Seismic Risk Analysis of Highway Systems: New Developments and Future Directions

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Abstract

A research project is being conducted to develop a new procedure for seismic risk analysis (SRA) of highway systems. The SRA procedure is multi-disciplinary, modular, and GIS-based, and includes new and improved models for scenario earthquakes, seismic hazards, bridge vulnerability, and transportation network analysis. The procedure has been used to evaluate the seismic performance of the highway system in Shelby County, Tennessee, in order to demonstrate the applicability of the method to an actual system. Future research will include the incorporation of improved models to estimate economic losses due to highway system damage, the continued development of the hazards, component, and system modules of the procedure, development of highway system database guidelines for SRA, and release of a public domain software package for SRA of highway systems.

Introduction

The Federal Highway Administration (FHWA) is funding a six-year research project titled "Seismic Vulnerability of Existing Highway Construction". This project, which is now in its final year, is being conducted by the Multi-Disciplinary Center for Earthquake Engineering Research (MCEER). A major task of this project is to develop a new procedure for seismic risk analysis (SRA) of highway systems.

Early efforts under this task included: (a) development of the framework of the SRA procedure; and (b) initial application of the procedure to the highway system

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in Shelby County, Tennessee using then-available models, in order to demonstrate the use of the procedure and to prioritize future research. These priorities have guided subsequent research that has led to improved models for scenario earthquakes, seismic hazards, bridge vulnerability, and transportation network performance.

Prior papers by the co-authors have summarized the basic framework and initial application of the SRA procedure (e.g., Werner et al., 1997). The current paper summarizes the most recent developments of the procedure, an updated SRA of the Shelby County highway system, and future research directions. Further detail on these developments is provided in Werner et al. (1999a and 1999b).

Basic Procedure

The SRA procedure (Fig. 1) can be carried out for any number of scenario earthquakes and simulations, in which a "simulation" is defined as a complete set of system SRA results for one set of input parameters and model uncertainty parameters. The model and input parameters for one simulation may differ from those for other simulations because of random and systematic uncertainties.

For each earthquake and simulation, this multi-disciplinary procedure uses geoseismic, geotechnical and structural engineering, transportation network, and economic models to estimate: (a) earthquake effects on system-wide traffic flows; and (b) economic impacts of highway system damage. The heart of the SRA procedure is a GIS data base comprised of four modules that contain the data and models needed to characterize the system, hazards, components, and economics (Fig. 1). Features of the procedure include: (a) its GIS framework, which enhances data management, analysis efficiency, and display of analysis results; (b) its modular GIS data base, which facilitates the incorporation of improved models from future research efforts; (c) its ability to develop aggregate SRA results that are either deterministic or probabilistic, thereby facilitating its usefulness for a variety of applications; and (d) its use of rapid engineering and network analysis procedures, which enhances its future use as a real-time predictor of system performance shortly after an actual earthquake.

New Developments

Improved procedures for characterizing scenario earthquakes, seismic hazards, bridge vulnerabilities, and transportation network analysis have been developed. These developments, which are summarized below, are now incorporated into a new beta software package named REDARS 1.0 (Risks due to Earthquake DAmage to Roadway Systems).

Scenario Earthquakes.. SRA of a highway system with spatially dispersed components requires use of scenario earthquakes to evaluate the simultaneous effects of individual earthquakes on components at diverse locations (including systemic consequences of damages). Scenario earthquake models being incorporated into

REDARS are an adaptation of work by Frankel et al. (1996) which was developed under the United States Geological Survey (USGS) National Hazard Mapping Program. Frankel et al. models for the Central (CUS) are summarized later in this paper. Adaptation of Frankel et al. models for California is now underway. All adaptations feature a "walk-through" analysis, which is a natural way to assess system loss distributions and their variability over time.

Seismic Hazards. The ground motion models for the SRA procedure include rock motion attenuation characteristics representative of the region where the system is located, as well as amplification of rock motions due to local soil conditions. For the Central United States, the Hwang and Lin (1997) rock motion attenuation relationships and soil amplification factors for NEHRP site classifications meet these requirements. Liquefaction hazard models are based on work by Youd (1998), and include: (a) geologic screening to eliminate sites with a low potential for liquefaction; (b) use of modified Seed-Idriss type methods to assess liquefaction potential during each earthquake and (c) for those sites with a potential for liquefaction during the given earthquake, estimation of lateral spread displacement and vertical settlement using methods by Bartlett and Youd (1995) and by Tokimatsu and Seed (1987).

Component Models. Component models for highway system SRA develop traffic state fragility curves, which estimate the probability of a given traffic state (i.e., open lanes at various times after the earthquake) as a function of the level of ground shaking or permanent ground displacement at the component site. Thus far, this research has focused on developing such models for bridges, which are prone to damage from both ground shaking and permanent ground displacement. These models estimate the bridge's damage state (locations and extents of all damage) under a given level of ground shaking or displacement, from which expert opinion assessments of damage repair requirements serve to establish corresponding traffic states. The SRA procedure now includes the Jernigan (1998) method for developing bridge fragility curves, which is summarized later in this paper. Work to also incorporate a new rapid-pushover method (Dutta and Mander, 1998) is underway.

Transportation Network Analysis. The SRA procedure contains two different transportation network analysis methods. For deterministic SRA for a limited number of scenario earthquakes and simulations, a User Equilibrium (UE) method is used. This is an exact mathematical solution to an idealized model of user behavior, which assumes that all users follow routes that minimize their travel times. For probabilistic SRA involving many scenario earthquakes and simulations, a new Associative Memory (AM) transportation network analysis procedure is used. This method has the following features: (a) it provides rapid estimation of network flows; (b) it represents the latest well-developed technology for estimating traffic flows; (c) it is GIS compatible; and (d) it uses transportation system input data that are typically available from Metropolitan Planning Organizations. The AM procedure is derived from the artificial intelligence field, and provides rapid and dependable estimates of flows in congested networks for given changes in link configuration due to earthquake damage (Moore et al., 1997).

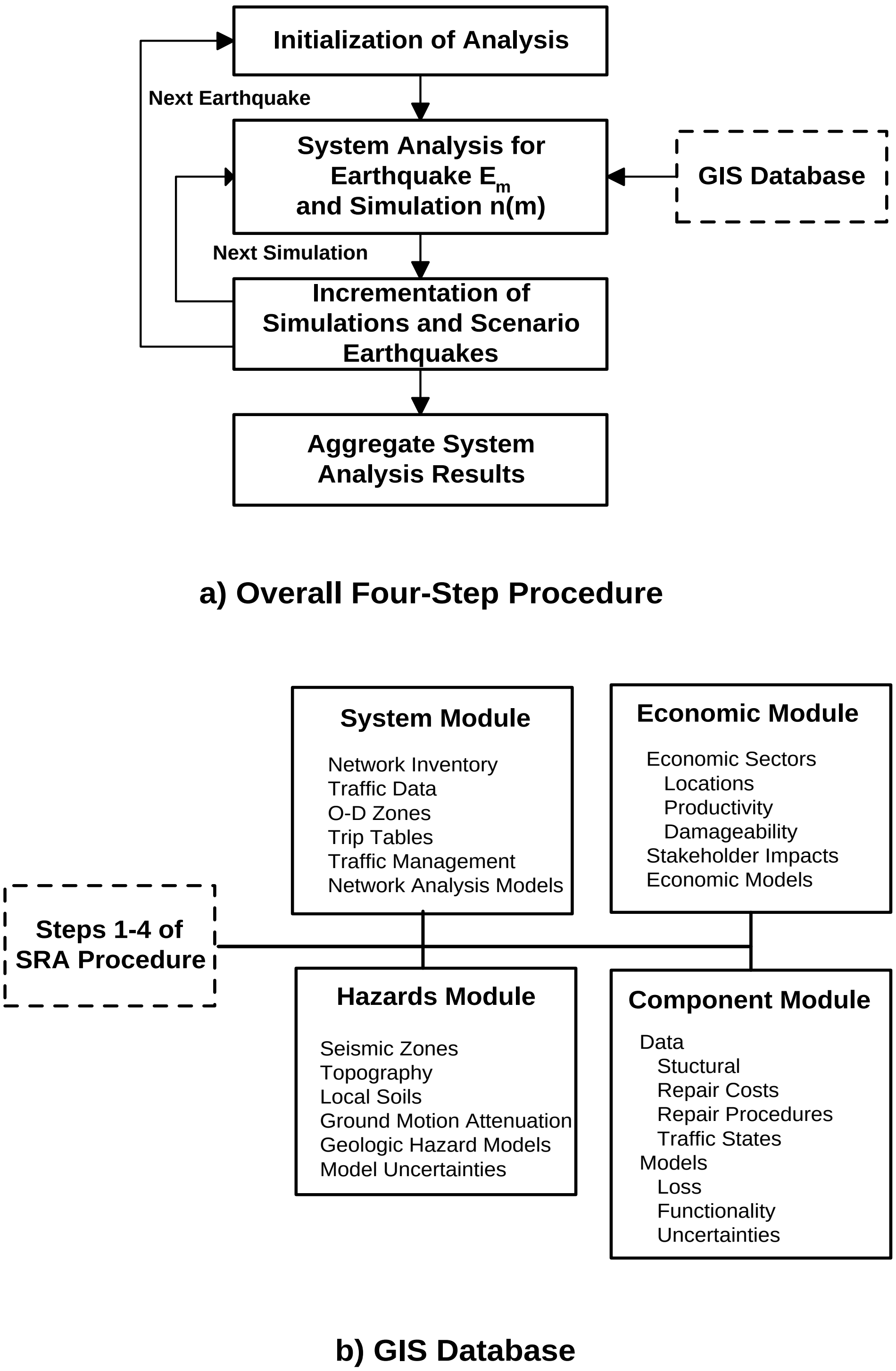

Figure 1. Procedure for Seismic Risk Analysis of Highway Systems

Demonstration Application

System Description. The foregoing procedure was used in a demonstration SRA of the highway system in Shelby County, Tennessee. Shelby County is located in the southwestern corner of Tennessee, just east of the Mississippi River. Its highway-roadway system contains a beltway of highways that surrounds, the city of Memphis, two major crossings of the Mississippi River, and major roadways that extend outward from the center of Memphis to the north, south, and east (Fig. 2). Traffic demands on the system are modeled by using trip tables that define the number of trips between all of the origin-destination (O-D) zones in the county. Figure 3 shows these O-D zones, as well as the particular zones for which post-earthquake travel times were monitored in this SRA.

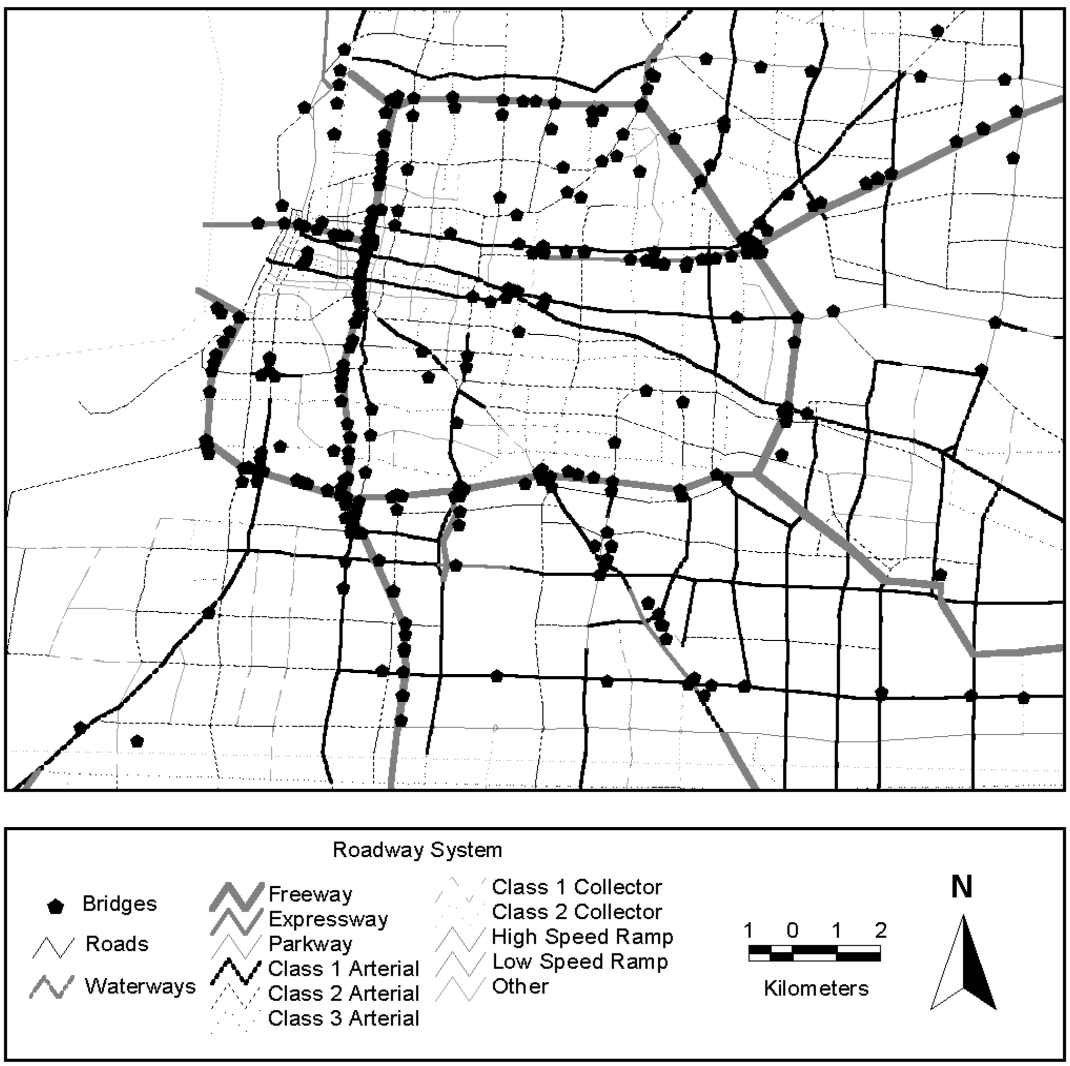

Figure 2. Shelby County Tennessee Highway System

Figure 3. Origin-Destination Zones in Shelby County, Tennessee

Input Data. The input data used in this SRA are as follows: (a) system input data describing the highway-roadway network geometry, traffic capacities, O-D zones, and traffic demands were based on the 1995 system model provided by the Shelby County Office of Planning and Development; (b) soils input data, in terms of NEHRP soil classifications and initial screening for liquefaction potential, were based on local geology mapping carried out by the Center of Earthquake Research and Development at the University of Memphis; and (c) bridge attribute input data were based on data compilation efforts described in Jernigan (1998).

Scenario Earthquakes. This SRA was conducted as a walk-through analysis that encompassed a duration of 50,000 years. Earthquakes occurring during each year of this duration were estimated by adapting the Frankel et al. (1996) models of the region. This process generated 2,321 earthquakes with moment magnitudes ranging from 5.0 to 8.0. Each earthquake was located into one of the 1,763 microzones (with lengths and widths of about 11.1 km) that encompassed the surrounding area.

Seismic Hazards. Only ground shaking hazards were considered in this SRA, and were modeled using the previously noted methods by Hwang and Lin (1997).

Component Damage States (*Bridges and Approach Fills).* For typical bridges, fragility curves for damage states due to ground shaking hazards were based on procedures developed by Jernigan (1998). The first step in this process was to assign each bridge in Shelby County (excluding the Mississippi River crossings) into one of six bridge groupings that represented different combinations of superstructure and substructure characteristics. Then, group fragility curves were developed by applying dynamic analysis and elastic capacity-demand procedures to representative bridges in each group, in which random combinations of uncertain input parameter values were considered. Special procedures were used to develop fragility curves for the Mississippi River crossings, which involved separate evaluation of dynamic response and limit states for each segment that comprised these bridges. Approach fill damage states were estimated by applying procedures developed under other tasks of the FHWA-MCEER highway project, as summarized in Werner et al. (1999b).

Component Functionality. A highway component's functionality (ability to carry traffic) at various times after an earthquake will depend on the level of damage, the redundancy of the component's structural system, the repair procedure and duration, whether the repairs will require partial or full closure to traffic, and the duration of these closures. From these considerations, estimates of traffic closure extents and times were developed from discussions with experienced bridge engineers and construction personnel. These estimates are lower bounds since they assume that all equipment, labor, and material resources to carry out the repairs are readily available. However, this may not be the case, if there is competition for scarce resources in the presence of widespread earthquake damage to a region's infrastructure. It is noted that sensitivity studies can be used to assess increased economic losses that would occur from longer closure times due to insufficient availability of repair resources.

Transportation Network Analysis. The GIS model of the Shelby County highway system contains 7,807 links and 15,614 nodes, and includes a full range of roadway types (Fig. 2). The previously described transportation network analysis procedures were used to estimate post-earthquake traffic flows from this models.

Economic Losses. Economic losses due to highway system damage were estimated by using simplified models that consider effects of increases in commute time only (as summarized in Werner et al., 1999). Anticipated future research will focus on the development of improved economic models.

Implementation. For each scenario earthquake, the SRA procedure estimated the ground shaking and the corresponding damage state and traffic state at each bridge site. Closures at these sites were incorporated into the highway network model, resulting in modified system states at various times after the earthquake. Then, the previously noted network analysis procedures were applied to each system state, in order to estimate increases in travel times due to highway system damage at times of 7 days, 60 days, and 150 days after the earthquake. Finally, economic losses due to these travel time increases were estimated. Once this process was completed for all scenario earthquakes, the results were used to develop deterministic and probabilistic estimates of: (a) economic losses due to highway system damage; and (b) increases in travel times to key locations at various times after the earthquake.

Sample Results. Figure 4 and Table 1 provide sample results from this analysis. Figure 4 shows probability distributions for economic losses caused by the array of earthquakes occurring over the 50,000-year duration considered in this SRA. These results are shown for exposure times of 1, 10, 50, and 100 years. Table 1 provides example deterministic estimates of increases in access time to the various locations in Shelby County that are shown in Figure 3.

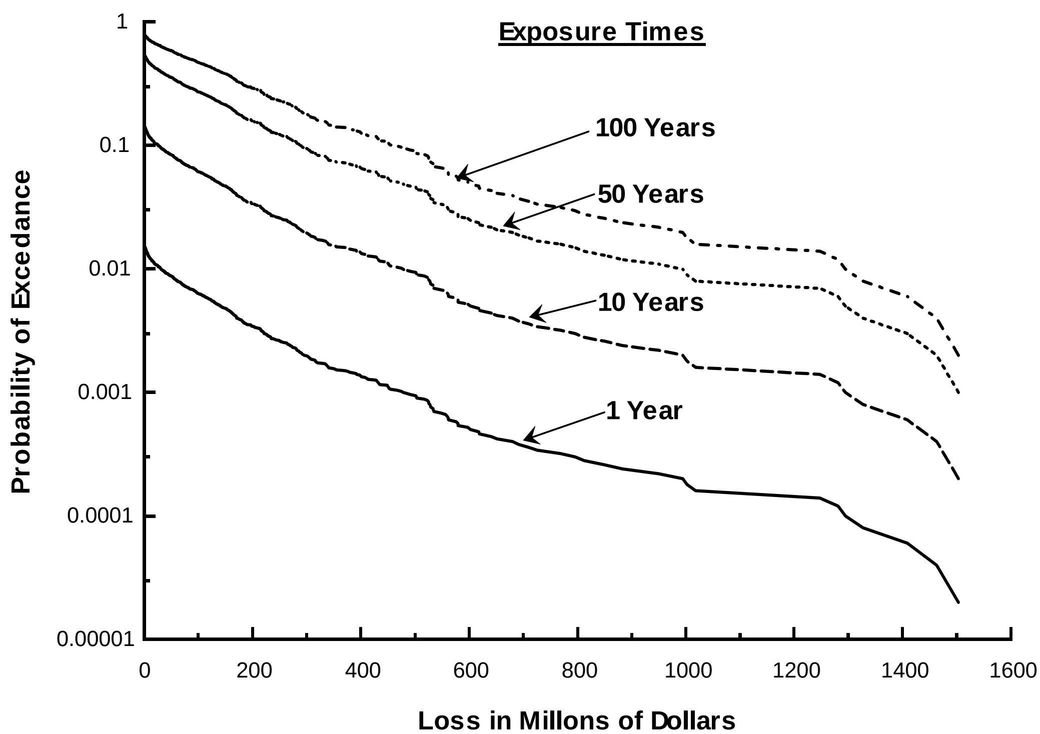

Figure 4. Probability Distribution for Economic Losses due to Earthquake-Induced Increases in Commute Times caused by Earthquake Damage to Shelby County Highway System

Table 1. Increase in Access Times to Locations in Shelby County due to Damage to Highway System caused by Earthquake 11140 (M_w = 6.8 centered 65.8 km Northwest of Government Center)

Origin-Destination Zone	Post-Earthquake Access Time		
	7 Days after EQ	60 Days after EQ	150 Days after EQ
9 (Government Center in downtown Memphis)	43.8%	5.8%	2.0%
28 (Major Hospital Center, just east of downtown Memphis)	44.6%	6.7%	2.0%
205 (Memphis Airport and Federal Express transportation center, south of beltway)	53.7%	4.0%	1.6%
73 (University of Memphis campus in central Memphis)	21.6%	4.3%	1.5%
310 (Germantown, residential area east of beltway)	2.9%	0.9%	0.4%
160 (President's Island, Port of Memphis at Mississippi River)	34.9%	6.1%	1.6%
246 (Hickory Hill, commercial area southeast of beltway)	3.9%	1.9%	1.1%
335 (Shelby Farms residential area northeast of beltway)	28.4%	4.8%	1.6%
412 (Bartlett, residential area north of beltway)	13.2%	3.0%	1.3%

Future Research Directions

Recommended research to further develop the SRA procedure include: (a) development of improved models to estimate economic losses due to highway system damage; (b) continued development of damage-state and traffic-state models for bridges and other highway components; (c) further development of transportation network analysis procedures, including improved treatment of post-earthquake traffic demands; (d) further development of hazards models, including models for estimating landslide and surface fault rupture hazards; (e) sensitivity analyses to guide treatment of parameter uncertainties; (f) development of highway system data base guidelines for SRA; and (g) continued development of the REDARS software package.

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