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Ronaldo Luna

Missouri University of Science and Technology, rluna@mst.edu

David J. Hoffman

William T. Lawrence

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Earthquake Hazard Input for Loss Estimation Study: St. Louis Highway System

Ronaldo Luna¹, David J. Hoffman², and William T. Lawrence³

¹ Associate Professor, Department of Civil, Architectural and Environmental Engineering, University of Missouri, Rolla, MO. 573-341-4484; Email: rluna@umr.edu

² Associate Research Engineer, Natural Hazards Mitigation Institute, University of Missouri, Rolla, MO. 573-348-7608; Email: dhoffman@umr.edu

³ Graduate Research Assistant, Department of Civil, Architectural and Environmental Engineering, University of Missouri, Rolla, MO. Email: lawre@umr.edu

Abstract

The long recurrence period and high consequence earthquakes events in the New Madrid Seismic Zone have caused some federal agencies (e.g., NEHRP, FHWA) to look at the more densely populated areas where higher seismic risk is present. This paper presents the data collection, interpretation, and analysis of the geotechnical information required for an earthquake loss estimation study in St. Louis metro area. The loss estimation study was limited to the highway transportation system, where only the major highways were considered. The project information was processed using a GIS, and the subsequent loss analysis was executed using the HAZUS-MH program.

Introduction

Earthquake hazards have been of special interest in the Midwest due to the presence of the New Madrid Seismic Zone. The long recurrence period of seismic events in this area is associated with the possible high consequences of a major event. Therefore, recently the focus of federal agencies (e.g., NEHRP, FHWA) has turned to look at the more densely populated areas (e.g., St. Louis, MO and Evansville, IN), where the impact may be greater (higher seismic risk). Earthquake loss estimation methodologies have been available for some time and their application has increased with the continued use of available GIS-based software. Small and medium size communities have taken advantage of these tools when they have a perceived risk (Olshansky and Wu, 2004). However, when the size of the community is large, like in a major metropolitan area, and the perceived risk is low these tools are seldom applied. This was the case of St. Louis, Missouri, located about 180 miles away from the well known New Madrid Seismic Zone (NMSZ). St. Louis is a metropolitan area that has not been subjected to a GIS based loss estimation study. This paper presents the data collection, interpretation, and analysis for the geotechnical information required for an earthquake loss estimation in the metropolitan area of St. Louis, Missouri. The loss estimation study was limited to the highway transportation system, that is, only the major highways in both states of Missouri and Illinois.

The use of the software program HAZUS was strongly encouraged by FEMA through the Project Impact initiative to become disaster resistant communities. A number of cities were designated as project impact communities and received funding to carry out loss estimation studies, e.g., Oakland, CA; Salt Lake City, UT; Anchorage, AK; Charleston, SC (FEMA, 2001). Few of these studies addressed transportation systems and even fewer specifically focused on the highway network (Veneziano, et al. 2002). 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 (Werner, et al. 2000).

Description of Study Area and Methodology

The study area encompasses the counties in the metropolitan St. Louis urban region, which includes the two neighboring states of Missouri and Illinois. The counties included in Missouri are St. Louis, St. Charles, Franklin and Jefferson plus the independent City of St. Louis and in Illinois are Madison, St. Clair and Monroe. All or part of 99 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]).

To estimate the economic losses after an earthquake event has occurred requires a series of steps before that dollar amount can be estimated (See Figure 2). The sequence of steps requires defining the earthquake source, the attenuation to the site of interest, the distribution of local soils, the peak ground acceleration at the site, the structure

(bridge) in question and an assessment of the structure damage. Then, based on economic analysis the direct and indirect losses can be estimated. If indirect losses due to the damage of the highway system are estimated, there is a need to assess the performance of the network and its impact to the economy.

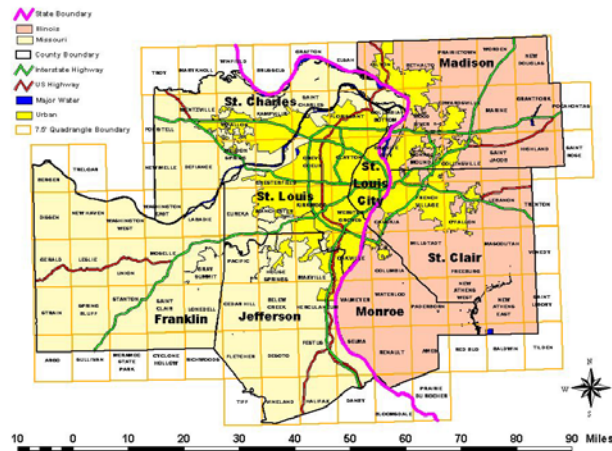


Figure 1. Map of St. Louis Metropolitan Study Area

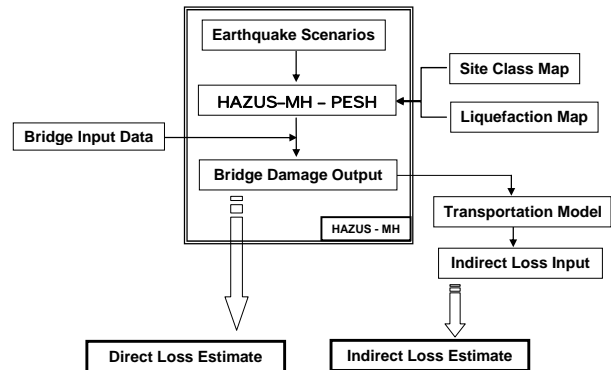


Figure 2. Flowchart Schematic of Methodology Used.

The selection of the methodology for use in this study was made primarily based on availability, since most methodologies are currently still being developed. The framework was adapted from the work done in the Memphis study (Werner, et al., 2000), 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 a transportation planning software was used to estimate the time delays with the earthquake distance modified for the different earthquake scenarios.

HAZUS-MH – Description of its Use in this Study

The Hazards United States – Multi Hazard (HAZUS-MH) 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 initial development and releases, HAZUS 97 and HAZUS 99, provided loss estimation analyses for earthquake hazards only. The January 2004 Version 1.0 of HAZUS-MH provides loss estimation for three hazards: earthquake, flood, and hurricane.

The HAZUS-MH loss estimation software comes with methods for earthquake ground motion computations built-in using national bedrock characteristics and default soils data. Some parameters of the ground motion computation may be selected, such as a choice of attenuation functions, or refined by user-supplied data, such as soil amplification mapping. Appropriate choices for the provision of these parameters allow the processing of refined loss estimations with more realistic results.

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 study the critical databases for bridges and soils were especially limited. As an example, the soils database map has the entire nation mapped as a single soil class 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 detailed regional soils map and liquefaction hazard map. At Level 3, users may supply their own techniques through third party model integration capability to study special conditions.

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. From the six attenuation functions available for the Central and Eastern United States (CEUS) the Project 2000 East attenuation function was selected. This 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 for earthquakes. 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 SQL database attenuation table had to be modified to include distances that extended beyond 200 km (125 miles) from the epicenter of the earthquake scenarios.

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)

Earthquake Scenarios Studied

A review of deterministic, historic, 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, a representative subset was selected for detailed loss estimation.

Description of Selected Earthquake Scenarios

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 around relatively short periods ($\sim T=0.2$) therefore affecting structures of similar period. Bridges that have longer periods ($\sim T=1.0$) are not affected as much as the shorter periods. After initial HAZUS runs and further identification of six earthquake scenarios, three were selected for actual study (see Table 1).

Table 1. Earthquake scenarios selected for the study – Missouri & Illinois

Name of EQ Source Zone (references)	Source Zone Fault or Structure	Source Lat.	Source Long.	Distance from STL (miles)	EQ Source Mag.	Evidence for EQ source	Most recent EQ. (yr)
New Madrid, MO (Crone, et al., 2002; Frankel, et al., 2002)	New Madrid seismic zone	36.55	-89.54	148	7.7	Historic earthquakes and paleo-liquefaction features	93
Germantown, IL (Tuttle, et al., 1999; Crone, et al., 2002)	Unknown	38.56	-89.5	38	7	Paleo-liquefaction features	< 3,990
St. Louis, MO (Frankel, et al., 2002)	USGS backgrnd. seismicity for M_{max} of the inboard "craton" background zone	38.63	-90.2	0	7	None: assumed possible anywhere in the Central U.S. inboard "craton" zone	Unkn.

The philosophy adopted for the selection process 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, $M=7.7$ 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, $M=7.0$ 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, $M=7.0$ 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.

Spatial Distribution of 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. 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 area west of the Mississippi River and south of the Missouri River, except as note above, has not been glaciated and is in the Ozark Plateau province.

The geohazard maps (liquefaction, landslides and lateral spreading) were assembled from Missouri and Illinois data sources. Existing state geological survey surficial materials or soils data for the study area were collected. 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 format at a scale of 1:250,000 for the entire study area in Missouri and Illinois (see Figure 3). These soil amplification maps were revised to show just 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 is also mapped and it represents soil failure due to liquefaction. A separate liquefaction potential map for the Missouri and Illinois study area was prepared for use in a GIS environment (Figure 4).

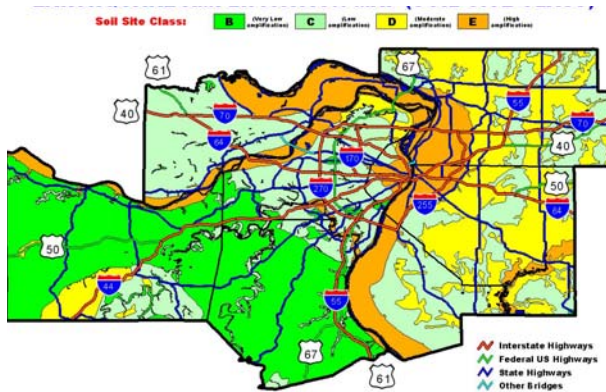


Figure 3. Soil Amplification Map for the area of study.

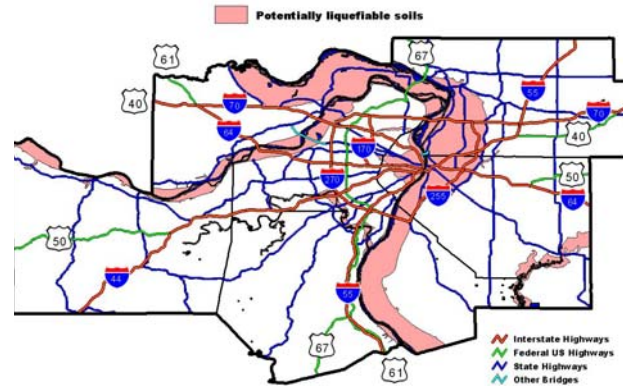


Figure 4. Soil Liquefaction Map for area of study.

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 3. 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 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. HAZUS-MH Version 1.0 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 NBI. The attributes tabulated for the individual bridges affect many aspects of the damage calculations for that structure. HAZUS-MH defines 28 basic bridge classes and uses additional factors to account for specific bridge attributes in the damage algorithms. 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. The bridge characteristics, along with the PESH model inputs, allow the bridge damage, cost to repair, expected functionality at certain times following an earthquake event, and the indirect economic impact for the study region to be estimated.

Direct Losses

Each of the earthquake scenarios was used in HAZUS-MH in order to define the bridges damaged, bridge restoration over time, and the direct economic loss as a result of the earthquake event. 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 (see Figures 3 and 4, respectively).

Probabilities of damage and losses were calculated for each bridge in the transportation module in a fairly comprehensive manner. The HAZUS-MH program uses formulas to determine earthquake damage based on the following input parameters: (1) earthquake moment magnitude, (2) earthquake epicenter depth, (3) earthquake latitude/longitude, (4) earthquake attenuation relationship, (5) bridge latitude/longitude, (6) bridge class, and (7) bridge specific data (skew angle, for example). The damage is estimated immediately following an earthquake event and 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 event chosen. An example of how the peak ground acceleration is distributed within the study area with the bridge inventory overlaid is shown in Figure 5. 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 damaged bridges are: none, slight, moderate, extensive, and complete. The range of damage states, therefore, covers from the probability of a bridge incurring no damage to the probability of a bridge incurring complete damage (needs replacement). The probability of being at each damage state for each bridge is important to estimate the overall direct loss, with each damage state causing a set percentage of damage to occur.

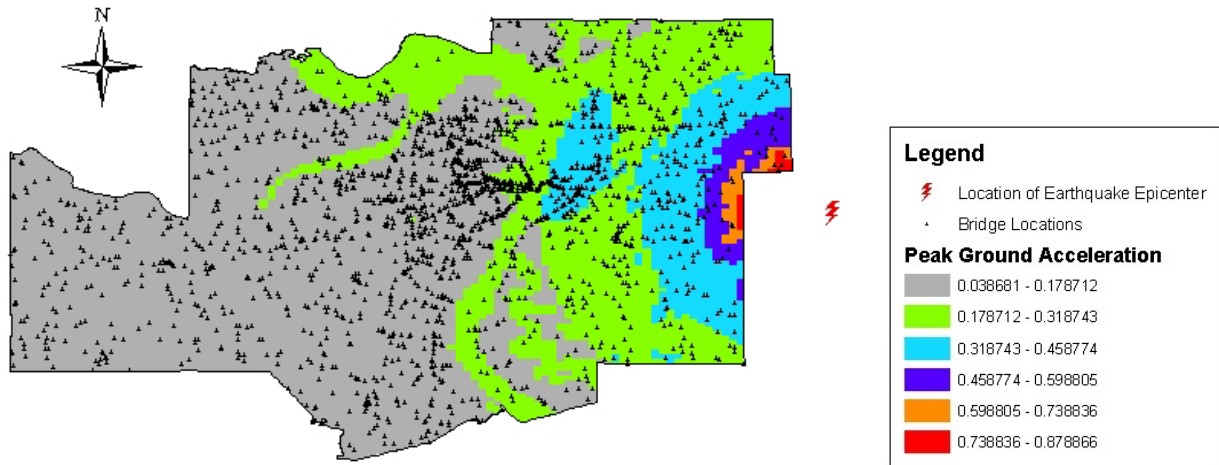


Figure 5. Germantown, IL scenario PGA Distribution within the Study area showing the bridge inventory.

HAZUS Results of Damage Loss for each Scenario

Direct losses can be defined simply as the cost to repair a bridge back to 100% capacity after incurring damage due to an earthquake event. “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).

The St. Louis earthquake scenario run shows the greatest probability for damage to the bridge structures in the study area. There were 564 bridges with a probability greater than 50% of incurring moderate damage. A reduction in bridge damage was observed as the analyses moved to earthquakes located further away from the study area. The number of bridges that have a 50% probability of incurring at least moderate damage in the Germantown scenario is just 50 bridges. The number of bridges in this category for the New Madrid scenario is only 5 bridges. It must be noted, though, 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 as a result of the earthquake scenarios was interpreted from the HAZUS-MH output. Table 2 shows the direct economic loss estimates to bridge structures due to each scenario. The bridge inventory for the study region is valued at \$4,971 million (in 2002 dollars). This dollar figure is the current output from HAZUS and was used as input to estimate the value in 2004 dollars, which corresponds to a present (2004) value of \$5,220 million. In order to update the dollar figure from the year 2002 to the year 2004, the Consumer Price Index (CPI) was used to convert these figures. These CPI values are obtained

from the Bureau of Labor Statistics (<http://www.bls.gov>). As shown in Table 2, \$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, MO. An M_w 7.0 earthquake in Germantown, IL, would cause an estimated \$174 million in damage to the bridge network in the study area, and a New Madrid, MO, M_w 7.7 earthquake is estimated to cause \$70 million in bridge damage.

Table 2. Summary of Direct Economic Loss Estimates (\$ figures in 2004 dollars).

Earthquake Scenario	Magnitude	Distance (miles)	Loss (million \$)
New Madrid, MO	7.7	148	70
Germantown, IL	7.0	38	174
St. Louis, MO	7.0	0	864

Conclusions

Most of the anticipated damage is on river crossings, old structures, and in East St. Louis, in the state of Illinois. Under an earthquake event of 7.0 and 7.7, damage and economic direct losses range from about \$70 to \$800 million. Due to its proximity to the St. Louis Metropolitan area, an M_w 7.0 earthquake event in St. Louis will cause over 12 times more direct economic loss than an earthquake event of M_w 7.7 in the NMSZ. Considering the very low likelihood of having an M_w 7.0 earthquake in St. Louis, the impact of an NMSZ earthquake within the life span of bridges could be as significant as nearby earthquakes.

Acknowledgements

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