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# NEW DEVELOPMENTS IN SEISMIC RISK ANALYSIS OF HIGHWAY SYSTEMS

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## SUMMARY

A new procedure has been developed for seismic risk analysis (SRA) of highway systems. The SRA procedure is multidisciplinary, 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 procedure to an actual system. Future research will incorporate improved models for estimating 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.

## 1. INTRODUCTION

The United States Federal Highway Administration has funded a six-year research project titled “Seismic Vulnerability of Existing Highway Construction”. This project has been directed by the Multidisciplinary Centre for Earthquake Engineering Research (MCEER) of Buffalo, New York. One of the major tasks of this project has been the development of 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 in Shelby County, Tennessee using then-available models, in order to demonstrate the use of the procedure and to prioritise 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 summarised the basis framework and initial application of the SRA procedure (e.g., Werner et al., 1997). The current paper summarises 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 contained in Werner et al. (1999a and 1999b).

## 2. BASIC PROCEDURE

The SRA procedure (Figure 1a) 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 of another simulation before of random and systematic uncertainties.

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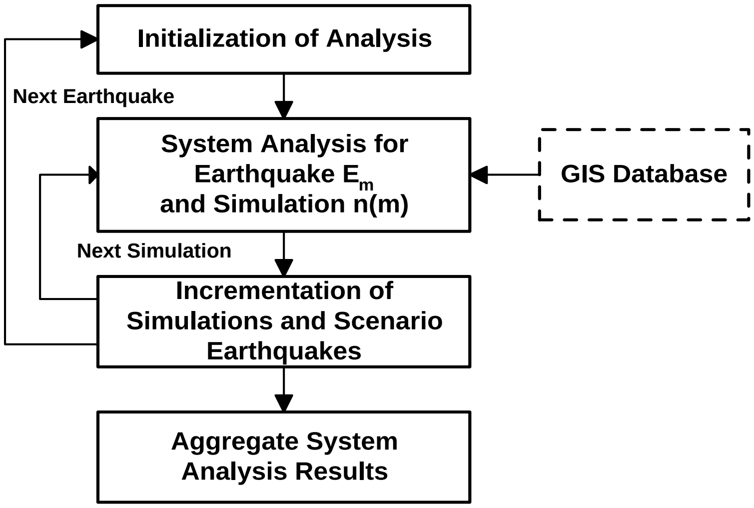
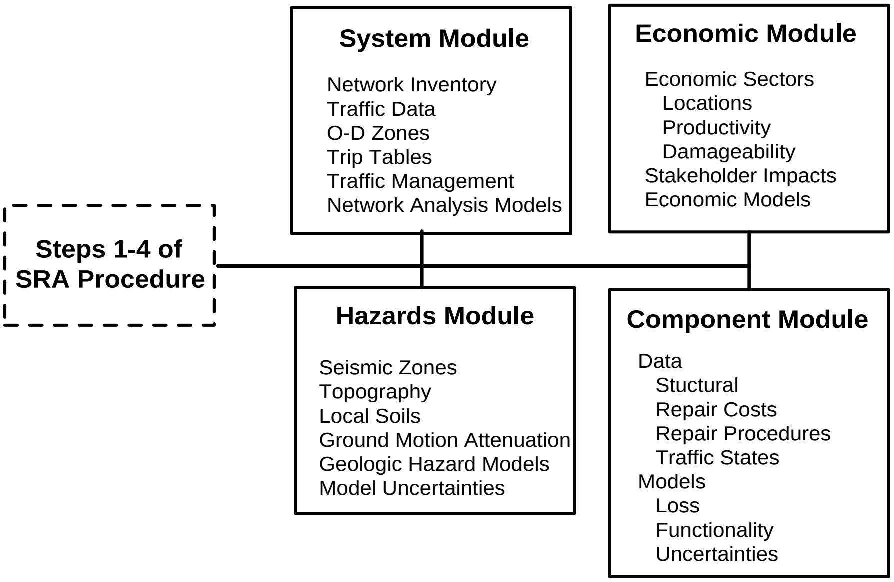


a) Overall Four-Step Procedure



b) GIS Database

**Figure 1: Procedure for Seismic Risk Analysis of Highway Systems**

For each scenario earthquake and simulation, this multidisciplinary 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 characterise the system, hazards, components, and economics (Figure 1b). Features of this 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.

## 3. NEW DEVELOPMENTS

Improved procedures for modelling scenario earthquakes, seismic hazards, bridge vulnerabilities, and transportation network flows have been included into a new beta software package named *REDARS 1.0* (Risks from Earthquake DAmage to Roadway Systems). These developments, are summarised below.

### 3.1 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 Geologic Survey (USGS) National Hazard Mapping Program. Frankel et al. models for the Central United States (CUS) are summarised 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.

### 3.2 Seismic Hazards

The ground motion models for the SRA procedure estimate: (a) site-specific rock motions, and how they are affected by earthquake magnitude and by increasing distance from the earthquake source; and (b) how the rock motions are amplified or de-amplified by local soil conditions. For the Central United States, the Hwang and Lin (1997) rock motion attenuation and soil amplification/de-amplification factors (for site conditions characterised using the latest National Earthquake Hazard Reduction Program (NEHRP) site classifications) are adapted into *REDARS*. 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 at each remaining site during each scenario 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).

### 3.3 Component Vulnerabilities

Component models now included in *REDARS* consist of traffic state fragility curves, which estimate the probability that the component is in a given traffic state (i.e., has some fraction of its lanes open to traffic at various times after an earthquake) as a function of the level of ground shaking and permanent ground displacement at the site. Thus far, this research has developed such models for bridges. The first step in developing the fragility curves is to estimate the bridge’s damage state (locations, types, and extents of damage) as a function of the level of ground shaking and displacement. Then, expert opinion models are used to estimate the traffic state corresponding to each damage state. For conventional bridges, REDARS now includes two approaches: (a) a model by Jernigan (1998) which was developed for bridges in the Central United States; and (b) a three-dimensional pushover method by Dutta and Mander (1999) that is useful for bridges for which only limited structural data are readily available (which is typical of bridge data in most regions of the United States). For major bridges, more detailed procedures are used on a case-by-case basis (Werner et al, 1999b).

### 3.4 Transportation Network Analysis

The SRA procedure contains two different transportation network analysis procedures. For deterministic SRA involving a limited number of scenario earthquakes and simulations, a User Equilibrium (UE) method is used. This is an exact mathematical solution to an idealised models of user behaviour, which assumes that all users follow routes that minimise their travel times. For probabilistic SRA involving many scenario earthquakes and simulations, a new Associative Memory (AM) procedure is used that has the following features: (a) it is particularly efficient for estimating network traffic flows for large numbers of earthquakes and simulations; (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 most Metropolitan Planning Organisations throughout the United States. 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).

## 3.5 Demonstration Application

### *3.5.1 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 south-central United States, just east of the Mississippi River in the south-eastern corner of the state of Tennessee. 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 centre of Memphis to the north, south, and east (Figure 2). Traffic demands on the system are modelled 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, and highlights those particular zones for which post-earthquake travel times were monitored in this SRA.

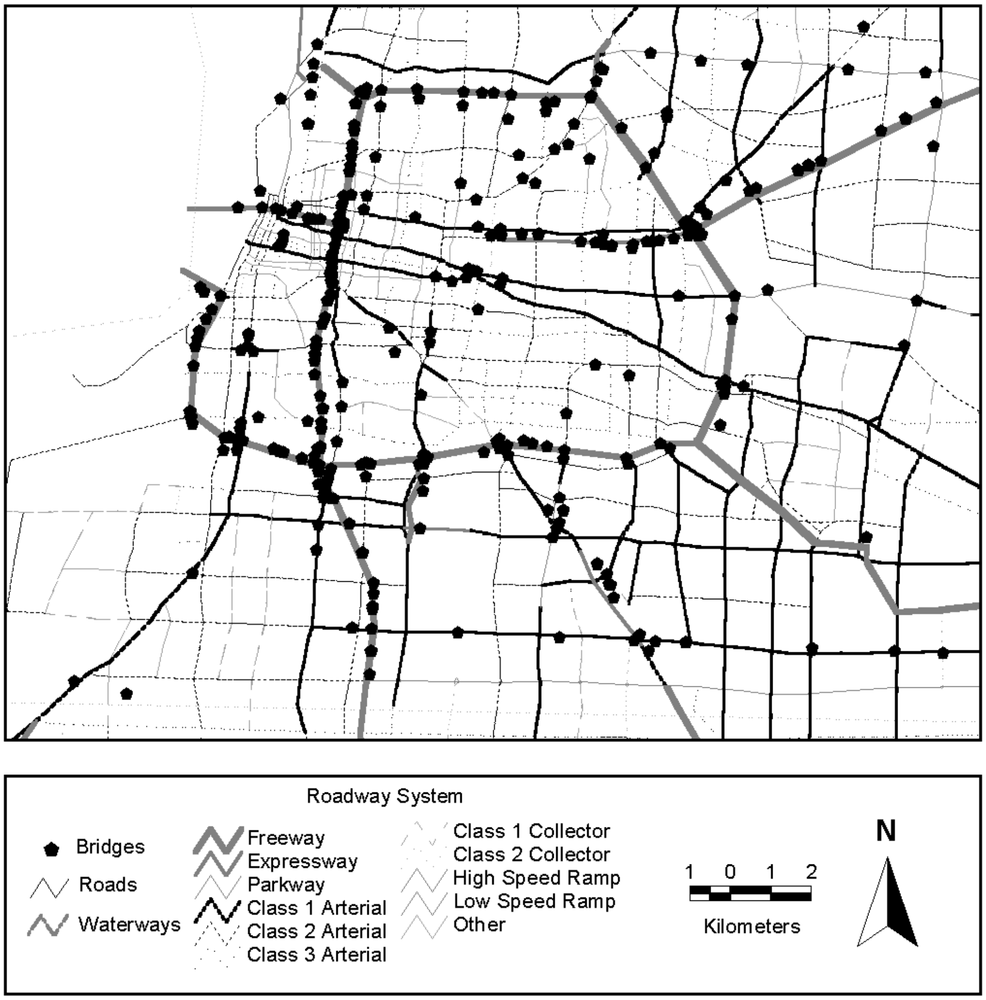


**Figure 2. Shelby County Tennessee Highway Roadway System**

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

### 3.5.2 Input Data

The input data for this SRA are as follows: (a) system input data describing the highway-roadway network geometry, traffic capacities, O-D zones, and traffic demands that 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 site classifications and initial screening for liquefaction potential, were based on local geology mapping by the Centre for Earthquake Research and Development at the University of Memphis; and (c) bridge attribute data, which were based on data compilation efforts described in Jernigan (1998).

### *3.5.3 Scenario Earthquakes*

This SRA was conducted as a walk-through 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 Central United States. 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.

### *3.5.4 Seismic Hazards*

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

### *3.5.5 Component Damage States (for 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 groups that represent different combinations of superstructure and substructure characteristics. Then, fragility curves for each group 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. For major bridges (e.g., the Mississippi River crossing), fragility curves were developed from special procedures which involved separate evaluations of dynamic response and limit states for each segment that comprised these bridges. Approach fill damage states were estimated by applying simplified methods summarised in Werner et al. (1999b).

### *3.5.6 Transportation Network Analysis*

The network model of the Shelby County highway system contains 7,807 links and 15,614 nodes, and includes a full range of roadway types. The network analysis procedures summarised in Section 3.4 were used to estimate post-earthquake traffic flows from this model.

### *3.5.7 Economic Losses*

Economic losses due to highway system damage were estimated by using simplified models that only include effects of increases in commute time (see Werner et al., 1999a). Future research will focus on the development of improved economic models.

### *3.5.8 Implementation*

For each scenario earthquake, the SRA procedure estimated the ground shaking hazard and the corresponding damage state and traffic state at each bridge site, together with any partial or complete earthquake-induced traffic closures at each bridge (including closures of underlying roadways, if the damage to the overlying bridge was sufficiently severe). Traffic closures estimated for each of three post-earthquake times (at 7 days, 60 days, and 150 days after the earthquake) were incorporated into the highway network model, to establish modified system states at each of these times. Next, the transportation network analysis procedures described in Section 3.4 were applied to each post-earthquake system state, in order to estimate increases in travel times due to highway system damage. Finally, economic losses due to these travel time increases were estimated. Once this process was completed for all scenario earthquakes occurring during each year of the walk-through, the results were used to develop probabilistic and deterministic estimates of: (a) economic losses due to highway system damage; and (b) increases in travel times to key locations at each of the above post-earthquake times.

### *3.5.9 Sample Results*

Figure 4 and Table 1 provide sample results from this analysis. Figure 4 shows probabilities of exceedance for various levels of economic loss caused by the array of scenario 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 shows example deterministic estimates of increases in access time to the various locations shown in Figure 3.

## 4. FUTURE RESEARCH DIRECTIONS

Future research to further develop the SRA procedure will focus on: (a) improved economic loss models due to highway system damage; (b) improved damage state and traffic state models for bridges and other highway components; (c) enhanced transportation network analysis procedures that treat how post-earthquake traffic demands vary with time after an earthquake; (d) improved hazard models, including models for landslide and surface fault rupture hazards; (e) sensitivity studies to improve treatment of parameter uncertainties; (f) highway system data base guidelines; and (g) continued upgrades of the *REDARS* software package.

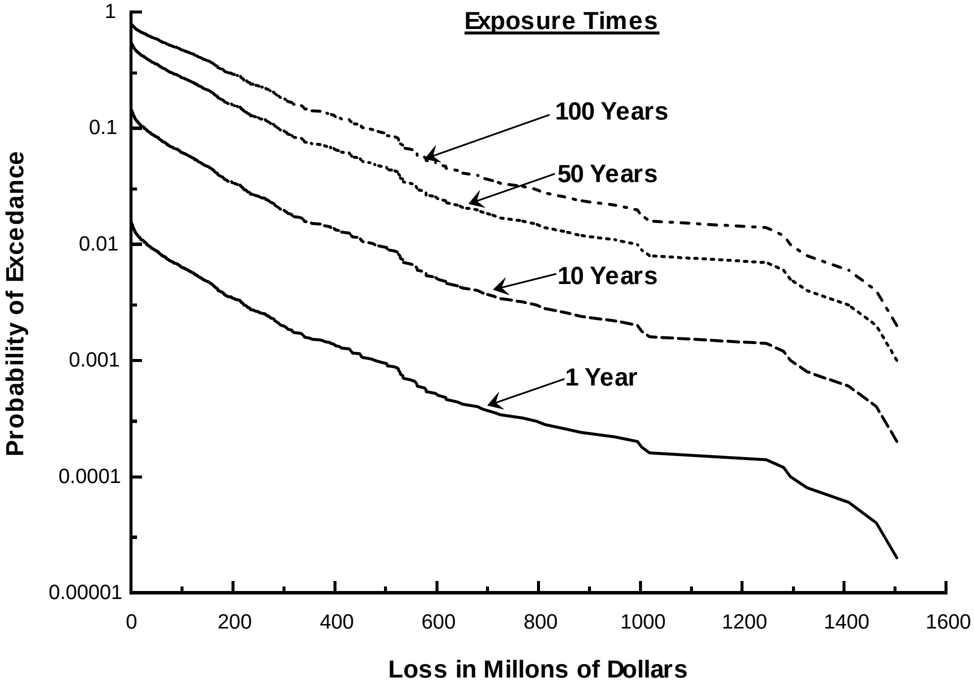


**Figure 4: Economic Losses due to Increases in Travel Times caused by Earthquake Damage to Shelby County Highway System**

**Table 1: Increases in Access Times in Shelby County due to Damage to Highway Systems caused by Earthquake 11140 (Moment Magnitude 6.8 centred 65.8 km Northwest of Government Centre)**

| Origin-Destination Zone | Percent Increase in Post-Earthquake Access Time | | |
|---|---|---|---|
| | 7 Days after EQ | 60 Days after EQ | 150 Days after EQ |
| 9 (Government Centre in downtown Memphis) | 43.8% | 5.8% | 2.0% |
| 28 (Hospital Centre east of downtown Memphis) | 44.6% | 6.7% | 2.0% |
| 205 (Airport and Federal Express transportation centre east of beltway) | 53.7% | 4.0% | 1.6% |
| 73 (University of Memphis in central Memphis) | 21.6% | 4.3% | 1.5% |
| 310 (Germantown residential centre east of beltway) | 2.9% | 0.9% | 0.4% |
| 160 (Port of Memphis along 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% |

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## ABSTRACT