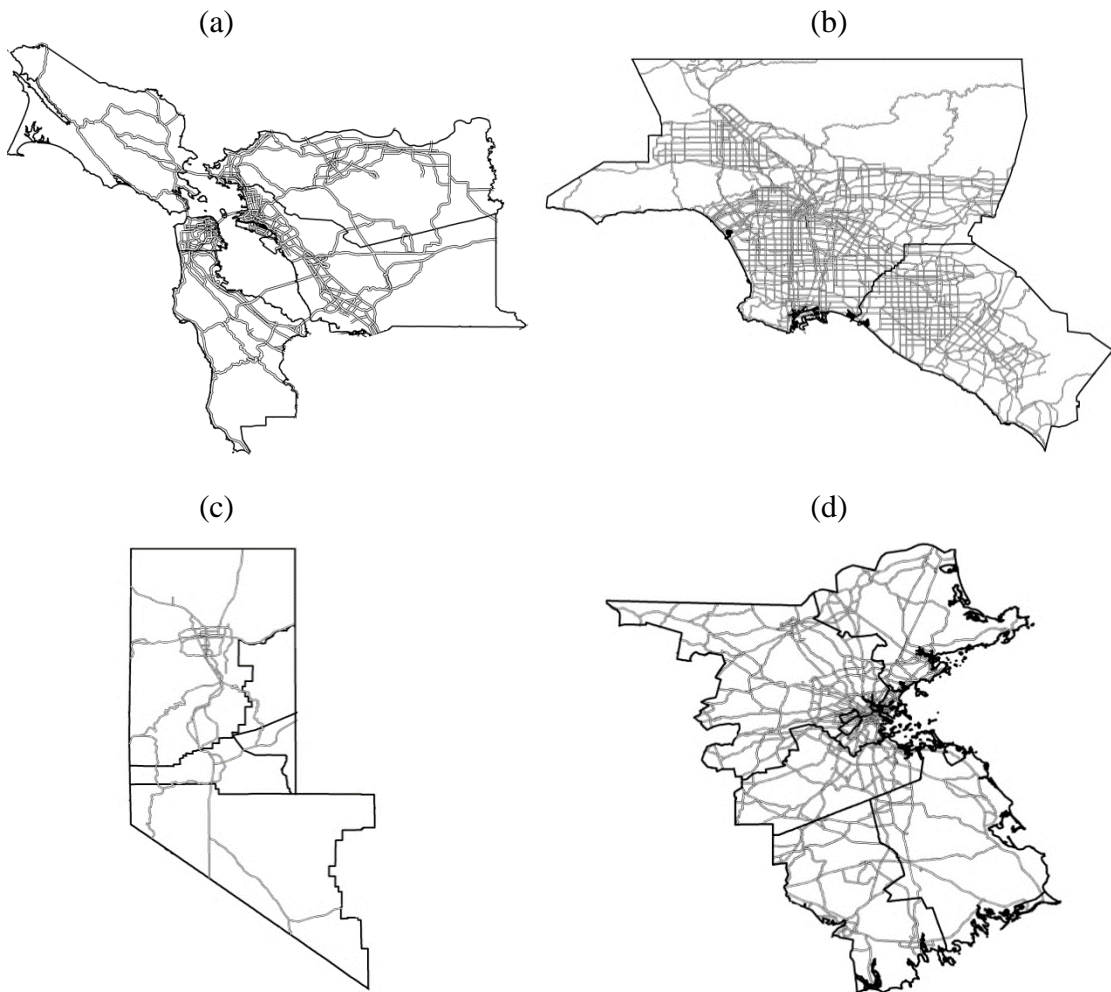
Figure 4.2: Highway networks for (a) San Francisco, (b) Los Angeles, (c) Reno, and (d) Boston

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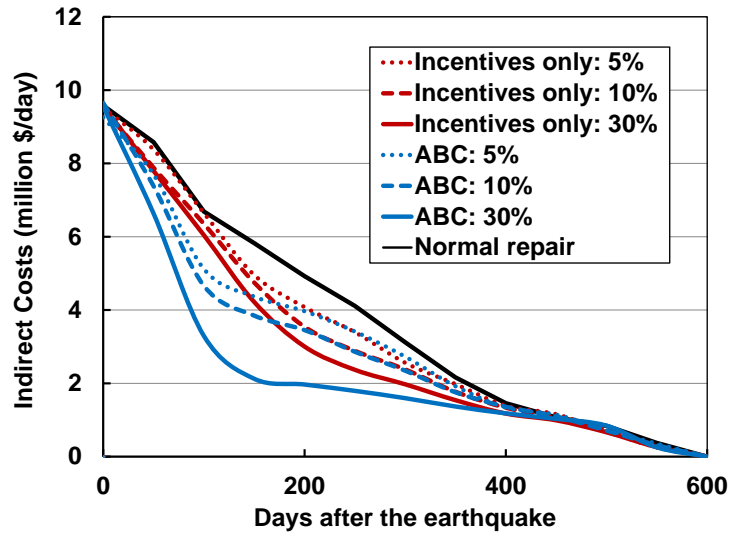
Figure 4.3: Effect of different repair strategies on traffic delay after the earthquake
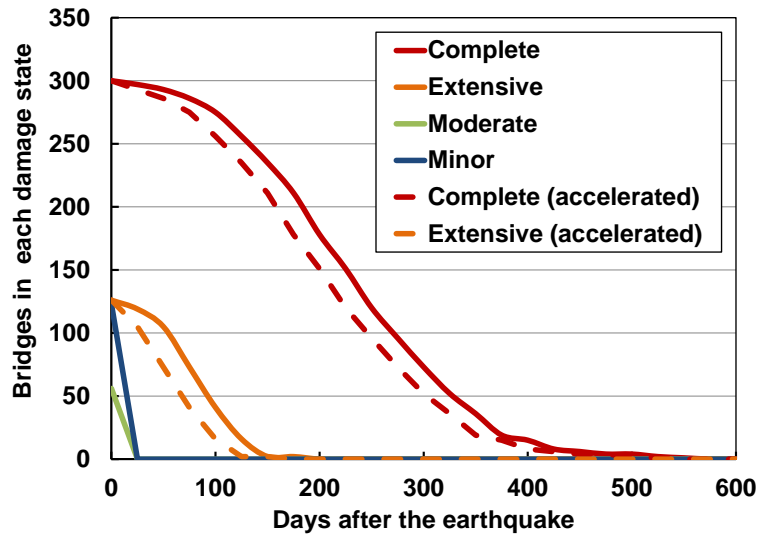
Figure 4.4: Number of bridges in each damage state throughout repair

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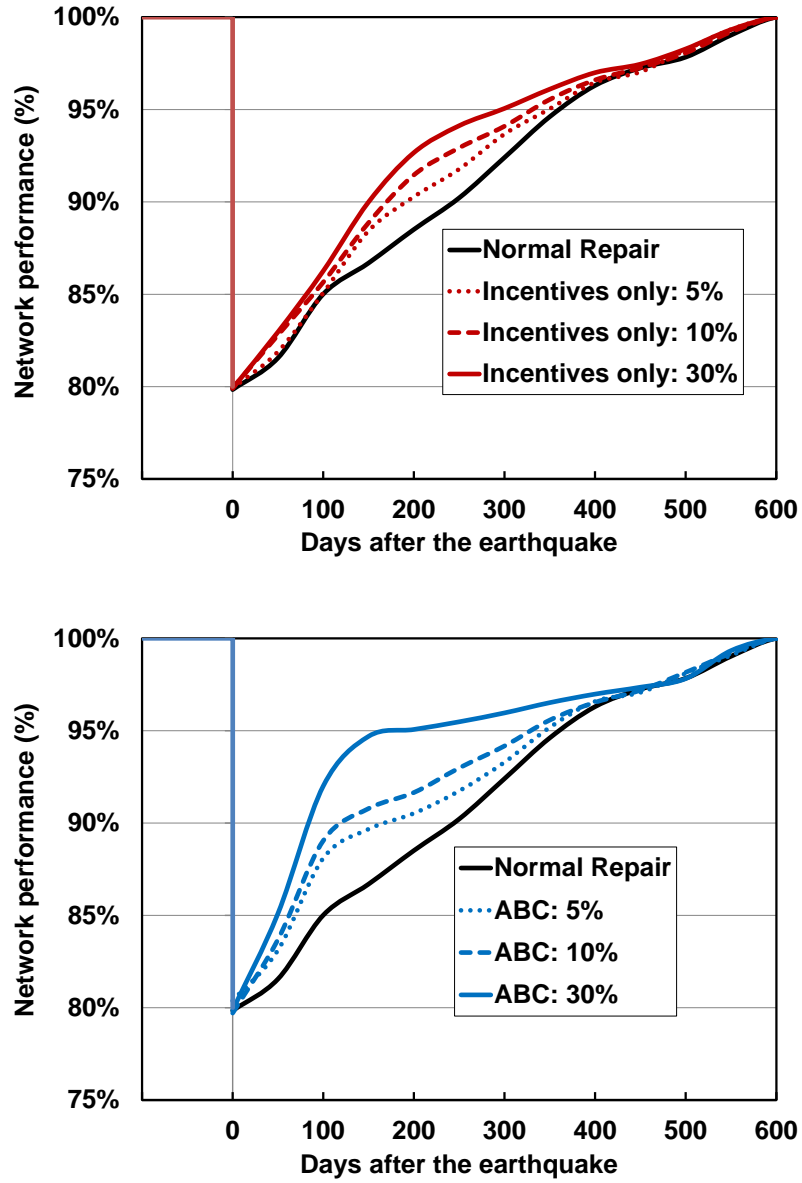
Figure 4.5: Performance curve for network delay with incentivization (top) and with incentivization and accelerated bridge construction technique (bottom)
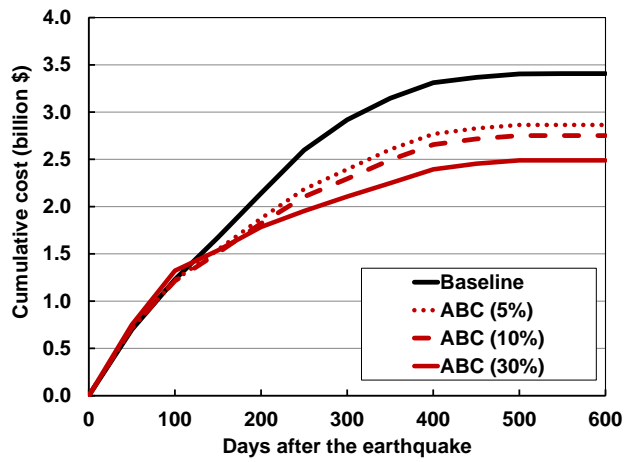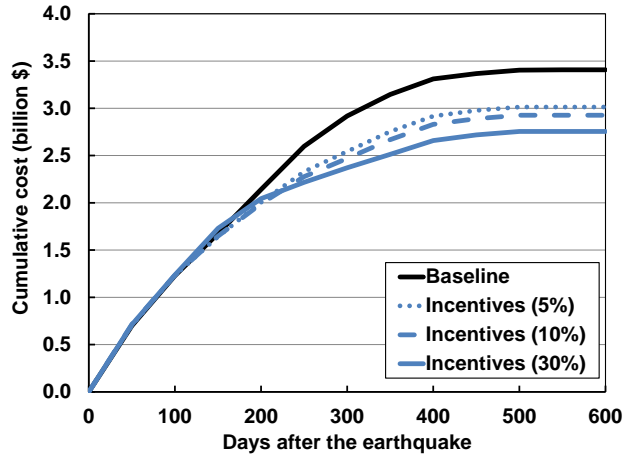
Figure 4.6: Total cost including incentivizing (left) and combination of incentivizing and ABC technique (right)
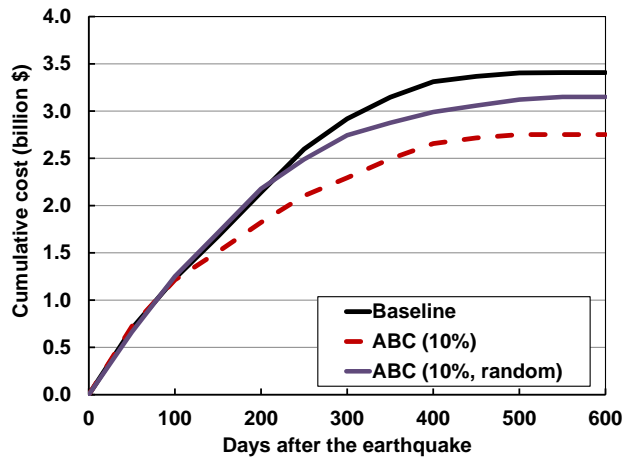
Figure 4.7: Comparison between repair processes with and without prioritization techniques

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CHAPTER 5

PRE-EVENT DAMAGE MITIGATION

5.1. Introduction

Much of the discussion thus far in the thesis as it pertains to resilience has been focused on the post-earthquake behavior of network but decision can be made prior to the event to bolster resilience as well. Retrofitting bridges is an effective way to lessen the initial impact of earthquakes and thus increases the robustness of the network. In 1971, the San Fernando earthquake struck the greater Los Angeles area causing extensive damage throughout the region. The general unpreparedness served as a wakeup call to engineers which lead to an increased awareness of the importance of proactive measures to reduce earthquake damage. Since then, seismic design became a crucial part of the bridge design process. Bridges were designed to be more ductile as to avoid sudden, catastrophic failure (Rafik and Liao 2003). However, the bridges built prior to 1971 are still key components of modern highway networks. Also, even when designed with seismic concerns in mind, bridges deteriorate over time and need to be brought up to par with seismic demand. It is for this reason that bridges that are vulnerable to seismic hazards are retrofit. Bridge retrofitting can extend the lifespan of bridges and in many instances do so in a cost-effective manner. Retrofit costs, while sometimes considerable, are oftentimes small compared the large-scale repair of a damaged bridge or the cost of a complete replacement of a bridge that is beyond repair. However, if the bridge is rarely or never subject to enough seismic demand to damage it, the retrofit is for naught.

After each major earthquake, the awareness of the need for retrofitting and better seismic design increases dramatically. California, being especially susceptible to

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earthquakes, has been acutely aware of the need for retrofit. Earthquakes serve as a learning experience as retrofitting methods and seismic design considerations thought to be adequate before the earthquake are shown to be faulty. Shortly thereafter, new, hopefully more effective methods are developed based on the data from previous earthquakes. Methods supported by Caltrans include seat extensions, cable restrainers, column jacketing, shear keys and additional piles among other methods (Roberts 2005).

Seismic retrofit practices differ across different geographical regions. Different regions are subject to different levels of seismic hazard and some areas are more affected by liquefaction and landslides than others. In the central and southeastern United States, bridges are threatened by earthquakes especially in the New Madrid Seismic Zone. Over 100,000 bridges existing in the states near the New Madrid Seismic Zone many of which are in danger should a major earthquake strike the area. Many of the bridges were constructed without seismic concerns in mind which further puts the area at risk to suffer extreme possible losses. There are five primary retrofit measures employed in the area: seismic isolation, longitudinal and transverse restrainers, seat extenders, column strengthening and bent cap strengthening (Wright et al. 2011).

The Pacific Northwest is another part of United States that is highly susceptible to earthquakes. There have been at least 20 damaging earthquakes in the past 125 years in Washington including the 6.8 M_w Nisqually earthquake which struck Northeast of the capital city Olympia, Washington in 2001. Oregon and Washington have made efforts to ensure the ability to protect bridges against these events. Like California, despite being in an area of high seismic hazard, there are many bridges still in operation from a time of more lax seismic design so the need to retrofit bridges is critical. Some retrofitting

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techniques used include restrainer bars and cables, replacement or modification of vulnerable bearing types and column jackets (steel usually but composite materials have been used in the past) (Fridley 2007).

5.2. Retrofit Methods

There are a range of retrofit methods that are employed by different agencies. Different retrofit methods benefit bridge strength in various ways from increasing the flexural capacity of specific bridge components to preventing the unseating of bridge spans. Below is an overview of some of the more common retrofit methods.

Seismic isolation increases in the fundamental period of vibration of the bridge which in turn can reduce the accelerations in the superstructure and decrease the inertia forces transmitted into the substructure. A consequence of this is that the relative displacement of the superstructure and the substructure increase but this displacement is designed to stay within acceptable levels. Isolation bearings are installed that remain stiff under normal conditions but will dissipate energy under earthquake loadings. Common types of bearings including elastomeric bearings where a (typically) lead filled bearing is utilized whose lead core deforms under extreme loading and friction based bearings where, after a friction coefficient is exceeded, slippage occurs and energy is dissipated by the friction caused by this slippage (FHWA 2006).

Restrainer cables and bars were among the first type of retrofit strategies used in California after the 1971 San Fernando earthquake. Restrainer bars and cables serve as a low cost means to prevent the loss of support between the superstructure and the bearing seats. Restrainer cables and bars are designed to stay in the elastic range under stress and usually only carry tension forces (Roberts 1971). Either bars or cables can be used but

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cables are more common for a variety of reasons. Cables are able to be used in shorter lengths which can often give cables an economic advantage over bars. Cables are also able to accommodate transverse and vertical movements while bars might require additional vertical and transverse restraint. While restrainer cables and bars have been effective in many situations, they have failed in larger earthquakes. This was demonstrated in recent times during earthquakes such as the 1989 Loma Prieta earthquake in California and the 1995 Kobe earthquake in Japan. Restrainer cables and bars are often used in conjunction with other retrofitting methods (Shafieezadeh et al. 2009).

Seat extenders widen bent caps and abutments and help prevent unseating of bridge spans. Seat extenders are additions of concrete or steel to the sides of bent caps and abutments that are flush with the top of these components. During an earthquake, this extra space will allow for more movement of bridge spans without unseating. For bridges at risk of unseating, seat extenders have been shown to be very cost effective as they are among the cheapest retrofit to prevent unseating. Catcher blocks are similar to seat extenders in many ways. These blocks are attached to the top of abutments or bents and "catch" the girders should the bearings fail. Catcher blocks are used in place of seat extenders with high bearings. The reason catcher blocks are used is that there may not be sufficient space in high bearing bridges to attach seat extenders (FHWA 2006).

Column jacketing is another form of retrofitting used often. In reinforced concrete columns, it is common that, when subject to earthquakes, the vertical reinforcement bows out reducing the strength of the column and possibly leading to the collapse of the bridge. This is due to inadequate strength in the hoops in the column. Column jacketing seeks to

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make up for this but enveloping the column in a material that will help prevent the column from bursting. Jacketing can be made from a variety of materials from steel to concrete to FRP. Steel is the preferred material by some agencies including Caltrans. In steel jacketing, two shells are wrapped around the column and welding along the vertical seam between them. The plates are usually given a small clearance between themselves and the column of 0.5 to 1 inch and this space is then filled with grout. The plates themselves are between 0.375 and 1 inch thick. Both circular and rectangular columns can be retrofitting with jacketing but rectangular columns benefit more from oval or circular shaped jacket than it would a rectangular one. Jacketing can be used for the entire height of the column or just a portion. In either case, space is left at the top and bottom of the column where there is no jacketing as to make sure the jacketing doesn't provide strength in the axial direction (FHWA 2006).

The main function of bent caps are to transfer loads from the bearings of the bridge down to the columns but during an earthquake, the shear strength and flexural capacity of the caps are tested in ways that aren't seen under normal service conditions. For this reason, bent caps are sometimes considered for retrofit. One common way to retrofit the caps is to add steel rods to increase compressive strength. To do this, posttensioned rods are added along the outside of the cap running lengthwise or prestressed rods are added through the bent cap itself. Another retrofit method is to add steel plates along the top and bottom of the bent cap. These two plates are attached by steel rods. This serves to brace the bent cap against shear forces. Yet another method is to encase the entire bent cap in concrete or steel which will increase flexural and shear strength (Wright et al. 2011).

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Shear keys are useful when trying to prevent excessive movement in the transverse direction. Shear keys are simply blocks that are placed between girders that serve to provide lateral restraint in the event that the superstructure sways during an earthquake. Typically, shear keys are made of reinforced concrete and are attached to the top of bent cables with dowels. Similar in purpose to shear keys are keeper brackets. Keeper brackets are steel brackets that are attached to the top of the bent cap and both side of bridge girders. As with the shear keys, keeper brackets allows a transfer of lateral force from the superstructure to the substructure (Wright et al 2011).

5.3. Retrofitting Standards

The FHWA's *Seismic Retrofitting Manual for Highway Structures* and its predeceasing documents serve as guidelines for many transportation agencies on how to design bridge retrofits and how to select bridges for retrofit. Specific types of bridges may have their own manual as well such as the *Seismic Retrofitting Guidelines for Complex Steel Truss Highway Bridges* which itself is largely based on the previously mentioned manual. These manuals serve as a useful tools to help design bridges and select bridges to retrofit but, especially on selecting bridges, are simplified and don't take into account the complexities that arise when considering entire networks of bridges.

The *Seismic Retrofitting Manual for Highway Structures* employed a rating system that assign a number to each bridge based on its likelihood to benefit substantially from retrofitting and using these ratings, transportation agencies and other bridge owners can determine the order of the bridges that need to be retrofit. A bridge's importance is based on a classification labeled "essential". As essential bridge is one has one or more of the following characteristics: the bridge is required for secondary life safety (necessary

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for emergency vehicles or carries an important lifeline such as water for example); the bridges loss would create major economic impact; the bridge is defined as critical by a local emergency plan; The bridge is critical to defense and security. The manual then recommends if the bridge should be retrofit or not based on an acceptable level of performance the bridge should meet given the importance of the bridge, the lifespan of the bridge and the hazard level of the bridge site.

The Indices Method can be used to rank bridges by giving them a rank. The bridges rank, R is the product of a vulnerability rating, V, and the seismic hazard rating, E. Both V and E rank from 1 through 10 meaning R ranks from 0 through 100. The vulnerability rating V is the maximum of two other rankings V_1 and V_2 where V_1 is calculated based on the vulnerability of the connections, bearings and seat widths and V_2 is a rating based on the vulnerability of the columns, abutments, and the vulnerability to liquefaction. A flow chart used to find these values can be found in Figure 5.1.

Another method in the manual is Expected Cost Method. This method is very much similar to how direct costs were calculated earlier in this study in that the expected level of damage is found for each bridge and the cost for each bridge will be the level of damage multiplied by both a repair cost ratio and a total replacement cost. The problem with the method as presented in the manual is that it is largely incomplete. The manual mentions that indirect costs should be considered but says that "quantifying these costs is extremely difficult and cannot be done without considering each bridge in its functional and societal context. Risk assessment models of complete highway systems are under development for this and other purposes, and are a promising tool for developing insight into the complex relationships that govern indirect costs." Also mentioned is the need to

consider the redundancy of the bridge in the network but the description is very much vague and leaves the level of redundancy and the effect of redundancy as a matter of judgment. The redundancy is largely a matter of availability of local detours but doesn't give any quantifiable method to determine redundancy and doesn't consider many of the complexities that come up when dealing with larger networks.

The last method mentioned is the Seismic Risk Assessment Method which involves using fragility functions to perform explicit analysis of highway networks and considers traffic flow and other considerations. Unfortunately, how exactly to use this method isn't explained as it seems more of a class of methods than one particular method itself. This method would be the most complex and the most complete.

If the benefit of retrofitting could be translated into changes in fragility curves, it would make the analysis of post-earthquake bridge networks much easier. Fragility curves, as mentioned earlier simplify bridge characteristics in a way that gives the probability of failure as a simple function of ground motion and bridge type. However, the fragility is still based on a more complex analysis bridges that considers the failure of individual components of the bridge. The benefit of retrofit is also complex as different retrofit techniques prevent different types of damage to specific bridge components. Because of this, simplifying the effect of retrofit can be a difficult task. Nonetheless, it has been attempted by various researchers. Some examples of such attempts are as follows.

Agrawal et al. (2012) looked at the retrofit of multi-span continuous steel bridges in New York. This study created a model bridge and compared the damage before and after a range of ground motion was applied to the bridge. The bridge itself was a three

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span bridge with outer spans of 30m and with the inner span crossing 36m. The bridge features 6 steel girders supporting a concrete slab. The retrofit schemes tested were elastomeric bearings, lead-rubber bearings, viscous damping and jacketing with carbon fiber reinforcement. Elastomeric bearings and lead-rubber bearings were tested individually and with a range of dampening applied. The effects of these retrofits were quite significant. The median PGA for each damage state for the retrofit schemes can be found in Table 5.1. It was also shown that the risk of rupture in the piers after applying the jacketing was very small showing that this type of retrofit can prevent one of the most catastrophic modes of failure.

Billah et al. (2012) compared the effects of different jacketing on the fragility of multicolumn bridge bents. The types of jackets include steel, concrete, engineered cementitious composite (ECC) and carbon-fiber reinforced polymer. This study used 40 ground motion excitations with 20 being near-fault and 20 being far-field. In this case, near-fault means that the site-to-source distance is less than 10 miles and far-field is the opposite of near-fault. Nonlinear time-history analysis was performed on a bridge and the retrofit schemes were compared. In this study, it was found that ECC and the carbon fiber reinforced jackets were most effective.

Kim and Shinozuka (2003) used two different example bridge types and subjected them to a large range of ground accelerations to create fragility curves for bridges retrofit with steel jacketing. The first bridge was a 3 span bridge with a total length of 34m and the second bridge was a 5 span bridge with a length of 242m and also had an expansion join in the middle span. 60 ground accelerations were used based on motions in the Los Angeles area. In these bridges, it can be seen that jacketing, while less effective in

preventing lesser damage, can greatly prevent more worrisome damage states. The number of damaged bridges in this study's simulations can be found in Table 5.2 and fragility curves can be found in Figure 5.2.

Fridley and Ma (2007) conducted a report for the Washington Department of Transportation that looked at the fragility of bridges before and after retrofit. The model bridge was a "typical Washington bridge" with 120ft spans. As often used in fragility analysis, peak ground acceleration will be used to describe seismic hazard. A range of jacketing efforts were looked at including quarter, half and full-height steel jacketing as well as full-height composite jacketing. As with the other studies, it can be seen that jacketing can greatly help prevent damage from earthquakes including the more major damage states. Fragility curve parameters can be found in Table 5.3. This data was also used to determine which retrofit should be selected by using design PGA and acceptable probably of failure.

Padgett and DesRoches (2008) present a method to develop fragility curves for retrofitted bridges. Retrofit methods used in the example include column jackets, elastomeric bearings, restrainer cables, seat extenders and shear keys. Emphasized in this methodology is how the state of the bridge is based on multi-component analysis. In the sample three-span bridge used for the demonstration, the bearings helped at lower damage states while jacketing and seat extenders helped more in the major damage states. This shows that the selection of retrofit should be based on the damage state of interest.

5.4. Retrofit Optimization Algorithms

Currently, it is very difficult for decision makers to properly select bridges for retrofit. Oftentimes, the bridge retrofit selection process considers the bridge by itself rather than

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considering it as a component in a large network. While selecting bridges for retrofit based on the expected physical damage can be done fairly easily, gauging the greater impact of the bridge failure is difficult. This is especially true in earthquake situations where there can be multiple simultaneous bridge failures. Because of this, the actual selection of which bridges in a network are retrofit aren't made in the most effective and efficient manner.

It would be of great benefit if there was an optimization scheme that minimizes losses from earthquakes without overspending on retrofits. There are numerous types of optimization algorithms that can be applied but the difficulty of implementation but the accuracy and the computational intensiveness of the algorithms make actually utilizing some these algorithms difficult. In this section, different types of optimization methods that have been used in retrofit selection problems will be detailed and a novel optimization method will be introduced that will provide an effective retrofit scheme that runs with reasonable computational resources.

The three existing optimization methods detailed will include genetic algorithms, neural networks and two-stage stochastic optimization.

5.4.1. Genetic Algorithms

Genetic algorithms mimic natural selection to find an optimal solution to a given problem. In a genetic algorithm, potential solutions are defined with a genome. In the biological sciences, a genome is the set of DNA for an organism and the DNA defines what an organism is. The algorithms genome behaves in a similar way. In the retrofit problem, the genome may be a binary list which bridges are retrofit with which types of bridge retrofit. Genetic algorithms have been used in problems that bear similarities to the

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goals in this thesis. Dong et al (2014) used genetic algorithms to find a set of pareto-optimal solutions that minimize retrofit cost and societal cost with particular focus on sustainability including CO_2 emissions. Elhadidy et al. (2013) created a visual basic program that utilizes a genetic algorithm to find the pareto-optimal solution set that helps decision makers decide if and when pavement should be rehabilitated in a network by minimizing maintenance cost and maximizing pavement condition. Bocchini and Frangopol (2012) used genetic algorithms to determine the optimal set of solutions for interventions on bridges on a highway segment where the objective is to minimize cost as well as increase resilience where resilience is based on the travel time in the network.

In nature, random mutations can change a genome for a particular organism. This mutation may affect how well the organism thrives in its environment. The organism may be more or less likely to thrive or the mutation may have no noticeable effect at all. If the organism is more likely to thrive, it will be more likely to pass on this mutation and its offspring will carry the benefits. If the mutation is not beneficial, the opposite is true. The genetic algorithm works much in the same way. Mutations are applied to the genome in a way that change the values in the genome. .With these new values will thus change the objective function. If the new genome improves the objective function, it will be more likely to produce offspring that may have mutations of their own. Through this process, the algorithm generally improves over time and the algorithm is stopped when convergence is found.

Genetic algorithms do carry significant drawbacks however. For one, the algorithm doesn't promise to find the globally optimal solution. Due to its nature as a stochastic search algorithm, it is prone to getting "stuck" at local maxima and minima.

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This can be remedied sometimes with starting the algorithm with different starting genomes but this is at the expense of computational resources and still doesn't guarantee the optimal solution. Also, genetic algorithms often take a long time to converge. This last point in particular is the reason why this class of algorithms will not be used in this study. Each evaluation of the objective function comes with computationally intensive processes such as calculating user equilibrium in a network so if the genetic algorithm requires a very large amount of evaluations of the objective, the computationally requirements will be extremely high.

5.4.2. Artificial neural networks

Artificial neural networks can be used to approximate solutions to optimization problems by mimicking how the human brain learns. Neural networks are machine learning models that, when given a set of inputs and outputs, try to establish a pattern that will allow for the model to create an approximate function that explains what effects the inputs have on the output. For example, a manufacturer may produce a product and may be curious as to which markets to expand to next. The manufacturer could use the input demographic data from their available markets as well as their sales in each of these markets. The model will then use this data to estimate how aspects such as total population, education and income effects sales of the product. From this, an approximate function that links the demographics and sales are created. Then, the demographics of possible markets are input into this function to estimate sales.

The most useful aspect of neural networks is the fact that it can approximate functions without needing to know the underlying behavior of the problem. In the previous example, the model doesn't actually need to know why income affects sales. It

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just determines if it does and how much. This type of model is considered a "black box" model where the input and outputs are known but the actual mechanisms in between are unknown. This would be useful in retrofit selection. If possible, a neural network would weigh bridges based on the impact it has after retrofitting without needing to involve complexities such as its probability of failure, its importance in the network, its capacity and so on.

Neural networks have previously been used in problems related to seismic damage. Jafarzadeh et al (2013) used neural networks to predict retrofit construction costs of buildings by using predictors such as structure types and using the retrofit net construction costs as the output. Gonzalez-Perez and Valdes-Gonzalez (2011) used neural networks to predict to structural damage to a vehicular bridge by using data populated from 12,801 damage scenarios developed using a finite element model. Arangio (2013) uses readings from accelerometers across a cable stayed bridge as well as 19 years of damage data to train a neural network model to help identify possible damage.

Neural networks were tested utilizing our previously mentioned cost metrics on small test networks. For the test networks, a number of simulations were run where earthquake affected the network, damaging bridges in the network. Bridges were retrofit at random and the bridges that were retrofit were more likely to survive the earthquake. From there, the direct and indirect costs were calculated for each simulation. The retrofit schemes and sum costs were used as inputs and outputs respectively into the neural network toolbox within MATLAB. Unfortunately, even for small networks, the model had a difficult time determining the weight of the bridges in the network. This is due to the large amount of randomness in the network. For example, it would be entirely

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possible for a bridge to survive an earthquake even when not retrofitted in one simulation but then fail in another simulation where the bridge is retrofit. In this case, the neural network may interpret this retrofit as negatively impacting the direct and indirect costs which is not the case. In order to eliminate these situations, many simulations need to be run in order to give the model a decent amount of data to learn from. The number of simulations needed for these test networks to produce a reasonable approximate function is quite high and for larger networks, it would take magnitudes more simulations to produce a function. For this reason, neural networks and other black box methods weren't used in this thesis.

5.4.3. Two-Stage Stochastic Model

The last method of optimization considered was the two-stage stochastic model. The premise behind a two-stage stochastic model is the decisions should be made using available data without knowing for certain future events. Usually this involves knowing a probabilistic distribution of possible events and finding a solution that minimizes some costs based on that probability. In the case of earthquakes, it is unknown if an earthquake will strike in a given time frame and it's just as difficult to predict its severity. Even then, it's impossible to say for certain which bridges will be damaged for a specific earthquake. However, it can be said how likely it is for an earthquake to happen as well as how likely it is for a bridge to fail after an earthquake. Using this information, we can try utilize the expected cost in a minimization function to help best choose a retrofit scheme that will give the greatest benefit. The two-stage stochastic model does just that by incorporating the expected cost and the cost of implementing decision variables (in this case the decision to retrofit) into an objective function in a minimization problem.

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The basic formulation of a two-stage stochastic problem is as follows:

$$\min_x c^T x + E[Q(x, \xi)] \tag{5.1}$$

where c^T is the cost vector for implementing first stage decision variable x and $E[Q(x,\xi)]$ represents the expected cost of the second-stage problem where $Q(x,\xi)$ is the solution to the second-stage problem and ξ is a set of random properties. In this particular formulation, the cost associated with decision variable x is written as a linear function but it doesn't necessary have to be formulated in this way. The second-stage problem is solved after the random properties have been realized. The second stage problem is:

$$\min_y q(y, \xi) \tag{5.2}$$

$$\text{s.t.} \qquad T(\xi)x + W(\xi)y = h(\xi)$$

where y is a vector of the second stage variables, $T(\xi)$, $W(\xi)$ and $h(\xi)$ are functions forming the constraints of the second stage problem which are themselves based on the realization of the random parameters.

Oftentimes, functions of ξ are unobtainable or at least difficult to implement. It would be useful to be able to use an approach that discretizes the expected value of the second stage as a means to reasonable estimate the expected costs of the stage. The expected cost term can be rewritten as follows:

$$E[Q(x, \xi)] = \sum_{k=1}^{K} p_k Q(x, \xi_k) \tag{5.3}$$

where K is a number of scenarios representing the full distribution of possible scenarios, p_k is the probability of scenario k occurring and ξ_k represents the random parameters associated with scenario k. If a sufficiently large number of simulations are run, the simulations can reasonable estimate the expected cost term. In this study, K will represent

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the number of earthquake simulations run, p_k will represent the probability that the earthquake will occur and ξ_k will contain random parameters such as bridge failures.

The two-stage problem lends itself very well to the retrofit problem. The first stage problem is where bridges are decided to be retrofit. The x becomes a binary vector that gives information on whether or not a bridge is retrofit (with 1 being retrofit and 0 being non-retrofit). This can be further extended if need to be considered for different types of retrofit fairly easily by having x as a vector of size 1 by [number of bridges×types of retrofit] and having the binary variables represent if a particular type of retrofit is conducted on a particular bridge. The second stage will contain variables pertaining to how the drivers behave after the earthquake. Variables will include flow rates for each link and have constraints related to the traffic demand after the earthquake.

Some work has been conducted so far on application of two-stage stochastic algorithms for finding the optimal. Liu et al. (2009) utilized a two-stage stochastic model to retrofit bridges in models for the Sioux Falls network as well as an Alameda County network. The study uses Benders decomposition, a well-known method of solving stochastic programming problems, to solve for an optimal retrofit scheme. This study shows that the method can be effective but it still showed some potential issues related to high-computational resources, simplifications to the failure process (retrofit bridges are assumed to never fail) and, since the networks were fairly small, questions about the scalability of the model. Fan and Liu (2010) expanded on the previous work by using a method progressive hedging instead of Benders decomposition as well as using a discretized model.

The two-stage model fits the problem quite well and if the difficulties regarding the computational intensiveness of the model can be solved, it would be better than many of the other families of optimization methods. Because of this, the two-stage model will be the method utilized in this thesis. In order to overcome the shortcomings of the model, some simplifications will be made in order to solve the problem quickly for fairly large-scale problems.

The formulation of the two-stage problem utilized in this study will be as follows starting with the first stage:

$$\min_x c_{retrofit} r + \sum_{k=1}^{K} p_k Q(r, \xi_k) \tag{5.4}$$

$$\text{s.t.} \qquad r \in \{0,1\}$$

where the second stage problem takes the form:

$$Q(r, \xi_k) := \min_x c_{repair}(r, \xi_k) + c_{indirect} \sum_a \int_0^{x_a^k} t_a^k (x_a^k, \xi_k)_0 \tag{5.5}$$

$$\text{s.t.} \qquad t_a^k = t_{0,a} \left(1 + 0.15 \left(\frac{x_a^k}{c_a^k} \right)^4 \right)$$

$$\sum_P f_{P,ij}^k = q_{ij}^k$$

$$x_a^k = \sum_i \sum_j \sum_P (\delta_{a,P}^{ij} * f_{P,ij}^k)$$

$$x_a^k \geq 0 \; ; f_{P,ij}^k \geq 0$$

where $c_{retrofit}$ is a vector represents the retrofit cost for each bridge, r is a binary vector representing the decision to retrofit a bridge, $c_{repair}(r, \xi_k)$ represents the total repair costs under scenario k, $c_{indirect}$ converts travel time into indirect costs by methods mention earlier in the paper, $t_a^k (x_a^k, \xi_k)$ is the travel time of link a under simulation k as a function

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of link flow x_a^k, $t_{0,a}$ represents the free flow travel time of link a, $\delta_{a,P}^{ij}$ is 1 if the link between i and k is in path P and 0 otherwise, c_a^k is the capacity of link a, $f_{P,ij}^k$ is the flow on path P between nodes i and j and q_{ij}^k is the trip rate between i and j. The constraint in the first stage establishes r as a binary vector. The objective function in the second stage establishes the repair cost for the simulation in the first term and sets the condition for user equilibrium in the second term. The first constraint is the BPR function as described in the traffic demand modeling section of the paper. Note that the capacity can change from simulation to simulation as the capacity is a dependent on the states of the bridges on that link. The next constraint makes sure that travel demand is met by having the sum of all flow on the used paths between i and j be equal to the demand between the nodes. Note that the demand will be calculated using the gravity model described earlier. The third constraint in the second stage connects the concepts of link flow and path flow. The final constraint prevents negative path and link flow.

From here, the user can use a solver capable of solving the problem. There are multiple commercial solvers that can be utilized such as AMPL and the MATLAB optimization toolbox. The software packages often include a variety of algorithms such as interior point algorithms and active set algorithms. Most of the algorithms follow the some overarching idea: the algorithm starts at a guess for the solution and the algorithm iterates towards a better solution until some sort of convergence criteria is met. These general algorithms can work well on smaller networks but as the network scales, the algorithms cannot be expected to solve the problem in a reasonable amount of time. When the bridges number in the thousands, there are at least an equal number of first stage decision variables. When a network has thousands of links and hundreds of

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simulations, there are hundreds of thousands of values for link flow that must be solved. The problem has to be simplified or a strong guess for the initial solution must be obtained.

After the algorithm is complete, it can either be used as is for an approximation for the solution to the two-stage stochastic problem or as a warm start to a more general solver. This being a greedy algorithm (As it makes decisions based on the locally optimum choice at each iteration), the program may stop closer to a local minimum which may not necessarily be the same as a global minimum. For this reason, this algorithm is best suited for situations where the network that is large enough to require a simplified method of evaluation and networks with different solution sets that are similar in their optimality.

5.5. Retrofit Optimization Study Area

To demonstrate the retrofit selection algorithm, a cutout of the larger San Francisco Bay area network will be used. This cutout will include the Oakland area, one of the busier areas in the whole network and extends eastwards towards the bounds of the previous case study. A map of the cutout region can be seen in Figure 5.3. This area will include 1017 bridges and 817 nodes. This scale will allow for a more compact demonstration of the algorithm while still utilizing a sizable network. The algorithm itself can be applied to networks larger or smaller than the Oakland area however.

Some simplifications and alterations will be utilized for the retrofit selection demonstration. Since most of the retrofits discussed previously aren't used in liquefaction scenarios and the Bay area happens to be an area of very high liquefaction susceptibility, the chance of liquefaction will not be incorporated into the demonstration. Also, the

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initial hazard levels and driver demand were set to values such that the effects of retrofitting can be easily visualized and may be different then the values used in the risk analysis section.

A retrofit technique that mirrors the qualities of steel jacketing will be selected for this demonstration. The change in fragility will be adapted from the results found in from Kim and Shinozuka (2003) which was mentioned in the previous section. This bridge type is similar to many types of bridges that might be seen in the area. A retrofit cost of $12000 per column will be used as a starting point. The number of columns will be estimated using NBI statistics and it will be assumed that every bridge could be a candidate for retrofit. As with the previous study, all bridges are considered to be in the pre-retrofit state to begin with. It will be assumed that there is enough resources to retrofit up to 600 of the bridges.

Retrofit selection at any iteration will be based on the expected detour and the expected repair cost of each bridge. The detour will be the shortest path from one end of the link with the bridge on it to the other if the bridge is closed or the capacity is reduced. The detour is generally longer in length than the original link and may be congested in the post-earthquake state. The expected time is then calculated based on likelihood of failure and the length of the detour after failure. This is multiplied by the number of users effected by the detour and is converted to a dollar value. This is then added to the expected repair cost and the bridges are then ranked by this value and selected for retrofit accordingly. At any iteration, the state of the network changes and the detours must be recalculated in order to reflect this change.

It is important to know how the retrofit selection process changes with the characteristics of the network and the characteristics of the retrofit technique itself. A network stakeholder might want to know if more or less bridges should be retrofit if the cost of retrofitting increase for instance. Because of this, the sensitivity of the retrofit selection to risk, cost of retrofit, and effectiveness of retrofit will be analyzed.

Multiple risk scenarios will be tested in order to show the sensitivity the retrofit selection process has to the hazard level. In the initial scenario, seismic hazard will be based off the probability of the earthquake scenarios on the Hayward fault site in the San Francisco case over a period of 50 years. Scenarios of lesser and higher risk will be tested as well. In a lesser risk scenario, this chance will be halved while in a higher risk scenario, the hazard will be increased by fifty percent. To show the sensitivity to cost, three levels of retrofit costs will be used. In the initial scenario, the costs mentioned previously will be used. In a cheaper scenario, this will be halved while in a more expensive scenario this will be doubled. Lastly, the effectiveness of retrofit strategies on the selection of number bridges for retrofit will be explored. Three scenarios will be used: the first scenario is a baseline scenario that behaves as one might expect from a steel jacketed retrofit, the second scenario will represent half the benefit (which will mean the change in the mean of the fragility curve will be halved), and the third scenario will assume that bridges that are retrofit do not fail. Some studies have selected bridges based on this assumption and it would be important to see if that assumption is reasonable.

5.6. Discussion of Results

The retrofit selection algorithm was applied to the Oakland network and from there, the information was used to determine which bridge to retrofit and how different parameters

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including seismic risk, retrofit cost and retrofit effectiveness can affect the selection. Figure 5.4 and Table 5.4 displays the change in costs as more and more bridges are retrofit. Costs are broken down into those associated with drivers' delay, retrofit and repair with the total cost being the sum of the three. Initially, no bridges are retrofit this leaves a state with no retrofit costs but higher delay and repair costs. The first bridges selected are based on the expected repair costs. As shown, the drop in repair costs outpaces the increase in retrofit cost at first. Shortly after 50 bridges, the change in repair costs and retrofit costs even out and then retrofit selection incorporates delay more in the selection process. At around 151 bridges, the cost starts increase slightly then begins to plateau. This makes the retrofit state at 151 a good choice for a retrofit scheme. Figure 5.5 shows the bridges that were selected for retrofit at the optimal stage (=150 bridges). Important factors include the distance from the site to the fault, the type of bridge, detour length and driver demand for the bridges. The general trend toward repairing bridges closer to the fault and those closest to the city of Oakland itself can be seen but incorporating these other factors requires detailed analysis as they may not be readily apparent from looking at the figure.

Figure 5.6 and Table 5.5 display the results for the total costs the network experiences under different risk scenarios. As expected, the initial cost without retrofit is proportional to the likelihood of the earthquake scenarios. In the lower risk scenario, fewer bridges are retrofit and less benefit can be seen for retrofitting these bridges optimally. This intuitively makes sense as if the network is unlikely to experience any earthquakes, only the few most important bridges will be retrofit even those only provide so much benefit when compared to the cost. The opposite is true in the higher risk

scenarios. The greater the risk, the more bridges selected for retrofit and the greater benefit they provide. In the higher risk scenario, the choice of retrofit is bounded by the limitation on the maximum possible retrofits though the benefits from retrofitting 600 against retrofitting a sizably lower amount isn't that large as the benefits begin to slow down greatly near the 200 bridge mark. This shows how important it is to understand the hazard level of the surrounding area when considering seismic retrofits.

The sensitivity to the cost of retrofit can be seen in Figure 5.7 and Table 5.6. The benefit and disadvantages of cheap and expensive retrofits respectively are made clear. With cheaper retrofits comes greater feasibility in retrofitting bridges. If the retrofit cost is halved, the number of bridges before the benefits plateau is slightly higher and the reduction in cost increases significantly. This shows the importance of developing cheap, effective retrofit techniques as the benefit can be quite large. The inverse is the case for expensive retrofits. The benefits of retrofitting begin to become a burden on the network quickly and thusly, not many bridges can be retrofit efficiently. This may be an issue in areas that do not have access to affordable retrofit techniques. One important factor to note is that during the first few retrofits, the curves for all scenarios are very close. This is because for especially important bridges that undergoes retrofit (which are retrofit first), the benefits far outweigh the costs even if the retrofit comes at a premium. This shows that for important bridges, expensive retrofits can still be well worth the price.

The last sensitivity parameter looked at is the change in retrofit selection with a change in retrofit effectiveness. Even after retrofitting, there's still a chance of failure. Similar to how more expensive retrofits limit the feasibility of retrofitting so does decreasing its effectiveness. The retrofit with halved effectiveness sees a significant

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decrease in benefit as does the expensive retrofits but the less effective retrofits also carry the disadvantage of requiring a larger number of bridges retrofit to achieve this already unimpressive benefit. This means additional resources such as man-hours used on a retrofit that doesn't perform up to par. The no-fail retrofits show a sizeable increase in the benefit received when retrofit. However, the number of bridges that are retrofit before plateauing did not increase all too much. This means that, at least in this network, the improved retrofits does more to increase the benefit of bridges that would be selected anyway rather than make retrofits more feasible on other bridges. This also shows however that the assumption used in some models that the post-retrofit failure can be ignored can lead to an overestimate on the benefit of retrofitting. The effect of the optimal retrofit scheme on the resilience curve of the network can be seen in Figure 5.9 for a 7.5 magnitude earthquake located near the city. As shown, the impact of retrofitting can be seen in the initial drop after the earthquake strikes. This furthers the idea that retrofitting increases what we labeled as the robustness of the network. This makes sense as the robustness is dependent on the fragility of the network elements before the event and retrofitting will make these elements less fragile. This also highlights the notion that robustness is based on pre-earthquake decisions. The retrofit curve shows a reduction in performance loss of 34% over the non-retrofit state.

Table 5.1: Median PGA for MSC bridges before and after retrofitting

Damage State	Minor	Moderate	Extensive	Complete
Original Bridge	0.6	0.66	1.07	1.19
Elastomeric bearings	0.74	0.89	>1.20	>1.20
Lead-rubber bearings	0.68	0.84	>1.20	>1.20
Elastomeric bearings + dampening	0.80-0.93	0.95-1.10	>1.20	>1.20

Table 5.2: Number of bridges damaged before and after column jacketing (Kim and Shinozuka, 2003)

	Bridge 1		Bridge 2	
Damage State	**Before Retrofit**	**After Retrofit**	**Before Retrofit**	**After Retrofit**
No Damage	56	53	51	50
Minor	51	44	47	41
Moderate	41	28	37	22
Extensive	34	15	30	10
Complete	17	2	14	4

Table 1.3: Fragility curve parameters for the retrofitted bridges (Fridley and Ma 2007)

		Minor	Moderate	Extensive	Complete
No Retrofit	c	0.45	0.8	1.04	1.66
	ξ	0.84	0.84	0.84	0.84
Steel Jacket	c	0.75	1.25	1.73	5.5
	ξ	0.84	0.84	0.84	0.84
Half-Height Steel	c	1.8	1.72	1.49	1.39
	ξ	0.21	0.18	0.16	0.15
Full-Height Steel	c	1.43	1.28	1.16	1.09
	ξ	0.2	0.2	0.18	0.17
Full-Height Composite	c	1.05	0.96	0.89	0.84
	ξ	0.21	0.17	0.15	0.14

Table 5.4: Drivers' delay, retrofit, repair and total costs for retrofitting the Oakland network under initial conditions (million $)

Bridges Retrofit	Delay Cost	Retrofit Cost	Repair Cost	Total Cost
0	276	0	151	427
100	264	18.5	85	368
200	253	35.0	77	366
300	243	48.5	76	368
400	230	62.8	74	367
500	212	79.1	71	362
600	212	95.3	68	375

Table 5.5: Bridge retrofit cost reduction for varying risk scenarios

Risk Scenario	Bridges Retrofit	Cost Reduction (Million $)
Lower Risk	83	26
Initial Risk	151	67
Higher Risk	600	133

Table 5.6: Optimal bridge retrofit for varying cost per retrofit

Retrofit Cost	Bridges Retrofit	Cost Reduction (Million $)
Half cost	247	115
Initial Cost	151	67
Double Cost	600	308

Table 5.7: Optimal bridge retrofit for varying retrofit effectiveness

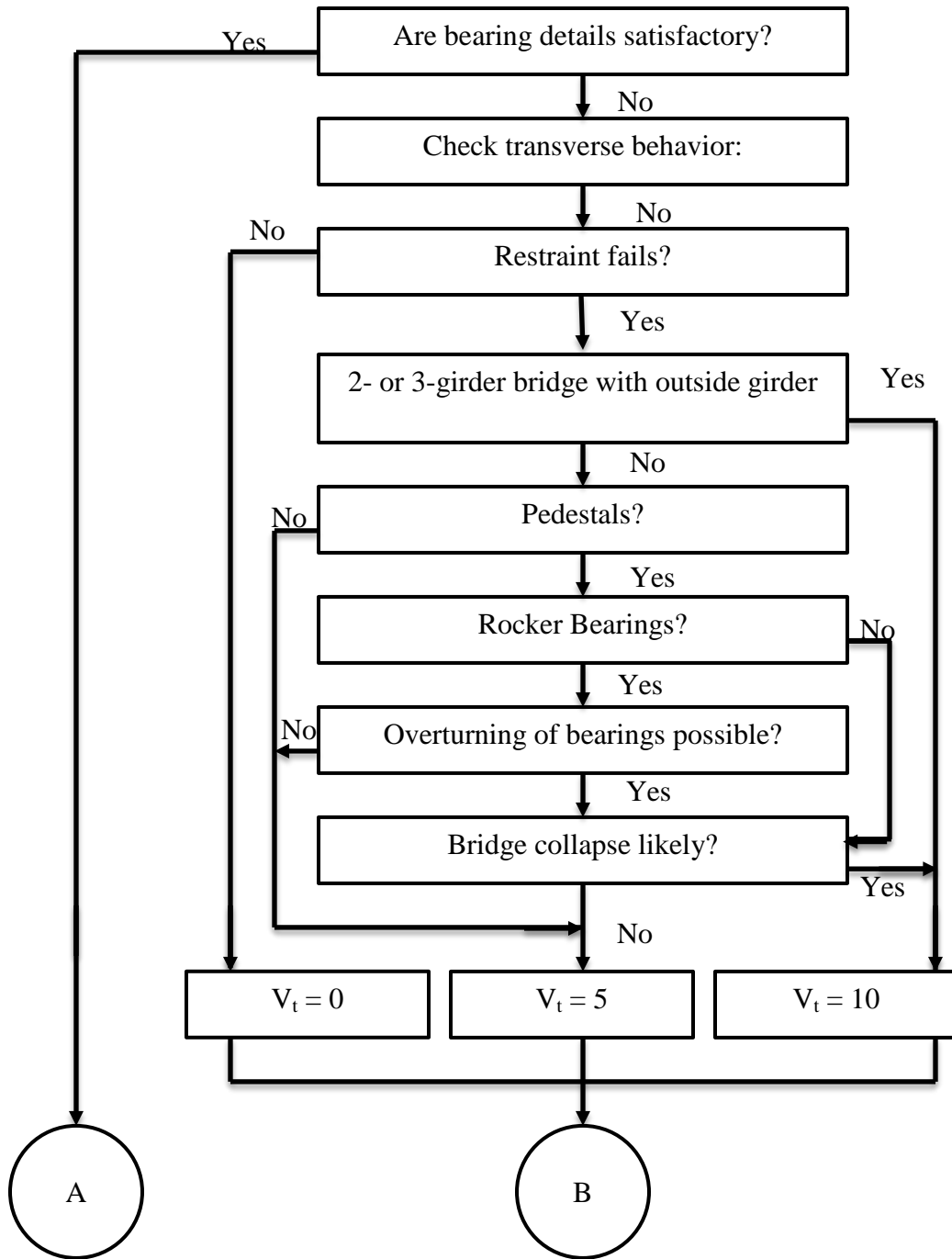| Effectiveness	Bridges Retrofit	Cost Reduction (Million $)
Lower effectiveness	103	35
Initial effectiveness	151	67
No failure possible	600	130

Figure 5.1: Flow chart for the values of V_1 and V_2 (recreated from Seismic Retrofitting Manual)
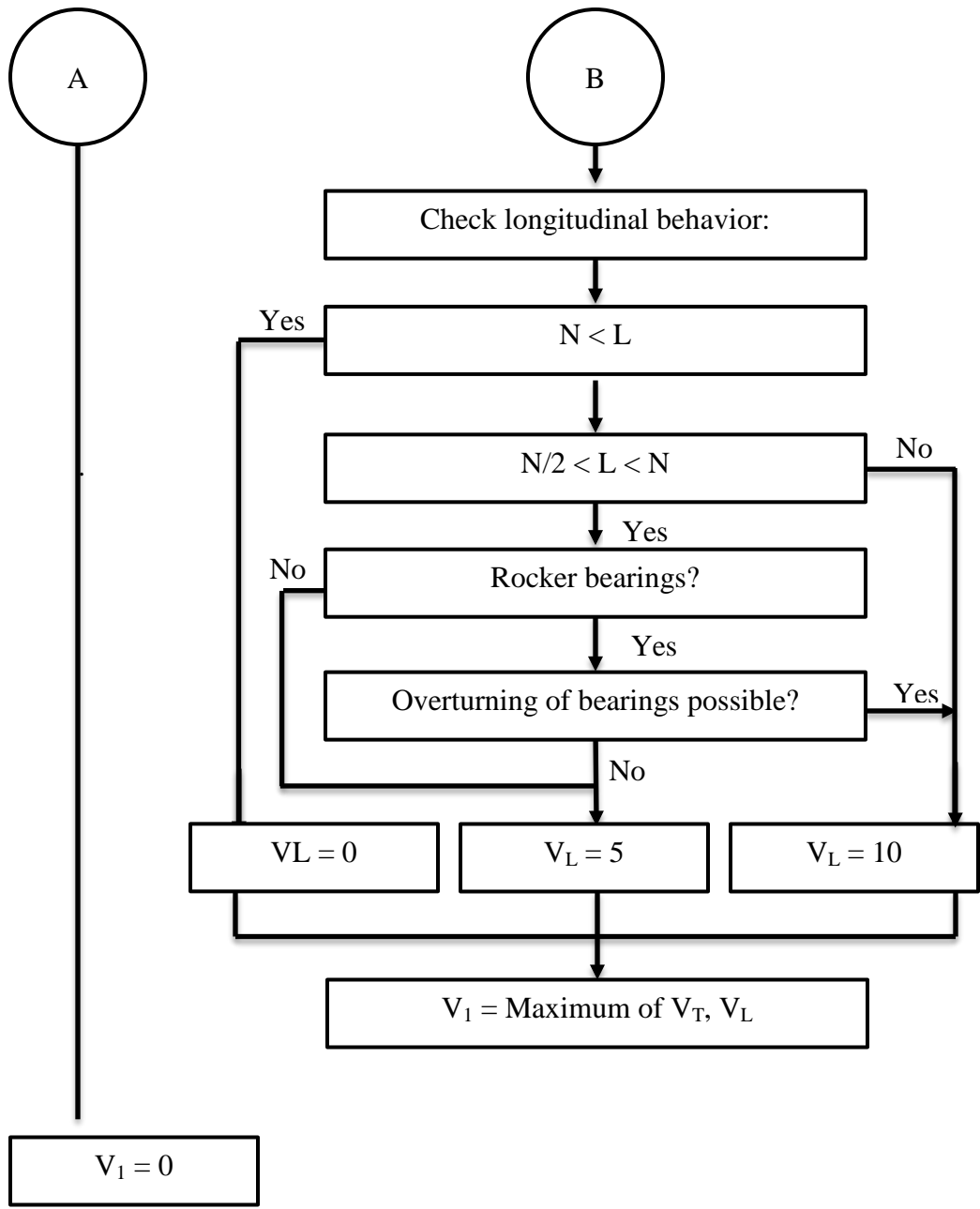
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Figure 5.1 (Contd.): Flow chart for the values of V_1 and V_2
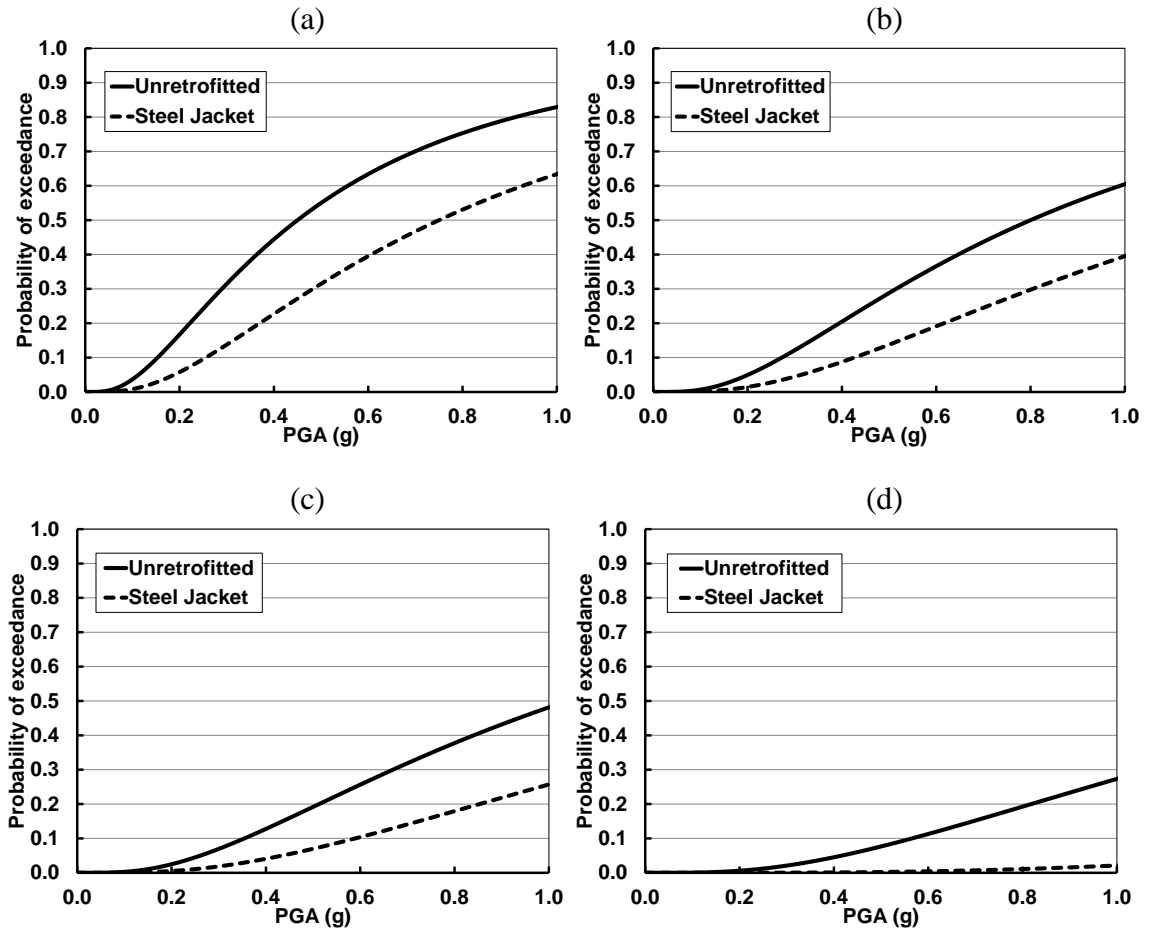
Figure 5.2: Fragility curves for the bridge with steel jacketing (Kim and Shinozuka, 2003)
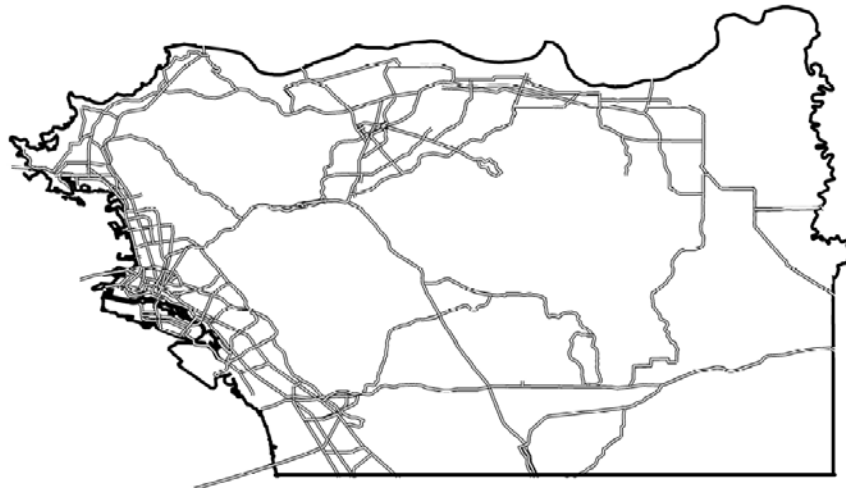
Figure 5.3: Highway network of the test bed (Oakland) for the damage mitigation strategies

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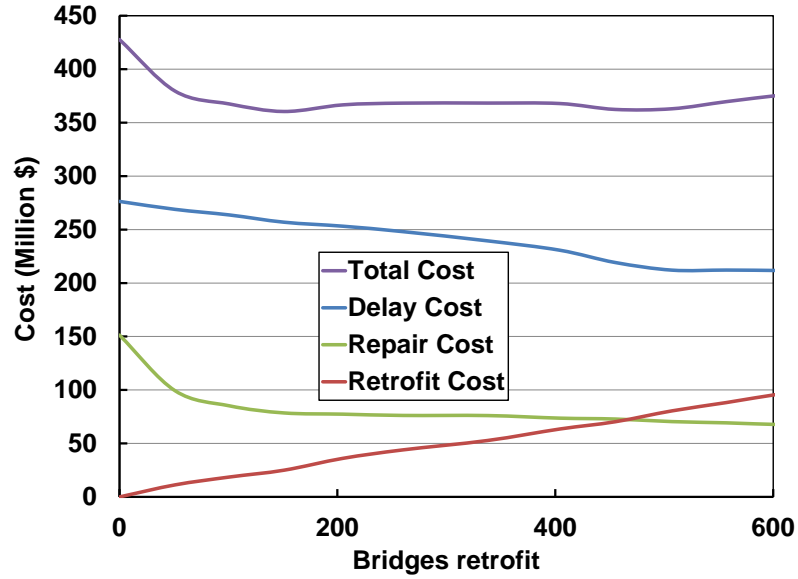
Figure 5.4: Delay, retrofit, repair and total costs for retrofitting the Oakland network under initial conditions
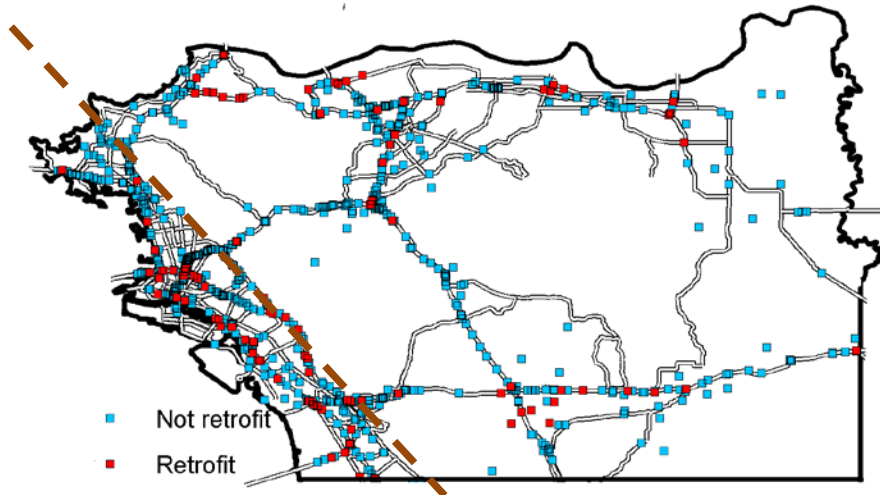
Figure 5.5: Bridges selected for retrofit in the initial scenario

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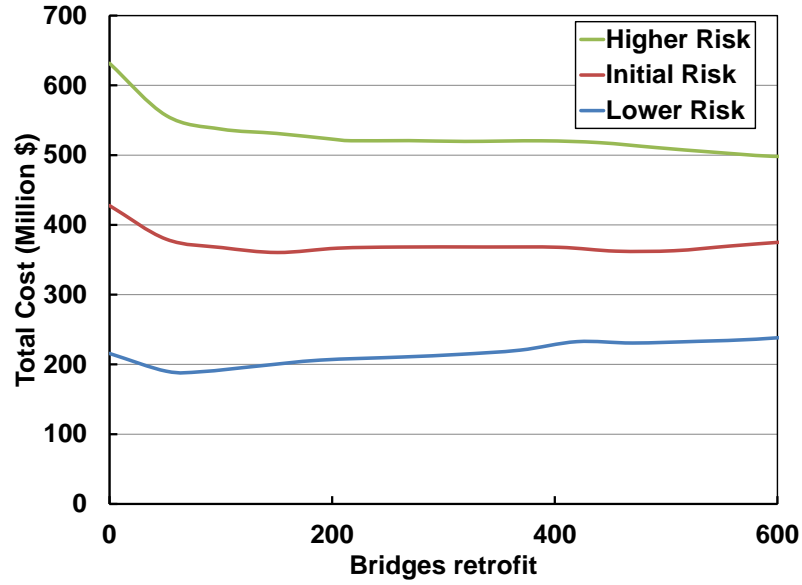
Figure 5.6: Total costs for retrofitting the Oakland network for varying risk scenarios

Figure 5.7: Total costs for retrofitting the Oakland network for varying cost per retrofit

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Figure 5.8: Total costs for retrofitting the Oakland network for varying retrofit effectiveness

Figure 5.9: Network performance with and without retrofit for a 7.5 M_w earthquake near Oakland

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CHAPTER 6

CONCLUSIONS

A large earthquake near a vulnerable or highly populated area can cause enormous losses to the critical civil infrastructure systems including the transportation infrastructure. Damage to transportation infrastr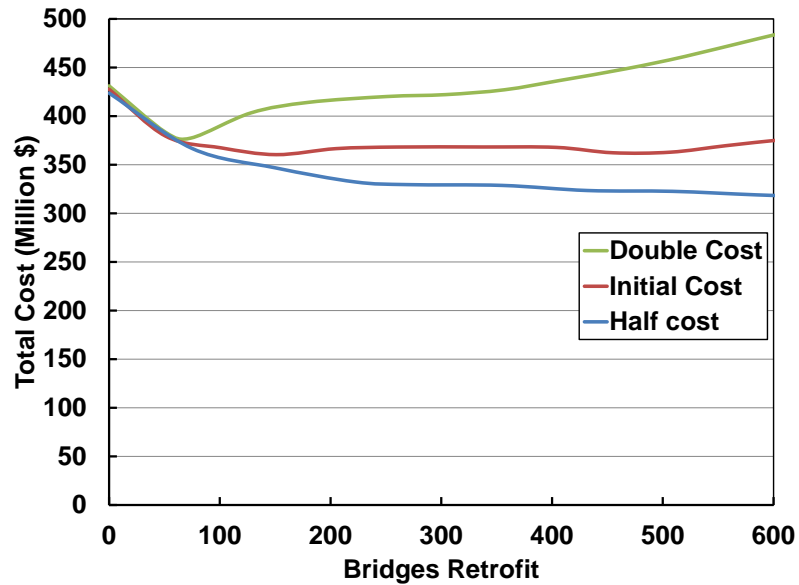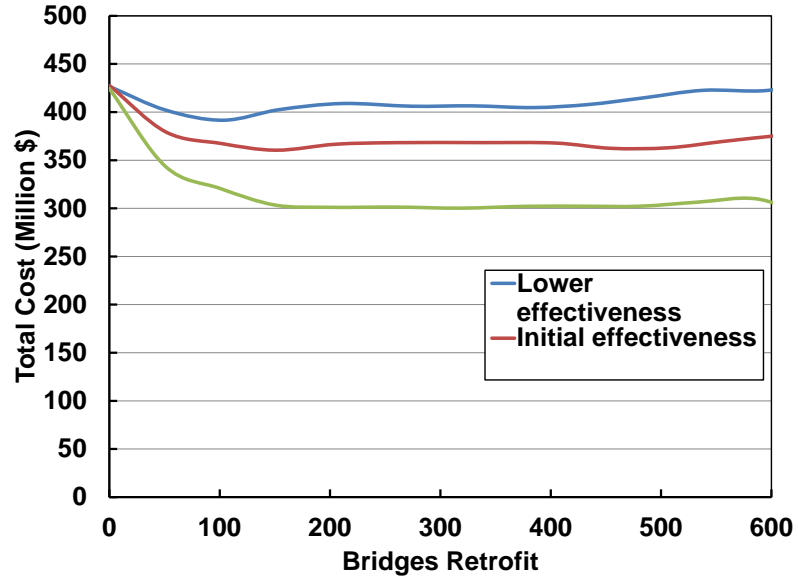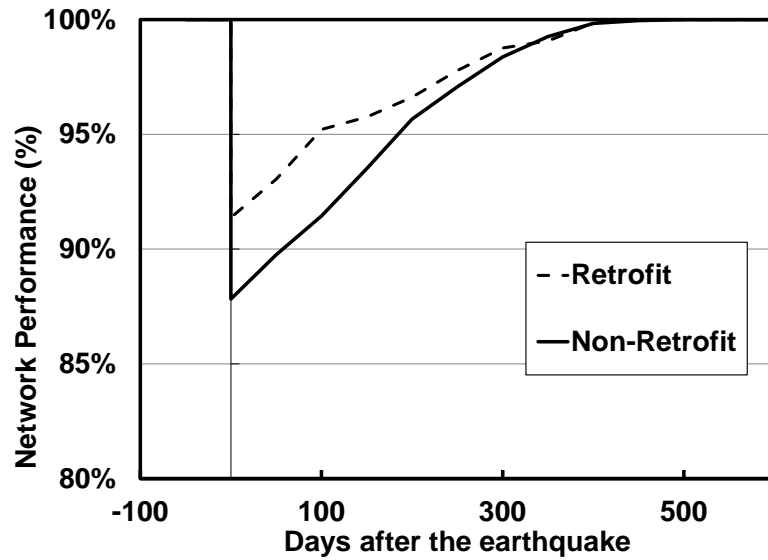ucture carries costs both in terms of repair costs and in decreased performance during the repair period. The goal of this study is to generate comprehensive resilience quantification framework that will provide the decision makers with the required tools to determine the vulnerability of highway network in face of calamities, plan for possible disruptions, and prepare for possible consequences with the final goal of decreasing the downtime in the functionality of the system.

Transportation networks are particularly important infrastructure networks to consider. There have been numerous historical events such as the 1989 Loma Prieta earthquake and the 1994 Northridge earthquake that caused great damage throughout the local transportation systems. For these and other instances, very large costs have been seen as network owners scramble to repair damaged bridges all the while network users see huge delays in their day-to-day lives which makes it difficult for society to functional normally. In order to prevent or limit the impacts from earthquakes on transportation networks, a deep understanding of the expected level of damage, the network recovery process and effect of additional precautions to help strengthen the network must be achieved.

This thesis sets out to provide methods to better describe how transportation networks respond to an earthquake by studying the resilience of the network. A resilient network should be able to recover quickly and limit the impact due to earthquakes.

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However there is an ongoing discussion between researchers, community leaders, and authority bodies on quantifying the resilience of a system. This thesis gives a detailed methodology that can be utilized by network owners to determine how well the individual bridges perform after an earthquake, what level of physical damage can be observed throughout the network, what level of indirect damage (including driver delay) can be expected, how providing additional resources to the repair process can help the network recover quickly and how to select pre-event actions in order to limit damage most effectively.

Resilience is a topic of growing concern in recent time. From its beginnings in the scientific literature as a descriptor of ecological behavior, it has expanded until fields including engineering and economics. Concern grew in the last decade due to disasters including hurricane Katrina and the 2008 economic crash and the importance of studying and measuring resilience has been recognized by those ranking up to the highest offices in the United States. Even with acceptance of the importance of the topic, works that can be applied to real world situations are fairly sparse and this thesis sets to create a framework for resilience that has tangible benefits to society.

This study follows an overarching definition of resilience set forth by Bruneau et al. (2003). In that study, resilience is seen as the sum of four characteristics called the four "R's" of resilience and four dimensions called TOSE. The four R's include robustness, redundancy, resourcefulness and rapidity. Robustness describes how well the system can absorb the impact of an event, redundancy describes how well the system can provide alternatives when needed, resourcefulness measures how well systems prioritize goals and provides resources to accomplish them and rapidity describes how quickly the

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system is restored. The four dimensions include technical, organizational, social and economic aspects (TOSE). Technical dimensions describe how well physical system stand up to disasters, organizational dimension refers to how well governmental and other deciding bodies respond to disaster, social dimension measures how well the system limits social losses and economic resilience describes how well a system limits economic losses.

A concept closely related to resilience is risk analysis, which helps determine probabilistically the level of damage expected in the system. In the study of earthquakes, it would be useful to know how often earthquakes occur, the severity of the earthquake and how susceptible the transportation infrastructure is to the earthquakes. The likelihood and severity of the earthquake can be considered its level of hazard and the susceptibility can be considered as the vulnerability of the community. Risk itself is seen as the product of hazard and vulnerability. Knowing the risk of a community informs the community leaders the extent of preparation needed for earthquakes and helps determine mostly affected parts of the community. A framework for the risk assessment of the transportation network in a seismic prone region has been provided. As a demonstration, a model of the San Francisco bay area has been presented. As a location of high seismic activity, dense population and high liquefaction susceptibility, it is a prime example of an area which benefits from seismic risk analysis. The seismic risk originated from both San Andreas and Hayward faults has been taken into account. There are three scenarios of rupture on San Andreas Fault and one on the Hayward fault. Six levels of magnitude from 6.0 to 8.5 have been studied adding up to a total of 24 scenario earthquakes.

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Hazards include ground shaking and liquefaction. Ground shaking is dependent on factors such as the magnitude of the earthquake, the distance from the source and the site, and site conditions. In our study area in particular, liquefaction is particularly important. Liquefaction happens when a large amount of pressure is applied to the soil and it starts behaving like a liquid which can lead to large displacements which in turn can lead to the failure of the bridge.

Two types of costs are considered: direct and indirect costs. Direct costs come from the actual repair of the bridge. This cost is calculated using the replacement cost of a bridge as well as its expected level of damage. The level of damage is calculated based off fragility curves which give an expected level of damage based on the intensity measure (such as level of shaking or ground displacement) and the classification of a bridge based on its general structural characteristics. Indirect damage originates from measuring drivers' delay and opportunity costs. In order to measure this, a four step transportation model is used. This model, including a trip generation, trip distribution, mode choice and traffic assignment step, predicts the flow rate throughout the network which is essential to calculate indirect costs.

Performance criteria are useful for establishing goals that the resilience must meet. Each of the four characteristics of resilience offers important insight into how the network recovers. Robustness shows damage that occurs directly after the earthquake. Robustness looks at the damage before any repair can be done so this means, for costs that accumulate over time, it gives the maximum daily damage that will occur after an earthquake. Robustness also predicts the base repair costs that will need to be spent in order to repair every bridge back to its fully functional state. A clear connection between

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hazard level and robustness is established as earthquakes of larger magnitude and earthquakes nearer to population centers are shown to have greater impact. Redundancy is used as a measure of how strong the network is as a graph. Here, indices including the alpha, beta and gamma index are used to quantitatively measure the redundancy of the network and comparisons are made to networks of same aerial size including Los Angeles, Reno and Boston. Resourcefulness is an aspect that ties into every other dimension of resilience and represents the decision making capability and capacity to provide whatever resources necessary to accelerate high priority projects. Resourcefulness in this study was used to describe how well network owners prioritize bridges for repair in the network and how well they used repair acceleration techniques to help repair bridges faster. Rapidity is used to measure how quickly the performance of the network returns to an acceptable level of performance and it becomes clear that this topic ties in with resourcefulness as a more resourceful network should repair more rapidly.

This study considers two types of acceleration techniques: incentivization and accelerated bridge construction. Incentivization involves competitive A+B bidding which reduces the expected repair time while paying the contractor a bonus for finishing ahead of schedule. Using the ABC technique the project is accomplished in a relatively short amount of time but increased construction costs are associated with it. Also compared are a well prioritized and a poorly prioritized repair process. The well prioritized network performed a significant amount better than the poorly prioritized network. This emphasizes on the importance of preparation before the event in order to assess the significance of each link in the network. It was shown that although the cost decreases

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with an increase of resourcefulness, the cost reduction results in diminishing returns. This shows that while it is important to be as resourceful as possible, it is especially important for relatively less resourceful networks to begin planning for seismic events in order to reap the most effective benefits.

This study also looks into the effects of pre-event retrofit actions that result in strengthening the network, hence increasing its robustness against earthquakes. A unique contribution of this study is that instead of looking into the increase in resilience of individual bridges, it takes a system level approach and considers the effect of retrofit on performance of the network in its entirety. Retrofitting is a set of techniques often used to strengthen bridges that have inadequate seismic strength or have deteriorated. Various retrofit techniques such as column jacketing, restrainer cables, shear keys, and base isolation are presented. These techniques are used across the seismically vulnerable portions of the United States and studies have shown a clear link between retrofitting and the fragility of bridges.

A novel retrofit selection algorithm was also created in this thesis. This algorithm considers repair cost and network performance that can be used on a sizeable and complex network. The sensitivities to hazard levels, repair cost, and effectiveness have been considered. It was shown that at higher hazard levels, the need to retrofit is especially pronounced while at lower hazard levels, the benefit is minimal. Furthermore, the results showed that the retrofit scheme is very much affected by the cost of the retrofit which highlights the need to develop cheap retrofit methods. The effectiveness of the retrofit method was also important. The assumption that retrofitted bridges will not fail during an earthquake can significantly overestimate the benefits of retrofitting.

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The retrofit scheme was tested across a portion of the San Francisco bay area. In this study, the Hayward fault possesses a serious risk to the transportation network of the Oakland area. A sizeable portion of the network was selected for retrofit with a method akin to column jacketing was utilized to strengthen the bridges against this threat. It was also shown that there is sensitivity in the selection process to risk as well as the cost and effectiveness of retrofits. A higher risk area is suited better than a lower risk area to retrofitting and a greater number of bridges are selected for retrofit. The benefit of retrofitting was also shown to correlate positively with its effectiveness and negatively with its cost.

Further work may be conducted to help further the study of resilience of transportation networks. Topics related to the change of driver behavior in the days after earthquake events are ongoing but incomplete. Traffic demand after an earthquake differs from pre-event demand but in ways that is not fully understood. The effect of retrofitting on fragility across a set of bridges that could be used to describe a network of a variety of bridges is also a topic that can be further explored. Also helpful to the study would be the implementation of different indirect costs and performance under one model. While other studies have used measures such as accessibility, network capacity and connectivity among other measures, connecting these different measures and comparing them in a single model would allow for a more complete understanding of resilience.

This thesis shows clearly the impact that earthquakes have on seismically prone areas and the consequences of not fully understanding the response the network would have to earthquake events. Valuable contributions were made that describe the different aspects of resilience as well as methods to increase the resilience of transportation

networks. With these contributions, this thesis will help government agencies and other network stakeholders prepare for seismic events by showing which aspects of the network are most critical. Network owners will be able to evaluate how resilient the network is and can use the model to test improvements to the network in order to better withstand earthquakes.

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