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IMPACTS OF THE 1811-1812 EARTHQUAKES ON EXISTING TRANSPORTATION NETWORKS IN MEMPHIS AREA

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ABSTRACT

Significant damage of transportation infrastructure systems usually occurs during a major earthquake event. The impacts of bridge damage include not only short-term costs of structural repair, but also long-term economic consequences. In addition to initial replacement or repair costs of damage to the transportation structures, large earthquakes increase delays because of network components severe loss of functionality. After a severe earthquake, different parts of a roadway system will receive various levels of damage, and the capacity of those severely affected portions will be reduced, which will cause further traffic congestion. This paper describes a simulation of the response of a hypothetical transportation network, located in Memphis Area, which contains damaged bridges as result of multiple New Madrid earthquakes. For this purpose, the bridges in the transportation network are subjected to successive ground motions that simulate the historical 1811-1812 earthquake sequence. Bridge damage levels are determined based on a rigorous finite element analysis and the traffic capacity of the network roadways is predicted accordingly. Finally, the results show that the effect of earthquake damage on travel time is highly significant.

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ABSTRACT

Significant damage of transportation infrastructure systems usually occurs during a major earthquake event. The impacts of bridge damage include not only short-term costs of structural repair, but also long-term economic consequences. In addition to initial replacement or repair costs of damage to the transportation structures, large earthquakes increase delays because of network components severe loss of functionality. After a severe earthquake, different parts of a roadway system will receive various levels of damage, and the capacity of those severely affected portions will be reduced, which will cause further traffic congestion. This paper describes a simulation of the response of a hypothetical transportation network, located in Memphis Area, which contains damaged bridges as result of multiple New Madrid earthquakes. For this purpose, the bridges in the transportation network are subjected to successive ground motions that simulate the historical 1811-1812 earthquake sequence. Bridge damage levels are determined based on a rigorous finite element analysis and the traffic capacity of the network roadways is predicted accordingly. Finally, the results show that the effect of earthquake damage on travel time is highly significant.

Introduction

The Midwest region of the Unites States is an important "hub" of the nation transportation systems. According to the 2002 Commodity Flow Survey by the Bureau of Transportation Statistics (BTS), more than 968 billion ton-miles, or about 31% of the total U.S. commodities originate, pass through, or arrive in the Midwest region [1]. The greater metropolitan areas of Memphis are particularly of significance. With regard to freight, the Federal Express Corporation (FedEx) worldwide headquarters and world hub are located in Memphis. The third largest U.S. cargo facility of the United Parcel Service, Inc. (UPS), also the only UPS facility capable of processing both air and ground cargo, is located in Memphis [2]. On the passenger side, the City of Memphis and surrounding metropolitan area is one of the two major population centers in the Midwest. The greater Memphis metropolitan area, however, is one of the most vulnerable

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regions to seismic hazards in the United States. The aging transportation infrastructure would sustain significant damage and more than one million population severely impacted. A catastrophic New Madrid Seismic Zone (NMSZ) earthquake sequence could not only disrupt the direct functioning of the Memphis metropolitan area but also have ripple effects throughout the nation economy and society.

The NMSZ was responsible for the devastating 1811-1812 New Madrid earthquakes, the largest earthquakes ever recorded in the contiguous United States. The chance of a moderate earthquake in the NMSZ in the near future is high. Scientists estimate that the probability of a magnitude 6 to 7 earthquake occurring in NMSZ within the next 50 years is higher than 90% [3]. According to a recent study completed by the Mid America Earthquake Center, a magnitude 7.7 earthquake in the NMSZ could cause $300 billion direct economic loss, tens of thousands of causalities, and hundreds of thousands left without homes in central states, the losses will be mainly concentrated in Memphis, TN and St. Louis, MO [4].

Bridges are typically considered the most seismically vulnerable components of a highway transportation system. Therefore, predictions of the resilience of these structures provide valuable information for updating of infrastructure prior to severe events, as well as restoring functionality of transportation networks following disasters. After a severe event of multiple earthquakes, different parts of a roadway system will receive various levels of damage after each individual earthquake, and the capacity of those severely affected portions will be reduced, which will cause further traffic congestion. This report considers Sioux Falls transportation network in order to understand the effects of earthquake damage on travel time. Network structure of Sioux Falls is shown in Figure 1. The network consists of 76 directional links and 24 origin-destination pairs.

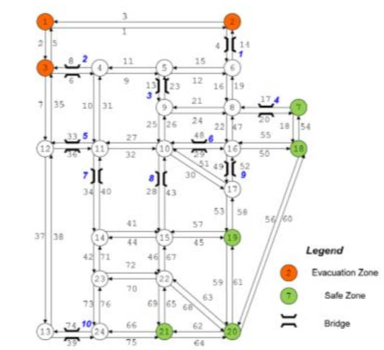

Figure 1. Sioux-Falls network and bridge locations on the network.

In this paper, the response of a hypothetical (Sioux Falls) network under New Madrid earthquakes is studied. The network contains ten bridges that are subjected to repeated earthquake ground motions predicted based on the City of Memphis conditions and its vicinity to the New Madrid fault system. Bridge models are established and their damage levels are determined from a rigorous nonlinear response history analysis. The serviceability level of the bridges is estimated based on the calculated damage levels. Lastly, the impact of bridges loss of functionality due to earthquake damage on the transportation system is presented.

Ground Motions

The “characteristic” seismic event is designed to reflect the historic 1811-1812 earthquake sequence, in which the characteristic means that large earthquakes have a trend of generating subsequently at proximate locations with the same magnitude at short time. There are three major segments of the primary fault of the NMSZ, the northeast segment, the Reelfoot Thrust segment, and the southwest segment, as shown in Figure 2 [5]. Such line source representation (on earth surface only) is based on the projections of presumed fault planes. The fault planes in the northwest and the southwest segments are assumed vertical, extending from 5 km to 15 km depth. The thrust segment is a dipping fault and not vertical, which dips to the southwest at 40 degrees with updip edge at 5 km below the surface and downdip at 15 km [5,6,7].

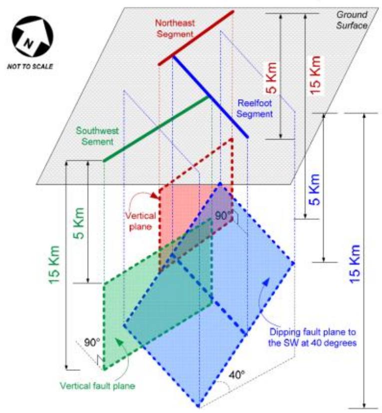

Figure 2. NMSZ structure.

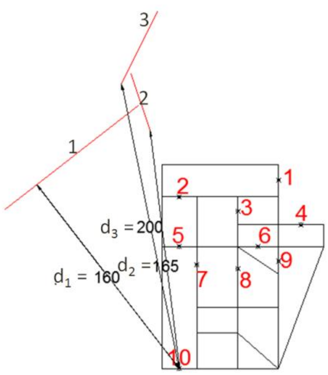

Figure 3. Fault-to-bridge distance.

Each fault segment of the three main segments in the NMSZ is capable of generating a 7.7 magnitude earthquake. In this study, an earthquake sequence that consists of three major 7.7 magnitude earthquakes is considered. The first earthquake is generated from the southwest segment (day 00) while the second and third earthquakes are generated from the Reelfoot (day

38) and northeast segments (day 53), respectively. The ground motions for the consecutive three fault ruptures M7.7 scenario are generated using Stochastic-Method SIMulation (SMSIM) software developed by [8]. The ground motions are attenuated through rock, and then propagated through the soil layer above the bedrock. The soil response analysis is conducted using SHAKE [9]. The site conditions are based on average soil properties of the City of Memphis. The source-to-site distance for each generated earthquake is determined using the shortest fault-to-bridge distance as shown in Figure 3 for bridge 10.

Bridge Model

A typical RC bridge design in Memphis is made. The bridge is a two-span with one pier at the mid-span. A rendering of the bridge geometry as defined in the analytical model is displayed in Figure 4. The bridge is modeled in the MAE Center fiber-based finite element tool, Zeus-NL [10]. Zeus-NL is a state-of-the-art 3D static and dynamic platform specifically developed for earthquake engineering applications. Its extreme efficiency, accuracy, verification and user-friendly graphical user interface has made it easier than ever to undertake inelastic large displacement analysis of complex bridges using the fiber approach, with a suite of material models and elements. Simulated ground motions are applied in the transverse and longitudinal directions of the bridge and different damage levels are determined.

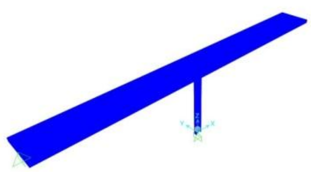

Figure 4. Rendering the overall bridge geometry (Zeus-NL).

A set of limit state threshold values are defined which are capable of capturing various local structural response mechanisms through the use of a minimal number of global parameters. The structural limits correspond to exceedance of serviceability, economic loss, and life safety, respectively. The three limit state threshold values need to be identified from the analysis of the response data in order to define the four performance levels of the bridge. The structural definition of these limit states is based on both local and global parameters, and for the sake of comparison in the vulnerability assessment, these parameters are mapped to one another. This mapping of local to global structural parameters allows for a simple and straightforward comparison of exceedance when the series of nonlinear time history analyses are performed. The characteristics utilized to identify each limit state are listed in Table 1.

The first step in identifying limit state threshold values involves an automated procedure that sorts through the data acquired in the numerical simulation. The data is sorted through to identify steps in the simulation where local strains exceed concrete rupture, steel yielding, and concrete crushing strains ($\varepsilon_c = +0.0005$, $\varepsilon_s = +0.002$, and $\varepsilon_{cu} = -0.004$ respectively). The corrected global hysteretic responses of the piers are plotted in several degrees of freedom, and the steps of the simulation where these identified strains occur are then plotted on each of the hysteretic responses. An example of these various definitions for the severe limit state plotted against the transverse displacement for the pier is displayed in Figure 5.

Table 1. Limit states threshold value definitions.

	LS1	LS2	LS3
Threshold Value	Slight	Moderate	Severe
Structural parameter	Concrete rupture strain, initial reduction of stiffness, cracking observed	Yield of reinforcing bars, reduction of global stiffness response	Concrete crushing strains, spalling observed, loss of load carrying capacity
Societal limit state definition	Serviceability	Economic loss	Life safety

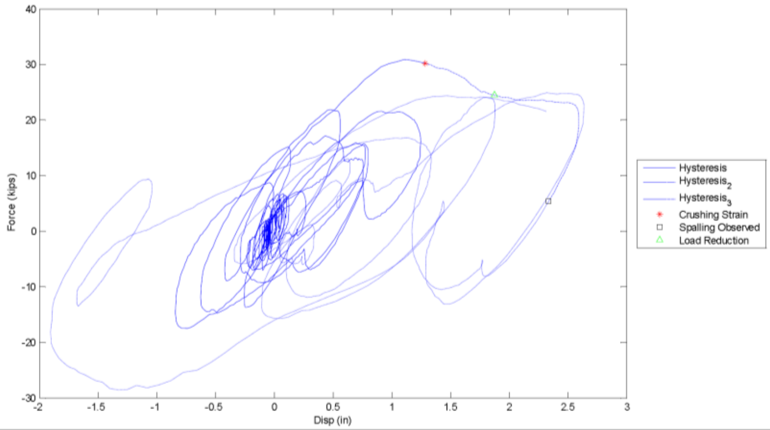

Figure 5. Transverse displacement limit state definitions.

The resulting limits states are translated into damage levels, which are used to assess the bridge condition after each earthquake. The amount of retrofit and associated duration are determined based on the bridge existing level of damage.

Impact on Transportation System

Table 2~~Table 2~~ and Table 3~~Table 3~~ show the percentage reduction in capacity of the ten damaged bridges without and with retrofitting scenarios respectively. For example, in Table 2~~Table 2~~ and based on the discussed limit states, the first bridge will have 36% reduction in capacity on the first day of the first earthquake. The same bridge capacity will be reduced to further 18% of the available 36% on the second earthquake on day 38; and so on. In contrast, Table 3~~Table 3~~ shows bridge operational capacity if retrofitting is allowed. Using bridge 1 as an example, the capacity of bridge 1 will be 30% after the first earthquake and it requires 19 days to complete the retrofit. After 19 days from the first earthquake, the bridge capacity should go back to 100%. After the second earthquake (38 days after the first one) the capacity of the bridge will be 21% due to the estimated damage in the bridge piers. The estimated time to complete the retrofit and return to 100% capacity is 24 days, however the bridge will experience a third earthquake before the completion of the retrofit after 15 days from second earthquake. The third earthquake will add more damage to the bridge to reduce its capacity to 8% of the initially undamaged bridge capacity.

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Table 2. First scenario assuming no retrofitting.

Bridge	Link #	Earthquake 1 / day 00 Capacity (%)	Earthquake 2 / day 38 Capacity (%)	Earthquake 3 / day 53 Capacity (%)
1	4 and 14	36	18	8
2	6 and 8	43	6	6
3	13 and 23	23	23	X
4	17 and 20	43	43	21
5	33 and 36	17	17	X
6	29 and 38	31	13	13
7	34 and 40	42	8	8
8	28 and 43	33	X	X
9	49 and 52	X	X	X
10	39 and 74	33	33	33

Note: X represents a fully damaged bridge

Table 3. Second scenario assuming retrofitting.

Bridge	Link #	Earthquake 1 / day 00		Earthquake 2 / day 38		Earthquake 3 / day 53	
		Capacity (%)	Duration (days)	Capacity (%)	Duration (days)	Capacity (%)	Duration (days)
1	4 and 14	36	19	21	24	8	28
2	6 and 8	43	17	6	28	6	17
3	13 and 23	23	23	44	17	X	X
4	17 and 20	43	17	51	15	21	24
5	33 and 36	17	25	44	17	X	X
6	29 and 38	31	21	12	26	12	23
7	34 and 40	42	18	8	28	8	21
8	28 and 43	33	20	X	X	X	X
9	49 and 52	X	X	X	X	X	X
10	39 and 74	33	20	56	13	47	16

Note: X represents a fully damaged bridge

User Behavior in Earthquake Affected Network

The route choice behavior of the users is analyzed by a user equilibrium traffic assignment procedure [11]. The user equilibrium assignment is based on Wardrop's first principle, which states that "no driver can unilaterally reduce his/her travel costs by shifting to another route" [11]. If it is assumed that drivers have perfect knowledge about travel costs on a network and choose the best route according toWardrop's first principle, this behavioral assumption leads to user equilibrium. This problem is equivalent to the following nonlinear mathematical optimization program,

$$Minimize \sum_{a} \int_{0}^{x_a} t_a(x_a)\, dx \quad (1)$$

subject to:

$$\sum_{r} f_{ij}^{r} = q_{ij} \quad (2)$$

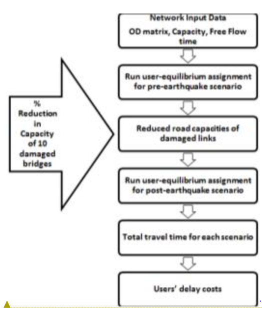
$$x_a = \sum_i \sum_j \sum_r f_{ij}^r \, \delta_{a,ij}^r \qquad (3)$$

$$f_{ij}^r, q_{ij}^r \geq 0 \qquad (4)$$

The objective function shows the sum of the integrals of the link performance functions. Notice that this function is just a mathematical formulation which solves equilibrium problems i.e. it doesn't have any behavioral or economical interpretation by itself. ~~The objective function shows minimization of total system travel times of the network as per Wardrop's first principle, which denotes that "no user can experience a lower travel time by unilaterally changing routes" [11].~~ . ~~In simple terms the equilibrium is achieved when the travel cost on all used paths is equal.~~ The two terms in equation (1) represent the total travel cost. The first term, t_a, is the travel time for link a, which is a function of link flow x_a. Equation (2) is a flow conservation constraint to ensure that flow on all paths *r*, connecting each Origin-Destination (O-D) pair (*i*-*j*) is equal to the corresponding demand. In other words, all O-D trips must be assigned to the network. Equation (3) represents the definitional relationship of link flow from path flows. In simple terms the flow on each link is the sum of the flows on all paths going through that link. Equation (4) is a non-negativity constraint for flow and demand. The travel time function $t_a(.)$ is specific to a given link 'a' and the most widely used model is the Bureau of Public Roads (BPR) function given by

$$t_a(x_a) = t_o\left(1 + \alpha_a \left(\frac{x_a}{C_a}\right)\right)^{\beta_a} \qquad (5)$$

where $t_o(.)$ is free flow time on link 'a', and α_a and β_a are constants (and vary by facility type). C_a is the capacity for link a. In the base model the objective is minimization of total system travel time.



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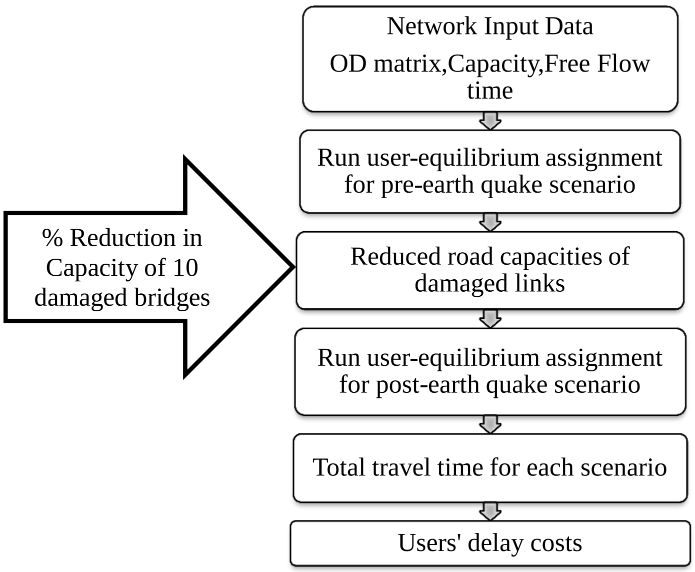

Figure 6. Methodology flow chart for delay estimation.

Table 4: Summary of symbols and notations.

Notation		Explanation
C_a	:	The capacity for link a
f_{ij}^{r}	:	Flow on path *r*, connecting each Origin-Destination (O-D) pair (*i-j*)
q_{ij}	:	Demand between each Origin-Destination (O-D) pair (*i-j*)
t_a	:	Travel time for link a
$t_a(x_a)$	:	Travel cost on link a as a function of flow
u_a	:	User cost for link a
x_a	:	Flow for link a
α_a	:	Constant, varying by facility type (BPR function)
β_a	:	Constant, varying by facility type (BPR function)
$\delta_{a,ij}^{r}$	:	Flow on link a, a subset of path *r*, connecting each Origin-Destination (O-D) pair (*i-j*)
$t_{\circ}$	:	Free flow time on link a

Earthquake related economic losses may be evaluated by examining the difference between network performance before and after an earthquake. The measure used for the network performance is total delay caused by the users of the network. This is defined as the increase in the total travel time caused by earthquake induced damages. Essentially, it is the difference between the total time of the damaged network and the total travel time of the undamaged network. The proposed methodology for estimating delay is shown in Figure 6~~Figure 6~~.

Results

The result section includes the performance of Sioux Falls network in terms of flow and delay caused by three earthquakes in a period of 53 days in two categories: (1) without retrofitting and (2) with retrofitting. Results of reduced flow in top 13 links without retrofitting are presented in Table 5~~Table 5~~. Because of capacity reduction, flow is dramatically increased in the neighbor

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links of the affected bridges. Users have chosen the undamaged neighboring links to arrive in their destinations. For example, between the origin pair 6->8, link-16 had base flow of 12,638 veh/hr, but because of damages to several bridges in the network the flow increased to 14,482 (a 15 percent increase). Similarly for day 38 and 53 flow becomes 18,488 (a 46 percent increase) and 21,184 (a 67% increase) respectively. In the network, link-60 becomes heavily congested.

Table 6~~Table 6~~ shows the flow on the neighbor links with retrofitting scenario, for example neighbor link #16, the base flow on this link was 12,638 veh/hr but after earthquake 1 occurs at day00 the volume is rise to 14482 because 10 bridges reduce their capacity. At day20 and day25, the flow is decreases to 13,598 and 13,124 because of 6 bridges and 9 bridges are fully repaired respectively within that time duration; and so on.

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Table 5. Traffic flow on neighbor links without retrofitting scenario.

Node i	Node j	Neighbor Link #	Base Flow (veh/hr)	Day 00 Flow (veh/hr)	Day 38 Flow (veh/hr)	Day 53 Flow (veh/hr)
6	8	16	12,638	14,482	18,488	24,184
8	6	19	12,682	14,526	18,504	24,246
8	16	22	8,462	11,078	19,376	22,594
10	11	27	17,700	18,434	19,686	28,588

Table 6. Traffic flow on neighbor links with retrofitting scenario.

From Node i	To Node j	Neighbor Link #	Base Flow	EQ 1 occurs	~~9~~ 6 Bridges Fully Repaired	~~6~~ 9 Bridges Fully Repaired	EQ 2	1 Bridge Fully Repaired	EQ 3
				Day 00 Flow	Day 20 Flow	Day 25 Flow	Day 38 Flow	Day 52 Flow	Day 53 Flow
6	8	16	12,638	14,482	13,598	13,124	17,406	15,568	22,448
8	6	19	12,682	14,526	13,626	13,162	17,430	15,614	22,506
8	16	22	8,462	11,078	7,874	7,762	14,870	13,194	12,610
10	11	27	17,700	18,434	17,852	17,586	19,984	21,318	28,646

Table 7~~Table 7~~ shows travel time in vehicle hours for both scenarios in Sioux Falls network system. Saving in delay can be determined as the difference between the total time of the damaged network with and without retrofitting. Retrofitting helped in reducing total vehicle hours of travel but with an additional cost of bridge construction in the time period between earthquakes. However, in this analysis, the manner in which construction is made and associated costs are not considered.

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Table 7. Result for both scenarios in terms of system travel time and delay (*vehicle-hours*).

Earthquake	Day	Travel Time W/O Retrofit (1000 veh-hours)	Travel Time W Retrofit (1000 veh-hours)	Saving in delay (1000 veh-hours)
EQ 1	0	115.2	115.2	-
	20	115.2	42.7	72.5
	25	115.2	25.7	89.5

EQ 2	38	816.1	25.7	790.4
	52	816.1	388.8	427.3
EQ 3	53	1,623.4	245.7	1,377.6

Conclusions

The goal of this study was to develop a methodology to model risk from catastrophic events, and explore the performance and disaster resilience for a transportation infrastructure system in Memphis Area under possible New Madrid Earthquakes. For this purpose, bridge models were established and subjected to multiple earthquakes. The damage in bridge systems was used to estimate traffic capacity and the impact on the transportation network was presented. Future work for developing decision support tools for emergency management.

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