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Estimation of Earthquake Loss due to Bridge Damage in the St. Louis Metropolitan Area: Part I - Direct Losses

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ABSTRACT

The risk associated with earthquake hazards on highway systems is dependent on the complexity of a network and its redundancy in providing traffic flow. Earthquake loss estimation studies can provide decision makers with an appreciation of the importance of having a highway network resistant to earthquakes and information to make the network resistant to these events. The direct economic loss was estimated for a major metropolitan area, St. Louis, MO, for a series of earthquake scenarios. The primary component of the study was damage to bridges within the highway system. The study zone covers the St. Louis metropolitan area and its surrounding suburban regions. The study region includes several major alluvial river valleys with liquefaction susceptible areas. Earthquake scenarios with epicenters in St. Louis, Missouri (Mw 7.0), Germantown, IL (Mw 7.0) and New Madrid, MO (Mw 7.7) were selected to contrast high impact/low probability and low impact/higher probability events. The losses to the bridge infrastructure were estimated to range from $70 to $800 million depending on the earthquake event. The data collection, generation and interpretation are described along with the procedures required to carry out the loss estimation using the GIS-based HAZUS-MH system. The output of this project was used as input for a hybrid indirect loss calculation presented in the companion paper.

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INTRODUCTION

Earthquake loss estimation methodologies have been available for some time and their application has increased with the use of improved GIS-based software. However, when the perceived risk is low these advanced tools are seldom applied. This was the case of St. Louis, Missouri, located about 200 miles away from the well known New Madrid Seismic Zone (NMSZ). St. Louis is a metropolitan area that had not been subjected to an earthquake loss estimation study of transportation highway systems. This paper presents the earthquake loss estimation study of the highway transportation network of the St. Louis metropolitan area focused on the direct losses. A companion paper (Enke, et al., 2007) expands on the analysis and methodology used to evaluate the indirect losses incurred by the damaged highway network after an earthquake.

The use of the software program HAZUS was strongly encouraged by FEMA through the Project Impact initiative to become disaster resistant communities (Olshansky and Wu, 2004). A number of cities were designated as project impact communities and received funding to carry out loss estimation studies, such as, Oakland, CA; Salt Lake City, UT; Anchorage, AK; Charleston, SC; Seattle-Tacoma, WA, etc. (FEMA, 2001a). Some of these studies addressed transportation systems and some specifically focused on the highway network (Veneziano et al. 2002; FEMA, 2001a, b). The progress made in assessing earthquake losses for transportation systems has been made possible by the Federal Highway Administration (FHWA) and the projects they have sponsored to develop methodologies to specifically address highway networks. Some transportation loss estimation methods are available in the literature, but few are available as software applications. Their application has focused on the highway transportation systems in metropolitan areas, such as Memphis and Los Angeles (Werner et al. 2000).

In this study a methodology similar to that developed by FHWA but using existing software applications in combination, was used to estimate the direct and indirect losses of a highway network in St. Louis, Missouri. HAZUS-MH was used to estimate the direct losses and a separate transportation model was used to estimate the indirect losses due to the impact on traffic delays. In this paper only the development of the loss estimation for the direct losses are presented and the companion paper (Enke et al. 2007) will focus on the (partial) indirect losses.

STUDY AREA AND SELECTION OF LOSS ESTIMATION METHODOLOGY

The study area encompasses the counties in the metropolitan St. Louis urban region in Missouri and Illinois. The counties included in Missouri are St. Louis, St. Charles, Franklin and Jefferson plus the independent City of St. Louis and the counties in Illinois are Madison, St. Clair and Monroe. All or part of ninety-nine USGS 7.5’ quadrangle sheets (1:24,000 scale) cover the extent of the study area (See Figure 1). Relevant data was collected for the study area using the following thematic data sets: seismology, geology, geohazards, surficial soils, state highway routes, and bridge inventory (based on the National Bridge Inventory [NBI]).

Estimating the dollar amount of economic losses after an earthquake event requires the following of steps, define the earthquake source, attenuate motion to the site of interest, distribute motion through local soils, determine site peak ground acceleration, determine structure (bridges) in question and assess the structure damage. Then, based on economic analysis the direct and indirect losses are estimated. If indirect losses due to the damage of the highway system are to be estimated, there is a need to assess the performance of the network and its impact on the economy.

Evaluating the economic loss of the highway transportation system in a metropolitan area is a significant and important task that can be used by decision makers to assign resources in accordance to the estimated economic risk. An important initial step was to select a methodology for loss estimation. For this purpose a literature review was conducted and the available methodologies were evaluated. One of the key publications used in the literature review was the FEMA Report No. 249 entitled "Assessment of the State-of-the-Art Earthquake Loss Estimation Methodologies." In the past ten years three major efforts were identified and considered for use in this project. The three methodologies are:

- FHWA methodology developed for urban areas was published in a MCEER report (Werner, et al. 2000). The methodology was well documented and used for a Midwestern city, Memphis, TN. It incorporated the elements of direct loss estimation in a traditional approach, but it also incorporated a highway transportation model to estimate the indirect losses due to the damaged network. Approximately five years were devoted to the development of the methodology which culminated in the implementation of the Memphis study. This project was originally directed to demonstrate the use of this methodology in other metropolitan areas. However, the software developed to implement the methodology, REDARS (Risks from Earthquake Damage to Roadway Systems), was not available for distribution at the time of the current study.

- FEMA has developed the loss estimation methodology HAZUS-MH (2003). This is a tool that local, state and federal government officials and others can use for earthquake-related mitigation, emergency preparedness, response and recovery planning, and disaster response operations. The earthquake module was developed first and is the hazard module that has been used the most. FEMA and the National Institute of Building Systems (NIBS) joined forces to develop this computer based system in the early 1990s. This public domain software has limited capabilities to estimate the indirect losses due to a highway transportation system. However, some have used it successfully to estimate losses for a transportation port-to-port corridor in the Seattle-Tacoma area (FEMA, 2001b)
- Mid America Earthquake (MAE) Center methodologies have been developed. These methodologies have focused on the regional networks including several lifelines. These researchers focused on a probabilistic method, which also includes uncertainty analysis. This project visited the MAE Center to inquire about the availability of tools for use in this study and none were available at that time.

Methodology Used in this Study

The selection of the methodology for use in this study was made primarily based on availability, since most methodologies are currently being developed. The framework was adapted from the one presented in the Memphis study (Werner, et al., 2000) described above, but using tools that produced similar results. The methodology to estimate direct losses is the one presented in HAZUS-MH (2003). However, for the indirect losses an additional transportation planning software was used to estimate the time delays. An economic analysis study was also developed to quantify the economic losses due to the decreased performance of the network from bridge damage. The methodology is shown as a schematic flowchart in Figure 2 to describe the general process.

The process followed starts by defining the earthquake scenarios based on published data for the Midwest Region, which primarily relies on geologic evidence of large ground motions. This deterministic approach was considered suitable to demonstrate the loss estimation methodology. The earthquake parameters, site class, and liquefaction data layers served as input to HAZUS-MH (Potential Earth Science Hazard [PESH] model). Bridge inventories were studied and modified for the St. Louis network based on specific data collected during the study. Once the data was updated, the impact of the damaged bridges was introduced into a transportation model to evaluate the loss in transportation performance or traffic flow following the earthquake damage. The approach and details on each of these steps are presented in the subsequent sections of this paper.

HAZUS-MH – DESCRIPTION OF ITS USE IN THIS STUDY

The Hazards United States – Multi Hazard (HAZUS-MH V1.0) software was developed for FEMA under a contract with the National Institute of Building Sciences (NIBS) and their contractors. The software version used runs on a Geographic Information System (GIS) platform using ArcGIS (ArcView 8.3). The HAZUS-MH software development has a regular process of maintenance, upgrading, refining, and technical support. Since this study was completed, two revisions have been released for this program in 2005 and 2006. The initial development and releases, HAZUS 97 and HAZUS 99, provided loss estimation analyses for earthquake hazards only. The HAZUS-MH program provides loss estimation for three hazards: earthquake, flood, and hurricane. Only the earthquake hazard portion of the software was used for this project and will be discussed further.

HAZUS-MH can be run at three different levels of sophistication. At Level 1, all data used for the analyses is provided by national databases included with the software. This gives crude results as the national databases tend to be limited in scope and detail. For this project the critical databases for bridges and soils were especially limited. As an example, the soils database map makes a simplifying assumption that the entire nation has a single soil type (NEHRP Site D) and therefore does not consider important variations in earthquake soil amplification during ground motion evaluation. At Level 2, the national data may be modified with local data for more site-specific results. The analyses for this study were done at Level 2 by incorporation of a more refined bridge database and more detailed regional soils mapping. At Level 3, users may supply their own techniques through third party model integration capability to study special conditions. The Level 3 analysis was not included in this study, but a similar process was used by taking the Level 2 results and applying them to a separate transportation model and another economic loss model.

The earthquake analyses in HAZUS-MH allow the user to select the earthquake scenario to be used, including the choice of either deterministic or probabilistic ground motion analysis. This study used the deterministic ground motion analysis based on earthquake scenarios developed. The user must also select an attenuation function. Six attenuation functions for the Central and Eastern United States (CEUS) are included in the software. This study used the Frankel et al.

(1996) and Project 2000 East attenuation functions. The Project 2000 East attenuation function is similar to the attenuation function average for the CEUS used by the U.S. Geological Survey (USGS) to produce the 2002 National Seismic Hazard Maps. However, the weighting factors given to the five attenuation functions have been slightly modified in the Project 2000 East. The standard HAZUS-MH software computes attenuation functions to a distance of only 200 km (125 miles) from the scenario earthquake epicenter. Therefore, the HAZUS-MH SQL database attenuation tables had to be modified to include distances that extended beyond 200 km (125 miles) from the epicenter of the earthquake scenarios for use in this study. This was done to specifically reach the subject site from a source earthquake originating from the NMSZ. The Frankel et al. (1996) attenuation tables were expanded to a hypocentral distance of 350km. This was achieved by establishing a SQL database link to the HAZUS-MH Frankel et al. (1996) attenuation tables and inserting published values of peak ground acceleration and spectral accelerations for distances of 250 km, 300 km, and 350 km.

HAZUS-MH evaluates only high frequency, near field, ground motion. However, economic losses in the St. Louis metropolitan area from the moderately distant New Madrid Seismic Zone (NMSZ), the best known regional source zone, are likely to be from low frequency, long wave length, far field, ground motion. Therefore, HAZUS-MH is likely to underestimate losses in the St. Louis area generated by a NMSZ earthquake scenario or other scenarios with distant earthquake sources. Because of the low attenuation in the CEUS, distant earthquake sources are an important consideration for the St. Louis study area. For example, light structural damage and injuries were incurred in St. Louis by the November 9, 1968, magnitude 5.5 southeastern Illinois earthquake approximately 180 km (110 miles) southeast of St. Louis (Gordon et al., 1968)

HAZUS-MH uses 2002 US dollars as the basis for its economic loss estimates. Physical damage state and percent functionality of transportation networks are estimated by HAZUS-MH. The physical damage state (none, slight, moderate, extensive or complete) and the associated costs only describe the repair and replacement costs for the damaged structures. However, the percent functionality (at day 0, day 1, day 3, day 7, day 30, day 90, etc.) allows the estimation of increased travel times due to bottlenecks and with third party models the associated increased travel time indirect costs. For earthquakes distant from St. Louis the indirect costs associated with the functionality of the transportation network can be much more significant than repairing the actual physical damage.

EARTHQUAKE SCENARIOS STUDIED

The selection of appropriate earthquake scenarios is a prerequisite to conducting a loss estimation study. A review of deterministic, historic and prehistoric, and probabilistic earthquake scenarios was performed to identify a suite of scenarios that were geographically appropriate for the St. Louis study area and could reasonably be expected to shake the critical transportation system infrastructure to a level it should be expected to withstand. These scenarios were documented and then based on bracketing the range of potential losses and the likelihood of the earthquake scenario occurring, an illustrative subset was selected for detailed loss estimation.

Description of Earthquake Scenarios Selected

The earthquake scenarios initially used were studied for the far field condition in light of the recently revised and released USGS National Seismic Hazard Maps (March 6, 2002) which became the National Earthquake Hazard Reduction Program (NEHRP) proposed revisions. Most of the changes identified in these new maps were noticed to have a relatively short period (~ T=0.2) therefore affecting structures of similar period. Bridges that have longer period (~ T=1.0) were not affected as much. The earthquake scenarios were identified to take into account several new references that were not available earlier. Table 1 and the corresponding map (Figure 3) list six illustrative earthquake scenarios that were considered for the St. Louis area. The table includes the scenario name and the earthquake source zone, location, distance from St. Louis and magnitude. Information on why these scenarios were initially identified and the respective references are included in Table 1. In addition, specific fault parameters for each scenario source have been estimated but not presented herein.

The initial six scenarios were reduced to three to be used in the loss estimation study. The philosophy adopted for the selection process of the final three scenarios was to bracket the range of earthquake losses expected by selecting scenarios that represented high, moderate and low probability events for damage in the St. Louis study area. The New Madrid, Missouri, M=7.7 scenario was chosen because of its historic significance and due to its distance from St. Louis. It represents the high probability but low consequence end of the loss range. The St. Louis, Missouri, M=7.0 scenario was chosen to represent a low probability event at the high end of the loss range because it is a high consequence event due to its location right at St. Louis. The

Germantown, Illinois, M=7.0 scenario was chosen to represent a moderate probability event with a moderately high consequence due to its close proximity to St. Louis and its large magnitude.

New Madrid, Missouri (36.55N, 89.54W), M 7.7

A large magnitude earthquake scenario with an epicenter located at New Madrid, Missouri is based on the widely recognized New Madrid Seismic Zone (NMSZ) and its known historical seismicity, large magnitude and relative proximity to St. Louis plus its well documented features. The large earthquakes in the NMSZ are estimated to have had moment magnitudes ranging from the low 7's to around 8 or above. Following the methods used by the USGS a magnitude 7.7 was selected as the scenario earthquake.

Germantown, Illinois (38.56N, 89.50W), M 7.0

A large magnitude earthquake scenario with an epicenter located near Germantown, Illinois in western Clinton County is based on a cluster of seismic paleoliquefaction features in the banks of the Kaskaskia River and its tributaries Shoal Creek, Mud Creek and Silver Creek recently documented by Tuttle, et al. (1999). Tuttle, et al. (1999) estimated a magnitude 7.0 earthquake at this location would be needed to cause all the liquefaction features identified along the Kaskaskia River, its tributaries and the lower Meramec River. This earthquake scenario was considered because of its high magnitude and close proximity to St. Louis plus its relatively well documented features.

St. Louis, Missouri (38.63N, 90.20W), M 7.0

A large magnitude earthquake scenario with an epicenter located at St. Louis, Missouri is based on the work of the USGS in developing the National Seismic Hazard Maps. During USGS meetings with the seismological and geological sciences research community and the engineering and other applied sciences community a consensus was developed that a low probability worst case scenario earthquake should be considered possible anywhere in the US inboard craton zone (Midwest, more or less anywhere between the Appalachian Mountains and the Rocky Mountains) during development of the USGS National Seismic Hazard Maps. An earthquake of magnitude 7.0 was the consensus earthquake selected. There is no fault or historic or prehistoric earthquake activity associated with this earthquake scenario and the epicenter location can be anywhere in the region. The scenario earthquake epicenter for our study was chosen to be 0 miles from the Arch in downtown St. Louis, Missouri. This earthquake scenario was considered because it represents a low probability, worst case event and therefore would provide a bounding limit to the range of possible earthquake loss estimates.

Regional Surficial Soils

The St. Louis study area straddles a major physiographic boundary near the Mississippi and Missouri Rivers. The Central Lowland province to the east of the Mississippi River in Illinois and north of approximately the Missouri River in Missouri has been glaciated and consist of till, loess and alluvium. Much of St. Louis County and the City of St. Louis are also part of the Central Lowland province although only a small portion of them have been glaciated. The non-glaciated area is in the Ozark Plateau province and has residual soils.

Spatial Distribution of Soil Layers

Unpublished NEHRP soil site class (soil amplification) mapping data based on the average shear wave velocity to a depth of 30 meters were available in GIS shapefile format at a scale of

1:250,000 for the entire study area from either the Missouri or Illinois state geological survey (see Figure 4). This NEHRP soil site class data is based on the surficial materials maps for Missouri and Illinois with the map units interpreted for their estimated shear wave velocities. The ArcView shapefile map format can be used directly by the HAZUS-MH loss estimation software. These NEHRP soil site class maps were modified to show only the five site soil classes used by the HAZUS-MH analyses (NEHRP soil classes A, B, C, D and E). The data in soil site class F as originally mapped represents soil failure due to liquefaction. This unit was modified to reflect its shaking characteristic which is NEHRP soil class E as used by HAZUS-MH. A separate liquefaction potential map consisting of the original class F for the Missouri and Illinois study area was prepared for use in the GIS environment (Figure 5).

In general the Central Lowland glacial soils have more severe soil amplification characteristics than the Ozark Plateau residual soils as can be seen in Figure 4. In the upland settings the glacial soils are either class C, low amplification, or class D, moderate amplification. The lowland glacial outwash alluvial soils of the major river valleys are class E, high amplification. The Ozark Plateau residual soils tend to have less severe soil amplification because in general they are stiff and not very thick. The majority of the Ozark Plateau in the study area is class B, very low amplification. The small areas of class C and D soils in the Ozark Plateau are due to thicker soils and differing bedrock parent material. As a consequence of the soil amplification characteristics, transportation loss estimates should be expected to be higher in the Central Lowland area than in the Ozark Plateau area. The most severe amplification conditions will be in the major alluvial valleys. These alluvial valley areas must be crossed by major transportation infrastructure and are often favored for location of these facilities as they are a less costly route for initial construction. However, these facilities, including costly major river bridges and related structures, are more vulnerable to shaking from earthquake ground motions.

TRANSPORTATION NETWORK INVENTORY

The transportation network for the study region consists of several major roadways and bridge structures. Major highways in the area include Interstates 70, 170, 270, 44, 55, 64 and US Highway 67. These roadways are well traveled and connect the study area with the surrounding counties for commerce, commuter workforce, entertainment, and utility trips. The HAZUS-MH program utilizes major road segments in its GIS spatial data, which is based on the year 2000 version of the TIGER/Line files, produced by the U.S. Census Bureau.

The focus of this report is on the bridge inventory, which HAZUS-MH incorporates into the hazard analysis based on key data from the National Bridge Inventory (NBI) produced by the Federal Highway Administration, Office of Bridge Technology. Major bridges in the study area include the following river crossing bridges shown in Table 2.

The bridges crossing the Missouri and Mississippi Rivers are of great importance due to the pinch-point or funnel effect that is introduced in the transportation network at these specific locations where redundancy is not present in the network. Due to the many important roadways in the area, there are a plethora of smaller bridges in the area that carry a significant traffic load every day. These bridges may seem insignificant to travelers, yet they are well traveled and abundant and, therefore, can greatly affect traffic in the region if damaged during an earthquake event.

Description of Bridge Data in HAZUS-MH

HAZUS-MH V1.0, incorporates 2,645 bridges and 771 road segments into its database for the region of study selected for this project. The information used by the HAZUS-MH Earthquake Module for each bridge is based on the National Bridge Inventory and is summarized in Table 3. The values tabulated for the individual bridges affect many aspects of the damage calculations for that structure in the program. The classification assigned to the bridge is a core element and is based on several factors, including the seismic design, number of spans, structure material, pier type, abutment type, bearing type, and span continuity of the bridge structure. HAZUS-MH defines 28 basic bridge classes and uses additional factors to account for specific bridge attributes in the damage algorithms. HAZUS-MH allows the bridge data to be updated as needed through the replacement of database files. The current bridge data used in the program was from the 2001 NBI database.

NBI Comparison (Selection of an appropriate bridge inventory)

One of the critical components of this project is the bridge inventory. The number of bridges in the bi-state region is large as a result of the convergence of the Mississippi, Missouri, and Meramec rivers and the large number of important highways in the area. An open minded approach was selected in appropriating a bridge inventory to use for the post-earthquake transportation network analysis. It was determined that there were several bridge databases for the area that had valuable information, including FEMA, FHWA, and the Illinois and Missouri Departments for Transportation, IDOT and MODOT, respectively (Table 4).

The MoDOT had two databases available for District 6 in spreadsheet form containing individual structure names and locations based on the intersection of two transportation features, e.g. Interstate 270 crossing Interstate 44. These spreadsheets were very useful to locate the "damaged" bridges on the actual road network following the HAZUS-MH earthquake scenario runs. MoDOT also provided GIS road and bridge layers for the state that contained basic data for the transportation network and allowed visual confirmation of the location of bridge structures within the Missouri portion of the study region.

IDOT provided data in GIS database form and printed maps. The Illinois Structure Information System (ISIS) and the associated Structural Information Management System (SIMS) are state run databases created to fulfill requirements set by the National Bridge Inspection Standards (NBIS). The ISIS database includes "bridge inventory and inspection data for all structures over 20 feet face to face of abutments on the roads maintained by the public agencies that are open to the public" (http://www.dot.state.il.us/sims/sims.html, 8/04). The data in ISIS includes the data fields from the federal NBI database and other data that is state specific. The SIMS also allows the bridges to be mapped in a GIS environment, which was convenient for locating the damaged bridges on the road network within the Illinois portion of the study area. IDOT District 8 maintenance maps were also very helpful in locating the structures on the road network.

The National Bridge Inventory contains 116 bridge classification items and is continuously being updated. This database is based on information sent to FHWA by the individual states and is particularly useful for this project since it contains the Missouri and Illinois bridge data in a consistent format. The HAZUS-MH program Earthquake Module utilizes only the bridge data from the 2001 NBI database needed for determining seismic damage. Therefore, the NBI contains a much richer database than that utilized by HAZUS-MH.

For several reasons the database selected for use in the damage analysis for bridge structures was the HAZUS-MH default database. First, the data included in the program is based on the NBI, which contains standardized categories of data over the bi-state study region. Second, similar FHWA evaluation parameters for each category are utilized by each state in the preparation of the data. Third, the data within the NBI database is fairly accurate and reliable. Although updated NBI data was available to replace the 2001 NBI database in the HAZUS-MH program, it was found to not be significant enough to justify updating the HAZUS-MH database.

DIRECT LOSSES

The earthquake scenarios investigated in detail, the M_W 7.7 New Madrid, the M_W 7.0 Germantown, and the M_W 7.0 St. Louis earthquakes, were run in HAZUS-MH in order to define the bridges damaged, bridge restoration over time, and the direct economic loss. A Level 2 HAZUS-MH analysis was run on each of these earthquake events with modifications made to the PESH model soil amplification and liquefaction maps (Figures 4 and 5). Table 5 shows the input parameters used in the HAZUS-MH analysis for each of the runs.

Probabilities of damage and losses were calculated for each bridge in the transportation module. The HAZUS-MH program uses formulas to determine earthquake damage based on the following input parameters: earthquake (1) moment magnitude, (2) epicenter depth, (3) latitude/longitude, (4) attenuation relationship, and bridge (5) latitude/longitude, (6) class, and

(7) specific data (e.g. skew angle). The damage is estimated for the earthquake is assigned a probability of being at a range of damage states. This allows the user to choose a confidence level which is reasonable for the earthquake chosen. An example of how the peak ground acceleration is distributed within the study area with the bridge inventory overlaid is shown in Figure 6. Notice how the soil layer amplifies the ground motion and is shown in the mapped distribution of PGA.

The five damage states assigned by HAZUS-MH to bridges are: none, slight, moderate, extensive, and complete. The probability of being at each damage state for each bridge is important in estimating the overall direct loss. The damage states and best estimates of damage for each state are shown in Table 6. The best estimate damage ratio represents the percentage of damage that would need to incur in order to be at a particular damage state, based on the dollar value of the bridge.

Direct losses can be defined simply as the cost to repair a bridge back to 100% capacity after incurring damage due to an earthquake. "Direct economic losses are computed based on (1) probabilities of being in a certain damage state, (2) the replacement value of the component, and (3) damage ratios for each damage state. Economic losses are evaluated by multiplying the compounded damage ratio by the replacement value, where the compounded damage ratio is computed as the probabilistic combination of damage ratios." [HAZUS-MH (2003) Technical Manual, Pg. 15-31]

HAZUS RESULTS OF DAMAGE FOR EACH SCENARIO

A seismic analysis was run in HAZUS-MH for the St. Louis, Germantown, and New Madrid scenarios. A summary of the number of bridges damaged can be seen in Tables 7 – 9.

The St. Louis scenario earthquake HAZUS-MH run shows the greatest probability for damage to the bridge structures. There were 564 bridges with a probability of at least 50% moderate damage (Table 7). A reduction in bridge damage was observed as the analyses moved to earthquakes located further away. The number of bridges that have at least 50% probability of moderate damage in the Germantown scenario is 50 (Table 8) and for the New Madrid scenario is 5 (Table 9). Note that the attenuation relationship for the New Madrid scenario is Frankel's 1996 relationship as opposed to the Project 2000 East relationship as used in the St. Louis and Germantown scenarios.

The direct economic damage experienced by the highway network was interpreted from the HAZUS-MH output. The replacement value of the various bridge types is shown in Table 10, which is based on ATC-13 and ATC-25 (Applied Technology Council). Figure 7 shows the direct economic loss estimates to bridge structures due to each scenario. The study region bridge inventory in HAZUS-MH is valued at \$4,971 million (in 2002 dollars). This dollar figure is the output from HAZUS and was used as input to estimate the value in 2004 dollars of \$5,220 million. The Consumer Price Index (CPI) was used to convert the dollar figure from the year 2002 to the year 2004. These CPI values are obtained from the Bureau of Labor Statistics (http://www.bls.gov). As shown in Figure 7, \$864 million (nearly 17% of the total inventory value) would be needed to repair the bridge network after an M_W 7.0 earthquake in St. Louis, Missouri. The bridge damage estimate for the study area from an M_W 7.0 earthquake at Germantown, Illinois and an M_W 7.7 earthquake at New Madrid, Missouri are $174 million and $70 million respectively.

CONCLUSIONS

1. Due to its proximity to the St. Louis Metropolitan area, an Mw7.0 earthquake in St. Louis will cause over 12 times more direct economic loss than an earthquake event of Mw7.7 in the NMSZ. The probabilistic weighted expected value of the two events may be comparable.
2. In combination with a transportation model, HAZUS can be used for earthquake loss estimation of highway systems. This process is complex and tedious, which can be eased by a more streamlined software system such as REDARS.
3. The loss estimation model was applied to the highway transportation system in the St. Louis Metropolitan area. Both direct and indirect losses have been calculated due to earthquake scenarios from the NMSZ and nearby.
4. The areas that were the most affected were located in the liquefaction susceptible alluviums. Most of the anticipated damage is on river crossings, old structures, and in East St. Louis, Illinois. For earthquakes of magnitude 7.0 and 7.7, economic direct losses range from $70 to $800 million.

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Table 1 – Earthquake scenarios for the area of study – Missouri & Illinois

Name of EQ Source Zone	**Source Zone Fault or Structure**	**Lat. of source**	**Long. of source**	**Distance from St. Louis (miles)**	**Mag. of EQ Source**	**Evidence for EQ source**	**Most recent EQ.**	**Ref.**
Arnold, Missouri	Unknown - possibly St. Louis fault or Valmeyer and Waterloo-Dupo anticlines	38.44	-90.4	18	5.2	Paleo-liquefaction features	< 2750	***A*** ***B*** ***C***
Germantown, Illinois	Unknown	38.56	-89.5	38	7	Paleo-liquefaction features	< 3,990	***A*** ***C***
Centralia, Illinois	Unknown - possibly Centralia fault-Du Quoin monocline	38.57	-89.17	56	7.5	Paleo-liquefaction features	< 3,990	***A*** ***C*** ***D***
Vincennes, Indiana	Wabash Valley fault zone	38.7	-87.51	146	7.5	Paleo-liquefaction features	6,100	***C*** ***E*** ***F***
New Madrid, Missouri	New Madrid seismic zone	36.55	-89.54	148	7.7	Historic earthquakes and paleo-liquefaction features	93	***C*** ***G***
St. Louis, Missouri	USGS background seismicity for Mmax of the inboard “craton” background zone	38.63	-90.2	0	7	None: assumed possible anywhere in the Central U.S. inboard "craton" zone	Unknown	***G***

References for Table 1:

A. Tuttle et al. (1999); ***B.*** Tuttle, (2001); ***C***. Crone et al. (2002); ***D.*** Bauer (2002); ***E.*** Munson and Munson (1996); ***F.*** Pond and Martin (1996); ***G.*** Frankel et al. (1996); ***H.*** Cramer et al. (2002).

Table 2 – Major Missouri and Mississippi River Bridges

Structure	**County**	**Feature Intersected**	**Facility Carried**	**Year Built**	**1999 ADT**	**Structure Length**
(NBI Item 8)	(NBI Item 3)	(NBI Item 6a)	(NBI Item 7)	(NBI Item 27)	(NBI Item 29,30)	(NBI Item 49, m)
A40171 2	St. Charles	MISSOURI RIVER	US 40 (E)	1991	39969	796.7
A5585 4	St. Charles	MISSOURI RVR	MO 364	1999	72400	986.9
A4557 2	St. Charles	MISSOURI RVR	MO 370 (N)	1992	9532	1053.1
A4557 3	St. Charles	MISSOURI RVR	MO 370 (S)	1993	9532	1053.1
J10004 3	St. Charles	MISSOURI RVR	US 40 (W)	1935	39463	796.7
A3047 4	St. Charles	MISSOURI RVR	US 67	1979	32567	848.3
A4278 4	St. Charles	MISSISSIPPI RVR	US 67	1994	28565	1408.2
A3292R 2	St. Louis	MISSOURI RIVER	IS 70 (E)	1978	143463	1155.8
L05617 3	St. Louis	MISSOURI RVR	IS 70 (W)	1958	87752	1244.5
A1850 3	St. Louis	MISSISSIPPI RVR	IS 255 (W)	1985	28859	1220.1
A4936 2	St. Louis	MISSISSIPPI RVR	IS 255	1990	26393	1220.1
A 890 4	St. Louis City	MISSISSIPPI RVR	IS 270	1964	52299	824.8
A4856 1	St. Louis City	MISSISSIPPI RVR	MO 770	1900	41076	1222.2
A1500R3 4	St. Louis City	MISSISSIPPI RVR	IS 70	1963	149848	659.9
K09691 1	Franklin	MISSOURI RVR	MO 47	1934	8811	780.9

(Source: FHWA, 2001)

Table 3. HAZUS-MH bridge inventory items used for analysis.
(Adapted from FEMA Metadata for HAZUS-MH V1.0)

Item Name	Description
Highway Bridge Id	HAZUS-MH Internal ID
Bridge Class	Analysis Class
Tract	Census Tract
Name	Bridge Name
Owner	Bridge Owner
Bridge Type	Structure Type
Width	Bridge Width (m)
Number of Spans	Number of Spans
Length	Total Bridge Length (m)
Max Span Length	Maximum Span Length (m)
Skew Angle	Skew Angle (degrees)
Seat Length	Seat Length (m)
Seat Width	Seat Width (m)
Year Built	Year Bridge Was Built
Year Remodeled	Year Bridge Remodeled
Pier Type	Pier Type
Foundation Type	Foundation Type
Scour Index	Scour Index
Traffic	Daily Traffic (cars/day)
Traffic Index	Traffic Index
Condition	General Condition Rating
Cost	Replacement Cost (thous. $)
Latitude	Latitude of Bridge
Longitude	Longitude of Bridge
Comment	Misc. Comments

Table 4: Summary of Bridge Inventories Investigated

Bridge Inventory	Media	Date Updated	Inventory Items
MoDOT GIS	GIS	2001	45
MoDOT District 6 (1)	Database	1999	6
MoDOT District 6 (2)	Database	2002	6
Illinois ISIS/SIMS	GIS/Database	2003	170
FEMA's HAZUS-MH	GIS/Database	2001	25
FHWA's NBI	GIS/Database	2002	116

Table 5. Summary of the Earthquake Input Parameters Used in HAZUS-MH

Name Earthquake Scenario	Latitude	Longitude	Moment Magnitude	Epicenter Depth	Attenuation Relationship
1. St. Louis, MO	38.63	-90.2	7	10 km	Project 2000 East
2. Germantown, IL	38.56	-89.5	7	10 km	Project 2000 East
3. New Madrid, MO	36.55	-89.54	7.7	10 km	Frankel (1996)

Table 6 Bridge Damage Ratios for the 5 Damage States

Damage State	Best Estimate Damage Ratio
None	0%
Slight	3%
Moderate	8%
Extensive	25%
Complete	100%*

* Note that the best estimate for complete damage on bridges with more than two span is equal to 2/(number of spans)
(source: HAZUS-MH, 2003, Table 15.18)

Table 7 Number of damaged bridges for St. Louis HAZUS-MH run.

Probability of Occurrence	Initial Damage State				
	Complete	Exceed Extensive	Exceed Moderate	Exceed Slight	None
=1	0	0	0	0	81
≥0.75	29	163	216	367	1448
≥0.5	188	469	564	732	1913
≥.25	521	836	997	1197	2278
>0	2216	2423	2480	2564	2645
≥0	2645	2645	2645	2645	2645

Table 8 Number of damaged bridges for Germantown HAZUS-MH run.

Probability of Occurrence	Initial Damage State				
	Complete	Exceed Extensive	Exceed Moderate	Exceed Slight	None
=1	0	0	0	0	406
≥0.75	0	0	2	32	2427
≥0.5	0	9	50	103	2542
≥.25	9	112	155	218	2613
>0	1483	1999	2146	2239	2645
≥0	2645	2645	2645	2645	2645

Table 9 Number of damaged bridges for New Madrid HAZUS-MH run.

Probability of Occurrence	Initial Damage State				
	Complete	Exceed Extensive	Exceed Moderate	Exceed Slight	None
=1	0	0	0	0	13
≥0.75	0	0	0	0	2494
≥0.5	0	0	5	58	2587
≥.25	0	29	67	151	2645
>0	1738	2306	2471	2632	2645
≥0	2645	2645	2645	2645	2645

Table 10 - Default Replacement Values of Transportation System Components

System	Replacement Value ($ thousands)	Label	Component Classification
Highway	20,000	HWB1 / HWB2	Major Bridges
	5,000	HWB8, 9, 10, 11, 15, 16, 20, 21, 22, 23, 26, 27	Continuous Bridges
	1,000	HWB3, 4, 5, 6, 7, 12, 13, 14, 17, 18, 19, 24, 25, 28	Other Bridges

Source: HAZUS-MH Technical Manual - Table 15.16: Default Replacement Values of Transportation System Components, p. 15-33.

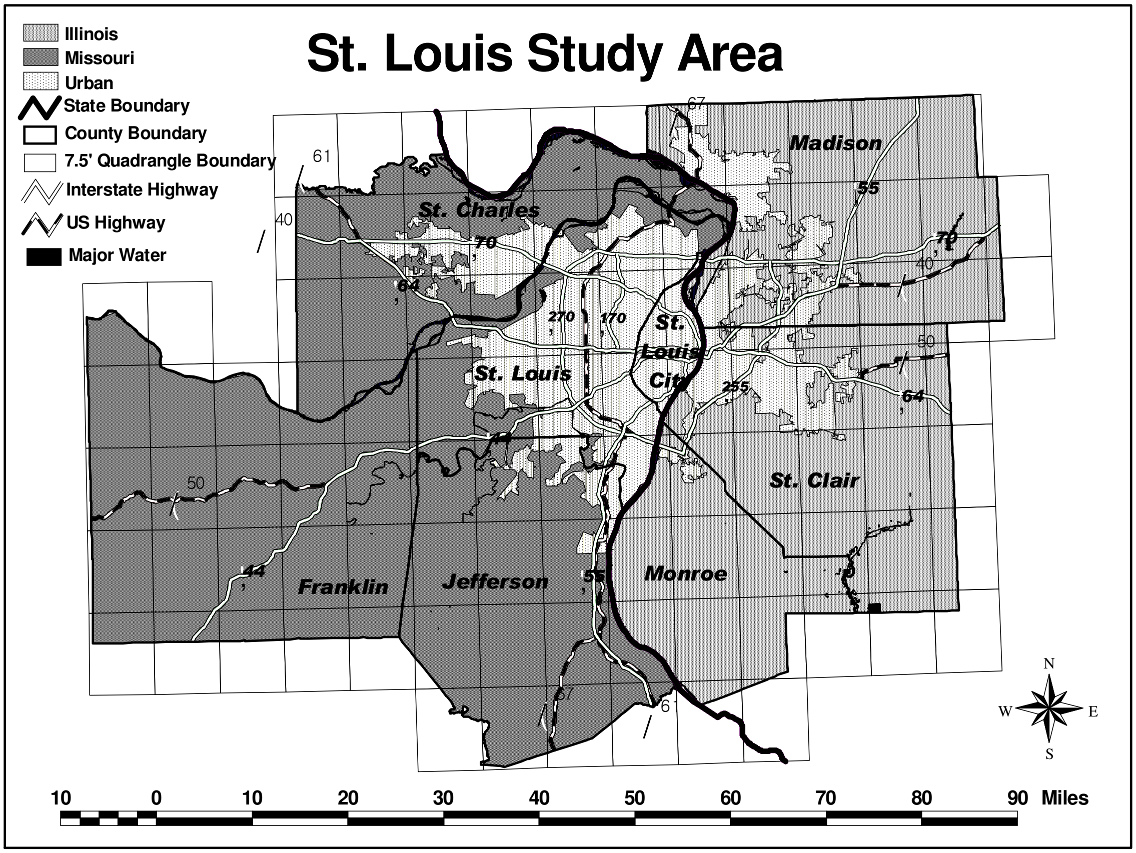

Figure 1 – Map of St. Louis Metropolitan Region showing the Study Area.

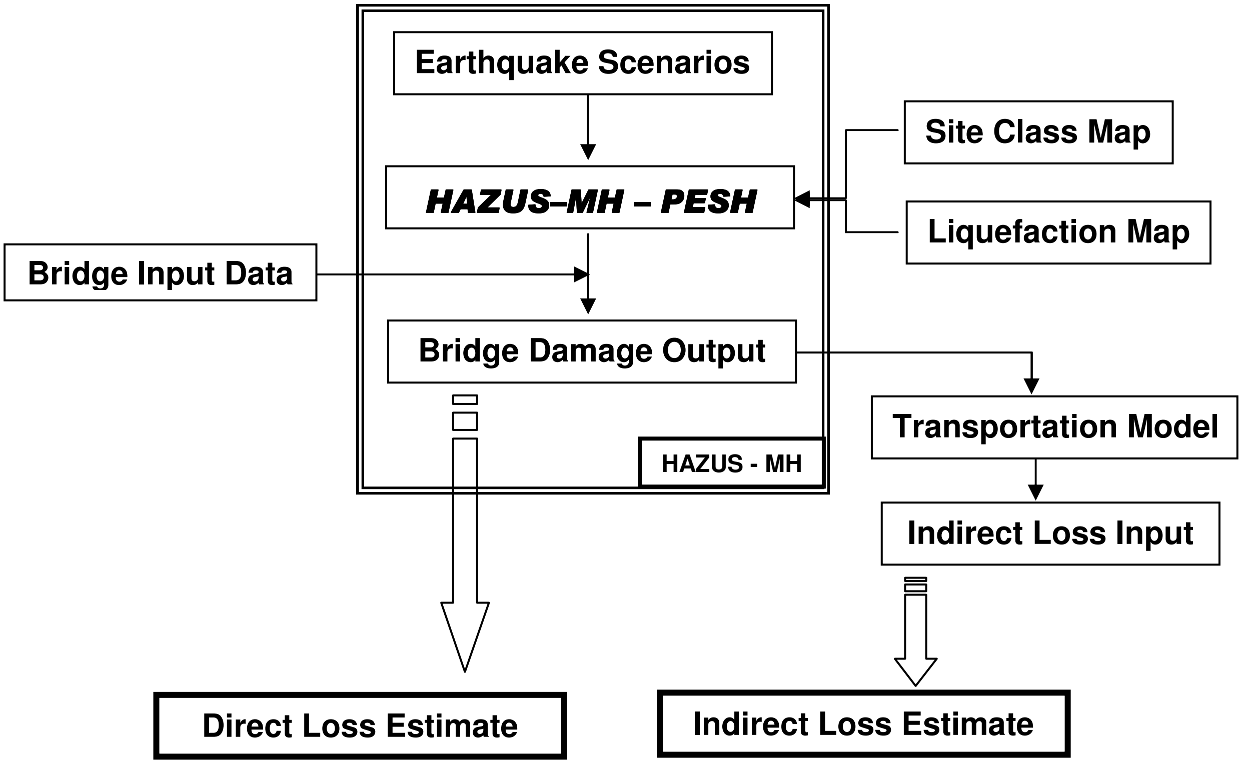

Figure 2 – Flowchart Schematic of the Methodology Used.

Figure 3 – Earthquake Scenario Sources for Area of study – Missouri & Illinois.

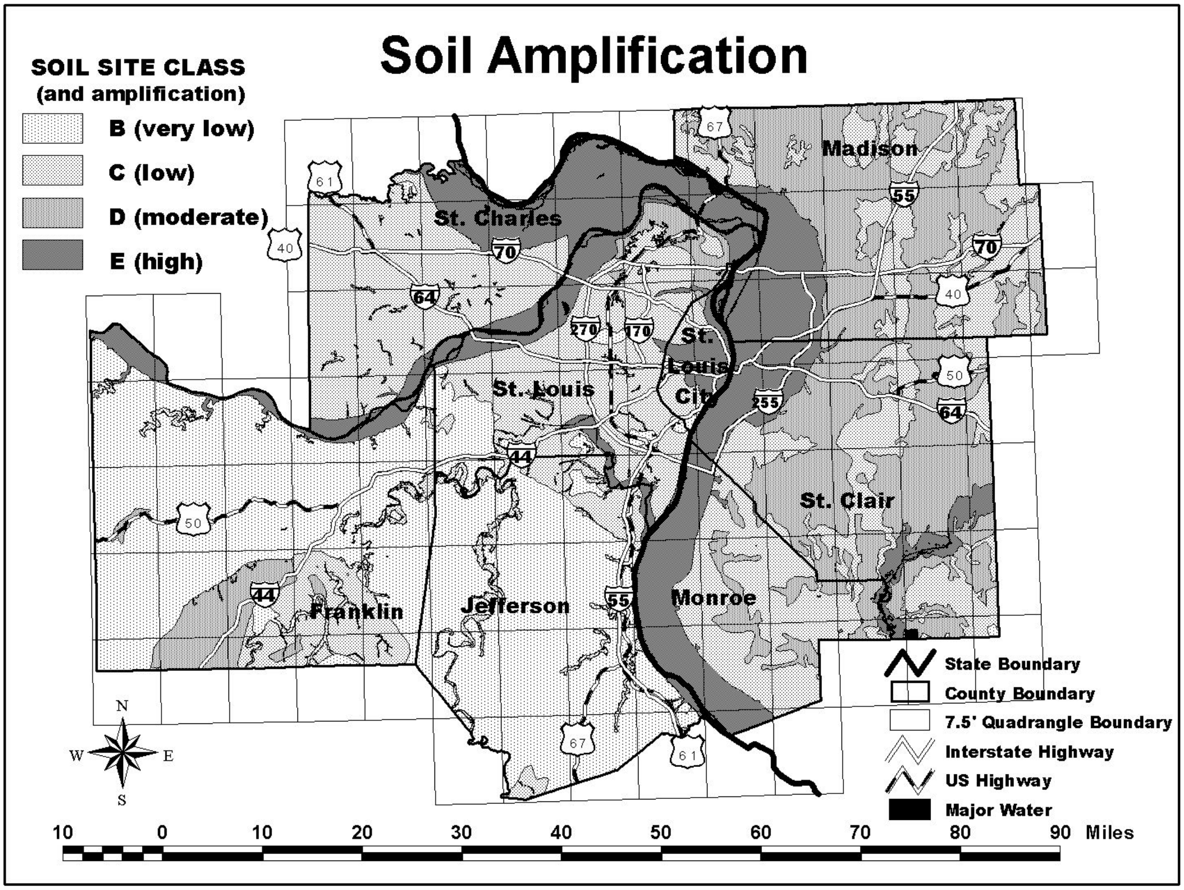

Figure 4 – Soil Amplification Map for the St. Louis area of study.

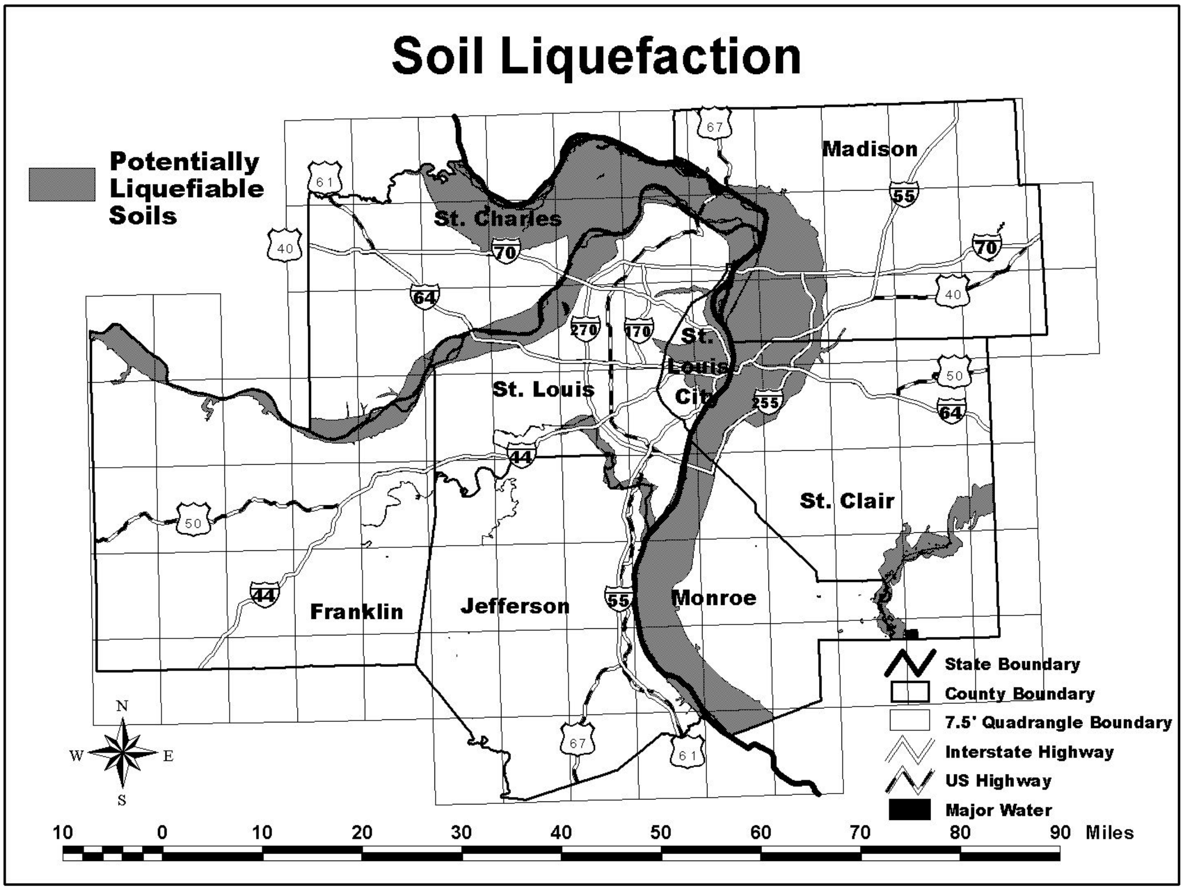

Figure 5 – Soil Liquefaction Map for the St. Louis area of study.

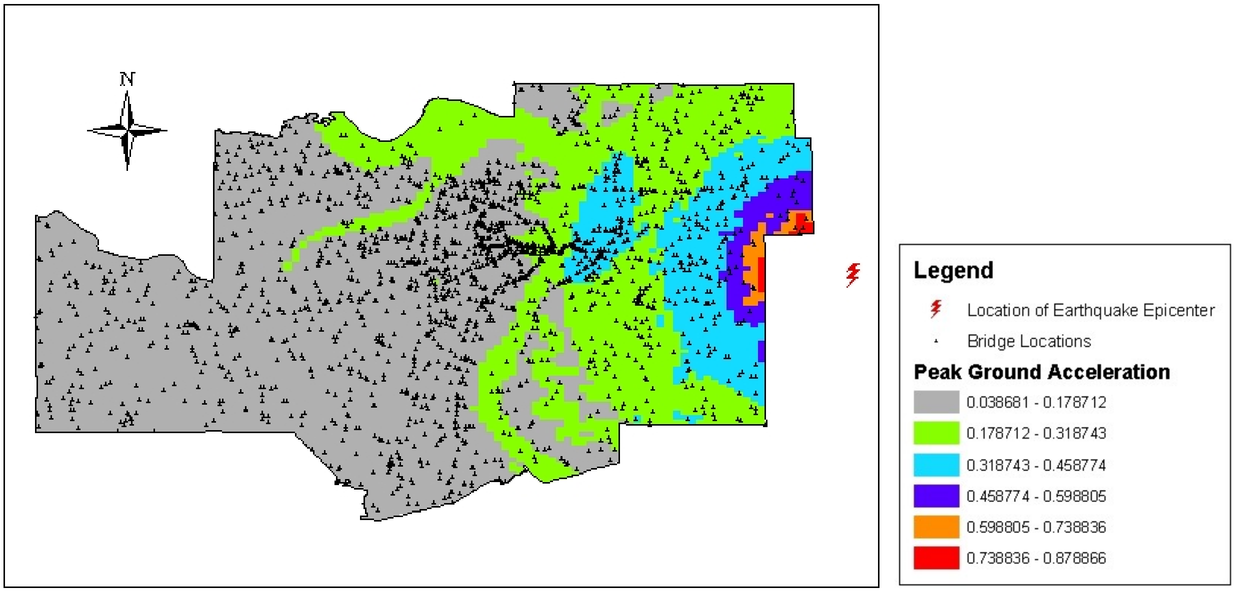

Figure 6 – PGA Distribution within the Study area showing the bridge inventory.

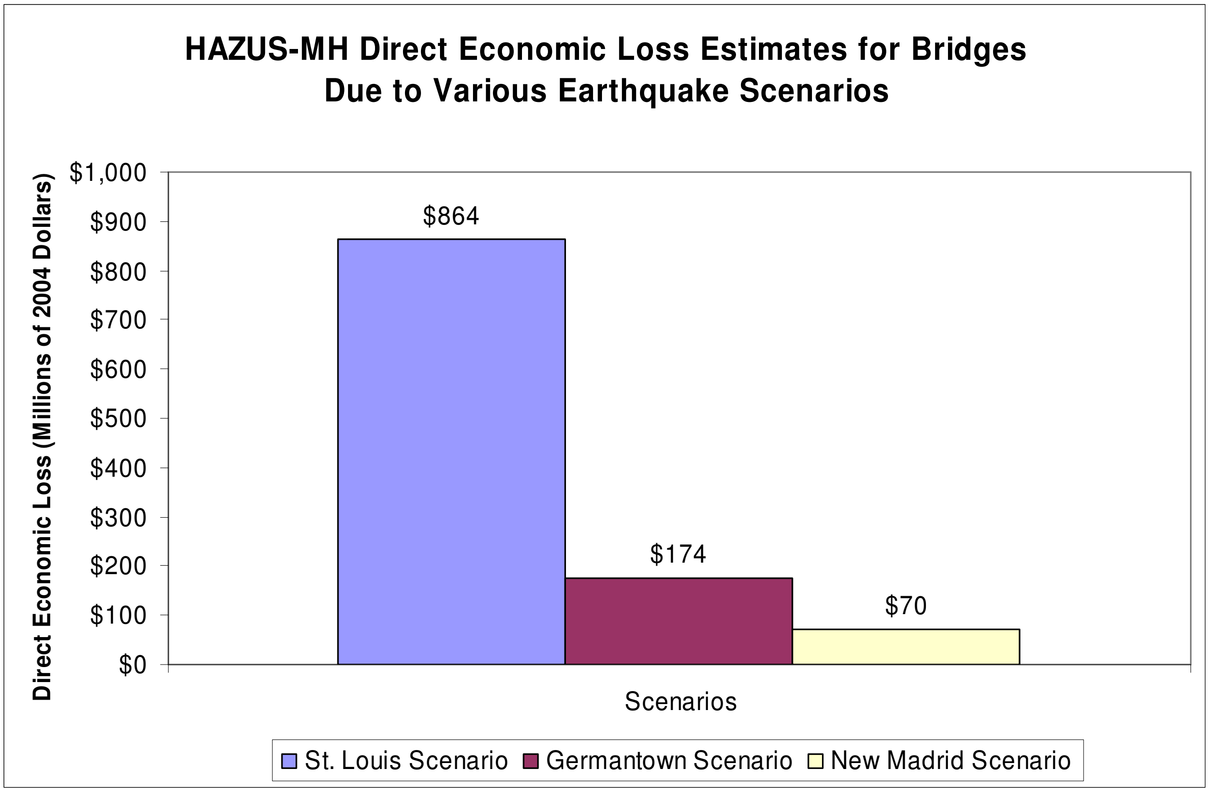

Figure 7 – Direct Economic Loss Estimate for Bridge Structures in the St. Louis Study Area (2004 dollars)

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