New Developments in Seismic Risk Analysis for Highway Systems

by

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ABSTRACT

This paper summarizes current research to develop a new seismic risk analysis (SRA) procedure for highway and roadway systems. The procedure synthesizes geoseismic, engineering, network, and economic models to assess earthquake effects on system-wide traffic flows and travel times. The SRA results provide an improved basis for prioritizing highway components for seismic retrofit, and for defining seismic performance requirements for these components.

KEY WORDS: earthquake, seismic, risk, highways, roadways, bridges, hazards, system, network

1. INTRODUCTION

Past experience has shown that earthquake damage to highway components (e.g., bridges, roadways, tunnels, retaining walls, etc.) can severely disrupt traffic flows and this, in turn, can impact the economy of the region as well as post-earthquake emergency response and recovery. 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 system 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 (e.g., Moore et al, 1997).

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., traffic flows) than will other components. Unfortunately, such system issues are typically ignored when specifying seismic performance requirements and design 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 performance. 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. These criteria do not account for the systemic effects associated with the loss of a given bridge, or for combinatorial effects associated with the loss of other bridges in the highway system. However, consideration of these systemic and combinatorial effects can provide a much more rational basis for establishing seismic retrofit priorities and performance requirements for highway components.

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In recognition of these issues, the National Center for Earthquake Engineering Research (NCEER) has included system seismic risk analysis (SRA) in its current six-year seismic research project entitled "Seismic Vulnerability of Existing Highway Construction." This paper describes the SRA research being conducted under the NCEER project including: (a) a new SRA procedure that has been developed under the project; (b) an initial demonstration application of the procedure to the Memphis Tennessee highway system; (c) current research to further develop the procedure; and (d) the applicability of the procedure for real-time post-earthquake loss estimation.

2. SEISMIC RISK ANALYSIS PROCEDURE

2.1 General Description

The highway system SRA procedure is shown in Figure 1. It 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 (Werner et al., 1996).

For each earthquake and simulation, this multi-disciplinary procedure uses geoseismic, geotechnical and structural engineering, transportation network analysis, and economic evaluation models to estimate: (a) earthquake effects on system-wide traffic flows (e.g., 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-earthquake traffic flows along vital roadways (to facilitate emergency response planning). Key to this procedure is a modular GIS data base that contains the data and models needed to implement the system SRA.

This SRA procedure has several desirable features. First, it has a GIS framework, to enhance data management, analysis efficiency, and display of analysis results. Second, the GIS data base 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 future use as a real-time predictor of system states and traffic impacts shortly after an actual earthquake.

2.2 GIS Data Base

The GIS data base consists of four modules with data and models that characterize the system, seismic hazards, component vulnerabilities, and economic impacts of highway system damage. To facilitate analysis efficiency, these modules are pre-processors to the four-step SRA procedure shown in Figure 1.

2.2.1 System Module

The system module contains the following information to characterize the highway system, as provided by transportation and urban planning specialists:

System Data – including: (a) system network configuration linkages, and component types and locations; (b) numbers of lanes, traffic flows, capacities, and congestion functions for each roadway link; (c) origin-destination zone locations and trip tables; and (d) any special system characteristics, such as certain roadways being critical for emergency response or national defense.

Traffic Management – including measures by transportation authorities for modifying the system to ease post-earthquake traffic flows

(e.g., detour routes, modifications of roadways from two-way to one-way traffic, etc.)

Transportation Network Analysis Procedures – to estimate post-earthquake traffic flows for each simulation and scenario earthquake.

2.2.2 Hazards Module.

The hazards module contains input data and models provided by geologists and geotechnical engineers for characterizing system-wide ground motion, liquefaction, landslide, and surface fault rupture hazards. Input data include: (a) the ensemble of scenario earthquake events developed during the initialization phase of the SRA (Sec. 3.1); (b) locations and topographic data for slopes within the system that could be prone to landslide; and (c) local soil conditions throughout the system, as needed to estimate local geologic effects on ground shaking and the potential for liquefaction and landslide. Models contained in the hazards module will estimate: (d) the attenuation of rock motions with increasing distance from the earthquake source, for a range of earthquake magnitudes; (e) the effects of local soil conditions on the motions at the ground surface; and (f) permanent ground displacements due to earthquake-induced landslide, liquefaction, and surface fault rupture. A deterministic representation of hazards models will use mean values of these quantities. A probabilistic representation will use probability distributions to account for uncertainties in the seismologic, geologic, and soil input parameters and in the hazard evaluation models.

2.2.3 Component Module

The component module contains input data and models provided by structural and construction engineers to characterize each component in terms of a "loss model" and a "functionality model". The loss model represents the component's direct losses (i.e., repair costs), and the functionality model represents its "traffic states" (i.e., whether the component will be partially or completely closed to traffic during the repair of the earthquake damage, the durations of these closures, and speed limits for traffic along the component during repair). Both models are a function of the level of ground shaking at the component's site, as well as the level of permanent ground displacement due to liquefaction, landslide, or surface fault rupture. The models for each component are developed by evaluating: (a) its seismic response to each designated level of ground shaking and permanent ground displacement; (b) its "damage state", (i.e., the degree, type, and locations of any earthquake damage to the component); (c) its damage repair procedures; and, from this (d) its traffic states at various times after the earthquake (to reflect the rate of traffic restoration as repairs proceed).

After each component's traffic states are obtained, they are incorporated into the highway system network model to obtain the overall "system state", i.e., the ability of each link in the system to carry traffic at various times after the earthquake (in terms of number of open lanes, speed limits, etc.). These system states will reflect the effect of each component's damage state on adjacent and underlying roadways. This, of course, will also depend on the location of the component within the overall system, as well as system network characteristics.

A deterministic representation of loss and functionality models will use mean values of the component repair costs and traffic states. A probabilistic representation will use probability distributions to account for uncertainties in the evaluation of the component seismic response, and in the estimation of the resulting repair costs and traffic states.

2.2.4 Socio-Economic Module

The socio-economic module contains models and data for evaluating broader social and economic impacts of earthquake-induced traffic flow disruptions. These impacts can include indirect dollar losses (e.g., to commuters and businesses), effects on emergency response (e.g., reduced access to medical, police, firefighting, airport, government centers, etc.), and societal effects (e.g., reduced access to residential areas, shopping areas, etc.). This module is developed by transportation specialists, urban planners, and economists.

3. ANALYSIS PROCEDURE

3.1 Step 1: Initialization of Analysis

The initialization of the SRA (Step 1) contains two parts. First, regional earthquake source models are used to define an ensemble of scenario earthquakes, in which each earthquake is most commonly defined in terms of its magnitude, location, and frequency of occurrence. Uncertainties in defining the values of the various earthquake input parameters may also be modeled at this stage. The second part of Step 1 establishes the total number of simulations for each scenario earthquake, as further described in Werner et al. (1996).

3.2 Step 2: Development of Each Simulation for Each Scenario Earthquake

Under Step 2, the following evaluations are carried out to develop each of the simulations for each scenario earthquake:

Hazard Evaluation. First, the data and models contained in the hazards module are used to estimate the earthquake ground motions and geologic hazards throughout the system.

Direct Loss and System State Evaluation. Once the hazards are estimated, the data and models from the component module are used to evaluate direct losses and system states (defined at various times after the earthquake).

Traffic Flow Evaluation. The system data and transportation network analysis procedure from the system module are applied to the pre-earthquake system and post-earthquake system states, to assess earthquake effects on system-wide travel times, travel distances, and travel paths, as well as traffic flows along roadways vital to emergency response.

Socio-Economic Impact Evaluation. Once the earthquake effects on traffic flows within the system are evaluated, the data and models from the socio-economic module are used to evaluate impacts of the impeded traffic flows in terms of: (a) indirect dollar losses; and (b) reduced access to and from emergency response centers.

3.3 Step 3: Incrementation of Simulations and Scenario Earthquakes

Under Step 3, the evaluations from Step 2 are repeated, in order to develop multiple simulations for multiple scenario earthquakes (if the SRA is to be probabilistic).

3.4 Step 4: Aggregate System Analysis Results

This final step in the SRA process is carried out after the system analyses for all simulations and scenario earthquakes have been completed. In this step, the results from all simulations and earthquakes are aggregated and displayed. Depending on user needs, these aggregations could focus on the seismic risks associated with the total system or with individual components. Furthermore, the system or component results could be provided: (a) for individual simulations, which is termed a seismic vulnerability analysis, and/or (b) for the broader (probabilistic) range of simulations, leading either to loss statistics (e.g., average annualized loss) or to loss distributions that show the severity of earthquake-induced system losses for different probability levels[7]. For research purposes, the impacts of incorporating uncertainties into the SRA will be of considerable interest. For other purposes, such as the planning of seismic strengthening programs for existing highway systems, outputs can be adapted and/or simplified to meet the particular requirements of each user audience.

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[7]The "loss" can be defined in several ways, such as direct repair cost, travel time delays due to earthquake damage (between certain key origin-destination zones or aggregated over all zones), indirect losses due to travel time delays, or other adverse consequences.

4. DEMONSTRATION ANALYSIS

4.1 Objective and Scope

Early in the NCEER Highway Project, the SRA procedure was used with then-available data and models to carry out a demonstration SRA of the Memphis, Tennessee highway-roadway system (Fig. 2). The objective of the analysis was to: (a) illustrate the application of the SRA procedure, and the types of results that can be obtained; and (b) provide a basis for identifying and prioritizing research needs to improve the procedure. Because of limitations in many of the then-available data and models, the results from this SRA are preliminary. Nevertheless, it is of interest to briefly summarize this SRA, in order to illustrate the applicability of the procedure. This SRA application is described in more detail by Werner and Taylor (1995).

4.2 Assumptions

The Memphis highway-roadway system is shown in Figure 2. This demonstration SRA consisted of deterministic analysis of the response of this system to four different earthquake events (Fig. 3a). This paper presents results from one of these earthquakes, termed Earthquake D, which has a moment magnitude of 5.5 and is centered about 35 km to the north of the northern segment of the beltway that surrounds the city of Memphis. Assumptions for this SRA are summarized below.

4.2.1 System Input Data

The system's network configuration was obtained from the University of Memphis. Traffic data, roadway traffic capacities, and O-D zones within the system were provided by the Memphis and Shelby County Office of Planning and Development (OPD). The traffic flow data were from their 1988 traffic forecasting model.

4.2.2 Network Analysis Procedure

The MINUTP traffic forecasting software (Comsis, 1994) was used to analyze pre- and post-earthquake traffic flows. This software was chosen because it is used at the Memphis-Shelby County OPD, and all regional traffic data were available in the input format for this software. MINUTP is based on the Urban Transportation Planning System (UTPS), which was developed over two decades ago by the U.S. Dept. of Transportation (see Sec. 5.5.1). Also, the then-available version of MINUTP was not GIS-compatible, which increased the effort needed for our system analysis.

4.2.2 Seismic Hazards

The system-wide ground shaking due to Earthquake D was represented in terms of peak ground acceleration (PGA), and was based on soil conditions obtained from prior local geologic mapping by the University of Memphis (Fig. 3b). The PGA at each bridge site was estimated by: (a) computing site-specific bedrock accelerations by using an early version of the Hwang and Huo (1997) attenuation equation; and (b) applying the Martin and Dobry (1994) soil amplification factors to these rock accelerations, to obtain corresponding ground surface PGAs that include effects of local soil conditions (Fig. 4).

4.2.3 Bridge Loss Models

Loss models previously developed under the ATC-25 project for conventional highway bridges were used to estimate direct losses for each bridge in the system due to each earthquake (ATC, 1991). In these models, the direct losses depend only on whether the bridge has simple spans or is continuous/monolithic; i.e., other bridge structural attributes that could impact seismic performance are not considered.

4.2.4 Bridge Functionality Models

Functionality models for this demonstration SRA represented bridge traffic states as the number of lanes open at discrete times after an earthquake, as a function of PGA and the original number of lanes along the bridge. They were developed by modifying ATC-25 bridge restoration models based on prior observations of the seismic performance and repair and reconstruction processes for California bridges during the Loma Prieta and Northridge Earthquakes (Werner and Taylor, 1995). Two different models were developed in accordance with the ATC-25 conventional highway bridge designations -- one for simple-span bridges and one for continuous bridges. In addition, to illustrate effects of bridge damage repair rates on post-earthquake system performance, functionality models were developed for two discrete times -- three days and six months after the earthquake.

4.2.5 Economic Model

Studies of economic impacts of earthquake-induced highway system damage have shown that indirect dollar losses due to such damage can far exceed the direct losses for repair of the damage (e.g., Gordon and Richardson, 1996). However, methods for estimating such impacts for future earthquakes are not yet well developed. Therefore, for this demonstration SRA, a simplified procedure from BAA (1994) was used to estimate costs due to deterioration in commute time only. These cost estimates are based on vehicle-hours of delay (as obtained from the MINUTP system analyses), corresponding person-hours of delay (based on an assumed average vehicle occupancy rate of 1.4 persons/vehicle), truck-hours of delay (assuming 30 percent of the vehicles are trucks), and excess fuel costs due to travel time delays.

4.3 RESULTS

4.3.1 Direct Losses

In accordance with the ATC-25 model used in this demonstration SRA, direct losses due to damage to the system's bridges are represented as a damage ratio, DMG (%), which is defined as the ratio of the repair cost for each bridge to its total replacement cost. For Earthquake D, the average damage ratio (averaged over all of the 286 bridges in the system) was 37.4%.

4.3.2 Travel Times and Distances

System State Results. Figure 5 shows the pre-earthquake system state and post-earthquake system states at times of three days and six months after Earthquake D. This figure indicates that, although Earthquake D has only a moderate magnitude ($M_W = 5.5$), its proximity to the northern segment of the Memphis highway system causes extensive roadway closures in that segment, with lesser impacts on other segments of the system.

Total System-Wide Travel Times. Table 1 contains the total pre- and post-earthquake travel times and distances for the Memphis highway system. This table shows that the modified system states due to Earthquake D result in a total system-wide travel time three days after the earthquake that is nearly 34 percent longer than the pre-earthquake values. At six months after the earthquake, the bridge repairs within that time have reduced the total travel time; however it is still nearly 20 percent longer than the pre-earthquake value.

Total System-Wide Travel Distances. Table 1 shows that the total system-wide travel distances at times of three days and six months after the occurrence of Earthquake D are not sensitive to the modified system states. This trend may be due to the significant loss of service along the faster but less direct highway segments at the north and northeastern portions of the beltway, because of the many damaged bridges along those segments. As a result, drivers would be forced to use ground surface routes with fewer damaged bridges that are shorter but slower than the beltway routes.

O-D Zone Travel Times. Table 2 shows that, at a time of three days after the earthquake, the travel times between the O-D zones listed in the table are, on the average, nearly 16 percent larger than those for the pre-earthquake system. The travel time increases are largest for northernmost of the highlighted zones, which are at Shelby Farms (Zones 249 and 252), Bartlett (Zone 264), and the Covington Pike

(Zone 274). This is because, as previously noted, it is this section of the Memphis area highway and roadway system that is most severely damaged. At a time of 6 months after the earthquake, Table 2 shows that the travel times to and from these zones have been reduced substantially, and are now only 5.3 percent larger than the pre-earthquake values.

O-D Zone Travel Distances. The travel distances to and from the O-D zones listed in Table 2 are insensitive to system damage from Earthquake D (Werner and Taylor, 1995).

Economic Impacts. Estimates of economic impacts for times of both three days and six months after the earthquake are shown in Table 3. They are based on total system-wide travel time delays per 24-hour day of 126,000 vehicle-hours and 73,000 vehicle-hours at times of three days and six months after the earthquake respectively (as previously shown in Table 1). From this, the BAA (1994) cost estimation procedure leads to a total cost per day of the earthquake-induced time delays of \$1.6 million at three days after the earthquake, and \$930 thousand at six months after the earthquake. We then estimated the total time delay costs over a one-year time period after Earthquake D, by assuming an average daily time-delay cost for the year of \$930 thousand (which corresponds to the above daily cost at a time of six months after the earthquake). From this, the total cost of the system-wide time delays over this one-year time period was computed to be 365 days x \$930,000 = \$340 x 10^6.

5.0 NEW DEVELOPMENTS

Since the above demonstration SRA was carried out, there have been significant further developments and improvements to the procedure. The improved procedure will be used in a re-analysis of the seismic risks to the Memphis highway-roadway system that is planned later during this year (1998). This analysis will be probabilistic, using multiple scenario earthquakes and simulations.

The new developments to the SRA procedure have focused on the establishment of improved models for: (a) multiple scenario earthquakes; (b) ground shaking and liquefaction hazards; (c) bridge vulnerability modeling; and (d) transportation network analysis. These new developments are summarized in the remainder of this section.

5.1 Scenario Earthquakes

In a SRA of a system with spatially dispersed components, individual scenarios are required to evaluate correlation effects of earthquakes, i.e., the simultaneous effects (including systemic consequences of damages) of individual earthquakes on components located at diverse sites. Scenario earthquake models for our SRA procedure for highway systems are based on an adaptation of work by Frankel et al. (1996) for the Central and Eastern United States (CEUS), as part of the United States Geological Survey (USGS) National Hazard Mapping Program.

The Frankel et al. work for the CEUS uses four different spatially smoothed models based on historical seismicity data, plus a special model for the New Madrid Seismic Zone (NMSZ). Our adaptation of these models is summarized in Sections 5.1.1 and 5.1.2.

5.1.1 Historical Seismicity Models

For developing scenario earthquakes for our SRA of the Memphis highway-roadway system, we have defined a large seismicity zone around Memphis that extends from 88.0 to 92.0 degrees longitude and from 34.0 to 38.0 degrees latitude. This zone has been divided into small microzones, with dimensions of about 11.1 km in both length and width.

Three different models are weighted to establish the earthquake activity within each microzone, based on historical seismicity data from a USGS catalogue that is an updated and improved version of the Seeber-Armbruster (1991) earthquake catalogue. These models are developed from earthquakes with the following magnitude cutoffs and completeness times: (1) magnitude 3+ earthquakes since 1924; (2) magnitude 4+ earthquakes since 1860; and (3) magnitude 5+ earthquakes since 1700. In addition, Frankel et al. include a fourth model (Model 4) that is a large background seismicity model that applies to the entire seismicity zone, and is weighted with the above three models to establish earthquake activities.

The number of earthquakes shown in the USGS catalog to exceed the respective minimum magnitude of Models 1 through 3 respectively is counted and, based on the starting and end date of the model (e.g., 71 years for Model 1), is converted to a frequency of occurrence. Then, to account for uncertainties in the locations of these earthquakes, a relatively flat gaussian model is applied that redistributes and smooths the earthquake locations among the microzones Given this redistribution of earthquake occurrences for each of Models 1-3, and assuming a threshold magnitude of 5.0 for the onset of earthquake damage, a "b" value of 0.95 in the Richter magnitude-frequency relationship is assumed (derived elsewhere) to estimate the frequency of occurrence of earthquakes with magnitude ≥ 5.0 in each microzone (for each of these models). For Model 4, a uniform distribution is used to allocate potential earthquakes with magnitudes ≥ 5.0 among all of the microzones.

Based on a method of adaptive weighting, we followed Frankel et al. in combining the four above-mentioned models in order to derive frequencies of occurrence of earthquakes of magnitude ≥ 5.0 in each microzone. Next, we summed these frequencies to determine the corresponding frequency of occurrence within the overall seismicity zone. Using this frequency and the frequencies in each microzone, we then developed a conditional cumulative probability matrix for the overall seismicity zone. This two-column matrix contains microzones (numbered) in one column, and cumulative conditional probabilities (from 0 to 1) in the other column. In addition, we used a Poisson model to convert the frequency of occurrence of earthquakes with magnitudes ≥ 5.0 in the overall seismicity zone to a corresponding probability of occurrence.

At this stage, a natural way to develop these scenarios for purposes of analyzing system performance and for eventually compiling information on loss distributions and their variability over a time dimension is to employ a "walk-through" analysis. (Daykin et al., 1994). The first step in such an analysis is to select an appropriate time frame over which the analysis would be carried out (e.g., one or more time frames of 10 years, 50 years, 100 years, etc.). Then, for each year in each time frame (starting with Year 1 and then repeating the process for each successive year), successive uniform random number generators are applied with the appropriate cumulative conditional probability distribution to evaluate: (a) whether or not at least one earthquake of magnitude ≥5.0 has occurred somewhere in the large seismicity zone during the year; (b) if so, whether or not a second earthquake has occurred in the zone during the year; and (c) for each earthquake that has occurred in the zone during the year, the microzone where the earthquake is located. We also use a random generation technique to estimate the earthquake magnitude, with the likelihood of diverse magnitude levels assumed to be represented by a Richter (lognormal) magnitude-recurrence relationship.

5.1.2 New Madrid Fault Zone

For modeling the New Madrid fault zone while the Frankel et al, approach was undergoing modifications, we have initially followed earlier USGS procedures described by Leyendecker et al. (1995). In this, we have: (a) modified the Der Kiureghian et al. (1977) approach to distribute earthquake occurrences within the fault zone; (b) applied estimates of the frequency of occurrence for earthquakes in the zone based on the Frankel et. al. approach and other relevant studies, and converted these to probabilities of occurrence using a Poisson model; and (c) postulated that the fault zone is comprised of four parallel linear faults.

Following this, a walk-through analysis is used to develop a random sequence of earthquakes occurring within the zone during the time period of interest. To illustrate, let us assume that the probability of occurrence of an earthquake with a given magnitude (say magnitude 8.0) within the New Madrid fault zone is 0.002. From this, the walk-through process for each year involves the use of successive random number generators to indicate: (a) whether an earthquake of this magnitude has occurred within the fault zone; and (b) if so, which of the four fault traces is the source of the earthquake. Then, subsequent steps involve: (c) estimation of the rupture length along the fault trace, using the Wells-Coppersmith (1994) relationship between rupture length and earthquake magnitude and including a normally distributed uncertainty factor (in log space) with a standard deviation of 0.22; and (d) estimation of the location of the rupture length within the overall fault trace, by using a polar method to generate a normally distributed uncertainty factor in log space (Law and Kelton, 1991)[8].

The results of this walk-through analysis of earthquakes occurring within the New Madrid fault zone are combined with the results of the walk-though analysis of potential earthquakes from the historical seismicity models (Sec. 5.1.1) to estimate the total earthquake activity during each year of the time frame of interest.

5.1.3 Current Status

The above approach has been used to develop an initial set of scenario earthquakes for the Memphis area. The modeling assumptions leading to these earthquakes are now being reviewed, prior to our developing a final set of scenario earthquakes for our forthcoming SRA of the Memphis highway-roadway system.

5.2 Ground Motion Hazards

The ground motion hazards for our updated SRA of the Memphis highway-roadway system will be represented as five-percent damped ground response spectra at the ground surface. The estimation of these spectra for a particular site will involve: (a) use of a rock motion attenuation relationship to estimate spectral amplitudes of rock motions; and (b) application of soil amplification factors to these rock motion spectra, to develop corresponding spectra of motions at the ground surface that incorporate effects of local soil conditions.

For our SRA of the Memphis highway-roadway system, we will be using: (a) the Hwang and Huo (1997) rock motion attenuation relationships for peak acceleration and for spectral accelerations over a wide range of natural periods; and (b) the Hwang et al. (1997) soil amplification factors for NEHRP site classifications A through E. These procedures have the following benefits: (a) they are internally consistent, i.e., they are intended for use together to compute ground surface peak accelerations and spectral accelerations (as the product of the Hwang and Huo rock motions and the Hwang et al. soil amplification factors); (b) they specifically focus on anticipated CEUS ground shaking characteristics; (c) the Hwang and Huo rock motion attenuation relationships compare well with other well-established relationships for the CEUS; (d) the Hwang et al. soil amplification factors are developed from state-of-the-practice analytical procedures; and (e) effects of uncertainties in various input parameters are considered.

5.3 Liquefaction Hazards

The treatment of liquefaction hazards within the multi-scenario framework of the SRA procedure involves the following steps: (a) compilation of soils data for the region; (b) for a given scenario

[8]In this, the difference between the rupture length and the total length of the fault is computed, and a uniform random number generator is used to indicate where the fault rupture is initiated relative to one end of the fault trace.

earthquake and simulation, evaluation of the potential for liquefaction throughout the highway-roadway system, including estimation of permanent ground displacements; and (c) estimation of traffic states at bridges and along roadways within the system due to these ground displacements. Our plans for carrying out these steps in our SRA of the Memphis highway-roadway system are summarized below.

5.3.1 Soils Data

Under a prior project carried out at the Center for Earthquake Research and Information (CERI) of the University of Memphis, data from 8,500 boring logs throughout Shelby County were compiled by Ng et al. (1989). Ng et al. then divided the county into a series of cells with dimensions of about 2,500 ft. by 3,000 ft., and used the data from the boring logs to develop the following information for those cells where boring logs were available: (a) estimated average values SPT blowcounts, natural soil density, and unconfined compressive strength for each soil layer, as well as ground surface elevation, and groundwater level; and (b) development of a representative soil log for the cell. A GIS data base containing these data has been made available by CERI for use in our SRA of the Memphis highway-roadway system. For those cells, where no data were available, soil properties have recently been estimated using data from the nearest cells with soils of the same geologic unit (Hwang and Lin, 1997). It is noted that CERI is currently updating this data base; however this updated data base will not be completed and available for use until early 1999.

5.3.2 Hazard Evaluation Procedure

Evaluation of the potential for liquefaction hazards to the Memphis highway-roadway system for a given scenario earthquake event will be carried out only for those cells that contain bridges and/or roadways within the system. This evaluation will consist of the following steps, which generally follow the approach by Youd and Gummow (1995):

Initial Screening. An initial screening of soils and geologic will be carried out to initially establish which cells in the system have a low potential for liquefaction and therefore can be eliminated from further analysis. Our initial screening efforts will be guided by prior liquefaction evaluations of the Memphis area by Hwang and Lin (1997) for earthquakes of magnitudes 6.5, 7.0, and 7.5 centered in Marked Tree, Arkansas.

Further Screening. For those cells shown by the initial screening to have a potential for liquefaction, further screening will be carried out through very simplified and conservative assessment of the range of possible ground shaking hazards in the cell due to the various scenario earthquakes for the SRA, in order to eliminate additional cells shown by this further screening to have a low liquefaction potential.

Seed-Idriss Procedure. For those cells that are still shown to have a potential for liquefaction, the Seed-Idriss (1982) procedure will be used for a final evaluation of liquefaction potential.

Permanent Ground Displacement. For the cells shown from the above steps to have potentially liquefiable soils, permanent ground displacements will be estimated as follows: (a) for bridge or roadway sites with gently sloping ground or a free face condition, the Bartlett-Youd (1995) procedure will be used to estimate lateral spread displacements; and (b) the Tokimatsu-Seed (1987) procedure will be used to estimate vertical settlements.

5.3.3 Liquefaction Effects on Traffic States

Estimation of the effects of liquefaction on traffic states along the bridges and roadways within the Memphis highway-roadway system will be based on analysis of: (a) empirical data compiled by Youd (1997) that describes bridge damage modes due to liquefaction-induced ground displacement for 116 bridges during earthquakes in the United States, Costa Rica, and Japan; and (b) liquefaction maps for the San Francisco Bay Area due to the 1989 Loma Prieta Earthquake that are now being completed at the USGS; and (c) a data base of liquefaction-induced road closures in the Bay Area following the Loma Prieta Earthquake (ABAG, 1997).

5.4 Bridge Modeling

5.4.1 Background

Essential to the SRA process is the incorporation of models for estimating bridge damage states and traffic states. This section describes candidate bridge models now under development.

Damage-state modeling of individual bridges can be carried out using conventional structural analysis tools that employ either the Capacity/Demand or Lateral Strength (pushover) methods of analysis, as described in the FHWA (1995) Retrofit Manual. However, application of these methods would lead to an intractable task if applied to each of the large number of bridges that will comprise a highway-roadway system. Therefore, any analysis tools that are used for bridge damage-state modeling for highway system SRA must be rapid and efficient to implement. In addition, to increase efficiency of the damage-state modeling process, we are exploring the feasibility of developing damage-state models for bridge groups rather than individual bridges (where each group would consist of bridges with certain similar attributes important to seismic response). To enhance analysis efficiency, the damage-state models (for individual bridges or groups) will be developed in a pre-processor to the main SRA procedure

As an option to the use of analytical models, an alternative damage-state modeling approach is the use of empirical models developed from experiential observations. However, the principal problems with such models are: (a) they use vague damage descriptors such as "slight", "moderate" or "extensive" that neither account for the post-earthquake serviceability of bridges nor provide a clear basis for estimating post-earthquake repair costs and traffic states; and (b) they are mostly based on California bridges, whose structural characteristics are often very different from those for the stock of bridges found elsewhere in the United States. These two reasons negate the use of empirical modeling techniques by themselves. However, empirical observations of the actual performance of bridges during past earthquakes will, of course, provide a valuable basis for validating analytical bridge damage state models that are developed.

For these reasons, it is our view that analytical procedures are the methods of choice for developing bridge damage-state models for highway system SRA. In this, alternative models with differing degrees of refinement will be incorporated into the component module, in which the selection of one of these models for a particular SRA application would depend on such factors as available bridge data, bridge characteristics, etc. Results from these models will then be used with expert-opinion and empirical information in order to estimate bridge traffic states due to each damage state.

With this as background, the remainder of this section is organized into three main parts. Section 5.4.2 describe one damage-state modeling approach that is being developed specifically for use with highway-roadway system SRA -- the "rapid-pushover" method by Mander and Dutta (1997). Following this, Section 5.4.3 summarizes other candidate damage-state modeling methods that are being developed under the NCEER Highway Project or other research programs. Finally, Section 5.4.4 summarizes our plans for developing bridge and roadway traffic states, once the damage states are established.

5.4.2 Rapid-Pushover Method

The rapid-pushover method (Mander and Dutta, 1997) is a new non-linear static (pushover) procedure for rapid estimation of bridge damage states. It accounts for the contributions of the piers and the arching (3D) action of the deck to the total base-shear capacity of the bridge system.

Deck Contribution. The contribution of the deck to the bridge system's total base shear capacity has been systematically overlooked in most capacity analyses. This contribution is due to the resistance of the deck resulting from plastic moments that are mobilized by the bearings working as a group. This action occurs because, as the deck rotates, there also occurs some lateral displacement which is resisted by frictional forces arising in each bearing. Mander and Dutta (1997) have evaluated this effect for bridges with multiple simply-supported spans and with continuous spans. For these cases, a plastic mechanism analysis is used to establish the deck capacity as the lowest capacity of all possible postulated failure mechanisms. These failure mechanisms incorporate the geometry of the deck spans, the relative flexibility of the pier bents, and resistance and the capacities of the bearings.

Pier Contribution. Under longitudinal or transverse excitation, a bridge pier is presumed to display a marked degradation of strength capacity as the earthquake shaking proceeds. The magnitude and rate of the strength decay will depend upon the design details at or near the potential plastic hinge zones -- particularly connection details such as lap splices and anchorage zones – and the shear capacity of the columns and the column-to-cap connections. Although sophisticated energy-based evaluation techniques are available for evaluating these sources of strength decay, a more simplified displacement-based method of analysis is instead proposed, in order to increase the speed and efficiency of the evaluation process. This method uses a simplified strength decay model for the bridge pier, in which the total pier capacity is assumed to consist of: (a) diagonal strut (or arch) action which constitutes the concrete resistance; and (b) resistance contributions arising from the longitudinal and transverse reinforcing steel. Mander and Dutta (1997) suggest that these contributions to the pier capacity can be simply expressed in terms of geometric factors alone, many of which may be obtained (or inferred) from existing Bridge Management System data bases.

Discussion of Rapid-Pushover Method. This method is a rapid yet technically rational approach for developing bridge capacity spectra. Furthermore, the capacity spectra include various displacement thresholds that each represent the onset of a new damage state. Each of these damage states are physically defined so as to facilitate their interpretation during subsequent estimation of bridge traffic states. For example, depending on a bridge's geometry and detailing, various damage states may be defined in terms of: (a) first yield; (b) the onset of cracking and spalling; (c) loss of anchorage; (d) concrete failure; (e) pier damage or collapse, due to such causes as splices in plastic hinge zones or inadequate transverse or longitudinal reinforcement; (f) deck unseating; (g) bearing failure; and (h) abutment backwall failure. In addition, although the rapid pushover method has been formulated as a deterministic approach, procedures are being studied that would extend it to be probabilistic as well, in which model and material property uncertainties are represented.

Capacity-Demand Resolution. Once the capacity spectrum is developed, a capacity-demand analysis is carried out to determine each bridge's damage state for a given scenario earthquake and simulation. The first step in this process is to establish the demand spectrum at the bridge site by adjusting the five-percent damped site-specific ground-response spectrum at each bridge site to account for increased effective damping due to increased yielding and damage to the bridge as the level of displacement increases. Then, the damage state for the given scenario earthquake and simulation is taken to correspond to that damage state within which the demand and capacity spectra intersect. This is determined analytically by computing the difference between demand vs. capacity base shear coefficients at displacement levels that represent the onset of each successive damage state, and then identifying the damage state where the sign of the difference first changes.

Current Status. Although the basic framework of the rapid-pushover method is established, it is still under development to incorporate such phenomena as effects of bridge skew, foundation damage modes, etc. In addition, the method is currently being validated through its application to actual bridges that have been subjected to earthquake shaking and have well-established seismic response characteristics. It is noted that a simplified version of the rapid-pushover method is currently under development for enhancing the transportation lifeline module in HAZUS (Basoz and Mander, 1998).

5.4.3 Other Damage State Models

This section briefly summarizes other candidate bridge damage state models. One model is being developed specifically for application to the large Mississippi River crossings in Memphis (Liu, 1997). The other models are presented as possible options or supplements to the rapid pushover method. These include modeling procedures currently being developed by Jernigan and Hwang (1997) and by Shinozuka (1998).

Major Bridges. The rapid-pushover method and the other bridge modeling methods described below would be applied to all bridges in the Memphis highway-roadway system, except the two large steel bridges that cross the Mississippi River along Interstate Highways 40 and 55. For these major bridges, capacity spectra will be developed from results of a prior detailed seismic vulnerability analysis of the Interstate 40 river crossing, and from an approximate assessment of the Interstate 55 river crossing, which has not yet been subjected to a detailed seismic vulnerability evaluation (Liu, 1997).

Jernigan and Hwang (1997). In an ongoing study to develop damage state fragility curves for the 452 bridges within the highway-roadway system in Memphis and Shelby County, Tennessee, Jernigan and Hwang (1997) are applying the capacity-demand method described in the FHWA (1995) seismic retrofit manual. This study has consisted of the development of a GIS data base of structural attributes for these bridges, a grouping of bridges according to superstructure and substructure characteristics, and the development of fragility curves for each grouping that establish the probability of achieving none/minor, repairable, or significant damage as a function of peak ground acceleration (ATC, 1996). Dynamic analysis is used to develop the demands for bridges within each group, whose attributes are selected from random sampling of the range of attributes for that group. To date (April 1998), fragility curves have been developed for most of the bridge groups defined for the Memphis and Shelby County bridges.

Shinozuka (1997). Another damage state modeling approach is being developed under the NCEER Highway Project by Shinozuka (1997). This approach will establish bridge damage state fragility curves through the use of numerical simulation based on rigorous dynamic analysis, in conjunction with professional judgment and quasi-static and design-code type analysis. The approach will be validated through comparisons of analytical predictions against observed performance of bridges during past earthquakes.

5.4.4 Traffic States

The final step in this bridge modeling process is the establishment of traffic states along the roadways at each end of the bridge, and also along roadways that pass beneath, above, or adjacent to the bridge. These traffic states represent the ability of the various roadways to carry traffic, in terms of the number of lanes that remain open to traffic and possibly any reduction in speed limit as well. Once they are established for a given scenario earthquake and simulation, they are incorporated into a system network model to establish overall post-earthquake system states (to which transportation network analysis procedures are applied to estimate earthquake effects on system-wide traffic flows). Therefore, the estimation of traffic states from the bridge damage states is a key step in the overall system SRA process.

These traffic states will vary with time after the earthquake, to reflect the estimated rate and type of post-earthquake repair of the bridge. This rate of repair will, in turn, depend not only on the type and extent of damage to the bridge, but also on construction practices within the region of the country that contains the highway system being analyzed. To account for these variables when establishing improved bridge models for the planned re-analysis of the Memphis highway system, an expert opinion approach is being developed that will involve: (a) establishing each possible damage state for the various bridges in the system; (b) having experienced bridge engineers from the Memphis area and the Tennessee Department of Transportation review these damage states and provide their opinion as to the costs, types, durations, and traffic impacts associated with the repair process for each damage state; (c) interpreting these estimates using bridge repair cost and functionality data from past earthquakes (in California and elsewhere); (d) from this, establishing models that provide repair costs and traffic states (at various times after the earthquake) for each bridge damage state; and (e) incorporating these models into the component module for the SRA procedure, for use during our subsequent SRA for the Memphis highway-roadway system.

5.5 Transportation Network Analysis Procedure

5.5.1 Background

As previously noted, the network analysis portion of our prior demonstration SRA of the Memphis highway system relied on MINUTP -- a standard program that implements Urban Transportation Planning System (UTPS) algorithms (Werner et al., 1996). Experience from that analysis showed that data preparation and implementation of MINUTP was unacceptably time consuming – partially due to the fact that MINUTP was not GIS-compatible. Also, although UTPS models and their derivatives are standard planning tools in cities receiving Federal support for local transportation projects, such models have the following deficiencies for SRA applications: (a) consideration of an adequate level of detail for representing the region served by the system (i.e., region boundaries, O-D zones, and the system network structure) is costly; (b) loss-of-service measures developed from UTPS network assignment models are inconsistent with loss-of-service measures from other UTPS models; (c) behavioral shifts due to major disasters such as large earthquakes are difficult to represent; and (d) the UTPS procedure has little capacity for considering time dependence of system performance characteristics.

In view of this, it became clear that an alternative transportation network analysis procedure was needed that: (a) provides a capacity for more rapid estimation of network flows; (b) represents the latest well-developed technology and circumvents technical limitations of the UTPS algorithms; (c) is compatible with the GIS-based framework of our current SRA procedure; and (d) provides a capability for using transportation system input data typically available from Metropolitan Planning Organizations (MPOs).

We have found that a new Associative Memory (AM) procedure for rapid estimation of traffic flows that was developed at the University of Southern California (USC) best meets the above objectives (e.g., Moore et al., 1997). The objective of this AM work has been to provide rapid and dependable estimates of flows in congested networks, given changes in link configuration due to earthquake damage, and to attach these changes to the decision-making procedures used to prioritize bridges for seismic retrofit. Such a procedure articulates well with existing efforts in the field, because these flow estimates are input to both total transportation system cost and accessibility measures.

5.5.2 Overview of AM Procedure

The AM procedure is derived from the artificial intelligence field to predict changes in highway system flows. These predictions are based on good approximate solutions to constrained optimization problems that represent the economic determinants of network flows, As such, the AM procedure has the capability to determine changes in the system's total commuting time due to changes in the highway system network. To illustrate, if one link of a freeway is being considered for retrofit, the change in the total system commuting time due to removal of this link is calculated by the following steps: (a) identification of equilibrium flows and commuting times for each link in the intact (pre-earthquake) network; (b) calculation of total system commuting times by summing the commuting times for all links; (c) removal of the link from the highway system, simulating closure due to earthquake damage; and (d) determination of the change in total system commuting time due to the link's removal.

5.5.3 Development of AM Matrix

The AM procedure focuses on the development of an AM matrix that is used to map given sets of system network configurations (stimulus) to lead to corresponding traffic flows (response). The AM matrix is developed from the following steps:

Step 1. Training and Test Cases. Standard numerical analysis is used to develop an ensemble of user equilibrium traffic flows for various network configurations, all of which represent the same general type of network and traffic flow characteristics. Most of these solutions are designated as training cases, with the remainder designated as test cases. These flows are computed for each link in the system in terms of equivalent passenger-car-units per hour.

Step 2, AM Training. The training cases from Step 1 are used to train the AM; i.e., to determine the elements of the AM matrix that minimize the mean-square difference between the true user equilibrium traffic flows for all training cases and the estimated flows using the AM matrix.

Step 3. AM Testing. The basic premise of this approach is that the AM matrix will provide a good estimate of traffic flows from other network configurations that represent similar conditions to those of the training cases, but have not been included in these cases. To check this, the AM matrix is used to predict traffic flows for each test case from Step 1, and these predicted flows are compared to the actual flows for the test cases as obtained during that step.

Step 4. AM Refinement. From past experience, Step 3 will usually lead to excellent comparisons between predicted and actual traffic flows if an adequate number of training cases has been selected. However, if needed, additional training and test cases can be developed in Step 1 and used to further refine the AM matrix and the accuracy of its traffic flow predictions.

5.5.4 Current Status

We are programming the AM procedure for rapid estimation of traffic flows developed at the University of Southern for incorporation into the SRA methodology. In addition, we have compiled network data for the Memphis highway-roadway system for an updated SRA of this system.

Our programming of the AM procedure considers that the procedure has two sub-modules -- the training and stimulus-response sub-modules. The training sub-module solves conventional user-equilibrium flow problems given different configurations for the Memphis network. The stimulus-response sub-module constructs an AM matrix that best fits these user equilibrium inputs (network configurations) and outputs (traffic flows). In this way, the exact user-equilibrium solutions "train" the AM, which then can be used to obtain very rapid estimates of traffic flows for other network configurations not included in the training sub-module. These AMs have been shown to provide good approximations of user-equilibrium flows associated with new network configurations, including networks in which capacity has been lost.

Creation of training data is a pre-processing step, but users of the SRA methodology will also have the opportunity use the training sub-module to solve for exact user-equilibrium flows for various post-earthquake network configurations. Regardless of why users might elect to solve these flow problems exactly, the results of the analysis can usually be added to the training data provided to the stimulus-response sub-module.

We have programmed user-equilibrium traffic-assignment and the generalized inverse-matrix modules in the C programming language, specifically Watcom C/C++ V11.0. These sub-modules must be integrated into one model to be tested and applied. We are now programming an integrated analysis environment that contains a transportation data-base management system, training module, stimulus-response module, and output generation module.

We have also been working with the Memphis and Shelby County Office of Planning and Development (OPD), who is the MPO for the Memphis region, to compile network input data for use in our forthcoming SRA of the Memphis highway-roadway system. The data for this system is based on OPD's most recent (1995) MINUTP model. These network data includes 665 origin-destination zones and associated trip tables, 3,853 nodes and their attributes, and 9,716 directional links and their attributes. These data have now been incorporated into the GIS data base for our Memphis system SRA.

6.0 REAL-TIME APPLICATIONS

Research is being carried out by earthquake scientists and engineers to develop procedures for estimation of seismic effects in real time. Such procedures facilitate rapid emergency-response decision making by using scientific and engineering monitoring systems and models for seismic data collection, analysis, initial real time prediciton of seismic effects, and updating of real-time predictions as new earthquake data becomes available (e.g., Eguchi et al., 1997; Taylor et al., 1998).

The highway system SRA procedure described in this paper features is well suited for real-time prediction of highway system seismic performance. Particular benefits of the procedure for such applications include its use of GIS-based modules with rapid procedures for: (a) predicting seismic hazards, component performance, and system-wide traffic flows; and (b) display of prediction results.

We envision that the use of the SRA procedure for real-time predictions of highway system seismic performance would require the following pre-earthquake steps, as a unified effort of regional government officials, emergency response planners, earthquake engineers, and transportation specialists.

System Inventory. Engineers and planners should: (a) identify the extent of the highway-roadway system to be analyzed; (b) compile relevant data for the system, including network, traffic, component, and origin-destination zone data as described earlier in this paper; and (c) identify locations and access routes for key emergency response/recovery facilities.

Real Time Information Needs. Government and emergency response planning officials should identify their particular post-earthquake information needs from the results of the real-time application of the SRA procedure. This could include information on: (a) locations of earthquake damage to the highway-roadway system; (b) impacts of this system on traffic flows, including alternative routes that would be taken by users immediately after the earthquake; (c) accessibility to and from hospitals, police and fire departments, airports, and other key emergency response centers; and (d) the effectiveness of alternative short-term traffic management procedures in reducing post-earthquake traffic congestion and improving access to emergency response facilities.

SRA Module Development. After the above steps have been carried out, systems and engineering information needed to rapidly carry out highway-roadway system SRAs in real time can be developed within the GIS-based SRA preprocessor modules. This would include development and incorporation of: (a) models for estimating seismic hazards throughout the system that are based on regional seismologic and geologic characteristics; (b) vulnerability and fragility models for characterizing damage states and traffic states of the bridges and other components that comprise the system; and (c) an AM matrix for estimating traffic flows for the highway-roadway system and its range of potential post-earthquake system states.

Integration into Real-Time Earthquake Damage Assessment System. We envision that this highway-roadway system performance predictions would be part of a larger real-time earthquake damage assessment system that would be in place for the region. Accordingly, the predictions developed in the previous step, together with the SRA procedure itself, should be integrated into this real-time system, so that information on future earthquake magnitudes and locations can be readily accessed for rapid estimation of post-earthquake system performance and losses.

6.0 CONCLUDING COMMENTS

This paper has described a new SRA procedure for highway systems. A demonstration application of the procedure to the Memphis highway system has provided preliminary results that show the type of information that can be obtained using SRA. Significant research has been carried out that will dramatically improve the reliability of the system performance results obtained using the SRA procedure.

SRA can enhance the prioritization, planning, and implementation of seismic risk reduction for highway systems. Its principal benefit is its ability to directly represent seismic performance of highway systems – in terms of post-earthquake traffic flow – and to represent systemic effects associated with the damage to various highway components. This information will provide a much improved basis for decision-making pertaining to such issues as prioritizing various components for seismic strengthening, establishing component seismic performance and design criteria, and justifying funding for seismic retrofit or other seismic risk reduction measures. In addition, because the SRA procedure uses rapid GIS-based methods for estimating seismic performance of highway-roadway systems, it can be readily adapted to real-time prediction applications.

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7.0 REFERENCES

Applied Technology Council (ATC) (1991) *ATC-25 -- Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous United States,* Redwood City CA.

Applied Technology Council (ATC) (1996). *ATC-32 -- Improved Seismic Design Criteria for California Bridges: Provisional Recommendations,* Redwood City CA.

Association of Bay Area Governments (ABAG) (1997). *Riding Out Future Quakes: Pre-Earthquake Planning for Post-Earthquake Transportation System Recovery in the San Francisco Bay Region*, Oakland CA, October.

Bartlett, S.F. and Youd, T.L. (1995). "Empirical Prediction of Liquefaction-Induced Lateral Spread" *Journal of Geotechnical Engineering ASCE,* 121(4), April, pp 316-329.

Barton-Aschman Associates (BAA) (1994). *Interstate 10 Recovery Report -- Northridge Earthquake Recovery* California Department of Transportation, District 7, Office of Operations, Los Angeles CA. September 15.

Basoz, N. and Mander, J. (1998). *Enhancement of the Highway Transportation Lifeline Module in HAZUS*, Draft Report to National Institute of Building Sciences, Washington D.C., April 3.

Comsis Corporation (1994). *MINUTP Technical Users Manual* Silver Springs MD, July.

Daykin, C. D., Pentikainen, T., and Pesonen, M. (1994). *Practical Risk Theory for Actuaries*, London: Chapman & Hall.

Der Kiureghian, A. and A. H-S. Ang, 1977, "A Fault Rupture Model for Seismic Risk Analysis," *Bulletin of the Seismological Society of America*, 64(4), pp 1173-1194, August.

Eguchi, R.T., Goltz, J.D., Seligson, H.A., Flores, P.J., Blais, N.C., Heaton, T.H., and Bortugno, E. (1997). "Real-Time Loss Estimation as Emergency Response Decision Support System: The Early Post-Earthquake Damage Assessment Tool", *Earthquake Spectra*, 13(4), November, pp 815-832.

Federal Highway Administration (FHWA) (1995). *Seismic Retrofitting Manual for Highway Bridges,* Publication No. FHWA-RD-94-052, Turner-Fairbank Highway Research Center, McLean VA, May.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E.V., Dickman, N., Hanson, S., and Hopper, M. (1996). *National Seismic Hazard Maps, June 1996 Documentation*, Preliminary Report prepared at U.S. Geological Survey, Denver CO, July 19.

Gordon, P., Richardson, H.W., and Davis, B. (1996). *Transport-Related Business Interruption Impacts of the Northridge Earthquake* Lusk Center Research Institute, University of Southern California, Los Angeles CA, March.

Hwang, H.H.M. and Huo, J-R. (1997). "Attenuation Relations of Ground Motion for Rock and Soil Sites in Eastern United States", *Soil Dynamics and Earthquake Engineering,* Vol. 16, pp 363-372.

Hwang, H.H.M. and Lin, H. (1997). *GIS-Based Evaluation of Seismic Performance of Water Delivery Systems,* University of Memphis, Memphis TN, February 10.

Hwang, H.H.M., Lin, H., and Huo, J-R. (1997). "Site Coefficients for Design of Buildings in Eastern United States", *Soil Dynamics and Earthquake Engineering*, Vol. 16, pp 29-40.

Jernigan, J.B. and Hwang, H.H. (1997). *Inventory and Fragility Analysis of Memphis Bridges*, Center for Earthquake Research and Information, University of Memphis, Memphis TN, September 15.

Law, A.M. and Kelton, W.D. (1991). *Simulation Modeling & Analysis*, New York: McGraw-Hill, Inc., New York NY.

Leyendecker, E. V., D. M. Perkins, S. T. Algermissen, P. C. Thenhaus, and S. L. Hanson, (1995). *USGS Spectral Response Maps and their Relationship with Seismic Design Forces in Building Codes*, Open-File Report 95-596, U.S. Geological Survey, Denver CO.

Liu, W.D. (1997). "Major Bridge Damage State Modeling", *Year 5 Research Plan, NCEER Highway Project,* National Center for Earthquake Engineering Research, Buffalo NY, October 3.

Mander, J.B. and Dutta, A. (1997). "A Simple Pushover Method for Rapid Evaluation of Bridge Capacity", NCEER Bridge Damage-State Modeling Workshop, San Francisco CA, August 6-7.

Martin, G.R. and Dobry, R. (1994). "Earthquake Site Response and Seismic Code Provisions" *NCEER Bulletin*, 8(4), pp 1-6.

Moore, J.E. II, Kim, G., Xu, R., Cho, S., Hu, H-H, and Xu, R. (1997). *Evaluating System ATMIS Technologies via Rapid Estimation of Network Flows: Final Report,* California PATH Report UCB-ITS-PRR-97-54, December.

Ng, K.W., Chang, T.S., and Hwang, H.H.M. (1989). *Subsurface Conditions of Memphis and Shelby County,* Report NCEER-89-0021, National Center for Earthquake Engineering Research, Buffalo NY, July 26.

Seeber, A. and J. G. Armbruster, 1991, *The NCEER-91 Earthquake Catalog: Improved Intensity-Based Magnitudes and Recurrence Relations for U. S. Earthquakes East of New Madrid,* Report NCEER-91-0021, National Center for Earthquake Engineering, Buffalo NY.

Seed, H.B. and Idriss, I.M. (1982). *Ground Motions and Soil Liquefaction during Earthquakes* Earthquake Engineering Research Institute, Berkeley CA, December.

Shinozuka, M. (1997). "Development and Validation of Bridge Fragility Curves", *Year 5 Research Plan, NCEER Highway Project: Seismic Vulnerability of Existing Highway Construction*October 3.

Taylor, C.E., Chang, S.E., and Eguchi, R.T. (1998). "Updating Real-Time Earthquake Loss Estimates: Methods, Problems, and Insights", *Proceedings of Sixth U.S. National Conference on Earthquake Engineering*, Seattle WA, May 31-June 4.

Tokimatsu, K. and Seed, H.B. (1987). "Evaluation of Settlements in Sands due to Earthquake Shaking" *Journal of Geotechnical Engineering Division, ASCE,* 113(8), August, pp 861-878.

Wells, D.L. and Coppersmith, K.J. (1994). "New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement" *Bulletin of the Seismological Society of America* Vol. 84, No. 4, pp 974-1002.

Werner, S.D. and Taylor, C.E. (1995). *Interim Year 2 Report for Task 106 E-7.3.1: Demonstration Seismic Risk Analysis of Highway/Roadway System in Memphis, Tennessee,* Report prepared for National Center for Earthquake Engineering Research, Buffalo NY, at Dames & Moore, San Francisco CA, September.

Werner, S.D., Taylor, C.E., and Moore, J.E. II (1996). *Volume 1 Strawman Report: Seismic Risk Analysis of Highway Systems*, Report prepared for National Center for Earthquake Engineering Research, Buffalo NY, at Dames & Moore, San Francisco CA, October.

Youd, T.L. and Gummow, G.A. (1995). *Screening Guide for Rapid Assessment of Liquefaction Hazard to Highway Bridges,* Draft Report to National Center for Earthquake Engineering Research, Buffalo NY, August 8.

Youd, T.L. (1997). Empirical Data: Performance of Bridges Subjected to Permanent Ground Displacement, Personal Communication to S.D. Werner and C.E. Taylor, July.

Table 1
Effects of Earthquake D on Total System Travel Times and Distances

PARAMETER	PRE-EARTHQUAKE VALUE	TIME AFTER EARTHQUAKE = 3 DAYS		TIME AFTER EARTHQUAKE = 6 MONTHS	
		Value	Percent Increase over Pre-EQ	Value	Percent Increase over Pre-EQ
Total vehicle hours traveled over 24-hour period (incl. congestion)	3.73×10^5	4.99×10^5	33.8	4.46×10^5	19.6
Total travel distance (mi) over 24-hour period	15.5×10^6	15.6×10^6	small	15.6×10^6	small

Table 2
Effects of Earthquake D on Travel Times to/from Origin-Destination Zones (24-Hour Time Period)

Origin-Destination Zone: Description	Number	Pre-Earthquake Travel Time (Hours)	3 Days After Earthquake: Travel Time (hrs)	3 Days After Earthquake: Percent Increase over Pre-Earthquake Time	6 Months After Earthquake: Travel Time (hrs)	6 Months After Earthquake: Percent Increase over Pre-Earthquake Time
Government Center (downtown Memphis)	7	128	143	11.7	133	3.9
	8	122	141	15.6	130	6.6
Medical Center	25	122	136	11.5	127	4.1
	26	114	129	13.2	121	6.1
	27	114	129	13.2	121	6.1
	28	115	129	12.2	121	6.2
	29	119	133	11.8	124	4.2
University of Memphis	111	119	131	10.1	122	2.5
President's Island (Port)	151	138	153	10.9	144	4.3
Memphis Airport	188	136	150	10.3	142	4.4
Federal Express	189	130	145	11.5	136	4.6
Mall of Memphis	201	127	145	14.2	133	4.7
Hickory Hill	213	171	185	8.2	177	3.5
Poplar-Ridgeway	230	130	148	13.0	136	4.6
	231	130	147	13.1	136	4.6
Germantown	236	141	157	11.3	147	4.3
	241	176	187	6.3	181	2.8
Shelby Farms	249	169	176	4.1	174	3.0
	252	127	211	66.1	152	19.7
Bartlett	264	148	199	34.5	155	4.7
Covington Pike	274	137	181	32.1	151	10.2
	TOTALS	2813	3255	15.7	2963	5.3

Table 3
Economic Impacts of Travel Time Delays due to Earthquake D

Time After Earthquake	Time Delay (Vehicle-Hours/24-Hour Day)			Cost/Day
	Total	Non-Trucks	Trucks	
3 Days	126,000	88,200	37,800	$\$1.6 \times 10^6$
6 Months	73,000	51,100	21,900	$\$9.3 \times 10^5$

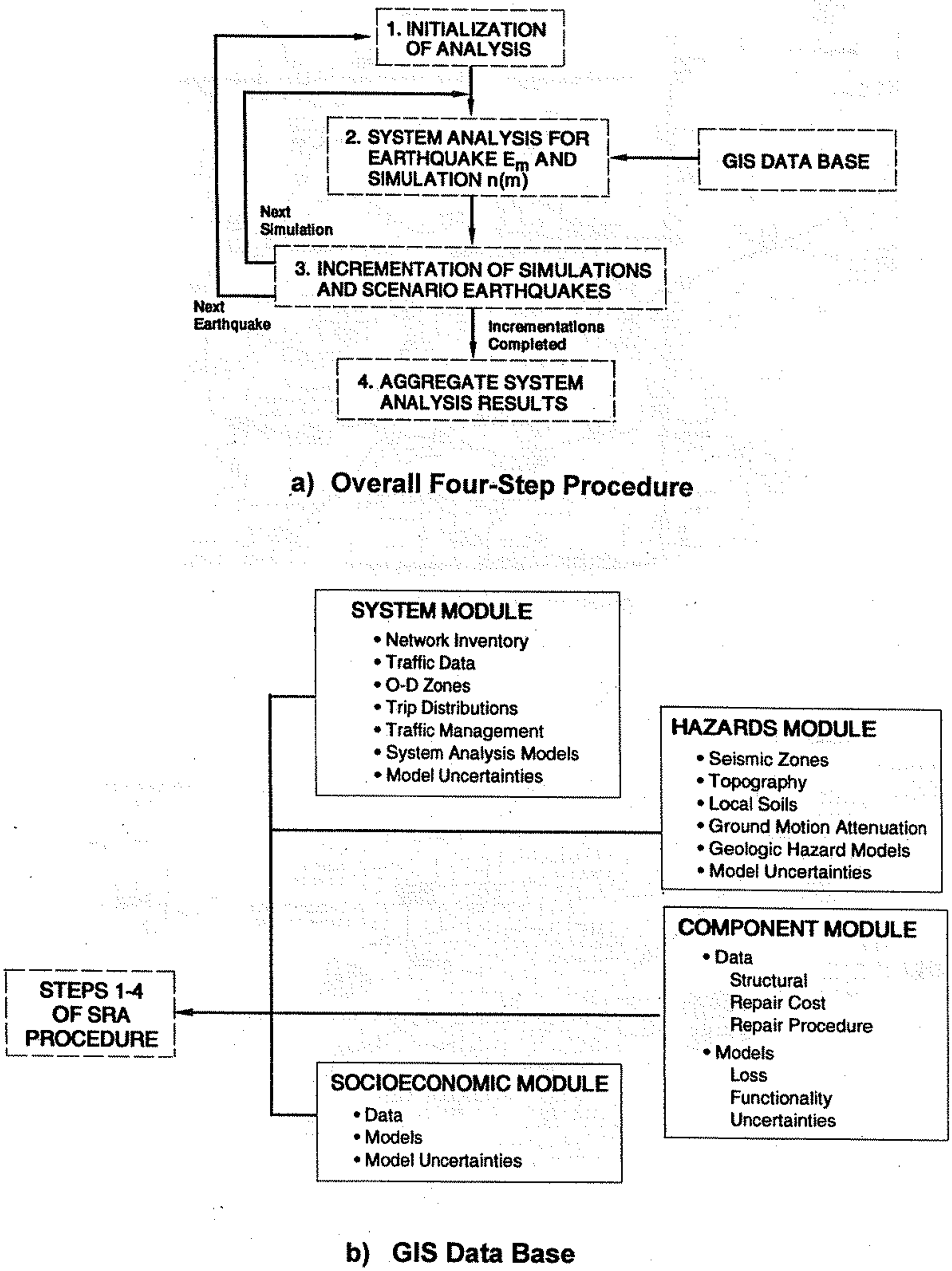
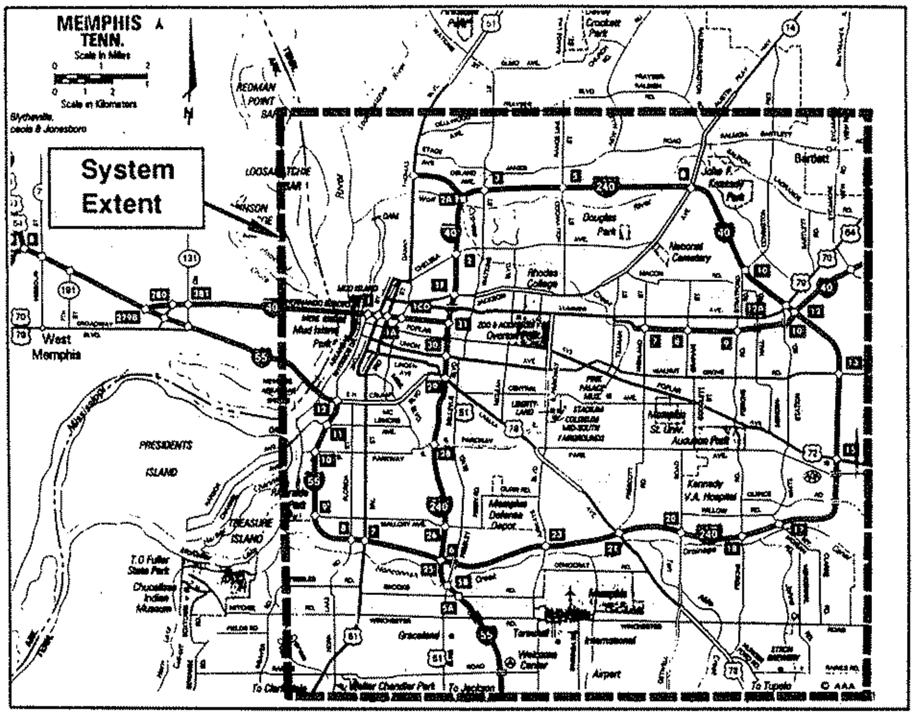
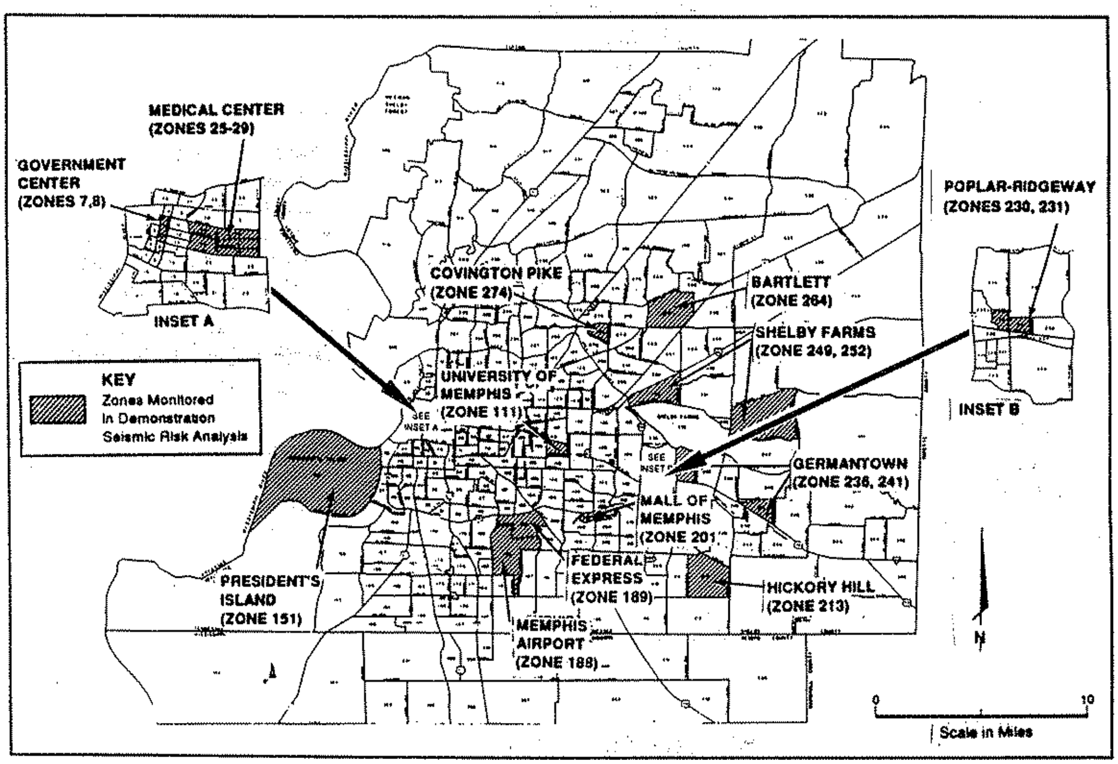


Figure 1. SRA procedure for highway transportation systems

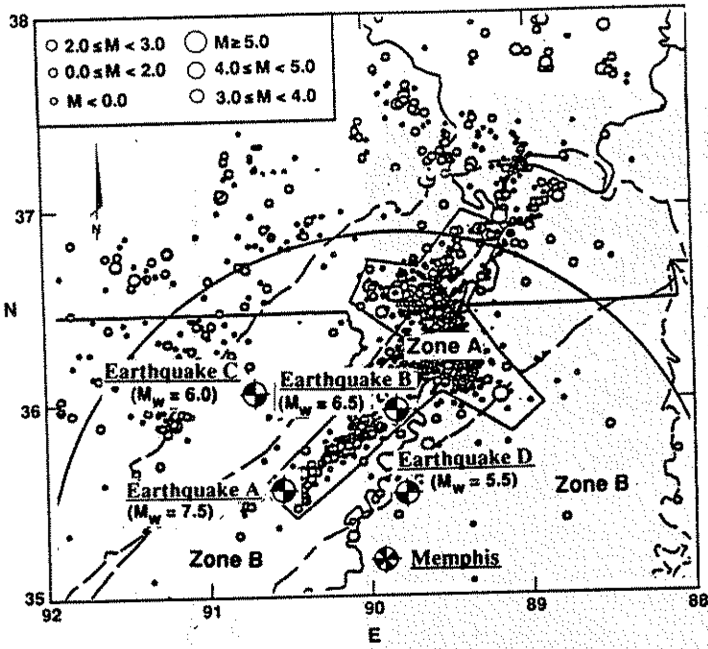


a) System Extent

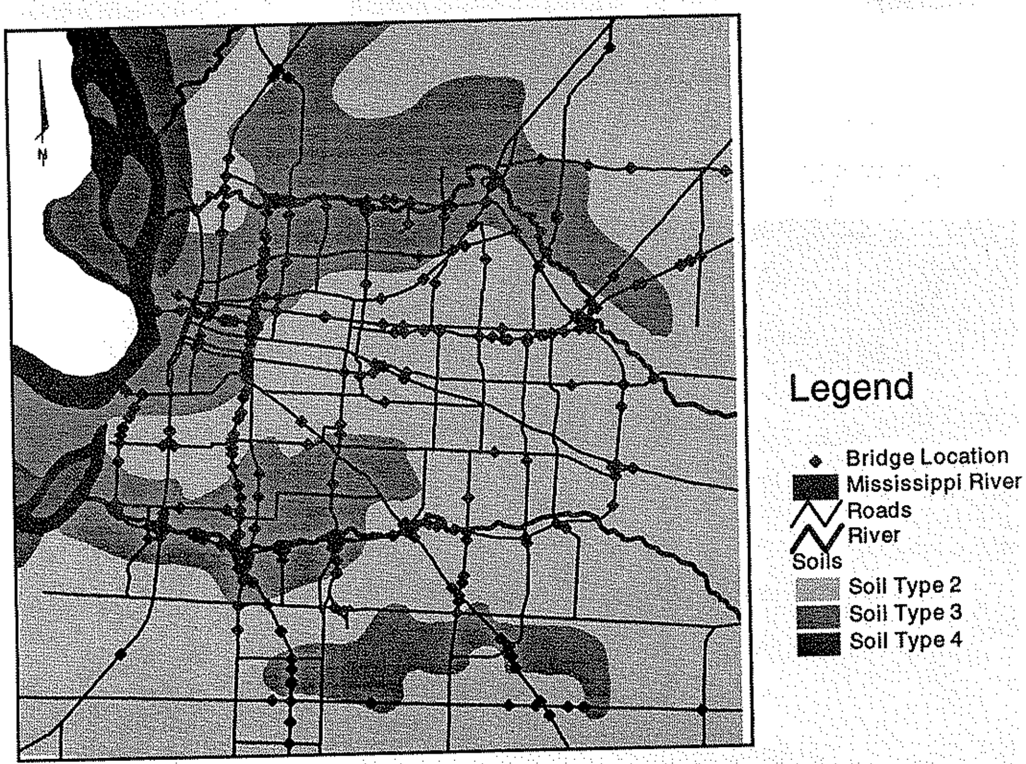


b) Origin - Destination Zones

Figure 2. Memphis area highway system



a) Scenario Earthquakes



b) Local Geology (Hwang and Lin, 1993)

Figure 3. Scenario earthquakes and local geology

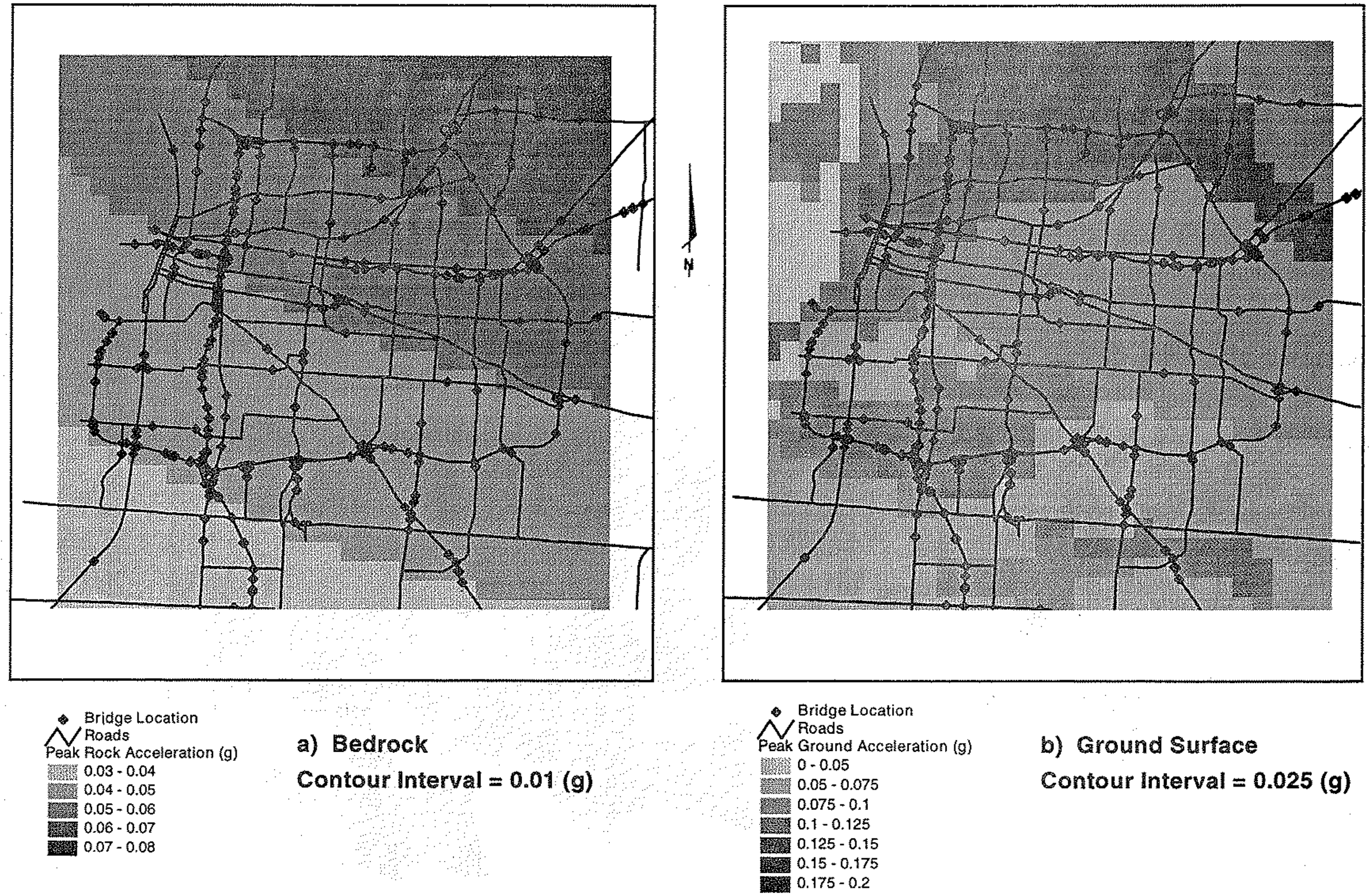
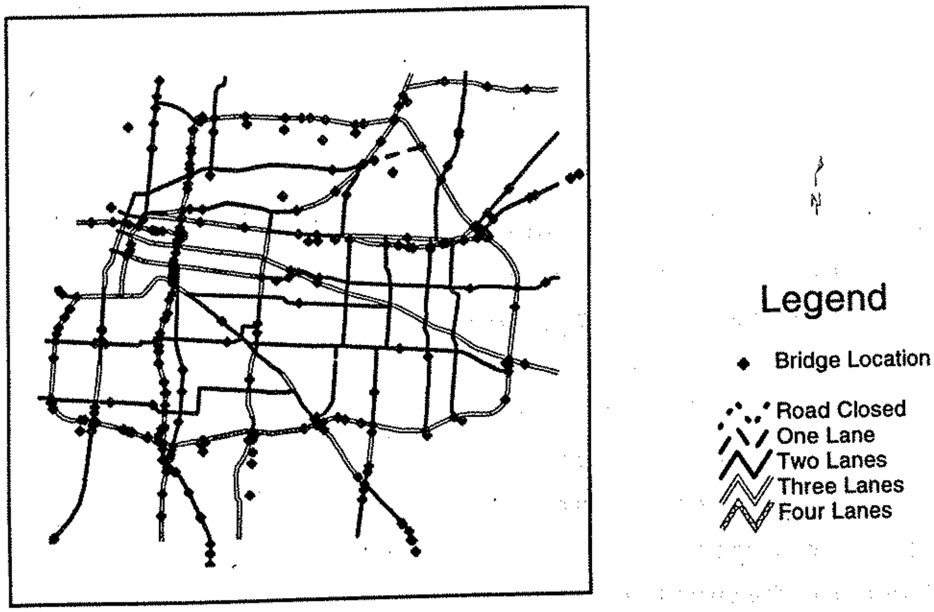
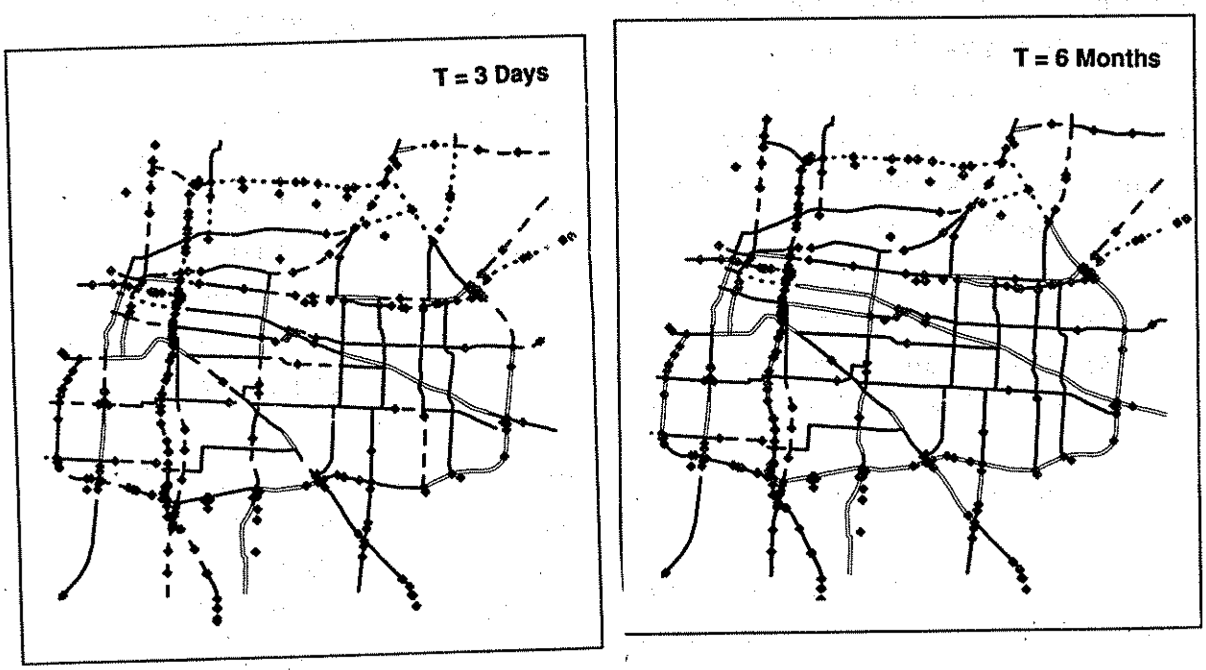


Figure 4. Peak acceleration (g) due to Earthquake "D."



a) Pre-Earthquake



b) Post-Earthquake

Figure 5. System states