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# Effect of seismic retrofit of bridges on transportation networks

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**Abstract:** The objective of this research is to determine the effect earthquakes have on the performance of transportation network systems. To do this, bridge fragility curves, expressed as a function of peak ground acceleration (PGA) and peak ground velocity (PGV), were developed. Network damage was evaluated under the 1994 Northridge earthquake and scenario earthquakes. A probabilistic model was developed to determine the effect of repair of bridge damage on the improvement of the network performance as days passed after the event. As an example, the system performance degradation measured in terms of an index, "Drivers Delay," is calculated for the Los Angeles area transportation system, and losses due to Drivers Delay with and without retrofit were estimated.

**Keywords:** fragility curves; seismic retrofit; probabilistic model; bridges; transportation networks; drivers delay; performance index; Northridge earthquake.

## 1 Introduction

Transportation systems, including highways, railroads, airports and harbors, represent a critical component of society's infrastructure systems. They are needed for the welfare of the general public, specifically for commercial, industrial and cultural activities in national as well as international scale, and also to facilitate transportation of search/rescue and medical teams, the injured to hospitals, repair and restoration news and materials, and daily supplies for citizens following disasters. In this respect, under a natural or manmade disaster (e.g., earthquake, flood, etc.), it is critically important that the transportation system remains operational or that its function be repaired or restored as soon as possible. Past experience has shown too often that earthquake damage to highway components (e.g., bridges, roadways, tunnels, retaining walls, etc.) can severely disrupt traffic flow, thus negatively impacting on the economy of a region as well as on post-earthquake naemergency response and recovery activities. Furthermore, the extent of these impacts will depend not only on the ture and magnitude of the seismic damage sustained by the individual components, but also on the mode of functional impairment of the highway system as a network resulting from physical damage to its components. In order to estimate the effect of the earthquake on the system performance of the transportation network, this paper develops an analytical framework to integrate bridge and other structural performance with a transportation network model in the context of seismic risk assessment developed by Shinozuka *et al.* (2000).

Highway transportation systems comprise numerous structural components and are located in equally complex natural and built environments. Among the engineered components, bridges are potentially the most vulnerable under earthquake conditions. In the previous study by Shinozuka *et al*. (2000), fragility information expressed as a function of peak ground acceleration (PGA) was utilized. Usually, PGA information is easier to obtain, however, peak ground velocity (PGV) may be an equally capable way to express the fragility information of structures.

The purpose of this research is to develop empirical fragility curves, expressed as a function of the ground motion intensity such as PGA or PGV, and compare them to the degradation of traffic capacity of Caltrans' (California Department of Transportation) network in Los Angeles and Orange County damaged by the 1994 Northridge earthquake. Furthermore, the results are shown with the aid of 3D animations (ArcGIS, 1999) to demonstrate post-earthquake traffic behavior. For this purpose, the spatial distributions of PGA and PGV resulting from the 1994 Northridge earthquake are acquired from the TriNet ShakeMap (2001). The network seismic risk evaluation method is then developed by integrating the seismic hazard represented by the 1994 Northridge earthquake and its associated system performance degradation. In

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this study, system performance degradation is measured in terms of an index, "Drivers Delay," that is calculated by equilibrium analysis of transportation systems (user optimizing deterministic assignment), on the basis of the 1991 origin-destination survey performed for the region including Los Angeles and Orange County. This index is strictly used as a measure of network degradation under the unchanged origin-destination (OD) matrix. In this sense, it does not precisely represent the network performance relative to the post-earthquake traffic demand. This dynamic aspect of the traffic flow problem is currently under study.

Furthermore, under certain assumptions, the process and progress of bridge repair is simulated by a Monte Carlo method to produce a chronological improvement of post earthquake system performance. These simulations are all made utilizing the PGA spatial distribution of 47 selected scenario earthquakes from the regional seismic hazard associated with Los Angeles and Orange County.

In addition, loss due to Drivers Delay is evaluated for the Caltrans freeway network with and without retrofit, and finally, loss due to ground shaking and liquefaction are evaluated for all bridges in Orange County with the aide of HAZUS (National Institute of Building Sciences, 1999) software.

## 2 Empirical fragility curves

Empirical fragility curves for bridges in the Los Angeles area freeway network are developed from records of damage to Caltrans bridges under the 1994 Northridge earthquake in conjunction with the PGA and PGV values acquired from the TriNet ShakeMap (2001).

In this study, the bridges are classified into different subsets according to three distinct attributes:

(a) It is either single span (S) or multiple span (M)

(b) It is built on either hard soil ($S_A$), medium soil ($S_B$) or soft soil ($S_C$) according to the definitions in UBC 1994 (Intl. Conference of Building Officials, 1994)

(c) It has a skew angle $q_1$ (less than 20°), $q_2$ (between 20° and 60°) or $q_3$ (larger than 60°).

To begin with, one might consider the first level hypothesis that the entire sample is taken from a statistically homogeneous population of bridges. The second level subsets are created by dividing the sample either (a) into two groups of bridges, one with single spans and the other with multiple spans, (b) into three groups, the first with soil condition $S_A$, the second with $S_B$ and the third with $S_C$, or (c) into three groups depending on the skew angles $q_1$, $q_2$ and $q_3$. The third and fourth level sub-groupings were also considered for the development of corresponding fragility curves under PGA as a ground motion intensity index (Shinozuka *et al.*, 2003).

It is assumed that the curves can be expressed in the form of two parameter lognormal distribution functions, and estimation of the two parameters (median and log-standard deviation) is performed with the aid of the maximum likelihood method. For this purpose, PGA and PGV values are used to represent the intensity of the seismic ground motion.

The likelihood function is expressed as follows:

$$L(c_1,c_2,c_3,c_4,\zeta)=\prod_{i=1}^{N}\prod_{k=1}^{5}P_{ij}(a_i;E_k)^{x_{ik}} \tag{1}$$

where $E_1$, $E_2$, $E_3$, $E_4$, and $E_5$, respectively, indicate the state of no, minor, moderate, major and collapse damage. $P_{ij}(a_i; E_k)$ in turn indicates the probability that a bridge $i$ selected randomly from the sample will be in the damage state $E_k$ when subjected to ground motion intensity expressed by PGA or PGV $=a_i$. $x_{ik}$ equals 1 or 0 depending on whether or not the damage state $E_k$ occurs for the $i$-th bridge subjected to $a_i$. $N$ is the total number of bridges inspected after the earthquake.

Under the current lognormal assumption, fragility curves take the following analytical form

$$F_j(a_i;c_j,\zeta_j)=\Phi\left[\ln\left(\frac{a_i}{c_j}\right)\Big/\zeta_j\right] \tag{2}$$

where $\Phi$ [ ] is the standardized normal distribution function, parameters $c_j$ and $\zeta_j$ are the median and log-standard deviation of the fragility curves for the damage state of "at least minor," "at least moderate," "at least major," and "collapse" identified by $j$ =1,2,3 and 4, respectively. From this definition of fragility curves, and under the assumption that the log-standard deviation is equal to $\zeta$ common to all the fragility curves, one obtains;

$$P_{i1}=P(a_i,E_1)=1-F_1(a_i;c_1,\zeta) \tag{3}$$

$$P_{i2}=P(a_i,E_2)=F_1(a_i;c_1,\zeta)-F_2(a_i;c_2,\zeta) \tag{4}$$

$$P_{i3}=P(a_i,E_3)=F_2(a_i;c_2,\zeta)-F_3(a_i;c_3,\zeta) \tag{5}$$

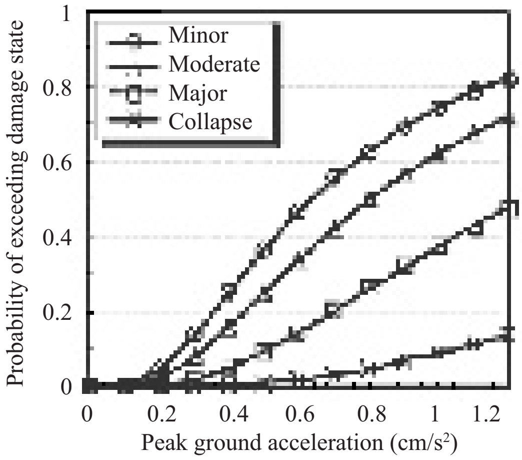
$$P_{i4}=P(a_i,E_4)=F_3(a_i;c_3,\zeta)-F_4(a_i;c_4,\zeta) \tag{6}$$

$$P_{i5}=P(a_i,E_5)=F_4(a_i;c_4,\zeta) \tag{7}$$

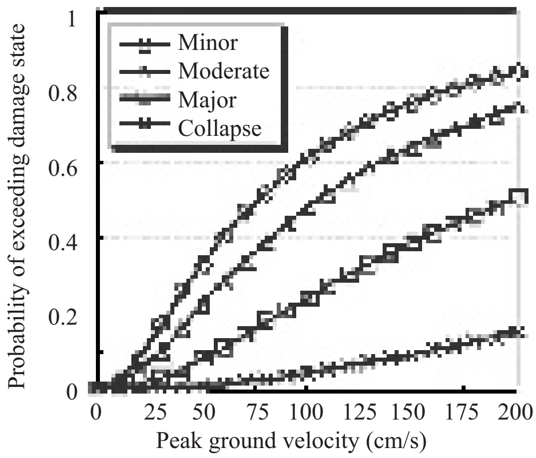
The maximum likelihood estimations $c_{0j}$ for $c_j$ and $\zeta_{0j}$ for $\zeta_j$ are obtained by solving the following equations,

$$\frac{\partial\ln L(c_1,c_2,c_3,c_4,\zeta)}{\partial c_j}=\frac{\partial\ln L(c_1,c_2,c_3,c_4,\zeta)}{\partial\zeta}=0 \qquad (j=1,2,3,4) \tag{8}$$

by implementing a straightforward optimization algorithm. The median values and log-standard deviations of all levels of attribute combinations are listed in Table 1. Note that if an element of a matrix in Table 1 is labeled N/A, it indicates that no sub-sample was found for the particular combination of bridge attributes signified by the element. The family of fragility curves corresponding to the first level is plotted in Fig. 1. The curve with a "minor" designation represents, at each PGA or PGV value *a*, the probability that "at least a minor" state of damage




(a) Fragility curves on the basis of PGA




(b) Fragility curves on the basis of PGV

**Fig. 1 Fragility curves for Caltrans' bridges (first level (composite))**

**Table 1 Median and log-standard deviation at different levels of sample sub-division**

(a) First level (composite)

| Damage state | PGA($m/s^2$) | | PGV(cm/s) | |
|---|---|---|---|---|
| | $c_j$ | $\varsigma$ | $c_j$ | $\varsigma$ |
| Min | 0.64 | 0.70 | 76 | 0.98 |
| Mod | 0.80 | 0.70 | 106 | 0.98 |
| Maj | 1.25 | 0.70 | 200 | 0.98 |
| Col | 2.55 | 0.70 | 555 | 0.98 |

(b) Second level (span)

| Span | Damage state | PGA($m/s^2$) | | PGV(cm/s) | |
|---|---|---|---|---|---|
| | | $c_j$ | $\varsigma$ | $c_j$ | $\varsigma$ |
| S* | Min | 0.89 | 0.66 | 129 | 0.98 |
| | Mod | 1.15 | 0.66 | 188 | 0.98 |
| | Maj | 1.76 | 0.66 | 357 | 0.98 |
| | Col | N/A | 0.66 | N/A | 0.98 |
| M* | Min | 0.56 | 0.66 | 63 | 0.92 |
| | Mod | 0.70 | 0.66 | 87 | 0.92 |
| | Maj | 1.09 | 0.66 | 163 | 0.92 |
| | Col | 2.16 | 0.66 | 428 | 0.92 |

*S: Single; M: Multiple

(c) Second level (skew)

| Skew | Damage state | PGA($m/s^2$) | | PGV(cm/s) | |
|---|---|---|---|---|---|
| | | $c_j$ | $\varsigma$ | $c_j$ | $\varsigma$ |
| $\theta_1$† | Min | 0.82 | 0.76 | 108 | 1.07 |
| | Mod | 1.10 | 0.76 | 164 | 1.07 |
| | Maj | 1.86 | 0.76 | 343 | 1.07 |
| | Col | 3.49 | 0.76 | 833 | 1.07 |
| $\theta_2$† | Min | 0.60 | 0.71 | 70 | 0.98 |
| | Mod | 0.72 | 0.71 | 90 | 0.98 |
| | Maj | 1.15 | 0.71 | 173 | 0.98 |
| | Col | 3.18 | 0.71 | 769 | 0.98 |
| $\theta_3$† | Min | 0.42 | 0.52 | 42 | 0.75 |
| | Mod | 0.52 | 0.52 | 56 | 0.75 |
| | Maj | 0.74 | 0.52 | 96 | 0.75 |
| | Col | 1.26 | 0.52 | 212 | 0.75 |

† $\theta_1$: Less than 20°; $\theta_2$: Between 20° and 60°; $\theta_3$: Larger than 60°

(d) Second level (soil)

| Soil | Damage state | PGA($m/s^2$) | | PGV(cm/s) | |
|---|---|---|---|---|---|
| | | $c_j$ | $\varsigma$ | $c_j$ | $\varsigma$ |
| $S_A$‡ | Min | 0.87 | 0.75 | 110 | 1.03 |
| | Mod | 1.10 | 0.75 | 151 | 1.03 |
| | Maj | 1.51 | 0.75 | 234 | 1.03 |
| | Col | N/A | 0.75 | N/A | 1.03 |
| $S_B$‡ | Min | 0.64 | 0.71 | 65 | 0.81 |
| | Mod | 0.84 | 0.71 | 91 | 0.81 |
| | Maj | 1.24 | 0.71 | 145 | 0.81 |
| | Col | N/A | 0.71 | N/A | 0.81 |
| $S_C$‡ | Min | 0.61 | 0.69 | 74 | 0.98 |
| | Mod | 0.76 | 0.69 | 102 | 0.98 |
| | Maj | 1.22 | 0.69 | 199 | 0.98 |
| | Col | 2.35 | 0.69 | 523 | 0.98 |

‡ $S_A$: Hard soil; $S_B$: Medium soil; $S_C$: Soft soil

will be sustained by a bridge (arbitrarily chosen from the sample of bridges) when it is subjected to PGA or PGV *a*. The same meaning applies to other curves with their respective damage state designations.

## 3 Methodology

### 3.1 Highway system: assessing structural component and network damage

Highway transportation systems comprise numerous structural components and are located in equally complex natural and built environments. Among the engineered components, bridges are the most vulnerable under earthquake conditions. Thus, bridges are the only structures considered to be seismically vulnerable in this analysis. For the purpose of simulation, every bridge in the study region is considered to be an independent structure and determination of the degree of damage to each bridge can be treated as an independent statistical experiment.

These fragility curves are utilized to generate, in Monte Carlo simulation, the state of damage for each Caltrans bridge in Los Angeles and Orange County under postulated scenario earthquakes, and hence, the following analysis applies only to the bridge prior to the post-Northridge retrofit.

The performance of the highway transportation system in the Los Angeles metropolitan area following the Northridge earthquake demonstrated some system resiliency that was achieved by enlisting and integrating some unaffected secondary highways and artillery streets into the expressway network. Therefore, in this analysis, the alternate routes are considered to exist although they have lesser traffic capability in terms of both free flow speed and capacity compared to those associated with the segment or the link of the expressway they replaced. Table 2 shows a loss of traffic capability depending on the degree of the state of the link damage. The link damage represents the worst state of damage to the bridges in that link (i.e., bottle-neck hypothesis; if, for example, at least one of the bridges in a link suffers major damage, and if that is the greatest state of damage, the link has the major damage). The values in table 2 are hypothetical and future research is needed to validate them.

**Table 2 Change in road capacity and free flow speed**

| State of link damage | Capacity change rate (%) | Free flow speed change rate (%) |
|---|---|---|
| No damage | 100 | 100 |
| Minor damage | 100 | 75 |
| Moderate damage | 75 | 50 |
| Major damage | 50 | 50 |
| Collapse | 50 | 50 |

### 3.2 Calculating a comprehensive system performance index: Drivers Delay

In order to define the network performance as a whole after an earthquake, a comprehensive index of performance is introduced. Following the method documented by Shinozuka *et al*. (2000), the index used here is the "Drivers Delay." This is defined as the increase in total daily travel time for all travelers, including commuters and commercial vehicles, caused by earthquake induced delays. Essentially, it is the difference between the total daily travel for all network travelers on the damaged network and that of the original undamaged network.

$$t_I = \sum_a x_a t_a(x_a) \tag{9}$$

$$t_D = \sum_a x'_a t'_a(x'_a) - \sum_a x_a t_a(x_a) \tag{10}$$

Equation (9) exhibits the calculation of the total daily travel time for all network users, in hours per day; as defined earlier, $x_a$ is the flow on link *a* (in passenger car units per day), and $t_a$ is the travel time on link *a* (in hours per Passenger Car Unit). Thus, the product of the two yields the total daily travel time for all network travelers on link *a*. The summation over all the links yields the total daily travel time on the entire network. Equation (10) exhibits the calculation of the Drivers Delay. The notation in Eq. (10) is the same as in Eq. (9) except that the primed variables denote the damaged network, and the unprimed variables refer to the original undamaged network. Note that "Drivers Delay," when calculated this way, has units of hours per day. In order to obtain a total "Drivers Delay" with units of hours, this expression must be integrated over all the days that a delay persists.

The travel time on a link is calculated by utilizing a link performance function developed by the United States Bureau of Public Roads, 1964:

$$t_a = t_a^0\left[1 + \alpha\left(\frac{x_a}{C_a}\right)^{\beta}\right] \tag{11}$$

where $t_a^0$ is the travel time at zero flow on link *a* (this is simply the link's length divided by the speed limit); $C_a$ is the "practical capacity" of the link, and $\alpha$ and $\beta$ are variable parameters. Ordinarily, and in this study, $\alpha = 0.15$ and $\beta = 4.0$. It is important to note that this empirically derived expression asserts that the travel time on a link carrying 100% of capacity is 15% greater than the free flow time.

Determining the flow on each link depends on the availability of origin-destination (OD) data. Given the difficulty of collecting such a set of traffic flow data over a regional dimension, the OD data are developed only occasionally over the years and hence lags behind the change in traffic patterns. Therefore, traffic flow characteristics are approximates. In this context, we developed a method by which a large OD matrix can be reduced to a manageable size following Shiraki (2000). This method relies upon the Thiessen function (an ArcGIS software) where the number of OD locations are reduced to the number of the nodes of the freeway network, each representing OD information within the Thiessen polygon developed around that node (see Fig. 2). This significantly reduces the matrix dimension and makes the OD matrix usable in the PC-based near-real-time traffic flow simulation. Upon producing a useable origin-destination matrix, the flow between links must be solved using an equilibrium analysis.

Using the methods discussed here, it is possible to develop a rudimentary measure of a system's performance as a network given any state of damage to its components (bridges).

### 3.3 Determining effects of repair efforts

Earlier, it was noted that the calculated value of Drivers Delay was actually in terms of hours per day, and it would be necessary to integrate the delay over the time that it persists in order to have a measurement of the total delay. Notably, the Drivers Delay is not constant over the time it persists. Repair efforts improve the state of damage to the network, thus decreasing Drivers Delay over time. In this connection, this paper accounts for the bridge repair process. Unfortunately, this is fairly difficult, as there is not much consistent and systematic data on the processes by which repair is conducted, and little documentation made available on the priorities selected by the engineers involved in the operation. Highway repair is conducted by and large using the best judgment of the engineers and management involved, and hence this process is not easily modeled. Nonetheless, a model is developed for this simulation to provide some numerical insight to the problem.

In this paper, the repair process is modeled as the time to complete a repair for each individual bridge damaged is assumed to be a random variable uniformly distributed over travels ($t_{i,\min}$ and $t_{i,\max}$) in which $i$=1, 2, 3 and 4 represent minor, moderate, major and collapse states of damage, respectively. For example, $t_{i,\min}$ = 10 days and $t_{i,\max}$ = 150 days indicates a bridge that sustained a state of minor damage requires most optimistically 10 days and most pessimistically 150 days to complete repair. Otherwise, repair time takes a uniformly distributed value between these two values, (see Fig. 3). Chances are uniformly distributed for completion. Other values of subscript $i$ apply most optimistic and pessimistic times to bridges subjected to different damage states. The size and importance of bridges are not factored into this simplistic analysis, and are the subject of future study.

Notice that the functions do not necessarily assume that all bridges can be repaired on Day 0, nor do they assume that the slopes (daily probabilities of repair), are the same. The choice of the parameters of the optimistic and pessimistic repair scenarios, (essentially, the first and last possible days a bridge of a given damage state can be repaired), are left to the best judgment of those developing the model. It is important to note that there are numerous ways that the repair of the system could be probabilistically modeled. For instance, link flow data could have been used to estimate the priorities for bridge repair. The method used here is chosen because there seems to be a

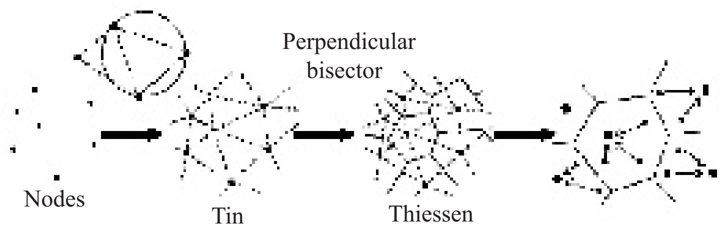



**Fig. 2 Making Thiessen polygon**

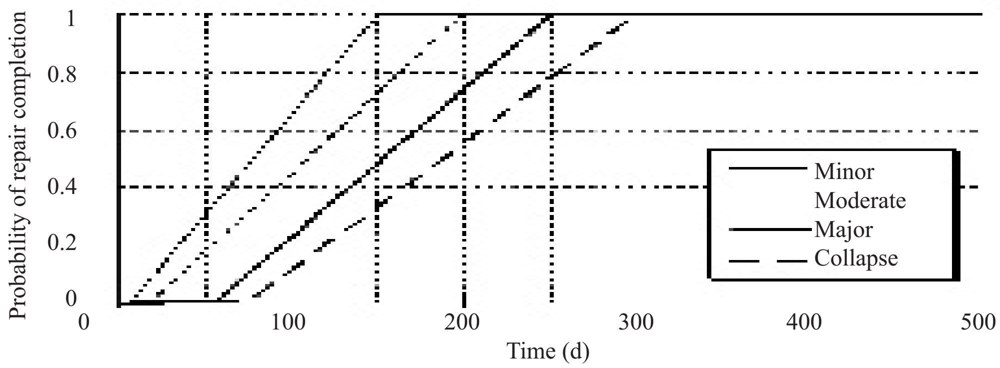



**Fig. 3 Probability distribution of function used to model repair processes**

correlation between the damage state of a bridge and the amount of time for a repair contract to be awarded, and for simplicity in simulation.

The repair process is simulated by another use of the Monte Carlo technique. Day 0 represents the day of the earthquake – when the system has the greatest extent of damage. The data available includes the damage state of each bridge, as well as the damage state of the link and the Drivers Delay. The bridge damage data is the relevant information for performing the repair simulation. Considering some arbitrary amount of time after the event, one can perform a Monte Carlo simulation in the same way as before with the repair distributions to determine if each bridge is repaired. This is done by considering each bridge one at a time. Based on the bridge's damage state, the time since the event, and the appropriate repair function for the damage state, one can use a random number generator to decide if the bridge is repaired. If the random value falls above the function for the given time since the event, it is not repaired; if it falls beneath the function, it is repaired. In this simulation, a repaired bridge shifts from its previous damage state directly to the no damage state, and its record is modified to reflect that change. This process is then repeated for every bridge in the study region. The result is a system with an entirely different state of damage. Link damage state and the Drivers Delay must be recalculated to reflect the changes to the system.

### 3.4 Developing a risk measure

Given the possibility of performing multiple simulations for a study region, measures of risk for a spatially distributed highway system can be developed using methods introduced in Chang *et al*. (2000). Using a number of earthquake scenarios, and calculating their probabilities of exceedance, risk curves can be produced for the system. A risk curve is a plot of the probability of exceeding a certain hazard level versus a measure of damage (in this case, Drivers Delay). A set of these is produced in the case study described later in this paper.

## 4. Application

### 4.1 Network model

Figure 4 displays the freeway and state highway network considered in this study. The study is limited to the freeway network in Los Angeles and Orange County in the Los Angeles Metropolitan Area.

This network model consists of 118 nodes and 185 links. The total number of bridges in this network is 2727. The network is defined in terms of nodes and links, where nodes consist of locations where two or more highways intersect (usually interchanges), as well as locations where a highway crosses the boundary of the study area. A link is defined by a line (not self-intersecting) between two nodes with no other nodes in between. The link characteristics are described by free flow speed and flow capacity. The free flow speed for a link is based upon its speed limit, which is considered to be 65 miles per hour on the freeway, and 35 miles per hour on the highway. This is done for analytical simplicity, and can be adjusted for regional differences. Similarly, the practical capacities for freeway and highway links are assumed to be 2500 and 1000 passenger car units per hour, respectively.

Fragility curves for the bridges in the study region are represented by the family of those corresponding to the first level population as shown in Fig. 1. The spatial distribution of PGA and PGV values for the 1994 Northridge earthquake are acquired from the TriNet ShakeMap. The bridge damage state is determined by Monte Carlo simulation based on the fragility information. The state of damage thus simulated for each bridge determines the link capacity as shown in Table 2 where the worst state of the bridge damage in the link determines the state of the link damage.

The origin-destination data used in this paper consists of 1991 southern California origin-destination survey results for 1527 traffic analysis zone. The reader is referred to SCAG report (Southern California Association of Governments, 1993) for details. As mentioned in section 4, Thiessen polygons are used to convert the 1991 SCAG survey data to node OD data of the freeway network shown in Fig. 4.

### 4.2 Traffic analysis

To perform the traffic equilibrium analysis numerically, the method of user optimizing deterministic assignment described earlier is used with the aid of the incremental assignment technique. Figures 5 and 6 show the average result over 10 simulations, including average damage state and average speed ratio. A speed ratio $\eta$ for each link, representing one measure of system performance degradation, is defined as:

$$\eta_a = \frac{S'_a}{S_a} \tag{12}$$

where, $\eta_a$ is the speed ratio on link $a$, $S_a$ is the flow speed on link $a$ under intact condition, and $S'_a$ is the flow speed on link $a$ under damaged condition.

In the 1994 Northridge earthquake, Goltz (1994) reported that bridges collapsed on I-10 (Santa Monica Freeway), on I-5 (Golden State Freeway), at I-5/SR-14 (Antelope Valley) intersection, and on SR-118 (San Fernando Valley). In the simulation, major or moderate damage to links are recognized at I-405, I-101 and I-210, as well as these four links (e.g., I-10, I-5, SR-14, and SR-118). The differences between the actual damage states and simulated results is caused by the fragility curves used in this study, where the bridges are assumed to have a statistically homogenous vulnerability to earthquake damage, which do not reflect the attributes of bridges

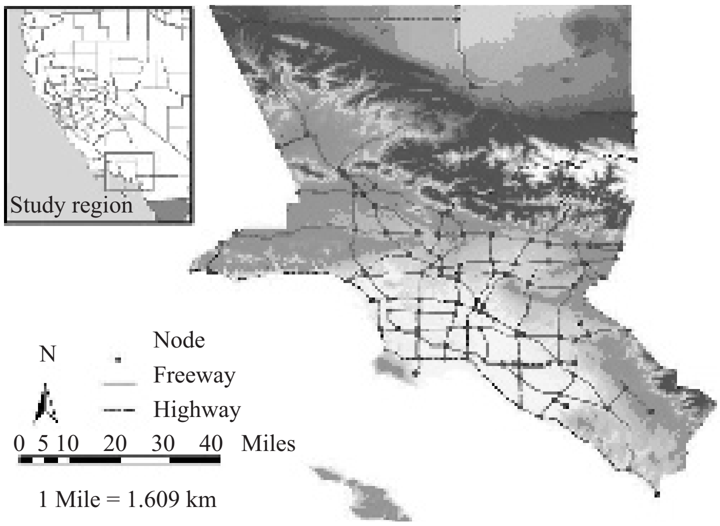



**Fig. 4 Los Angeles area highway network**

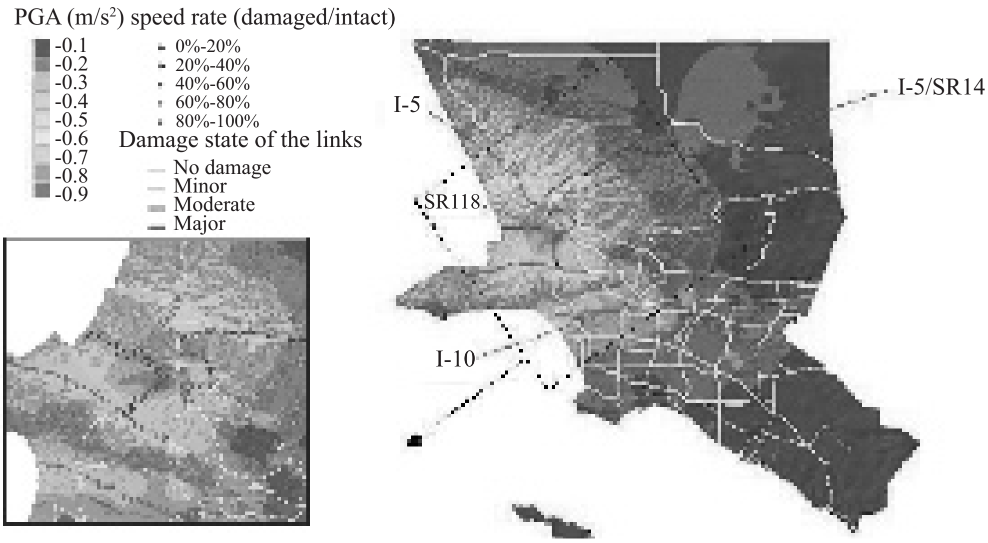



**Fig. 5 The 1994 Northridge earthquake PGA distribution, average damge state of links, and average speed ratio of links (Using fragility curves on the basis of PGA)**

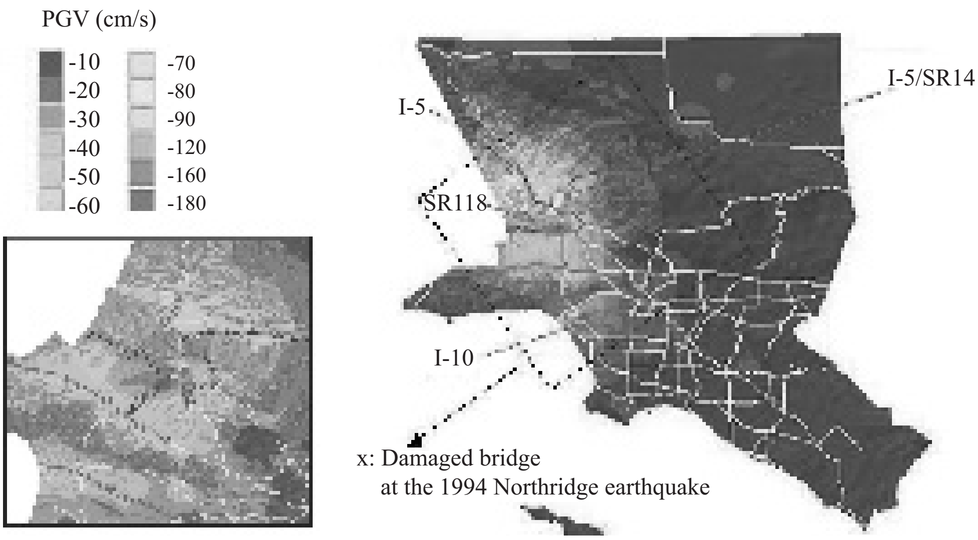



**Fig. 6 The 1994 Northridge earthquake PGV distribution, average damge state of links, and average speed ratio of links (Using fragility curves on the basis of PGV)**

such as skew, number of spans and soil conditions. When compared to the results based on PGA and PGV, only one different damage state is seen at I-5 and I-10. This is caused by the spatial distribution of PGA and PGV, and is not significant.

Figures 7 and 8 display the result of post-earthquake ground motion intensity and traffic behavior in 3D animations. The legends in Fig. 7 and 8 are the same as in Fig. 5 and 6. These 3D animations show the detail of traffic congestion in the damaged area, and thus are useful for developing pre-event emergency response strategies.

The computed average Drivers Delay is shown in Table 3. The total travel time under intact conditions is $8.90\times10^5$ hours. Drivers Delay based on PGA and PGV increased 78% and 73% from the total travel time under intact condition, respectively. Drivers Delay based on PGV was 7% shorter than based on PGA, which is not a significant difference. This shows that if PGA or PGV are used consistently, the difference between the actual data and simulation network analysis is insignificant.

**Table 3 Average Drivers' Delay**

| Case | Total travel time ($10^5$ h) | Drivers' Delay ($10^5$ h) | Drivers' Delay (min/PCU) |
|---|---|---|---|
| Simulation based on PGA | 15.87 | 6.97 | 14.30 |
| Simulation based on PGV | 15.40 | 6.50 | 13.34 |

*Total number of PCU (Passenger car unit) = 2921668

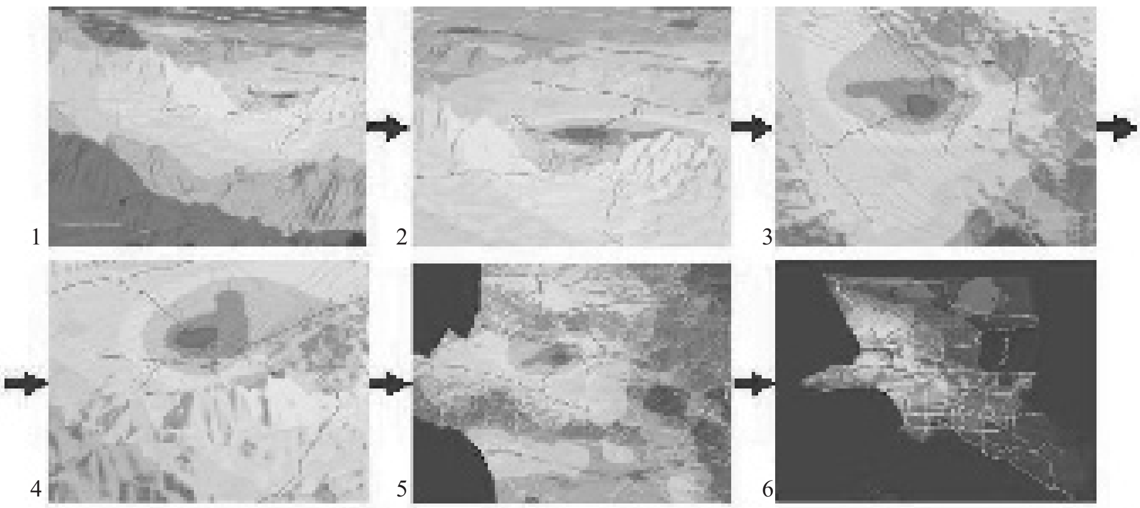


**Fig. 7 3D animation for the 1994 Northridge earthquake (PGA)**

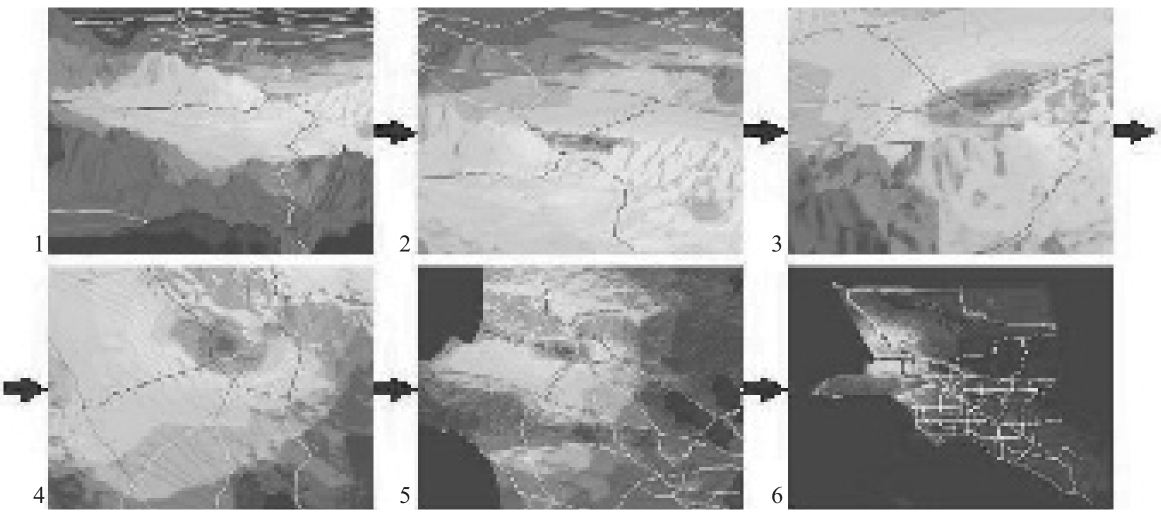


**Fig. 8 3D animation for the 1994 Northridge earthquake (PGV)**

### 4.3 Risk curves for repair efforts

A set of 47 earthquake scenarios were considered, consistent with Chang *et al*. (2000). The spatial PGA distributions for the selected event scenarios are modeled using the USC-EPEDAT (Early Post Earthquake Damage Assessment Tool) software, jointly developed by University of Southern California and EQE, adapting original EPEDAT (Eguchi *et al*. 1997) to the present study.

The simulation is conducted by executing ten runs for each of the 47 earthquake scenarios. The Drivers Delay results are then averaged to offset the variability inherent in the implementation of the Monte Carlo method. The resulting data from each scenario's simulation includes: the damage caused to the network by the earthquake, the resulting Drivers Delay, and the variation of the Drivers Delay over time after the event. Using the Drivers Delay data, and the calculated probabilities of exceedance for each scenario event, risk curves are developed for the system.

Figure 9 plots the system risk curves for the Drivers Delay on Day 0, 28, and 84. Though there is a good deal of noise in the Day 84 curve, it is apparent that the probability to exceed large Drivers Delays is virtually eliminated 12 weeks after an event.

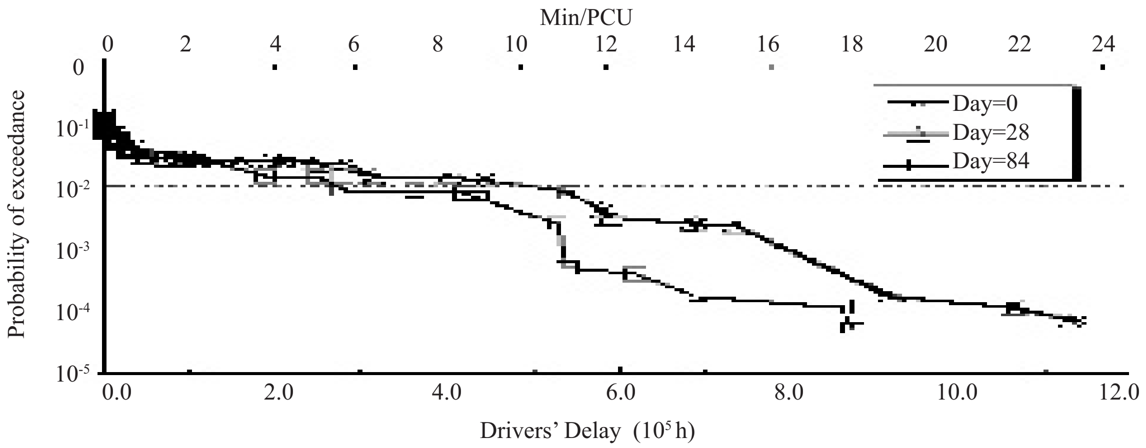



**Fig. 9 Risk curves, separated by time after event**

### 4.4 Loss estimation

Similar simulations are performed for 47 scenario earthquakes using the fragility curves as a function of PGA with and without retrofit. The effect of retrofit is demonstrated by the ratio of the median values of the fragility curves for a retrofitted column to that of the column before retrofit (Shinozuka *et al*., 2002). This ratio is referred to as fragility "enhancement." The fragility enhancement shows 55%, 75%, 104%, and 143% improvement for the minor, moderate, major and collapse damage, respectively. It is assumed that the fragility enhancement thus obtained applies to the development of fragility curves with the retrofit for the empirical fragility curves (Fig. 1 (a)). Figure 10 represents the fragility curves with and without retrofit. Figure 11 plots the risk curves for Drivers Delay with and without retrofit. The results of Drivers Delay based on enhanced fragility are reduced almost 90% over the results from without retrofit.

Furthermore, using these results, loss due to Drivers Delay is computed on the basis of $50 per one hour delay. Table 4 shows the results simulated for the representative scenario earthquakes. Estimated losses with retrofit are less than 10% of those without retrofit, and thus shows that the effect of retrofit is significant. Particularly, in the simulation for Malibu Coast, almost $50 million loss is avoided every day after the bridges are retrofitted, if repair is not made and if the same OD matrix is used.

**Table 4 Daily loss due to Driver's Delay**

| Scenario Earthquake | Without retrofit | With retrofit |
|---|---|---|
| Newport-Inglewood(S.) *M* 7.0 | 4.74 | 0.27 |
| Newport-Inglewood(N.) *M* 7.0 | 10.60 | 0.98 |
| Elysian Park *M* 7.1 | 15.73 | 1.02 |
| Malibu Coast *M* 7.3 | 56.94 | 6.25 |

A preliminary estimation of direct loss due to ground shaking and liquefaction is performed with the aid of HAZUS (National Institute of Building Sciences, 1999) software. In this estimation, 1307 bridges, including local bridges in Orange County, are studied. Using HAZUS software, together with information available elsewhere for scenario earthquakes defined by $M_M$ (moment magnitude) and the liquefaction susceptibility map shown in Fig. 12, permanent ground displacement (PGD) for lateral spread and ground settlement is evaluated. Integrating PGD, fragility curve, damage ratio, replacement value and probability of liquefaction, loss due to liquefaction is estimated. The reader is referred to HAZUS Users' Technical Manual for the details. For the present analysis, the soil type is assumed to be stiff, and ground water depth is assumed to be five feet for the all bridges. Average replacement values of $150 per deck area (square foot) obtained from Caltrans data is used. Loss due to ground shaking plus liquefaction is estimated by simply adding

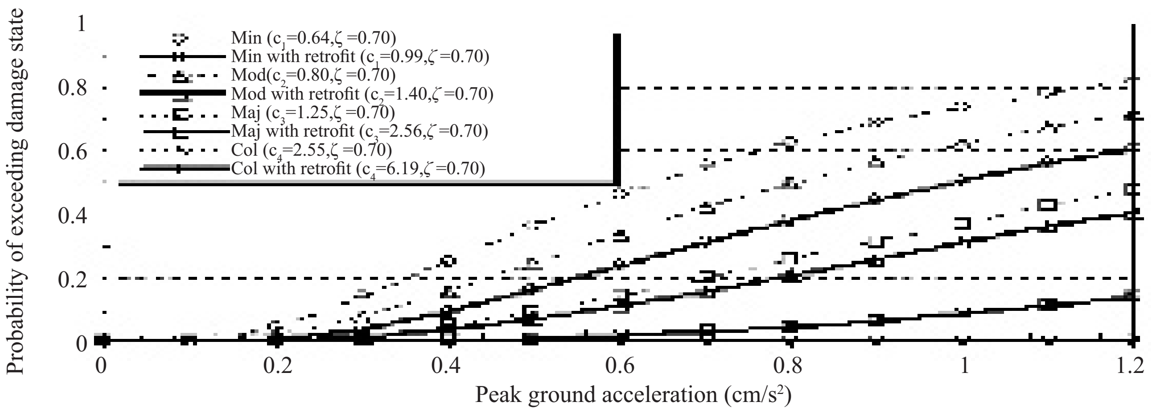



**Fig. 10 Fragility curve, with and without retrofit**

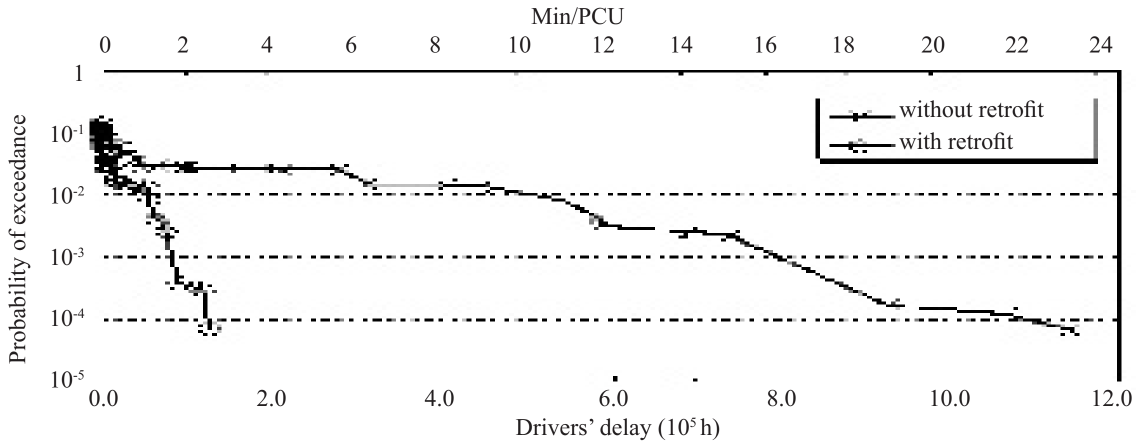



**Fig. 11 Risk curves for drivers delay with and without retrofit**

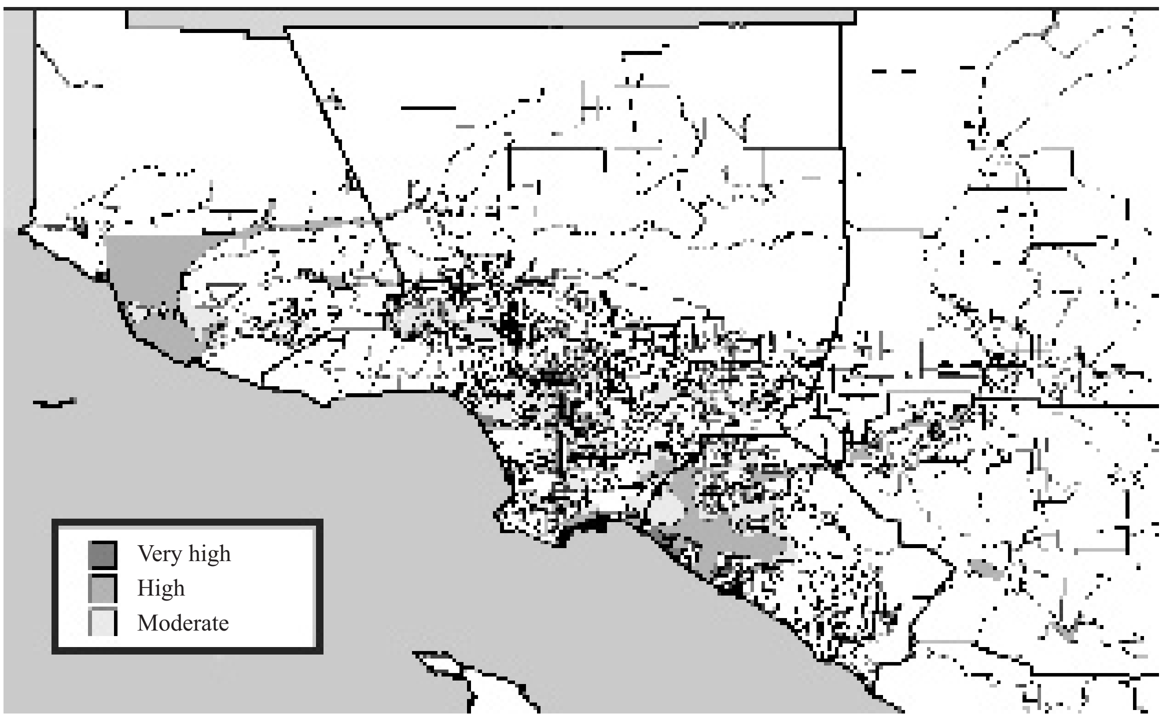



**Fig. 12 Liquefaction susceptibility map from EPEDAT (Eguchi *et al*., 1997)**

both losses to be conservative and the results are shown in Table 5. From the table, losses due to liquefaction are almost 55% of loss due to ground shaking, and thus the effect of liquefaction is significant.

**Table 5 Loss due to ground shaking and liquefaction**

$M

| Scenario earthquake | Ground shaking | Lique-faction | Ground shaking & liquefaction |
|---|---|---|---|
| Newport-Inglewood (S.) $M_M$7.5 | 39.70 | 20.99 | 60.69 |
| Newport-Inglewood (S.) $M_M$6.9 | 29.27 | 15.97 | 45.24 |
| Elysian Park $M_M$6.7 | 16.63 | 9.40 | 26.03 |

## 5 Conclusions and future research

This study empirically developed four fragility curves associated with four different states of damage to Caltrans bridges using damage data compiled from the 1994 Northridge earthquake. Two-parameter lognormal distribution functions were used to represent the fragility curves. ShakeMap data were used for PGA and PGV at each bridge site.

Integrating the fragility information into the Monte Carlo analysis of traffic flows, degradation of traffic capacity of Caltrans' network in Los Angeles and Orange County damaged by the Northridge earthquake was evaluated. The simulation results were compared to the actual performance of Caltrans' network in the aftermath of the earthquake. Both simulation results were very reasonable, and it was concluded that the choice of ground motion intensity, whether PGA or PGV, does not significantly influence the network simulation results. Visual insight provided by the 3D animation of simulated traffic flow was useful in developing pre-event emergency response strategies.

A probabilistic model was developed to evaluate the effect of bridge damage repair on the improvement of the transportation network performance as days passed after the event. Notably, given the low probabilities of exceeding even moderate Drivers Delays, as evidenced by the risk curves, it can be said that the system exhibits remarkable resilience. This model could benefit from further work by considering the attributes of bridges, such as skew and number of spans, on the model repair processes.

Losses due to Drivers Delay with and without retrofit were computed by assuming the loss of $50 per one hour delay. The results show that the effect of retrofit was significant. Losses due to ground shaking and liquefaction were estimated with the aid of HAZUS software as a first step to incorporate PGD in the analysis. The effect of liquefaction is an important factor to be taken into account in the transportation network simulation.

Future study will emphasize the following subjects: dynamic aspects of traffic flow problems relative to post-earthquake traffic demand; link damage definition and related link occupancy; modeling the repair process as a function of the size and importance of bridges; and perform uncertainty analysis to take advantage of the integrated insight acquired through this and other studies on modeling, numerical analysis and statistical interpretation.

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