FHWA SEISMIC HAZARD MITIGATION RESEARCH PROGRAM

W. Phillip Yen, PhD, PE[1]

Abstract

This paper describes the Federal Highway Administration's (FHWA) seismic research program to mitigate earthquake loss of highway infrastructures. Since 1992, FHWA has initiated three major research projects in the seismic hazard mitigation; they are Seismic Vulnerability Study for Existing and New Highway Constructions, Seismic Vulnerability of Highway System, and the SAFETEA-LU Seismic Research Program. Major products of these three research programs were introduced and future developments under the current studies and recommended future studies due to the effects of recent large devastated earthquakes were also discussed.

Introduction

The public relies on highways for the safe transport of goods and people across the country. Because roads serve as critical lifelines in the delivery of basic daily needs, they need to function even in the face of adverse weather and natural hazards. From 1993–1996, the United States spent approximately $250 million per week responding to the impacts of natural disasters, with earthquakes, hurricanes, and floods being the major causes of monetary losses. At times, earthquakes can top the list. One of the most costly natural disasters in the United States between the late 1980s and late 1990s was California's Northridge Earthquake of 1994, which resulted in $20 billion in damages.

The loss of life and extensive property damage inflicted by the 1989 Loma Prieta and 1994 Northridge earthquakes emphasized the need to minimize seismic risks to the U.S. highway system. Seismic research projects conducted by the Federal Highway Administration (FHWA) are developing mitigation approaches to reduce those risks, including a method for assessing seismic risks and various structural designs and retrofitting measures.

Since 1992, FHWA has initiated a series of comprehensive seismic research studies targeting retrofitting, design, and risk analysis issues and the seismic research has produced a number of nationally applicable seismic retrofitting manuals and design and risk analysis tools.

[1]Principal Bridge Engineer, Office of Bridge Technology, Federal Highway Administration, 1200 New Jersey Ave. S.E., Washington, DC 20590 USA, Email address: Wen-huei.Yen@dot.gov

Early Earthquake Mitigation Research

FHWA initiated its earthquake investigations after the 1964 Prince William Sound Earthquake in Alaska. FHWA's followup focused on how bridge engineers could learn from the Alaska earthquake in terms of geotechnical issues such as soil properties.

Following the defective performance of bridges during the San Fernando Earthquake in 1971, FHWA and the California Department of Transportation (Caltrans) began exhaustive studies of the seismic performance of bridges. FHWA and Caltrans invested $3 million in basic research to develop national guidelines for bridge seismic design. The study evaluated the criteria used at the time for seismic design, reviewed findings from seismic research for potential use in a new specification, updated guidelines for seismic design, and evaluated the impact of those guidelines on construction and costs.

In 1979, FHWA and Caltrans completed the guidelines, which the American Association of State Highway and Transportation Officials (AASHTO) adopted in 1983 as its *Guide Specification for Seismic Design of Highway Bridges*. This specification became the national standard in 1992, following the Loma Prieta Earthquake. The design philosophy underlying this specification was to prevent collapse of any span or part of a span during large earthquakes. In small to moderate seismic events, the code's intent was for bridges to resist seismic loads without significant damage to structural components. Under this code, the design earthquake has a 475-year return period.

ISTEA and the Seismic Research Program

FHWA's earthquake research did not end with the adoption of this 1992 standard. The agency renewed its commitment to mitigating effects on highway structures by establishing a seismic research program, as called for in the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. The National Center for Earthquake Engineering Research, later renamed the Multidisciplinary Center for Earthquake Engineering Research (MCEER), conducted this program for FHWA. Under ISTEA, Congress funded the research with more than $14.5 million between 1991 and 1997, and the program covered all major highway system components (bridges, tunnels, embankments, retaining structures, and pavements). Approximately 65 percent of the Nation's 600,000 highway bridges were constructed prior to 1971, with little or no consideration given to seismic resistance. In recognition of that situation, the FHWA seismic research program initiated two comprehensive studies. In the fall of 1992, the program began studying the seismic retrofitting of existing highways, and in spring 1993 began studying the seismic design of new highways.

The first product of this research, *Seismic Retrofitting Manual for Highway Bridges* (FHWA-RD-94-052), appeared in 1995 and summarized lessons learned from more than 20 years of earthquake engineering research and implementation, and provided procedures for evaluating and upgrading the seismic resistance of existing bridges. In 1999 the program published *Impact Assessment of Seismic Design of*

Highway Structures, which became the major documentation used to develop recommendations for the seismic design of new bridges. In 2006, FHWA issued the final products of this research, *Seismic Retrofitting Manual of Highway Structures–Part I (Bridges)* (FHWA-HRT-06-032) and *Part II (Retaining Structures, Slopes, Tunnels, Culverts, and Roadways)* (FHWA-HRT-05-067). These new seismic design specifications were performance-based, and the major difference between them and the 1992 design code was that they had a two-level design criterion. The higher level was based on a 1,000-year return period, and the lower on a 100-year period.

Seismic Research Under TEA-21

In 1998 FHWA launched a congressionally mandated seismic research program under the Transportation Equity Act for the 21st Century (TEA-21), funded by another $12 million, to study seismic vulnerability. In cooperation with MCEER, the program conducted a series of studies to develop tools for evaluating and assessing the social costs and impacts of earthquakes on the U.S. highway system. The goal was to reduce the likelihood of damage to existing and future highway structures caused by moderate to significant seismic events.

The main tasks undertaken within this program were the following:

- Development of loss estimation methods for highway systems
- Preparation of a manual for the seismic design and retrofitting of long-span bridges
- Development of protective systems and a systems design manual for bridges
- Specialized ground motion, foundation, and geotechnical studies

Under TEA-21, FHWA worked with the National Cooperative Highway Research Program (NCHRP) in 2001 to develop new seismic design specifications. The project number and name was NCHRP 12-49, Comprehensive Specification for the Seismic Design of Highway Bridges. AASHTO then reviewed and revised the new design specifications and adopted them in 2007. The NCHRP 12-49 specification was developed from the 1999 recommendations and is about the same. The 2007 specification is a one-level design criterion for a 1,000-year return period.

With the TEA-21 seismic research program, FHWA developed a software package called REDARS: Risks from Earthquake DAmage to Roadway Systems to estimate the loss of highway system capacity due to earthquakes. The tool helps bridge owners estimate how earthquake damages affect post-earthquake traffic flows and enables them to consider those effects during pre-earthquake planning and prioritizations, and in post-earthquake responses, such as rescue and management of damage investigations. The seismic research program released REDARS in 2006.

REDARS is a multidisciplinary tool for seismic risk analysis of highway systems nationwide. For any given level of earthquake, REDARS uses state-of-knowledge models to estimate seismic hazards (ground motions, liquefaction, and surface fault rupture); the resulting damage (extent, type, and location) for each component in the highway system; and repairs of each component's damage, including costs, downtimes, and time-dependent traffic (that is, the component's 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 to form a set of system-states that reflect the extent and spatial distribution of roadway closures at various times after the earthquake. REDARS then applies network analysis procedures to each system-state in order to estimate how these closures affect systemwide travel times and traffic flows. Finally, REDARS estimates corresponding economic losses and increases in travel times to and from key locations or along key lifeline routes. Users can apply these steps for single earthquakes with no uncertainties (deterministic analysis) or for multiple earthquakes and in estimates of seismic hazards and component damage (probabilistic analysis).

Although REDARS adequately replicated the performance of the highway system in the San Fernando Valley during the Northridge Earthquake, much work still needs to be done to enable engineers to use the methodology with confidence. Indeed, the researchers developed REDARS with the expectation that new and more sophisticated modules will be developed over time to improve its accuracy and expand its range of application.

Also in 2006, the program published the *Seismic Retrofitting Manual for Truss Bridges*, particularly addressing truss bridges that are more than 500 feet (152 meters) long. The program also released a third report, *Isolation Bearing Design/Retrofit Manual*, in 2006.

SAFETEA-LU Seismic Research

In 2005, Congress passed the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). Under the new legislation, FHWA oversaw $12.5 million in seismic research to work with the bridge engineering community and enhance the earthquake resistance of U.S. highway bridges.

Also, SAFETEA-LU mandated a technology exchange and transfer task, which FHWA conducted through a series of bridge engineering workshops and conferences held nationally and internationally. The meetings involved exchange of technical information and performance of cooperative studies.

The outcomes of the succession of programs held over the past four decades include greater understanding in three areas: seismic vulnerability of specific locations, geotechnical hazards, and infrastructure vulnerability. Building on this increased body of knowledge, FHWA currently is developing improved seismic designs for new and retrofitted bridges, plus instrumentation to monitor performance.

(1) Assessing Seismic Vulnerability: Hazard Maps

To design a bridge to resist earthquakes, understanding the seismic vulnerability or earthquake intensity of the bridge's location is essential. This vulnerability usually is described as seismic hazard. The U.S. Geological Survey (USGS) publishes National Seismic Hazard Maps that display various probability levels of earthquake ground motions across the United States. The seismic provisions of building codes, insurance rate structures, risk assessments, and other public policy provisions commonly apply probability levels based on the hazard maps.

A 2003 update of the maps incorporates new findings on earthquake ground shaking, faults, and seismicity (that is, how prone a region is to earthquakes). USGS derived the new maps for a grid of sites across the United States by calculating seismic hazard curves that describe the frequency of exceeding a set of ground motions. Currently, the new seismic design and retrofitting criteria for bridges use a 1,000-year return period for a given level of earthquake, which represents not greater than a 7 percent probability of that earthquake occurring during a bridge design life of 75 years. AASHTO and USGS issued the new maps and computer software for obtaining seismic hazards by entering ZIP Codes or longitudes and latitudes.

(2) Assessing Geotechnical Hazards

Another factor in designing and retrofitting highway bridges is the geotechnical hazards that earthquakes can trigger, such as soil liquefaction and settlement, slope failure (landslides and rockfalls), surface fault ruptures, and flooding. Assessing geotechnical hazards is a two-part procedure. First, engineers conduct a quick screening evaluation, generally using information available from field reconnaissance.

If various criteria are satisfied, they consider the risk to be low and require no further evaluations. If a hazard cannot be screened out, they conduct more detailed and rigorous evaluations, which usually require obtaining additional data to assess the hazard and its consequences.

(3) Assessing Infrastructure Vulnerability

To assess the seismic vulnerability of the U.S. bridge inventory, researchers often use an indices method to determine a seismic rating. The method involves assessing a bridge's structural vulnerability, the site's seismic and geotechnical hazards, the socioeconomic factors affecting the structure's importance, and other issues such as bridge redundancy and nonseismic structural issues. Through this method, researchers arrive at a final, ordered determination of the retrofitting priority of individual bridges and, ultimately, for the Nation's entire infrastructure inventory.

The rating system has two parts. The quantitative part produces a seismic rating based on structural vulnerability and site hazard. The qualitative part modifies the rank in a subjective way that accounts for importance, network redundancy, nonseismic deficiencies, remaining useful life, and similar issues to arrive at an overall priority index.

(4) Mitigation Design of New Bridges

Based on advanced seismic research and experience with destructive earthquakes, AASHTO, NCHRP, and FHWA have improved seismic designs for new bridges. The results include design details that directly affect bridge performance under increased loadings due to earthquakes and other natural hazards.

The performance of U.S. highway bridges in recent large earthquakes has shown that the current state of the art has saved many bridges from collapse caused by unseating of the superstructure or shear failure of the columns,"

The fundamental design objective of current seismic specifications in small to moderate events is to resist seismic loads within an elastic range without significant damage to structural components. The objective in large earthquakes is that no span, or part of a span, should collapse. The specifications consider limited damage to be acceptable in these circumstances, provided it is confined to flexural hinging (that is, a hinge that allows an angle to be adjusted while it remains in place) in pier columns. Further, damage above ground is preferable so that it is visible in sections of the bridge that are accessible for inspection and repair.

Under current specifications, the seismic performance objective is no collapse based on a one-level rather than a two-level design approach. The current single-level design criterion is based on a 1,000-year return period event with not greater than a 5 percent probability of occurring during a bridge's 50-year design life. As an operational objective, a bridge's designers may use a higher, two-level performance level, but only with authorization from the bridge's owners. Current specifications, however, do not provide guidance beyond the one-level approach.

(5) Seismic Retrofitting of Existing Bridges

Retrofitting is the most common method of mitigating risks; in some cases, however, the cost might be so prohibitive that abandoning the bridge (total or partial closure with restricted access) or replacing it altogether with a new structure may be favored. Alternatively, doing nothing and accepting the consequences of damage is a possible option. The decision to retrofit, abandon, replace, or do nothing requires careful evaluation of the structure's importance and degree of vulnerability. Limited resources generally require that deficient bridges be prioritized, with important bridges in high-risk areas being retrofitted first.

Bridges constructed prior to 1971 in particular need to be retrofitted, based on seismicity and structural types. Toward this end, FHWA issued several publications, including *Seismic Retrofitting Guidelines for Highway Bridges* (FHWA-IRD-83-007) in 1983 and *Seismic Design and Retrofitting for Highway Bridges* (FHWA-IP-87-06) in 1987. In 1995, FHWA updated these manuals with more current knowledge and practical technology; *FHWA Seismic Retrofitting Manual of Highway Bridges* (FHWA-RD-94-052).

Then, as mentioned earlier, FHWA published *Seismic Retrofitting Manual of Highway Structures–Part I* and *Part II.* This two-volume manual contains the following procedures for evaluating and upgrading the seismic resistance of existing highway bridges:

- 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
- Retrofitting approaches and techniques for increasing the seismic resistance of existing bridges
- A methodology for determining the overall effectiveness of alternative retrofitting

measures, including cost and ease of installation

The manual does not prescribe rigid requirements as to when and how bridges are to be retrofitted. The decision to retrofit depends on a number of factors, several of which are outside the engineering realm. These other factors include, but are not limited to, the availability of funding and a number of political, social, and economic issues. A bridge may be exempt from retrofitting if it is located in a seismic zone with very little ground motion or has limited remaining useful life. Temporary bridges and those closed to traffic also may be exempt.

Future Developments

The recent huge earthquakes in Japan, Chile, and China have challenged earthquake engineering communities around the world. The intensity of peak ground accelerations and long duration of shaking in large earthquakes create greater difficulties for designing and retrofitting highway bridges. FHWA's seismic research program is exchanging technical information and collaborating on research with seismically active States in the United States and with other countries, including Chile, China, Italy, Japan, Taiwan, and Turkey.

Over the past 15 years, the program has held a series of conferences around the United States and bilateral workshops with other countries to promote new technology and exchange technical information. In 2009, the 25th U.S.–Japan Bridge Engineering Workshop, held in Tsukuba, Japan, marked the silver anniversary of this technology exchange and cooperation.

Under SAFETEA-LU, FHWA is working with MCEER, located at The State University of New York at Buffalo, and the University of Nevada, Reno, to initiate two major seismic research studies to help highway infrastructure face the challenges of big earthquakes yet to come. These studies focus on innovative protection techniques and seismic resilience.

(1) Developing Innovative Technologies

The first study's objective is to improve the seismic resistance of the U.S. highway system by developing innovative technologies, expanding their applicability, and developing cost-effective methods for implementing design and retrofitting technologies. As FHWA applies accelerated techniques to construction of new bridges and maintenance of existing bridges in high seismicity areas, this study is attempting to develop more advanced design details to accommodate large ground motions and increase the mobility and safety of the surface transportation system.

(2) Improving Seismic Resilience

Life-safety (no collapse and no loss of human life) is no longer the sole requirement for success in designing a highway system capable of resisting the impacts of a major earthquake. The traveling public now expects resilience as well—

that is, rapid recovery and minimal impact on the socioeconomic fabric of modern society.

The need for resilience has led to development of the concept of performance-based seismic design. 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. Thus, these measures allow resilience of a highway system to be defined and measured in quantitative terms, such as the time it takes to restore the system's pre-earthquake capacity. Accordingly, local transportation authorities can develop financial and societal incentives that will improve resilience and at the same time reduce risk to life and property.

FHWA and others have made substantial progress 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.

This project's objective is to study the resilience of highway systems with a view to improving performance during major earthquakes. By improving current loss estimation technologies such as REDARS, the FHWA researchers will develop a comprehensive assessment tool to measure highway resilience. They will identify factors affecting system resilience, such as damage-tolerant bridge structures and network redundancy, and develop design aids for curved bridges and structures in near-fault regions. To the extent practical, they will implement the new methodologies and technologies in REDARS and conduct outreach to improve seismic safety.

Concluding Remarks

The greatest difficulty in mitigating earthquake hazards is that seismic events occur without any notice and without any way of accurately predicting when they will occur, nor what their magnitude will be. Earthquakes are devastating, often resulting in a large number of deaths, injuries, and extensive infrastructure damage. These losses occur within minutes. Systematic approaches to evaluating earthquake risks, including indirect losses such as economic impacts, have become an important issue to the engineering community. Hazard mitigation methods to reduce earthquake losses require an enormous effort for development and implementation. FHWA is working closely with AASHTO and NCHRP to mitigate earthquake hazards and reduce losses, and the efforts to implement all practical measures to enhance the safety and mobility of the highway infrastructure are in a race against time with earthquakes.

Reference:

FHWA Congressional Seismic Research Studies under the ISTEA, TEA-21, and SAFETEA-LU Program.