# OPTIMAL SEISMIC BRIDGE RETROFIT STRATEGY UNDER BUDGET CONSTRAINT

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**ABSTRACT:**

Highway transportation networks, an important lifeline system in urban areas, are highly vulnerable to strong seismic ground motions. Particularly due to possible bridge failures resulting from a severe earthquake, network characteristics may change and traffic flow capacity may significantly drop suddenly, causing excessive societal disruption and indirect economic losses. Pre-event seismic retrofitting of bridges therefore is desirable in order to reduce bridge damageability and minimize the extent of post-event societal disruption and economic losses. However, in most cases, funding available for retrofitting is limited and hence, an optimal strategy is needed to prioritize the selection of bridges and the order in which they are to be retrofitted.

This paper aims to perform a simulation-based study on retrofit prioritization in order to identify the best strategy. For this purpose, Los Angeles area network spanning Los Angeles and Orange County with more than 3000 bridges is utilized as a testbed and analyzed under several tens of scenario earthquakes that represent the regional seismic hazard consistent with USGS hazard map. The study first analyzes the original network without retrofit under each scenario earthquake. Degradation of transportation network caused by post-event damaged bridges is measured in terms of social cost under the pre-event origin-destination (OD) matrix and is used as baseline measure of the network degradation immediately after an earthquake event. In the second stage, the same network with some retrofitted bridges is analyzed under all scenario earthquakes and under the same pre-event OD matrix. The result is a smaller value of social cost that represents the effect of retrofit by definition under the specific retrofit strategy and under each scenario earthquake. The retrofit strategy that produces the largest expected reduction is the optimal retrofit strategy determined starting from a particular scenario earthquake. In particular, an effort is made on the basis of the principle of optimality to find an analytical solution to the problem of retrofit prioritization under budget constraint.

**KEYWORDS:**
Highway transportation system, Seismic bridge retrofit, Drivers' delay, Loss of opportunity, Budget constraint

## 1. INTRODUCTION

Highway transportation network is a typical example of spatially distributed systems. Components of a highway network such as bridges, roadways, tunnels, and some other structural components are distributed over a wide geographical region, but connected internally to serve the required functionality of this system. The 1994 Northridge and many other past earthquakes showed that highway transportation network is extremely susceptible to severe earthquakes. Following a devastating event, network functionality may drop significantly due to possible damage of its components, particularly bridges. In consequence, this costs a major economic loss to the society, mainly due to social cost arising from drivers' delay (i.e., delay in making trips) and loss of opportunity (i.e., unable to make trips) in the damaged network. This economic loss can be minimized by retrofitting bridges within the network prior to any earthquake event. In fact, California Department of

Transportation (Caltrans) has retrofitted all bridges in southern California, USA after the event of the 1994 Northridge earthquake.

The paper aims to perform a simulation-based study on retrofit prioritization of bridges in order to find the best strategy that will enhance, at the highest level, seismic performance of highway transportation networks under limited budget condition. This issue has practical importance as seismic retrofitting of an entire transportation network requires a large amount of funding which may not be available totally. Also, state Department of Transportation (DOT) agencies generally have limited annual expenditure for highway retrofit or rehabilitation purposes. Therefore, a strategy must be developed by means of which seismic risk of highway networks can be minimized under budget constraint. Acknowledging the significance of this problem, researchers paid attention and developed prioritization techniques to be utilized for this purpose (Bazon and Kiremidjian 1995, Nielson and DesRoches 2003, Nuti and Vanzi 2003, Na et al. 2008,). It should be noted here that retrofit prioritization changes depending on stakeholders, and thus it is extremely difficult to establish an ultimate best solution for this problem.

The current study is carried out utilizing Los Angeles area transportation network spanning Los Angeles and Orange County as shown in Figure 1 which consists of more than 3000 bridges. To predict the seismic risk associated with this system, several tens of scenario earthquakes that represent the regional seismic hazard consistent with USGS hazard map are considered. This study first analyzes the original network without retrofit under each scenario earthquake and simulates bridge damage states. Degradation of transportation network caused by these damaged bridges is measured in terms of social cost arising from drivers' delay (DD) and opportunity cost (OC), and is used as baseline measure of the network degradation immediately after an earthquake event (at Day 0). This is done by developing a traffic flow model that utilizes pre-damaged origin-destination (OD) data of the network. Some of the bridges in the original network that were damaged in the simulation under each scenario earthquake are then chosen and (virtually) retrofitted as long as the total retrofit cost is within the available budget. Network with these retrofitted bridges is analyzed again under all scenario earthquakes and under the same pre-event OD matrix. The results are smaller values of DD and OC for each scenario earthquake. This reduction in social cost represents the effect of retrofit by definition under the specific retrofit strategy and under each scenario earthquake. Expected benefit from bridge retrofitting is therefore computed with respect to the annual occurrence probability of each scenario earthquake. The same procedure is repeated several times by selecting different bridges that are to be retrofitted, and corresponding values of expected benefits are obtained. The parameter 'expected benefit' is taken here as the key component on basis of which the retrofit prioritization strategy is decided.

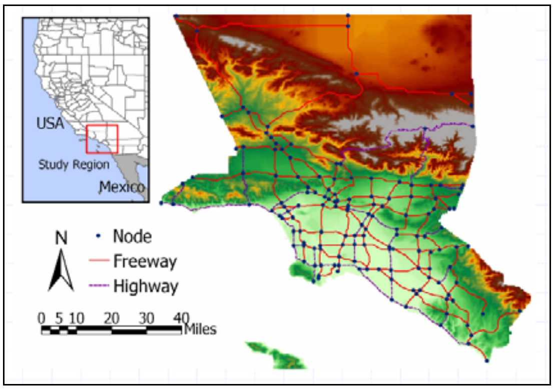



Figure 1 Caltrans' highway transportation network in Los Angeles and Orange County

## 2. NETWORK MODELING

Modeling of highway transportation network under seismic events includes (i) estimation of regional seismic hazard, (ii) simulation of bridge seismic damageability, (iii) assignment of link damage states, and (iv) analysis of traffic flow using Origin-Destination data.

### *2.1. Regional Seismic Hazard*

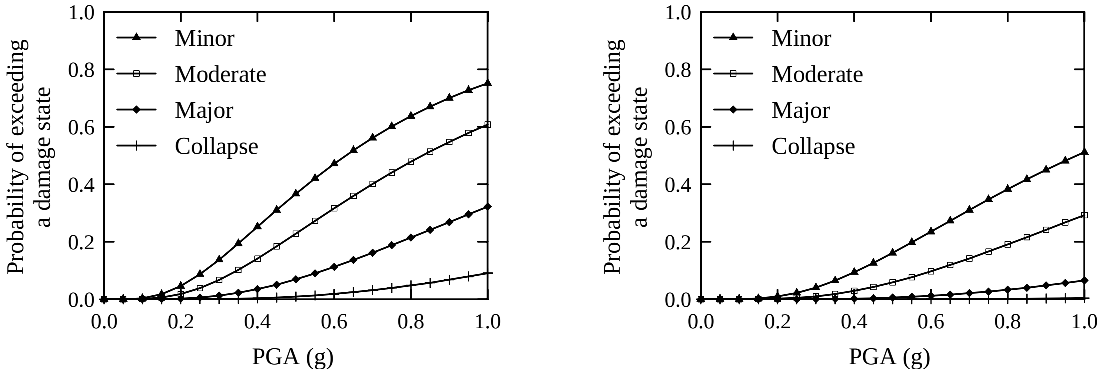
The area of Los Angeles is having a number of active seismic faults. According to USGS regional hazard map, the current study uses 47 scenario earthquakes consisting of 13 maximum credible events (MCE) and 34 user-defined events (U/D) as listed in Chang et al. (2000). A set of attenuation relationship is utilized to estimate the peak ground acceleration (PGA) at each bridge site within the service area of this network. For detailed information, please refer to Shinozuka et al. (2005), Zhou and Shinozuka (2006), and Zhou et al. (2008).

### *2.2. Seismic Damageability of Bridges*

The highway transportation network model considered in this study is consisting of 3133 bridges, and several nodes and links. Links represent roadway segments, and are connected to other segments of the network at points called nodes (usually interchanges). In a link, it is assumed here that only bridges are seismically vulnerable. Therefore, bridge damage states need to be simulated first in order to obtain the post-earthquake seismic performance of links. This indicates that the information on bridge seismic damageability is one of the key input parameters on basis of which bridge damage states under various scenarios are predicted.

The current study utilizes fragility curves to express the bridge seismic damageability. Fragility curve, by definition, represents the probability of failure of bridges in certain damage state under a given ground motion intensity, such as PGA. Previous studies (Shinozuka et al. 2000 and Shinozuka et al. 2003) documented bridge fragility curves for the same highway network utilizing bridge damage data of more than 2000 bridges obtained from the 1994 Northridge earthquake. These set of data were used to generate empirical bridge fragility curves in four different subset levels namely (i) Level 1 or Composite considering bridges in the same statistical population, (ii) Level 2 using bridge classes according to span, soil type and skewness, (iii) Level 3 using bridge combinations of any two among span, soil type and skewness, and (iv) Level 4 with all possible bridge combinations of span, soil type and skewness. Among these, Level 4 is most sophisticated in statistical sense as bridge categorization is done in this subset by considering bridge configuration and site soil condition. 18 different bridge combinations are composed in this level for each of which fragility curves at different damage states are generated. Figure 2(a) shows a set of fragility curves developed in Level 4 for a combination of bridge with ‘multiple span’, soil type ‘C’ and skewness ‘$0^0$ ~ $20^0$’. In a previous study with the same network model (Zhou et al. 2008), bridge seismic damageability was defined by assigning fragility curves from Level 1 subset. The current study updates this previous analysis (Zhou et al. 2008) by considering bridge fragility curves from Level 4 subset, and evaluates the system performance which is discussed later in this paper.

After the Northridge earthquake, Caltrans retrofitted all bridges in southern California, USA by utilizing several retrofit techniques. Among them, lateral confinement of bridge columns by externally applying steel jackets is the most commonly used technique. Previous research (Kim and Shinozuka, 2004) showed that such retrofit can sufficiently enhance column ductility and thus, can improve bridge seismic damageability. This literature analytically computed enhancement factors that can be applied on bridge fragility curves without retrofit in order to generate the same when bridges are retrofitted. For example, Figure 2(b) represents bridge fragility curves generated in Level 4 for the same combination of bridge as in Figure 2(a), but considering these bridges are retrofitted. Therefore, such curves from Level 4, with and without retrofit, are incorporated in the current analysis to simulate bridge damage states under 47 scenario earthquakes. As Figure 2 shows, the value read from the curve is equal to the probability that the bridge will fail under certain PGA value. Hence, in order to predict post-event damage state of bridges, attenuation relations are utilized to evaluate PGAs at each bridge site for each scenario earthquake. Knowing PGA values and bridge fragility characteristics, bridge damage states of under scenario earthquakes are predicted by performing Monte Carlo simulation.




(a) (b)

Figure 2 Fragility curves developed in Level 4 subset for a combination of 'multiple span', soil type 'C' and skewness '$0^0 \sim 20^0$' of bridges (a) without seismic retrofit and (b) with seismic retrofit

### *2.3. Link Damage State and Its Residual Traffic Capacity*

Link damage is represented by the worst state of bridge damage within a link. Highway network system is generally designed in such a way that it is possible to reroute traffic when one or more links are damaged. Hence, alternative routes are considered in this study. The ability of handling traffic through alternative routes expresses the residual traffic capacity of a link. Therefore, all links in a network must have some residual traffic capacity at any state of link damage. Depending on the degree of link damage, table 1 represents three different link residual capacities as 'high', 'moderate' and 'low' assigned to the current highway network model.

Table 1. Residual link traffic capacity

| Link damage | Residual link traffic capacity (%) | | |
|---|---|---|---|
| | High | Moderate | Low |
| Minor | 100 | 100 | 100 |
| Moderate | 75 | 50 | 25 |
| Major | 50 | 25 | 10 |
| Collapse | 50* | 25* | 10* |

* Non-zero values for alternative routes

### *2.3. Traffic Flow Analysis using Origin-Destination Data*

This study utilizes the 1996 southern California origin-destination (OD) survey data for 3217 traffic analysis zones (TAZ) that covers five-county area namely Los Angeles county, Orange county, Ventura county, part of Riverside county, and San Bernardino county. The current study region is a part of this survey region, and is consisting of 2631 TAZ. However, for the simplification of the current problem, the original OD data is condensed to generate a 148 by 148 matrix by developing Thiessen polygon as detailed in Zhou et al. 2008. This condensation produced 231 network links.

#### *2.3.1 Drivers' delay*

The total travel time in the network can be expressed as $\sum x_n t_n(x_n)$, where $x_n$ and $t_n$ respectively represent the flow and travel time in a link $n$. After a devastating earthquake, OD matrix changes resulting an increase in total travel time in the damaged network. This difference in total travel time in a damaged network to the same in a intact network is represented with a comprehensive index namely drivers' delay ($\lambda$) measured in terms of hours.

This can be defined as

$$\lambda = \sum x'_n t'_n(x'_n) - \sum x_n t_n(x_n) \quad (2.1)$$

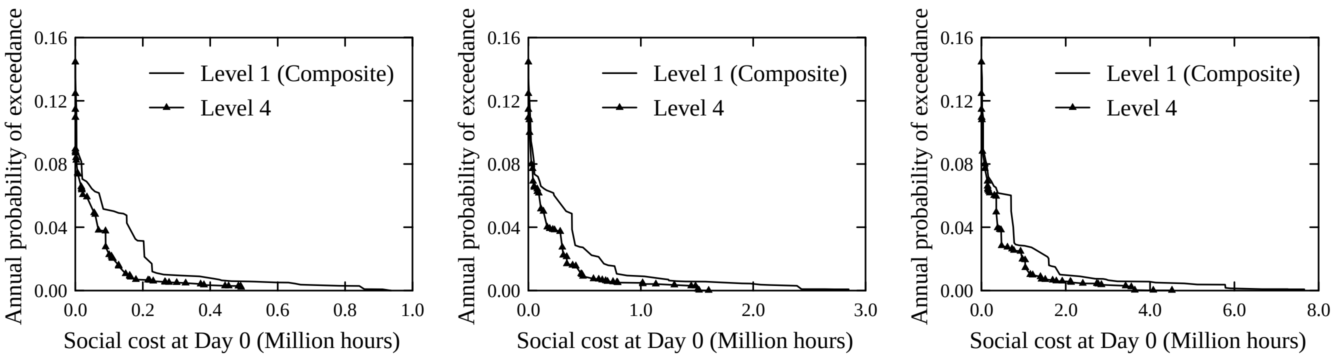
where $x_n$ and $t_n$ are the parameters in the intact network, and $x'_n$ and $t'_n$ are the same parameters in the damaged network.

*2.3.2 Opportunity cost*

After an earthquake, travelers/drivers fail to make trips in the degraded network due to high travel cost. In consequence, they cannot perform activities associated with those trips such as working, shopping. If these activities have economic value, drivers lose the value by not performing these activities (or trips). This imposes another type of social cost, namely opportunity cost which is also measured in terms of hours. Hence, opportunity cost is a loss resulting from the cancellation of trips in a post-event damaged transportation network and calculated according to type of trips. Readers are referred to Zhou et al. 2008 for further detail.

*2.3.3 Total social cost at the day of the earthquake (Day 0)*

Degradation of system performance after an earthquake is expressed as social cost. This is the total loss arising from drivers' delay and loss of opportunity in the network after an earthquake event. This study represents the social cost in hours. Figures 3(a), (b), and (c) represent the total social loss in the entire network at Day 0 for 'high', 'moderate' and 'low' link residual capacities. Each of these figures shows two curves which are obtained considering bridge fragility curves from (i) Level 1 (composite) and (ii) Level 4 subsets. In all cases, fragility curves for Level 4 subset provide less social loss. As previously mentioned, Level 4 contains the most sophisticated fragility curves, so this level is considered as standard. Therefore, result indicates that the consideration of fragility curves from composite level always underestimate the system performance under earthquake events, and thus over-predict the post-event social loss.




(a) (b) (c)

Figure 3 Social cost in the damaged network at Day 0 for (a) high (b) moderate and (c) low link residual capacities

## 3. OPTIMAL RETROFIT STRATEGY IN HIGHWAY NETWORK

As discussed previously, bridge retrofitting can significantly enhance the seismic damageability of the highway network and its post earthquake functionality. Figure 4 represents two curves showing the social costs at Day 0 in the post-event damaged network without and with seismic retrofit of bridges when low link residual capacity is considered. This clearly indicates a considerable reduction in social loss if all bridges in the network are retrofitted prior to any earthquake event. However problem arises when retrofitting of all of these bridges cannot be made due to fund limitation. Therefore, based on the principle of optimality, a retrofit prioritization strategy is developed here which will maximize the expected benefit from seismic retrofitting under any future earthquake. Nevertheless, the strategic plan will change depending on stakeholders, such as Caltrans in this case. In order to enhance the seismic damageability of a link, all bridges within that link must be retrofitted so that individual seismic performance of links gets improved. As the study network consists of 3133 bridges, it is extremely difficult to develop a strategy by selecting bridges as per their damage states and by ranking them according to their impact on network performance if retrofitted. Besides, for traffic flow analysis, link damage is one of the important inputs in the computational scheme. Therefore, this study uses link damage states rather than bridge damage states as the key parameter in developing optimal prioritization strategy.

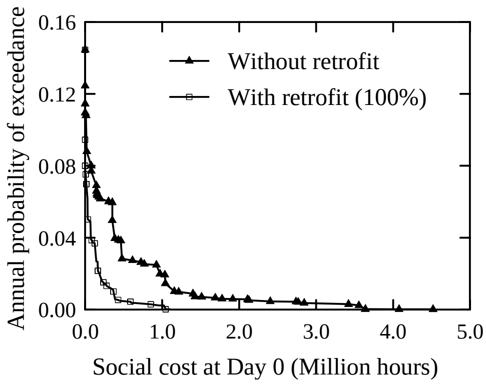



Figure 4 Social cost at Day 0 in the post-event damaged network without and with seismic retrofit of bridges considering low link residual capacity

### *3.1 Network Analysis to Determine Optimal Retrofit Strategy*

Under each of the 47 scenario earthquakes, original network (without retrofit) with pre-event OD matrix is analyzed first to simulate the damage in the network and to evaluate the expected social cost immediately after an earthquake event *m* (i.e., at Day 0). In this analysis, bridge damage states are simulated by using fragility curves of bridges without retrofit (exemplified in Figure 2a). Post-event degradation of transportation network is measured in terms of expected social cost at Day 0, and is used as baseline measure of the network degradation for this scenario. Thereafter, the same network (pre-damaged) with pre-event OD matrix is analyzed again under the same scenario earthquake ($m^{th}$) considering one link (say, with index *n*) in the network is retrofitted. To do this, bridges in that particular link are assigned to have enhanced fragility characteristics defined by bridge fragility curves with retrofit (exemplified in Figure 2b). This results in a smaller value of expected social cost at Day 0 than the baseline measure. Hence, this reduction in expected social cost signifies the expected benefit under $m^{th}$ scenario earthquake with certain annual occurrence probability if only $n^{th}$ link in the network was retrofitted prior to this earthquake. The analysis is repeated for all 47 scenario earthquakes. Therefore, the largest expected benefit among these 47 cases represents the maximum benefit from seismic retrofitting of bridges in link *n* which can be written as follows.

$$B_n = \max_m [B_{nm}] = \max_m \left[ \left\{ (SC_0)_{nm} - (SC_0)_{nm}^R \right\} \times p_m \right] \text{ in hrs for } m = 1, 2, ..., 47 \quad (3.1)$$

where $B_n$ is the maximum benefit (in hrs) from seismic retrofitting of bridges in link *n*, $B_{nm}$ is the benefit (in hrs) from seismic retrofitting of bridges in link *n* under scenario *m* (= 1, 2, …, 47), $(SC_0)_{nm}$ and $(SC_0)_{nm}^R$ are respectively the social costs (in hrs) in the network at Day 0 without and with retrofit of bridges in link *n* under scenario *m*, and $p_m$ is the annual occurrence probability of scenario *m* that can be found from Chang et al. (2000).

The above procedure is carried out for all 231 links in the current network, considering one link at a time. Therefore 231 values of $B_n$ (*n* = 1, 2, .., 231) are obtained and arranged in a column with descending order. The first link in this column, ranked as 1, has the largest $B_n$ and hence, represents the maximum impact on the post-event network performance among 231 links if retrofitted. Thus the second link in this column (Rank as 2) has second largest impact and so on. In summary, this column represents the ranking of network links according to their individual impacts on the post-event network performance if retrofitted. Table 2 partly shows this column in which only first 10 links with their Link IDs as specified in the network model are shown. This table also presents the $B_n$ values computed for each link. It should be noted that the decision-making criterion considered here is based on the expected benefit measured from the social cost at Day 0. Costs associated with system repair/restoration and bridge retrofit process are not taken into account for this current analysis. If these are considered, the rank of prioritized links may change from the current outcome. Moreover, this entire study is based on Monte Carlo simulation. Therefore, it is not logical to expect the exact same amount of benefit from seismic retrofitting at each time the procedure is repeated. However, the optimization strategy is universal and applicable under any initial consideration.

Table 2 Ranking of network links according to $B_n$

| Rank # | Link ID | $B_n$ in hrs |
|---|---|---|
| 1 | 141 | 858.5 |
| 2 | 44 | 619.5 |
| 3 | 24 | 585.7 |
| 4 | 92 | 543.1 |
| 5 | 148 | 301.5 |
| 6 | 19 | 202.4 |
| 7 | 144 | 65.7 |
| 8 | 145 | 34.2 |
| 9 | 91 | 24.2 |
| 10 | 137 | 14.5 |

**4. CONCLUSIONS**

The current study involving Caltrans' highway transportation network represents a sequel to earlier studies entitled "Socio-economic effect of seismic retrofit of bridges for highway transportation networks: A pilot study" (Zhou et al. 2008) and "Resource allocation for seismic retrofit of highway network" (Na et al. 2008) from the view point of Caltrans as stakeholder. In these previous studies, it was assumed that all bridges in the network have the same seismic fragility characteristics (i.e., fragility curves from Level 1 or composite) in spite of their configurations and site conditions. The current study, however, utilized bridge fragility curves developed in Level 4 subset. Therefore, different fragility characteristics of bridges depending on their span, soil type and skewness are assigned to the current network model. This modification improved the performance of highway transportation networks under regional seismic hazard and thus, resulted in a considerable reduction in post-event social cost in the damaged network.

Retrofit prioritization is an important issue since state DOT agencies generally have a limited annual fund to allocate for retrofit or rehabilitation of existing highway bridges. As a solution to this practical problem, a prioritization strategy is developed here on the basis of the principle of optimality. According to this strategy, fund must be allocated to retrofit those bridges/links that have maximum impact on the network in terms of social cost under future scenario earthquakes at the day of earthquake. Social cost arose in the post-event damaged network from its disrupted traffic flow capability. Analysis showed that bridge retrofitting can enhance the post-earthquake network functionality and can reduce the social loss from non-retrofitted situation. Therefore, expected benefit from seismic retrofitting is computed from reduced social loss by taking the annual occurrence probability of scenario earthquakes into consideration. These values of expected benefit are arranged in descending order to see most important links and their impact on the network performance. In practice, bridge retrofitting must be performed following this order, and can be continued as long as the total budget permits. Hence, this optimization method provides a feasible way to prioritize bridges for retrofit purpose under budget constraint. The main disadvantage of this procedure is that the computational time is quite high as analysis has to be carried out for $m \times n$ cases where $m$ and $n$ respectively represent number of scenario earthquakes and links in the network. In addition, it should be noted that the decision-making criterion discussed here only considers the social cost at Day 0, although several days may be required after an earthquake to restore the original functionally of the network. So cost-benefit analysis of seismic retrofitting must consider costs associated with system repair/restoration and bridge retrofit process. Future study for retrofit prioritization will consider all of these issues. Also, more sophisticated techniques such as genetic algorithm will be utilized to obtain the most reasonable solution to this very important and practical problem.

## REFERENCES

Basoz, N. and Kiremidjian, A.S. (1995). Prioritization of bridges for seismic retrofitting. *Technical Report* MCEER-95-0007.

Chang, E.S., Shinozuka, M. and Moore, J., (2000). Probabilistic earthquake scenarios: extending risk analysis methodologies to spatially distributed systems. *Earthquake Spectra* **16:3**, 557 – 572.

Kim, S.H. and Shinozuka, M., (2004). Development of fragility curves of bridges retrofitted by column jacketing. *Probabilistic Engineering Mechanics* **19:1-2**, 105–112.

Na, U.J., Shinozuka, M., Franchetti, P., Da Lozzo, E. and Modena, C. (2008). Resource allocation for seismic retrofit of highway network. *The Fourth International Conference on Bridge Maintenance, Safety and Management*. Seoul, Korea, July 13-17

Nielson, B. and DesRoches, R. (2003). Seismic fragility curves for bridges: Retrofit prioritization, *Advancing Mitigation Technologies and Disaster Response for Lifeline Systems*, Technical Council on Lifeline Earthquake Engineering, Monograph No. 25.

Nuti, C. and Vanzi, I. (2003). To retrofit or not to retrofit?. *Engineering Structures* **25**, 701-711.

Shinozuka, M., Feng, M.Q., Kim, H.-K., Uzawa, T., and Ueda, T. (2000). Statistical analysis of fragility curves. *Journal of Engineering Mechanics, ASCE* **126:12**, 1224-1231.

Shinozuka, M., Feng, M. Q., Kim, H., Uzawa, T., and Ueda, T., (2003). Statistical analysis of fragility curves, *Report MCEER-03-0002*, Multidisciplinary Center for Earthquake Engineering Research (MCEER), The State University of New York at Buffalo, NY.

Shinozuka, M., Zhou, Y., Kim, S.H., Murachi, Y., Banerjee, S., Cho, S. and Chung, H., (2005). Socio-economic effect of seismic retrofit implemented on bridges in the Los Angels highway network. *Report CA F/CA/SD-2005/03* California Department of Transportation, Division of Research and Innovation, Sacramento, CA. Available online at: http://shino8.eng.uci.edu/Pdf/Caltrans%20Report_Shinozuka_2005.pdf

Zhou, Y. and Shinozuka, M., (2006). Development of probabilistic scenario earthquakes for seismic risk analysis of spatially distributed systems. *8th National Conference of Earthquake Engineering*, San Francisco, April 18-22.

Zhou, Y., Banerjee, S. and Shinozuka, M. (2008). Socio-economic effect of seismic retrofit of bridges for highway transportation networks: A pilot study. *Structure and Infrastructure Engineering*. Accepted for publication.