A Risk-Based Methodology for Assessing the Seismic Performance of Highway Systems

by Stuart D. Werner

Research Objectives

The objective of this research is to develop, apply, program, and disseminate a practical and technically sound methodology for seismic risk analysis (SRA) of highway-roadway systems. The methodology's risk-based framework uses models for seismology and geology, engineering (structural, geotechnical, and transportation), repair and reconstruction, system analysis, and economics to estimate system-wide direct losses and indirect losses due to reduced traffic flows and increased travel times caused by earthquake damage to the highway system. Results from this methodology also show how this damage can affect access to facilities critical to emergency response and recovery.

Past experience has shown that effects of earthquake damage to highway components (e.g., bridges, roadways, tunnels, etc.) may not only include life safety risks and post-earthquake costs for repair of the components. Rather, such damage can also disrupt traffic flows and this, in turn, can impact the economic recovery of the region as well as post-earthquake emergency response and reconstruction operations. Furthermore, the extent of these impacts will depend not only on the seismic response characteristics of the individual components, but also on the characteristics of the highway system that contains these components. System characteristics that will affect post-earthquake traffic flows include: (a) the highway network configuration; (b) locations, redundancies, and traffic capacities and volumes of the system's links between key origins and destinations; and (c) component locations within these links.

From this, it is evident that earthquake damage to certain components (e.g., those along important and non-redundant links within the system) will have a greater impact on the system performance (e.g., post-earthquake traffic flows) than will other components. Unfortunately, such system issues are typically ignored when specifying seismic performance requirements and design/strengthening criteria for new and existing components; i.e., each component is usually treated as an individual entity only, without regard to how its damage may impact highway system per-

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formance. Furthermore, current criteria for prioritizing bridges for seismic retrofit represent the importance of the bridge as a traffic carrying entity only by using average daily traffic count, detour length, and route type as parameters in the prioritization process. No attempt is made to account for the systemic effects associated with the loss of a given bridge, or for the combination of effects associated with the loss of other bridges in the highway system.

To address these issues, current and recent highway research projects conducted by MCEER and funded by the Federal Highway Administration (FHWA) have included tasks to develop a SRA methodology for highway systems. This paper describes this methodology, presents results from a demonstration application of the methodology to the highway system in Shelby County, Tennessee, and summarizes plans for the further development, application, programming, and dissemination of the methodology. Further details on this methodology and its applica-

tion are contained in the report by Werner et al. (2000).

Methodology Description

The SRA methodology (Figure 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 particular 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 multidisciplinary process uses geoseismic, engineering (geotechnical, structural, and transportation), network, and economic models to estimate: (a) earthquake effects on system-wide traffic flows and corresponding travel times, paths, and distances; (b) economic impacts of highway system damage (e.g., repair costs and costs of travel time delays); and (c) post-earth-

> **This SRA methodology will provide cost and risk information that will facilitate more rational evaluation of alternative seismic risk reduction strategies by decision makers from government and transportation agencies involved with improvement and upgrade of the highway-roadway infrastructure, emergency response planning, and transportation planning. Such strategies can include prioritization and seismic strengthening measures for existing bridges and other components, establishment of design criteria for new bridges and other components, construction of additional roadways to expand system redundancy, and post-earthquake traffic management planning.**

quake traffic flows to and from important locations in the region. Key to this process is a GIS data base that contains four modules with data and models that characterize the system, seismic hazards, component vulnerabilities, and economic impacts of highway system damage (Figure 1b). These are incorporated into the four-step SRA procedure shown in Figure 1a.

This SRA methodology has several desirable features. First, it has a GIS database, to enhance data management, analysis efficiency, and display of analysis results. Second, the GIS database is modular, to facilitate the incorporation of improved data and models from future research efforts. Third, the procedure can develop aggregate SRA results that are either deterministic (consisting of a single simulation for one or a few scenario earthquakes) or probabilistic (consisting of many simulations and scenario earthquakes). This range of results facilitates the usefulness of SRA for a variety of applications (e.g., seismic retrofit prioritization and criteria, emergency response planning, planning of system expansions or enhancements, etc.). Finally, the procedure uses rapid engineering and network analysis procedures, to enhance its possible future use as a real-time predictor of component damage states, system states and traffic impacts after an actual earthquake.

Recent 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 pre-beta software package named REDARS 1.0 (Risks due to Earthquake DAmage to Roadway Systems).

(a) Overall Four-Step Procedure

(b) GIS Database
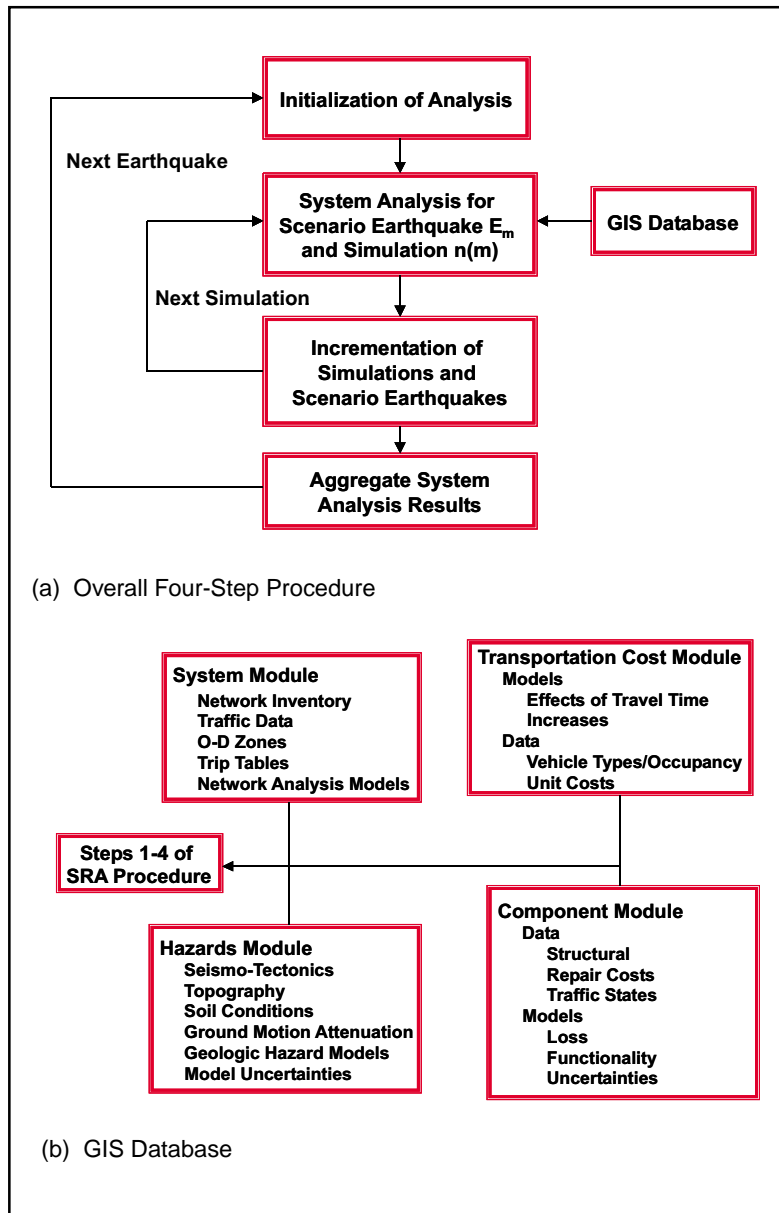
■ **Figure 1.** Risk-Based Methodology for Assessing Seismic Performance of Highway Systems

Assessing the Seismic Performance of Highway 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). Earthquake models now being incorporated into REDARS are adaptations 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 models for California (which also builds on work by the California Division of Mines & Geology) 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. Models appropriate to other regions of the country are now being incorporated. 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 Youd and by Tokimatsu and Seed (1987) respectively.

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 only. These models estimate the bridge's damage state (damage types, locations, and extents) under a given level of ground shaking or displacement, and then obtain corresponding traffic states by using expert-opinion damage-repair models. The SRA methodology now includes three options for modeling damage states of bridges due to ground shaking: (a) an elastic capacity-demand approach by Jernigan (1998); (b) a simplified but rational mechanics-based method by Dutta and Mander (1998) that develops rapid estimates of damage states based on bridge-specific input parameters inferred from the FHWA National Bridge Inventory database; and (c) user-specified fragility curves, which can be developed for any bridge in the system, but are most appropriate for complex or unusual bridges. In addition, the SRA methodology includes a first-order

model for estimating bridge damage states due to permanent ground displacement.

Transportation Network Analysis

The SRA procedure contains two 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 earthquakes and simulations, a new Associative Memory (AM) transportation network analysis procedure is used. This method provides rapid estimation of network flows, represents the latest well-developed technology for estimating traffic flows, is GIS compatible, and uses transportation system input data that are typically available from Metropolitan Planning Organizations. It 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).
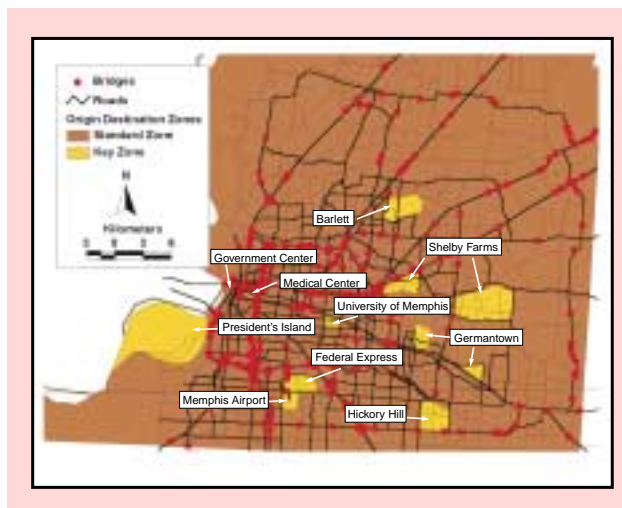
Demonstration Application

System Description

The SRA methodology was used in a demonstration application to the highway system in Shelby County, Tennessee. Shelby County


■ **Figure 2.** Shelby County Tennessee Highway System Model (7,807 Links and 15,604 Nodes)

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

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 from the center of Memphis to the north, south, and east (Figure 2). Traffic demands on the system are modeled by trip tables that define the number of trips between all of the origin-des-
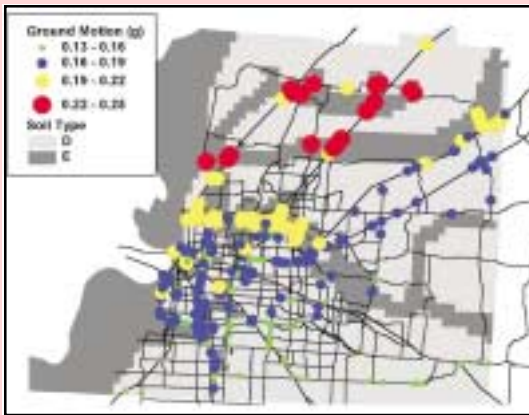
■ **Figure 4.** Ground Motion Hazard. Spectral Acceleration at Period of 1.0 Sec.

■ **Figure 5.** Liquefaction Hazard. Permanent Ground Displacement.
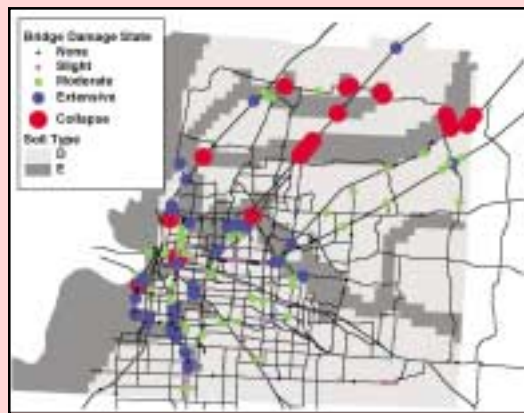
■ **Figure 6.** Bridge Damage States

tination (O-D) zones in the county. Figure 3 shows these O-D zones, as well as those zones for which post-earthquake travel times were monitored in this SRA.

Input Data

The input data for this SRA are as follows: (a) system input data describing the roadway network geometry, traffic capacities, O-D zones, and traffic demands were developed from a working file for the County's projected network for the year 2020 that was 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) attribute input data for each of the 384 bridges in the network were based on data compilation efforts by Jernigan (1998).

Scenario Earthquakes

This SRA was conducted as a walk-through analysis with 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 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.

## Typical Results for One Scenario Earthquake and Simulation

To illustrate the form of the results for one earthquake and simulation, we consider a scenario earthquake with moment magnitude of 6.9 centered about 65 km northwest of downtown Memphis. For this event, ground shaking hazards and liquefaction hazards were estimated by the previously noted methods by Hwang and Lin (1997) and Youd (1998) respectively. (Figures 4 and 5). Next, the Dutta-Mander (1998) approach was used to estimate bridge damage states (Figure 6), and associated system states at various times after the earthquake were developed by applying the first-order repair model given in Werner et al. (2000) to these damage states (e.g., Figure 7). Network analysis procedures summarized earlier in this paper were then applied to each system state, to obtain corresponding system-wide traffic flows and travel time delays. Finally, simplified economic analysis methods adapted from California Department of Transportation models and summarized in Werner et al. (2000) were used to estimate corresponding economic losses (due to commute time increases only).

Economic Losses

After results of the type shown above are developed for each scenario earthquake and simulation during each year of the walkthrough, they can be aggre-
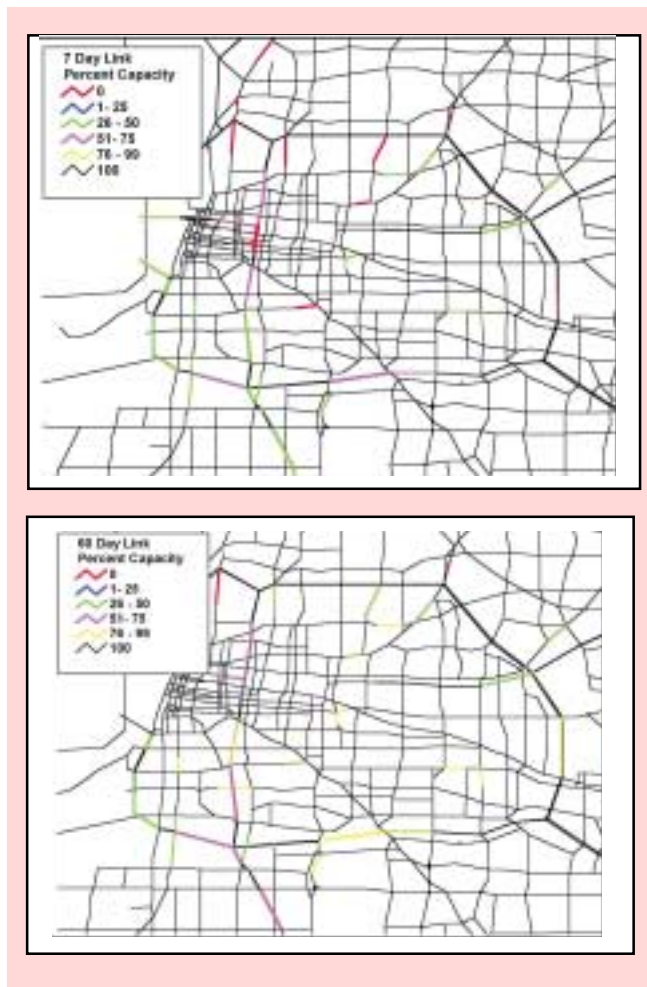
■ **Figure 7.** System States at 7 Days (top) and 60 days (bottom) after Earthquake
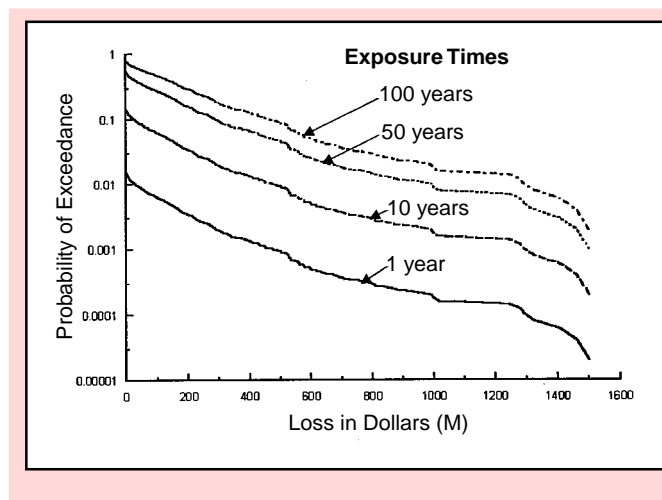
■ **Figure 8.** Economic Losses due to Earthquake-Induced Increases in Commute Times in Shelby County, Tennessee

Assessing the Seismic Performance of Highway Systems

■ Table 1. Increase in Access Times to Locations in Shelby County due to Damage to Highway System from Earthquake with Magnitude 6.8 centered 66 km Northwest of Downtown Memphis

Origin-Destination Zone (see Fig. 3)	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%

gated to obtain probablistic estimates of economic losses. Figure 8 shows results of this type for exposure times of 1, 10, 50, and 100 years. Deterministic estimates of economic losses can also be obtained for selected individual earthquake events.

Travel Times for Selected Locations

For emergency planning purposes, it may be of interest to estimate how travel times to and/or from selected key locations in the region may be affected by earthquake damage to the highway system. Such results can be developed as aggregated probabilistic curves (similar in form to Figure 8) or as deterministic estimates for selected earthquake events (see Table 1).

Conclusions/Future Directions

The risk-based methodology described in this paper estimates how

earthquake damage to highway systems can affect post-earthquake traffic flows and travel times. It is a technically sound and practical approach that will enable decision makers to consider system-wide traffic effects when evaluating various seismic risk reduction options for highway components and systems.

Although the basic SRA methodology is in place, further work remains before it can be disseminated and applied to highway systems nationwide. For example, the REDARS 1.0 pre-beta software package that is based on this methodology is now being independently validated and applied. This will help to identify future directions for further development of this software. Additional improvements now being planned include: (a) incorporation of models for estimating scenario earthquakes and ground motion hazards nationwide; (b) development of models for estimating system-wide landslide and surface fault rupture hazards; (c) de-

velopment of improved component repair models; (d) development of vulnerability/fragility models for retrofitted bridges as well as other highway components such as tunnels, slopes, pavements, walls, and culverts; and (e) development of the system module to accommodate post-earthquake traffic demands that differ from pre-earthquake demands.

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