Seismic Hazard Mitigation Strategies and Measures of Highway Bridges

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SUMMARY:

This paper introduces the current mitigation measures and strategies in reducing vulnerability and the loss of highway bridges in the US, including (1) Mitigation Design of New Bridges - Based on advanced seismic research and experience with destructive earthquakes. The will include the fundamental design objectives of current seismic specifications and one-level design criterion is based on a 1,000-year return period event; (2) Seismic Retrofitting of Existing Bridges - based on the recent published Seismic Retrofitting Manual of Highway Structures-Part I and Part II. This two-volume manual contains the three major procedures (Prioritization Screening, Detail Evaluations and Retrofitting Measures) for evaluating and upgrading the seismic resistance of existing highway bridges; (3) Risk Analysis and Loss Estimations - A methodology and a multidisciplinary tool (REDARS - Risks from Earthquake DAmage to Roadway Systems) which can be used for seismic risk analysis of highway systems nationwide.

Keywords: Bridge Seismic Design, Seismic Retrofitting, Earthquake Engineering, and Seismic Risk Analysis.

1. INSTRUCTION

1.1 **Background**

Our highways are built to transport goods and people, and connect nations, states and cities. As such, they are our lifelines to deliver daily needs such as food, water, and communication with other locations. Built to serve human needs in this modern world, they are also constructed to resist all natural hazards and protect our lives and properties. As a result of natural hazards in the U.S. from 1993-1996, approximately one quarter billion dollars per week was spent on meteorological natural disasters [FEMA, 1997]. Among these natural hazards, earthquakes, hurricanes and floods were the major causes of monetary loss. Figure 1.1 compares the impacts of most costly natural disasters in the U.S. from 1988 –1997.

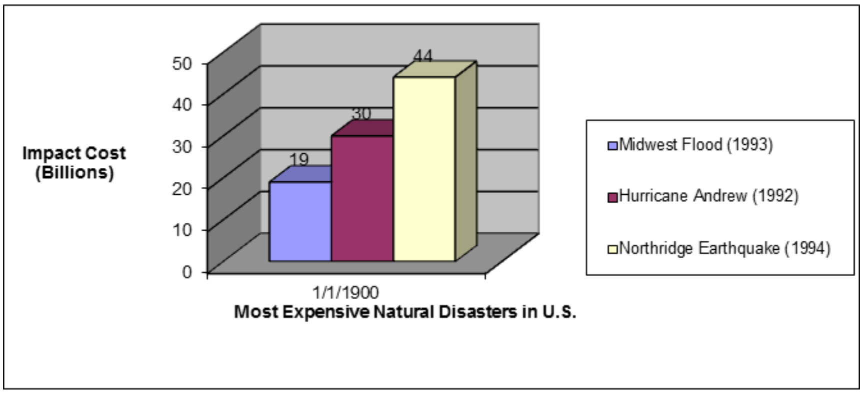

Figure 1.1 Impact of Natural Hazards

1.2 Earthquake Hazard

An earthquake is a sudden ground motion or trembling caused by an abrupt release of accumulated strains acting on the tectonic plates that comprise the Earth's crust. They often trigger other devastating events such as lateral spreads, landslides and fires; and damage bridges, buildings, dams and other infrastructure components. An earthquake may also add a Tsunami to coastal areas if it triggers in the ocean. Although the probability of large destructive earthquakes is relatively much lower than other natural hazards such as hurricanes and floods, an earthquake can, without warning, devastate an area within one to two minutes through ground shaking, surface fault rupture and ground failures.

The loss of life and extensive property damage inflicted by the 1989 Loma Prieta, and 1994 Northridge earthquakes emphasized the need to minimize earthquake risks to our highway system. Table 1.1 summarizes the damage from significant American earthquakes (Stover and Coffman) between 1964 - 1994.

Table 1.1 Significant Earthquake Damages in the U.S. 1964-1994

Location	Date	Magnitude	Damages (in Millions)	Deaths
Prince William Sound, AK	03/27/1964	8.4	$311.0	125
San Fernando, CA	02/09/1971	6.6	$505.0	65
Loma Prieta, CA	10/17/1989	7.1	$6,000.0	63
Northridge, CA	01/17/1994	6.7	$20,000.0	61

(Sources: From Stover and Coffman, 1993, FEMA 1994)

Mitigation approaches discussed in this paper include new planning (seismic risk assessment method), structural design and retrofitting measures from the Federal Highway Administration's (FHWA) various seismic research projects.

2. SEISMIC VULNERABILITY AND HAZARD

2.1 Seismic Hazard Maps (USGS) & Ground Motion

Bridge design to resist earthquake is required to understand the seismic vulnerability or earthquake intensity of the bridge location. This vulnerability is usually described in terms of seismic hazard. The U.S. Geological Survey (USGS) National Seismic Hazard Maps display earthquake ground motions for various probability levels across the United States and are applied in seismic provisions of building codes, insurance rate structures, risk assessments, and other public policy. This update of the maps incorporates new findings on earthquake ground shaking, faults, seismicity, and geodesy. The resulting maps are derived from seismic hazard curves calculated on a grid of sites across the United States that describe the frequency of exceeding a set of ground motions. Currently, the seismic new design and seismic retrofitting criteria uses 1000-year return period which is about 7% of probability not to exceed the design life of 75 years. AASHTO works with USGS and published a set of Seismic Hazard Maps for the whole US and issued a CD with a computer program tool to obtain the seismic hazard or ground motion by enter either zip code or longitudes & latitudes.

2.2 Geotechnical Hazard

Another factor to add on the highway bridges and constructions is geotechnical hazard. Geotechnical hazards at highway bridge sites that can be triggered by earthquakes include soil liquefaction, soil settlement, slope failure (landslides and rock falls), surface fault rupture, and flooding. Assessing geotechnical hazards is a two-part procedure. In the first part, a quick screening evaluation is conducted. Generally, this can be accomplished using available information and field reconnaissance.

If the criteria are satisfied, the risk is considered to be low and further evaluations of the hazard are not required. If a hazard cannot be screened out, more detailed evaluations are conducted in the second part of this procedure. This usually requires obtaining additional data to more rigorously assess the hazard and its consequences.

2.3 Assessment of Infrastructure Vulnerability

To assess the bridge inventory in the seismic vulnerability, a method, called Indices Method is often used. In this method, the seismic rating of a bridge is determined by its structural vulnerability, the seismic and geotechnical hazards at the site, and the socioeconomic factors affecting the importance of the structure. Ratings of each bridge are first found in terms of vulnerability and hazard, and then modified by importance (societal and economic issues) and other issues (redundancy and non-seismic structural issues) as necessary to obtain a final, ordered determination of retrofitting priority (Buckle, 1991; FHWA, 1995). This rating system has two parts: quantitative and qualitative. The quantitative part produces a seismic rating (‘bridge rank’) based on structural vulnerability and site hazard. The qualitative part modifies the rank in a subjective way that accounts for importance, network redundancy, non-seismic deficiencies, remaining useful life, and similar issues to arrive at an overall priority index.

3. HAZARD MITIGATION MEASURES

3.1 Seismic Design

The performance of US highway bridges in recent large earthquakes has shown that good design details have saved many bridges from collapse due to unseating of superstructure or shear failure of columns. Seismic design methods have evolved over the past 30 years and have produced details that directly affect bridge performance under earthquake and other natural hazard loadings. Design methods have steadily improved based on experience with destructive earthquakes and advanced seismic research. The current seismic design specification, adopted as a standard in 1992 by AASHTO, was primarily developed by US highway agencies, including FHWA and CALTRANS. Realistic seismic provisions first entered this code after the 1971 San Fernando earthquake. The fundamental design objective of the current seismic specifications is to prevent collapse in large earthquakes. In small to moderate events, the intent of the code is to resist seismic loads within the elastic range without significant damage to structural components. The objective in large earthquakes is that no span, or part of a span, should collapse. However, the AASHTO specifications consider limited damage to be acceptable in these circumstances, provided it is limited to flexural hinging in pier columns. Further, it is desirable that the damage occurs above ground in regions that are visible and accessible for inspection and repair.

3.1.1 Design Performance Criteria

Under the AASHTO’s newly adopted seismic design guide specifications, the seismic performance objective is life safety (no collapse) based on a one-level rather than two-level design approach. This single level design criterion is based on a 5% probability of exceedance in 50 years (1000-year return period event). Higher performance levels (such as the operational objectives) may be used with the authorization of the bridge owners; however, these provisions do not provide guidance beyond the one-level approach.

3.2 Seismic Retrofitting

Bridges constructed according to newer design codes, in general, respond better to large earthquakes than those built using current codes. By now, it is well known that about 65% of the 600,000 highway bridges in the U.S. were constructed prior to 1971, with little or no consideration given to seismic forces. These bridges are very vulnerable to earthquake strikes, and need to be retrofitted based on seismicity and structural types. Toward this end, FHWA has issued several publications. Seismic Retrofitting Guidelines for Highway Bridges was first issued in 1983, and was followed in 1987 by Seismic Design and Retrofitting for Highway Bridges. In 1995, FHWA updated these manuals with more current knowledge and practical technology. In 2006, FHWA published two volumes Seismic Manual of Highway Structures, including Bridges and other Structures.

3.2.1 FHWA New Seismic Retrofitting Manual

Retrofitting is the most common method of mitigating risks; however, its cost may be so prohibitive that abandoning the bridge (total or partial closure with restricted access) or replacing it altogether with a new structure may be preferred. Alternatively, doing nothing and accepting the consequences of damage is another possible option. The decision to retrofit, abandon, replace, or do-nothing requires that both the importance and degree of vulnerability of the structure be carefully evaluated. Limited resources will generally require that deficient bridges be prioritized, with important bridges in high risk areas being given the first priority for retrofitting.

This manual contains procedures for evaluating and upgrading the seismic resistance of existing highway bridges. Specifically, it contains:

- A screening process to identify and prioritize bridges that need to be evaluated for seismic retrofitting.

- A methodology for quantitatively evaluating the seismic capacity of a bridge and determining the overall effectiveness of alternative retrofitting measures, including cost and ease of installation.

- Retrofit approaches and corresponding techniques for increasing the seismic resistance of existing bridges.

This process is illustrated in Figure 3.1. A bridge may be exempt from retrofitting if it is located in the lowest seismic zone, or has limited remaining useful life. Temporary bridges and those closed to traffic, may also be exempt.

This manual does not prescribe rigid requirements as to when and how bridges are to be retrofitted. The decision to retrofit a bridge depends on a number of factors, several of which are outside the realm of engineering. These include, but are not limited to, the availability of funding and a number of political, social, and economic issues. This manual focuses on the engineering factors.

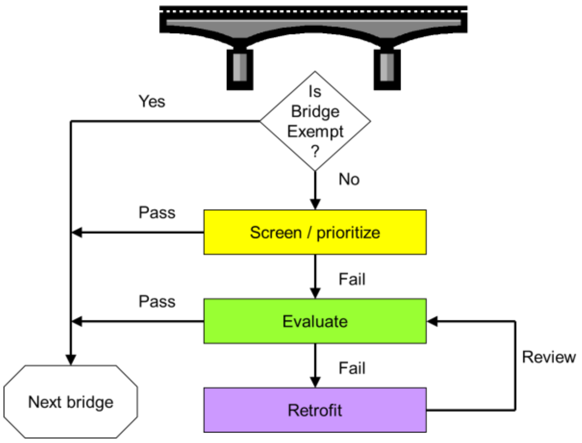

Figure 3.1 Overview of the retrofitting process for highway bridges.

3.3 Risk Analysis and Loss Estimations

Earthquakes are inevitable natural hazards with the potential for large numbers of fatalities and injuries, major property and infrastructure damage and serious disruption of everyday life. However, earthquake losses may be reduced to the minimum through a systematic risk assessment process. This has been recently recognized as a methodology of “Risk Management”, a process of determining what should be done for a hazard, deciding which hazards and at what scale magnitude should be managed, and in what priority order.

Effects of earthquake damage to highway components (e.g., bridges, tunnels, roadways, etc.) can go well beyond life-safety risks and costs to repair the damaged components. Such damage can also disrupt traffic flows which, in turn, can impact the region’s economic recovery and emergency response. These impacts will depend not only on the seismic performance of the components, but also on the characteristics of the overall highway system such as its network configuration and roadway-link characteristics (e.g., link locations, redundancies, and traffic capacities) with the GPS locations. Unfortunately, such traffic impacts are usually not considered in seismic risk reduction activities at state transportation departments. One reason for this has been the lack of a technically-sound and practical tool for estimating these impacts. Therefore, since the mid-1990s, the FHWA has sponsored multi-year seismic-research projects that have included development and programming of such a tool. This has led to new software named REDARS (Risks from Earthquake DAmage to Roadway Systems) that was released for public use in March 2006.

REDARS is a multi-disciplinary tool for seismic risk analysis (SRA) of highway systems nationwide. For any given earthquake, REDARS uses state-of-knowledge models to estimate: (a) the seismic hazards (ground motions, liquefaction, and surface fault rupture) throughout the system; (b) the resulting damage states (damage extent, type, and location) for each component in the system; and (c) how each component’s damage will be repaired, including its repair costs, downtimes, and time-dependent traffic states (i.e., its ability to carry traffic as the repairs proceed over time after the earthquake). REDARS incorporates these traffic states into a highway-network link-node model, in order to form a set of system-states that reflect the extent and spatial distribution of roadway closures at various times after the earthquake. Then, REDARS applies network analysis procedures to each system-state, in order to estimate how these closures affect system-wide travel times and traffic flows. Finally, REDARS estimates corresponding economic losses and increases in travel times to/from key locations or along key lifeline routes. These steps can be applied for single earthquakes and no uncertainties (deterministic analysis) or for multiple earthquakes and simulations in which uncertainties in earthquake occurrence and in estimates of seismic hazards and component damage are considered (probabilistic analysis).

4. THE IMPACT FROM RECENT LARGE EARQUAKES

The recent huge earthquakes in China, Haiti and Chile have brought the big challenges to the earthquake engineering communities around the world. The large intensities of peak ground accelerations and much longer duration of shaking have brought to much greater difficulty in design and retrofitting of our highway bridges. FHWA’s Seismic Research Program is working with seismic active States in the US as well as with other leading countries in the earthquake engineering, including Japan, Italy, China, Turkey, Chile and Taiwan, for the cooperation in exchanging technical information and collaborating in mutual interested research tasks.

FHWA is working with Multi-disciplinary Center of Earthquake Engineering Research (MCEER) of New York State University at Buffalo and University of Nevada at Reno (UNR) to initiate two major seismic research studies and started in 2007 to face the challenge of increase of traffic demand and seismic resilience of the highway infrastructure. The following are the summary of these two new studies:

4.1 The Innovative Technologies and Their Applications to Enhance the Seismic Performance of Highway Bridges

The objective of this study is to improve the seismic resistance of our highway system, by developing new innovative technologies and their applications, by developing cost-effective methods for implementing design and retrofitting technologies, and by refining and expanding applicability.

This project is to increase the mobility and safety of our surface transportation system as the FHWA envisions reducing the construction/ maintenance time of new and existing highway structures. Applying accelerated bridge construction technology to high seismicity area requires more advanced connection detail to accommodate the large ground motions. Innovative technologies and their applications are continuously sought to refine and expand their applicability to enhance the seismic performance of our surface transportation system. The major tasks of this study are: Developing Detailed Technology to Apply Accelerated Bridge Construction (ABC) in Seismic Regions and Innovative Seismic Protection Technologies.

4.2 Improving the Seismic Resilience of the Federal-Aid Highway System

As life-safety is no longer the sole requirement for the successful design of a highway system for a major earthquake. Resilience is now expected by the traveling public as an integral component of any design strategy, so as to ensure rapid recovery and minimal impact on the socio-economic fabric of modern society. This realization has led to the concept of performance-based seismic design which is a relatively new development in the design and construction of civil infrastructure. Nevertheless substantial progress has been made in this area, particularly with respect to the performance of individual components of the built environment, such as buildings and bridges. But the real potential for performance-based design comes when these concepts are applied to systems and subsystems of the infrastructure, such as transportation networks, subject to both service load conditions and extreme events.

Performance measures calculated by REDARS include congestion and delay times. These measures allow system-level performance criteria to be specified for earthquakes of various sizes, such as maximum permissible traffic delay times and minimum restoration times. Accordingly the resilience of a highway system may be defined and measured in quantitative terms, such as the time it takes to restore the system's pre-earthquake capacity, as illustrated in Figure 4.1. In doing so, financial and societal incentives can be developed that will improve resilience and at the same time reduce risk to life and property.

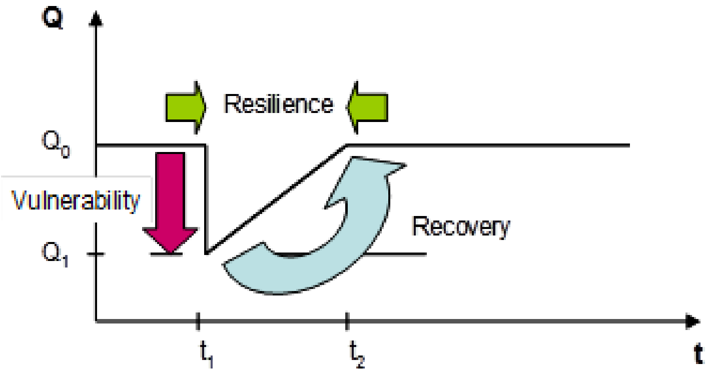

Figure 4.1. System resilience, after Bruneau (Buckle and Lee, 2006).

Whereas REDARS is the result of a decade-long period of development, and recently shown to adequately replicate the performance of the highway system in the San Fernando Valley following the 1995 Northridge earthquake, there is still much to be done to enable the methodology to be used with confidence and be widely applicable. REDARS has been developed with the expectation that new and more sophisticated modules will be developed overtime, in order to improve its accuracy and expand its range of application. This is considered a critical step in the drive towards quantifying the resilience of the highway system.

The objective of this project is to study the resilience of highway systems with a view to improving the performance of these systems subject to major earthquakes. A comprehensive assessment tool to measure highway resilience shall be developed by improving current loss estimation technologies, such as REDARS; factors affecting system resilience will be identified such as damage-tolerant bridge structures and network redundancy; design aids for curved bridges and those structures in near-fault regions will be developed; new technologies will be developed for improving the seismic performance of bridges; methodologies and technologies developed herein will be implemented in REDARS to the extent practical; and outreach to improve seismic safety will be conducted.

6. CONCLUDING REAMRKS

Hazard mitigation methods to reduce earthquake losses need a great effort for development and implementation. The most difficulty with mitigating earthquake hazards is that earthquakes come without any notice. There is no way to accurately predict when an earthquake will occur, nor what its magnitude will be. Earthquakes are devastating, often resulting in a great number of deaths, injuries and extensive infrastructure damage. Losses will occur in just one or two minutes. Systematic approaches to evaluating earthquake risks, including direct and indirect losses such as economic impact, have become an important issue in our engineering community.

Since 1992, US Dept. of Transportation initiated a series of comprehensive seismic research studies targeted on retrofitting, design and risk analysis issues, and have produced many national applicable seismic retrofitting manuals, design and risk analysis tools. The FHWA is working closely with AASHTO and NEHRP agencies to mitigate the earthquake hazard and reduce the earthquake loss. This is indeed running against the time to implement all possible measures to enhancing our highway infrastructure safety and mobility even with the challenges of earthquake hazard.

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