Effect of Seismic Bridge Retrofit on the Risk of Transportation Networks

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ABSTRACT: In this paper, the effect of seismic retrofitting on the transportation network system is investigated by considering the change in expected direct losses from un-retrofitted to retrofitted bridges. For this purpose, the bridge inventory and transportation network data for the San Francisco Bay Area are obtained from the California Department of Transportation (CALTRANS) and the Metropolitan Transportation Commission (MTC), respectively. Bridge damage and direct losses before and after retrofitting are estimated for the bridges in the Bay area for scenario earthquakes that can occur on the San Andreas and Hayward Faults. The results from these analyses show a significant decrease in losses and traffic delays. In the paper, example results from the Hayward and San Andreas fault scenarios analyses are included.

1 INTRODUCTION

The risk to transportation systems from major seismic events has been long recognized. Programs to retrofit and upgrade components of the system to withstand the seismic forces have been in place for sometime and the question raised most often is how cost effective are these programs. As part of the transportation risk assessment process, it is of interest to determine the benefit gained in both decreased losses due to direct damage to bridges and that due to decreased travel costs. In this paper the general seismic risk assessment process is presented first. Recent studies on transportation risk assessment include Basoz and Kiremidjian (1996), Werner et al. (2000), Chang et al. (2000) and Kiremidjian et al. (2002). The seismic effects that are included in the analysis are ground shaking, liquefaction and landslides. The methodology is applied to the San Francisco Bay Area and results for four scenario earthquakes are obtained to illustrate the risk to the region. Data on retrofitted bridges and performance measures for these bridges are not currently available to enable a direct assessment of the effect of retrofit on the estimated losses. Thus, an approach is considered where the capacity of the bridge is incrementally increased and the corresponding performance of the system is evaluated.

In a current study by the authors (Kiremidjian et al. 2004), a framework for risk assessment of a transportation system is postulated that considers the direct cost of damage and costs due to time delays in the damage system. The site hazards include ground shaking, liquefaction and landslides. In this paper, the effect of each ground hazard on the direct damage to bridges is evaluated. The effect of these hazards on the transportation network is also being investigated, but it is expected that the primary conclusions based on the component analysis will hold for the network analysis as well.

2 MODEL FORMULATION

The risk to transportation network systems is defined as the expected cost of damage and loss of functionality of the system when subjected to a severe earthquake, denoted by *E[Loss]*. For a given earthquake event Q_i, the expected loss from the system can be estimated as:

$$E[Loss \mid Q_i] = \int_0^1 l(D \mid Q_i) f_D(d \mid Q_i) dd + \int_0^1 l(t \mid D, Q_i) f_D(d \mid Q_i) dd \tag{1}$$

where

$l(D \mid Q_i)$ = cost of repair of individual components of the system at damage D due to an event Qi, where the damage is $0 \le D \le 1.0$,

$f_D(d \mid Q_i)$ = probability density of damage D due to an event Qi,

$l(t \mid D, Q_i)$ = costs associated with time delays due to detours of route losures per event Qi.

The annualized risk of loss for the transportation system from all possible events Q_i that may affect the system, occurring with rates ν_i, is:

$$\begin{aligned} E[Loss] &= \sum_{allevents} E[Loss \mid Q_i] \nu_i \\ &= \sum_{allevents} \nu_i \left\{ \int_0^1 l(D \mid Q_i) f_D(d \mid Q_i) dd + \int_0^1 l(t \mid D, Q_i) f_D(d \mid Q_i) dd \right\} \end{aligned} \tag{2}$$

The direct loss functions $l(D \mid Q_i)$ in equations 1 and 2 include losses due to damage from ground shaking and ground deformations such as those due to liquefaction, landslides and differential fault displacements. For a given event Q_i, losses due to time delays arise from delays in commuter and freight traffic. The time delays result from closure of particular routes because of excessive damage to key components such as bridges, or due to reduced flow capacity (either from imposed lower speed limit or closure of number of available traffic lanes) due to minor or moderate damage. Figure 1 summarizes the major components of the overall risk assessment methodology.

The focus of this paper is on the computation of direct damage to bridges and losses resulting from this damage due to earthquake ground shaking, landslides and liquefaction. Thus, only the fist integral in equations 1 and 2 is considered. Expanding this integral to take into account ground shaking, liquefaction and landslides, the equations become:

$$\begin{aligned} E[Loss \mid Q_i] &= I_A \int_D \int_A l(D \mid A, Q_i) f_D(d \mid A, Q_i) f_A(a \mid Q_i) da\, dd \\ &+ I_L \int_D \int_{S_H} l(D \mid S_H, Q_i) f_D(d \mid S_H, Q_i) f_{S_H}(s_H \mid Q_i) ds_H\, dd \\ &+ I_L \int_D \int_{S_V} l(D \mid S_V, Q_i) f_D(d \mid S_V, Q_i) f_{S_V}(s_V \mid Q_i) ds_V\, dd \end{aligned} \tag{3}$$

where,

$$I_A = \begin{cases} 1 & \text{if there is no liquefaction or landslides at a site} \\ 0 & \text{if there is liquefaction or landslide at a site} \end{cases} \tag{4}$$

$$I_L = \begin{cases} 1 & \text{if there is liquefaction or landslides at a site} \\ 0 & \text{if there is no liquefaction or landslide at a site} \end{cases} \quad (5)$$

A = ground shaking severity and can represent either peak ground acceleration or response spectral acceleration, or another appropriate parameter;
S_H = horizontal ground displacement due to either liquefaction or landslides
S_V = vertical ground displacement due to either liquefaction or landslides.

It is assumed in this formulation that either liquefaction or landslides occur at a site but not both. Similarly, if there is either liquefaction or landslide, they govern the damage and preempt any damage due to ground shaking alone.

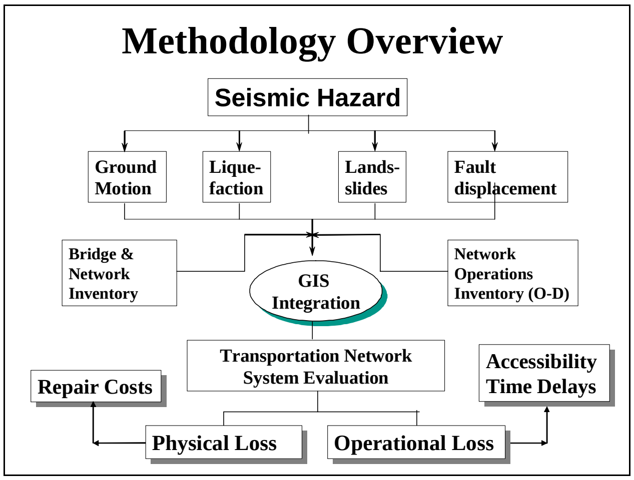

Figure 1. Risk assessment methodology for highway network systems

The total risk has to take into account all possible events Q_i, $i=1,2,\ldots N$ that can occur in the region of the transportation network and is given by the sum of the losses from all events weighted with the likelihood of occurrence of each event. The assessment of time delays requires extensive network analysis, which may prove to be unwieldy and computationally expensive if performed for all possible events. Thus, for the purposes of illustrating the methodology, the analysis is performed for four scenario earthquakes. They include magnitudes 7.5 and 8.0 events on the San Andreas Fault and 7.0 and 7.5 events on the Hayward Fault. In this paper, the results are shown for several of these scenarios.

In order to evaluate the contribution of each hazard, it is necessary that an appropriate system be in place with the various risk analysis components integrated within the system. Geographic information systems (GIS) provide the tools for information storage, overlay, integration and display that are particularly suitable for application to the problem of transportation network risk assessment. ARC/INFO^{TM} GIS is used to develop the different components of the hazard and loss estimation.

The bridge inventory for the San Francisco Bay region was obtained from the California Department of Transportation (CalTrans). There are 2,640 bridges in five counties in the study area. Information in the database that is particularly important for risk analysis includes bridge location, bridge superstructure and substructure type, number of bridge spans, type of connections (simple or continuous), skew angle and design date. The information, however, is not complete for all bridges, and it had to be inferred. Furthermore, the inventory is for pre-retrofitted bridges.

Peak ground accelerations and spectral accelerations are estimated for the four scenario earthquakes using the Boore at al. (1997) attenuation function. The geologic map for the Bay Area was obtained from the California Geological Survey and the ground motions were amplified according to the local soil at the site of the bridges. Basoz and Mander's (1999) fragility functions are used to estimate the damage to the bridges for the different scenario events resulting from ground shaking. The fragility functions define the probability of being or exceeding one of five damage states for a given ground motion level. The five damage states are: 1) no damage, 2) minor, 3) moderate, 4) major and 5) complete. Figure 2 shows the distribution of peak ground acceleration for the Hayward 7.0 earthquake and the resulting damage state for each bridge in the database. From the figure it can be observed that the ground shaking varies from 0 g to 0.7 g with the largest shaking near the Hayward fault. As expected, bridges near the fault are also found to have the highest damage

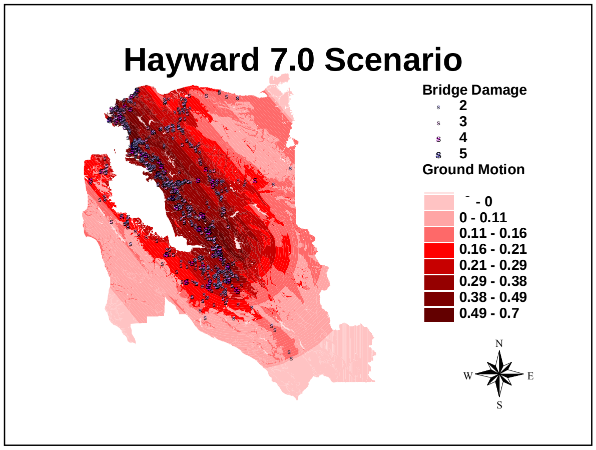

Figure 2. Distribution of bridge damage from ground shaking resulting from a magnitude 7.0 earthquake on the Hayward fault in the San Francisco Bay area

The liquefaction analysis follows the formulation presented in HAZUS (1999). There are six liquefaction susceptibility categories included in the analysis. The transportation network is overlaid on the liquefaction susceptibility map identifying the sections of the network that are most likely to be subjected to liquefaction failure. Using the liquefaction susceptibility information, the magnitude of the event, and the peak ground acceleration at the site of a bridge, the horizontal displacement from lateral spreading is estimated. Similarly, the vertical displacement from settlement due to liquefaction is evaluated using the same parameters. The maximum of the two displacements is used to determine the damage state to a bridge resulting from liquefaction.

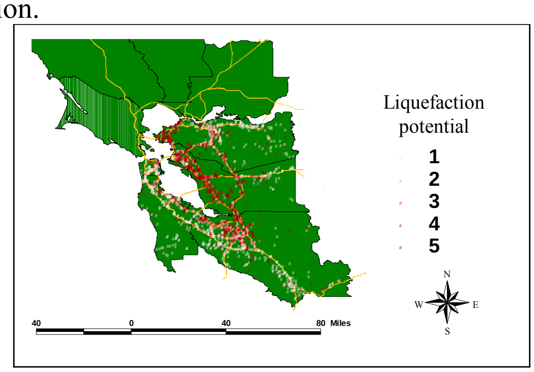

Figure 3. Distribution of bridge damage due to liquefaction in the San Francisco Bay Area from a 7.0 magnitude event on the Hayward fault

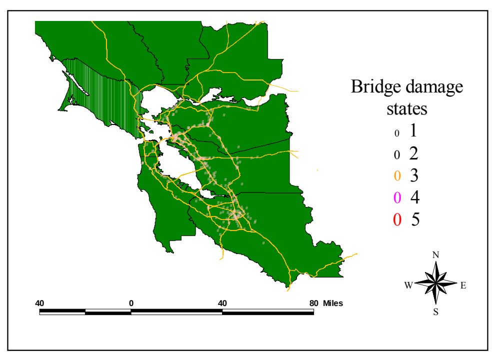

Figure 4. Distribution of pre-retrofitted bridge damage due to landslides in the San Francisco Bay Area from a 7.0 magnitude event on the Hayward fault

The distribution of bridge damage from liquefaction resulting from a magnitude 7.0 scenario event on the Hayward fault is shown on Figure 3. As can be seen from this figure, there appear to be significantly more bridges in damage state 4 and 5 due to liquefaction than there are from ground shaking alone. This result is expected in general, but to a great extent is most likely a function of the ground deformation assessment method. A review of the ground motion displacements predicted by the liquefaction analyses revealed that indeed some of these displacements may not be very realistic or at least difficult to substantiate with actual observations. An additional investigation on this subject is deemed necessary to obtain more reliable results.

Analysis for landslides also follows the HAZUS (1999) formulation. The landslide susceptibility map was obtained from the California Geological Survey which identifies eleven severity categories. This information is combined with the predicted ground motion data and the magnitudes of the event to estimate the amount of ground deformation. Damage to bridges is evaluated based on the predicted ground displacements. Figure 4 shows the distribution of bridge damage resulting from landslides. The number of damaged bridges is significantly smaller than that due to liquefaction. This result is expected since the landslide potential is high only in the hilly regions of the Bay Area that have recent geologic deposits. Many or these regions fall outside of the study area.

Loss estimates presented in this paper are limited to repair costs due to damage to bridges. Losses due to time delays in traffic are currently being investigated. Repair cost depends on the size of the bridge and the expected damage state of the bridges. The expected damage state for each bridge is evaluated by computing the probability that a bridge will be in each of the five damage states and then computing the expected value of damage for that bridge. These are the damage states shown in Figures 2, 3 and 4. Repair cost for a given bridge is given by *Repair Cost = Repair Cost Ratio * Area * Cost*, where the *Repair Cost Ratio (RCR)* is a function of the damage state of the bridge. The *RCR* values are given in Basoz and Mander (1999). Since these values are difficult to obtain, a best estimate, high and low values are provided. Repair cost estimates are provided with all three values for the *RCR*, however, only the best estimate is reported here for brevity.

The area of the bride is computed using the following simple formula *Area = bridge length * bridge (deck) width*, where information on the bridge length and width is obtained from the CalTrans bridge database. The repair cost for different types of bridges was provided by Jack T. Young (personal communication, CalTrans, Jan 2000). The average repair costs vary from $117.5 per square foot to $165 per square foot of bridge deck depending on the bridge type.

Table 1 provides the repair cost estimates for all the bridges in the study area for the four scenarios. Repair costs are obtained for damage due to ground shaking, ground shaking and liquefaction, ground shaking and landslides, and the total due to ground shaking, liquefaction and landslides. From this table it can be observed that the losses due to liquefaction dominate. This corresponds to the high damage distribution observed with liquefaction occurrence. The losses from liquefaction, however, are significantly higher primarily because if liquefaction occurs the bridge is considered to be in damage state 4 or 5 resulting in very large repair costs. Landslides do not appear to have a major contribution to the overall repair cost which is consistent with the estimated damage states for this hazard.

Table 1 Summary of losses from ground shaking, liquefaction and landslides to bridges in the San Francisco Bay Area from the four scenario events *(times 1,000){pre-retrofitted brdges)*

	Ground Shaking Only	Ground Shaking + Liquefaction	Ground Shaking + Landslides	Ground Shaking + Liquefaction + Landslides
Hayward 7.0	$ 494,046	$ 1,392,593	$ 571,497	$ 1,416,405
Hayward 7.5	$ 594,894	$ 1,855,247	$811,580	$ 1,861,046
San Andreas 7.5	$ 517,164	$ 1,686,116	$ 677,670	$1,704,257
San Andreas 8.0	$ 799,343	$ 2,188,848	$ 1,060,300	$2,233,668

3 TRANSPORTATION NETWORK ANALYSIS

Information on the highway transportation network for District 4 in California, which corresponds to the San Francisco Bay Area, was obtained from the Metropolitan Transportation Commission (MTC). The MTC Bay area highway network model consists of 1,120 zones and 26,522 links. These links are defined by 15,582 nodes with geographic coordinates. Each node corresponds to a traffic analysis zone.

Table 2. Summary of Vehicle Hours by Link Congestion Status, Fixed Travel Demand

Total Vehicle Hours		Frwy to Frwy Ramps	Freeways	Expressways	Collectors	On/Off Ramps
	V/C<1	223,448	6,633,475	1,539,282	2,500,326	681,289
	V/C>1	37,519	8,235,451	236,547	1,261,654	464,950
BASELINE	TOTAL	260,967	14,868,927	1,775,829	3,761,980	1,146,239
	V/C<1	349	13,415	1,248,891	189,264	1,619
	V/C>1	1,936	8,322,682	1,375,029,766	17,563,861,312	86,816
HW1	TOTAL	2,285	8,336,098	1,376,278,658	17,564,050,576	88,435

Total Vehicle Hours		Centroid Connectors	Major Roads	Metered Ramps	Golden Gate Bridge	Grand Total
	V/C<1	850,444	7,580,948	32,903	47,866	20,089,981
	V/C>1	8,320	2,195,583	41,591	0	12,481,616
BASELINE	TOTAL	858,764	9,776,532	74,494	47,866	32,571,596
	V/C<1	6,744	7,433,922	52	0	8,894,256
	V/C>1	0	84,905,952,296	0	0	103,853,254,808
HW1	TOTAL	6,744	84,913,386,218	52	0	103,862,149,065

A significant effort was devoted to importing the highway network information within the *ARC/INFO*^{TM} GIS. The bridge data were then linked to the highway network and corrected to match bridge locations with network locations. Baseline analysis was conducted on the transportation network pre-earthquake scenario. The post-earthquake scenario for a magnitude 7.0 event on the Hayward fault was modeled in EMME/2, a transportation systems network analysis software. Similar results were also obtained for scenarios on the San Andreas Fault zon. Based on this analysis closed links within the system were identified, shown in Figure 5. Table 2 summarizes the vehicle hours by link congestion status. The baseline calculations correspond to the pre-event conditions and demands. The post-event analysis results are listed under the Hayward (HA1) row. Fixed travel demand is assumed in these analyses.

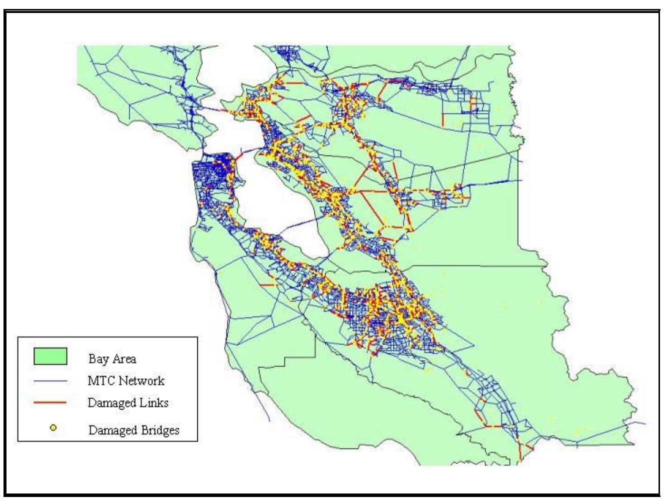

Figure 5. Closed highway links for pre-retrofit bridge damage in the San Francisco Bay Area for a scenario earthquake of moment magnitude 7.0 on the Hayward Fault.

A method was developed in this project to treat variable travel demand. The results from the variable demand model are summarized in Table 3 for the four scenario earthquakes. Again the base line analysis corresponds to the pre-event conditions and the subsequent columns summarize the analysis for the vehicle hours after damaged bridges are closed following the scenario event.

Table 3. Summary of Total Vehicle Hours by Link Type, Variable Travel Demand

TYPE	BASELINE	HW1	HW2	SA1	SA2
Frwy to Frwy Ramps	3,510	273	747	34	50
Freeways	133,228	5,948	6,308	1,375	1,397
Expressways	22,176	234,966	9,910,183	2,629	25,979
Collectors	28,650	974,053,825	293,379,322	2,195,236	175,811
On/Off Ramps	12,387	38,367	2,051	873	865
Centroid Connectors	10,540	4,674	4,975	3,826	4,076
Major Roads	99,142	55,629,479	27,334,268	122,997	95,273
Metered Ramps	1,195	42	22	10	13
Golden Gate Bridge	562	0	0	0	0
Grand Total	311,390	1,029,967,575	330,637,877	2,326,980	303,464

4 'WHAT-IF' RETROFIT ANALYSIS

In the effort to reduce the risk of damage and failure of bridges, the California Department of Transportation (Caltrans) has been retrofitting and seismically upgrading bridges in the state under a federally and state funded programs. In order to obtain an estimate of the benefits of this program, a simple approach is considered for retrofitted bridge risk assessment. A more rigorous analysis is not possible at this time because fragility functions for retrofitted bridges have not been developed. In order to obtain a simple estimate of the expected loss reduction and thus risk reduction from retrofitting, the fragility functions of Basoz and Mander (1999) are *modified by shifting the median value of the ground shaking capacity,* $\bar{a}$*,* with a γ percentage value to a higher damage state. Based on this assumption, the analyses can be repeated with replacing the modified median value $\bar{a}$ by the retrofitted median value $\bar{a}$ for different γ values, where

$$\bar{a} = \bar{a}\,(1+\gamma) \tag{6}$$

Table 4 Expected total repair costs by hazard case and by retrofit category for the scenario event *SA8.0*

	Retrofitting Cases	Shaking Only	Liquefaction Only	Landslide Only	Shaking + Liquefaction + Landslide
Best Mean	No-Retrofit	$634,299,134	$1,482,277,580	$468,546,772	$1,539,516,936
	γ=5%	$592,014,441	$1,464,717,311	$460,476,258	$1,519,696,920
	γ=10%	$552,923,554	$1,448,290,627	$450,503,299	$1,501,177,773
	γ=20%	$483,309,878	$1,418,708,731	$425,912,053	$1,467,954,174

Based on the assumption stated above, a retrofit analysis is performed for different γ values. The expected loss for the scenario *SA8.0* by the four different retrofitting cases are shown in Table 4. As expected the losses decrease in proportion of the retrofitted rate. For example, when all the hazard types are considered together, the expected repair cost drops from $1,540M to $1,467M, which accounts for 6% reduction in cost. The reductions in cost are most dramatic when the loss estimate is based on ground shaking only. *In that case, a 20% increase in capacity results in a 24% reduction in loss*. For landslide and liquefaction, the increase in bridge capacity does not appear to have a significant effect on the loss reduction. This observation, however, reflects the fact that these hazards require special retrofit measures that are only partially related to increased strength and column capacity of bridges. They are governed by the ground deformation and the current HAZUS methodology is not detailed enough to enable a more sensible analysis.

5 CONCLUSIONS

A method is presented for evaluating the direct losses from damage to bridges in a highway transportation network. This method is used to investigate the contribution of ground shaking, liquefaction and landslide hazard to the total repair costs. For this purpose, the repair costs for four scenario events are evaluated in the San Francisco Bay area. The repair costs from these scenario analyses is found to be the highest from liquefaction. In comparison, landslides appear to have a very small contribution to both the damage estimates and the repair cost estimates. In general, the contribution of liquefaction hazard to the repair cost is region dependent, however, in this analysis it is also attributed to the method used for estimating the ground deformations. A more robust model for liquefaction displacement assessment and associated fragility functions is needed in order to obtain reliable damage and loss estimates.

The transportation network was evaluated for changes in vehicle travel times under two assumptions – constant post-event demand and variable post-event demand. The total vehicle hours increase in post-earthquake networks relative to the baseline network, but not as dramatically in the variable-demand case as for the fixed-demand model. The variable demand model assigns fewer trips to the network. This results in fewer total vehicle hours of travel. However, less total time delay does not indicate lower costs. The trips being eliminated because of high travel costs have value. These absences impose an opportunity cost. Therefore, the total losses should count both the total observed delay and the value of the trips forgone. As in the case of the fixed-demand model, some freeway links are isolated by network damage, even though they are otherwise fully functional. The Golden Gate Bridge is a consistent example across all earthquake scenarios.

Investigations of the effect of retrofitting on losses from repair costs showed that the reduction in losses is most significant for ground shaking. Liquefaction and landslide losses do not appear to be affected as much by increase in bridge column capacity. For ground shaking hazard, it is found that a 20% increase in seismic capacity results in 24% reduction in loss.

6 ACKNOWLEDGMENT

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7 REFERENCES

Basoz, N. and Kiremidjian, A. (1996). "Risk Assessment of Highway Transportation Systems", *The John A. Blume Earthquake Engineering Center Report No. 118*, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305.

Basoz, N., and Mander, J. (1999). "Enhancement of the Highway Transportation Module in HAZUS", in *Report to National Institute of Building Sciences*. Washington, D.C.: [GET PUB].

Boore, D., Joyner, W., and Fumal, T. (1997). "Equations for Estimating Horizontal Response Spectra and Peak Acceleration from North American Earthquakes: A Summary of Recent Work", *Seism.Res.Let*., 687(1), 128-154.

Chang, s., Shinozuka, M., and Moore, J. (2000). "Probabilistic Earthquake Scenarios: Extending Risk Analysis Methodologies to Spatially Distributed Systems", *Earthquake Spectra* 16(3), pp.557-572.

HAZUS (1999). *"Earthquake Loss Estimation",* Technical Manual, National Institute of Building Sciences, Washington, DC.

Kiremidjian, A.S., Moore J., Basoz, N., Burnell K., Fan Y. and Hortacsu A. (2002). "Earthquake Risk Assessment for Transportation Systems: Analysis of Pre-Retrofitted System", Proceedings for the 7th *National Conference on Earthquake Engineering*, EERI, Boston, July 21-25.

Werner, SD., Taylor, C.E., Moore, J.E., Walton, J.S. and Choet, S. (2000). "Risk-Based Methodology for Assessing the Seismic Performance of Highway Systems." MCEER-00-0014, SUNY Buffalo, Buffalo, NY. December.