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Seismic Risk Assessment of Transportation Network Systems

ANNE KIREMIDJIAN

Department of Civil and Environmental Engineering, Stanford University, Stanford, California, USA

JAMES MOORE

Department of Civil and Environmental Engineering, Public Policy and Management, Industrial and Systems Engineering, University of Southern California, Los Angeles, California, USA

YUE YUE FAN

Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, California, USA

OZGUR YAZLALI

Department of Management Science and Engineering, Stanford University, Stanford, California, USA

NESRIN BASOZ

CATRisk Technology Research, St. Paul Fire and Marine Insurance, Concord, California, USA

MEREDITH WILLIAMS

GIS Consultant, Earth Science Library, Stanford University, Stanford, California, USA

When evaluating the earthquake risk to transportation system it is important to take into account the integrated effect of ground motion, liquefaction, and landslides on the network components and system. In this article, the risk from earthquakes to a transportation system is evaluated in terms of direct loss from damage to bridges and travel delays in the transportation network. The contribution of site effects to the loss from damage to bridges is estimated using the San Francisco Bay area as a test bed. Damage and loss to bridges from ground shaking and ground displacements (vertical and horizontal) from liquefaction and landslides are computed for a magnitude 7.0 scenario earthquake

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Address correspondence to Anne Kiremidjian, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305; E-mail: ask@stanford.edu

on the Hayward fault in California. It is found that liquefaction damage is the largest contributor to the repair cost which is used as a measure of the loss from damage. The performance of the transportation network is evaluated in terms of travel delay times. Travel delays resulting from damage due to ground shaking and changes in travel times are evaluated for the scenario event under the assumptions of fixed and variable travel demands. It is found that with fixed travel demand, the post-event travel times increase significantly. Travel times remain relatively unchanged and decrease with the variable demand time assumption.

Keywords Network Component Risk; Transportation System Risk; Direct Loss; Functionality Loss; Earthquake Hazards

1. Introduction

Transportation systems are spatially distributed systems whereby components of the system are exposed to different ground effects due to the same earthquake event. The ground effects that various components of the system are subjected include ground shaking, vertical displacements due to settlement, and horizontal displacements due to lateral spreading and sliding. The ground displacements occur because severe ground shaking causes liquefaction and landslides under the appropriate environmental conditions. Bridges are key components of transportation systems and are particularly susceptible to liquefaction and landslides as they are located over streams and rivers with piers situated over sandy saturated deposits; or they may be over canyons with high slopes that may result in slope instability. Thus, it is important to integrate the effect of local site conditions in the overall earthquake risk of a transportation system.

Consideration of the spatial dependence of individual components is an important factor in the evaluation of the network system connectivity and traffic flow through the system. Risk assessment methods require that not only the component performance is assessed, but the overall system performance is evaluated. Most recently, Werner *et al*. (2000) and Basoz and Kiremidjian (1996) considered the problem of transportation network systems subjected to earthquake events. In both of these publications, the risk to the transportation system is computed from the direct damage to major components such as bridges and the connectivity between a predefined origin-destination (O-D) set. Basoz and Kiremidjian (1996) also consider the time delay and use the information primarily for retrofit prioritization strategies. The current software HAZUS (1999) for regional loss estimation developed by the National Institute for Building Standards (NIBS) for the Federal Emergency Management Agency (FEMA) considers only the direct loss to bridges in the highway transportation network. The connectivity and traffic delay problems resulting from damage to components of the system are not presently included in that software. Chang *et al*. (2000) propose a simple risk measure for transportation systems to represent the effectiveness of retrofit strategies by considering the difference in costs associated with travel times before and after retrofitting.

In this article, a method for risk assessment of a transportation system is postulated that considers the direct cost of damage and costs due to time delays in the damaged system. The method is applied to the transportation network within five counties in the San Francisco Bay Area and conclusions are drawn on the basis of the application. The site hazards considered in the direct loss estimation include ground shaking, liquefaction and landslides. The effect of bridge damage from ground shaking hazard on the transportation network is studied under the assumption that traffic demand following the earthquake is either constant or variable.

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 Q_i, where the damage is $0 \leq D \leq 1.0$,

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

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

The event Q_i is specified by its magnitude and rupture location, thus also defining the distance from each site to the rupture zone of the seismic source. Only significant events (e.g., events with moment magnitudes larger than 6.0) are damaging to transportation systems in most developed regions in the world. Such events occur rarely with return periods much larger than one year. Thus, assuming that at most one event of significance will occur in any given year, the annualized risk of loss for the transportation system from any possible event Q_i that may affect the system, occurring with a rate 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 Eqs. (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. Network components are assumed to be independent when estimating losses from direct damage. For a given event Q_i with annual occurrence rate of ν_i, the losses due to time delays arise from delays in commuter and freight traffic. The time delays can 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 article is on the computation of direct damage to bridges and evaluation of traffic travel-time delays. Expanding the first integral in Eq. (1) to take into

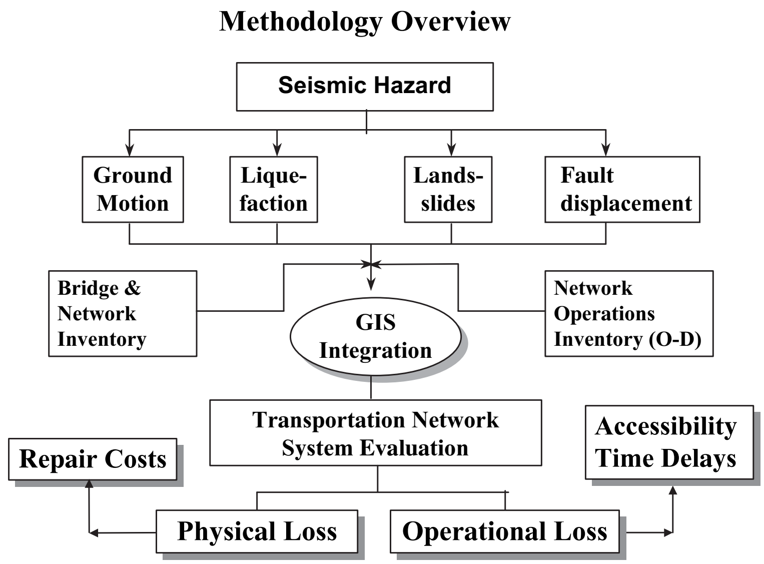

FIGURE 1 Risk assessment methodology for highway network systems.

account ground shaking, liquefaction, and landslides in the direct loss computations, the equations become:

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

where,

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

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

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.

The total risk has to take into account all possible events Q_i, $i = 1,2,\ldots N$, where N is the total number of events 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.

3. Direct Loss Assessment Application

For the purposes of illustrating the methodology, analysis is performed for a moment magnitude, $M_w = 7.0$ event on the Hayward fault. This earthquake is selected because it has a high probability of occurrence in the San Francisco Bay Area [USGS, 2002].

In order to evaluate the contribution of each hazard, it is necessary that an appropriate computational environment be in place with the various risk analysis components integrated within this environment. 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 5 counties in the study area. Information in the database that is particularly important for risk analysis includes bridge location, superstructure and substructure type, number of spans, type of connections (simple or continuous), skew angle, and design date. This information, however, is not complete for all bridges, and it had to be inferred. Inferences on various attributes were obtained by performing statistical analysis of available information in the database. In some cases, the information was inferred based on the age, location, and structural type. Furthermore, the inventory is for pre-retrofitted bridges. Thus, all results shown in this article are for pre-retrofitted bridges.

Peak ground accelerations and spectral accelerations are estimated for the scenario earthquake using the Boore *et al*. [1997] attenuation function. These relationships provide information on the median and standard deviation of the logarithm of the ground motion at bridge sites for a given magnitude and distance of the earthquake. Thus, the uncertainty of ground motion $f_{AiQ}(a \mid Q_i)$ defined in Eq. (3) is modeled with a lognormal distribution [Boor *et al*., 1997]. The geologic map for the Bay Area is obtained from the California Geological Survey and the ground motions are 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 scenario event 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. The probability of being in a particular damage state is represented as a probability mass function replacing the probability distribution of damage, $f_{D|A,Q_i}(d \mid A, Q_i)$, given in Eq. (3). 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 at a given ground motion. Then the expected damage state independent of the ground motion is obtained by integrating over all ground motions. All integration operations in Eq. (3) are performed numerically.

Figure 2 shows the distribution of median peak ground acceleration for the Hayward 7.0 earthquake and the resulting mean damage state for each bridge in the database. From the figure it can be observed that the median value of ground shaking varies from 0–0.7 g

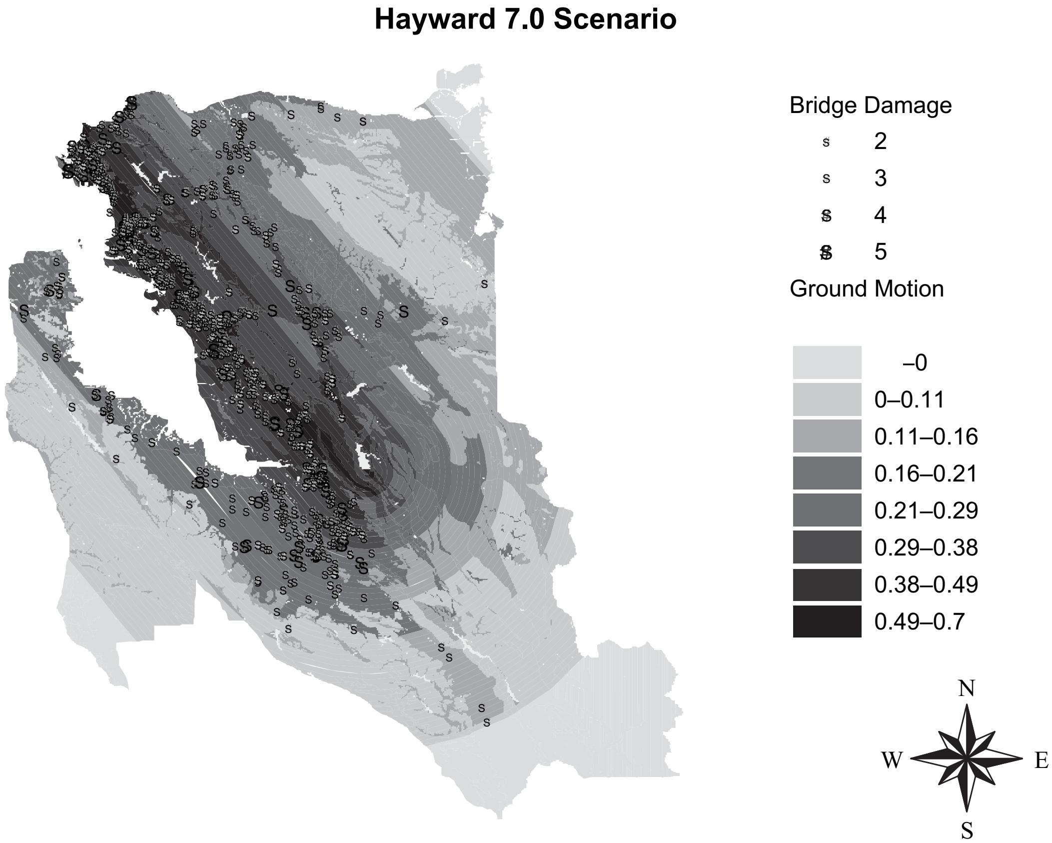

FIGURE 2 Distribution of mean bridge damage at the median ground shaking resulting from a $M_w = 7.0$ earthquake on the Hayward fault in the San Francisco Bay area.

with the largest shaking near the Hayward fault. As expected, bridges near the fault are also found to have the highest damage.

The liquefaction analysis follows the formulation presented in HAZUS [1999]. The liquefaction susceptibility map for the region is shown in Fig. 3 with the highest liquefaction potential along the bay. Information on liquefaction susceptibility in the San Francisco Bay area was obtained from the US Geological Survey [USGS, 2000]. There are six liquefaction susceptibility categories included in the analysis as shown in that figure. 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 and vertical displacement from settlement due to liquefaction are estimated using empirical formulas given in HAZUS [1999]. This information is used to develop $f_{S_H|Q_i}(s_H \mid Q_i)$ and $f_{S_V|Q_i}(s_V \mid Q_i)$ specified in Eq. (3). The maximum of the two displacements is used to determine the mean damage state to a bridge resulting from liquefaction. HAZUS [1999] provides fragility functions for bridges subjected to ground deformation (lateral spreading or settlement). These fragility functions are used to determine the probability of a bridge being in a particular damage state given horizontal and vertical ground displacement, $f_{D|S_H,Q_i}(d \mid S_H, Q_i)$ and $f_{D|S_V \cdot Q_i}(d \mid S_V, Q_i)$ in their discrete form.

The distribution of bridge damage from liquefaction resulting from a magnitude 7.0 scenario event on the Hayward fault is shown on Fig. 4. As can be seen from this figure,

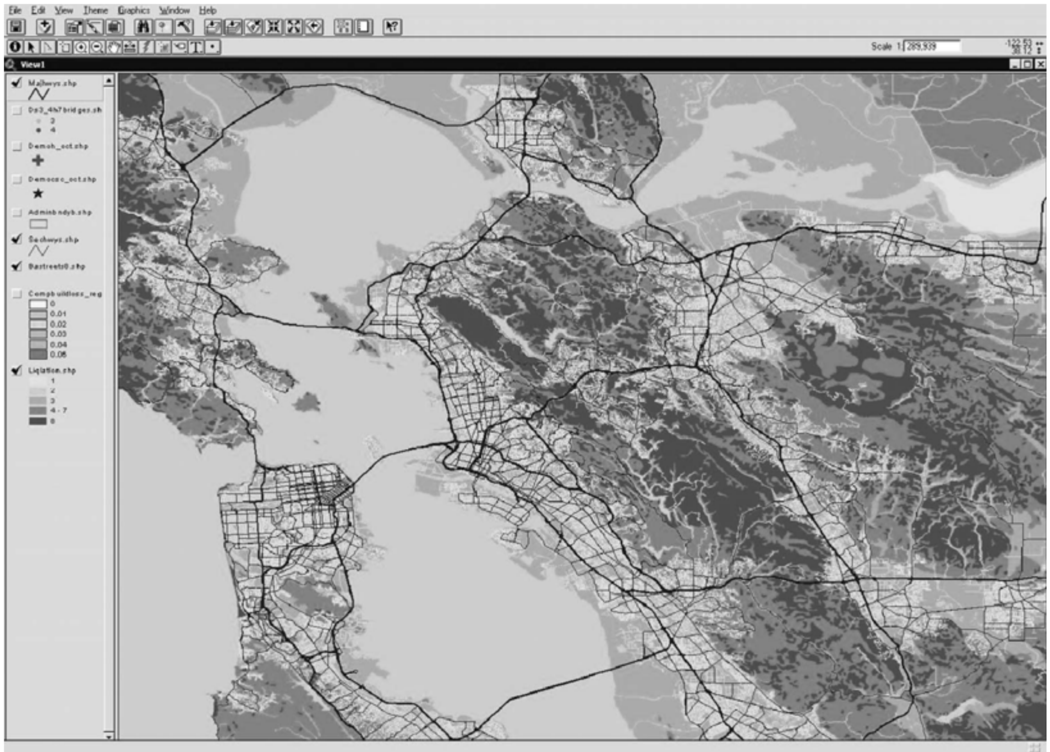

FIGURE 3 Liquefaction potential and the transportation network system.

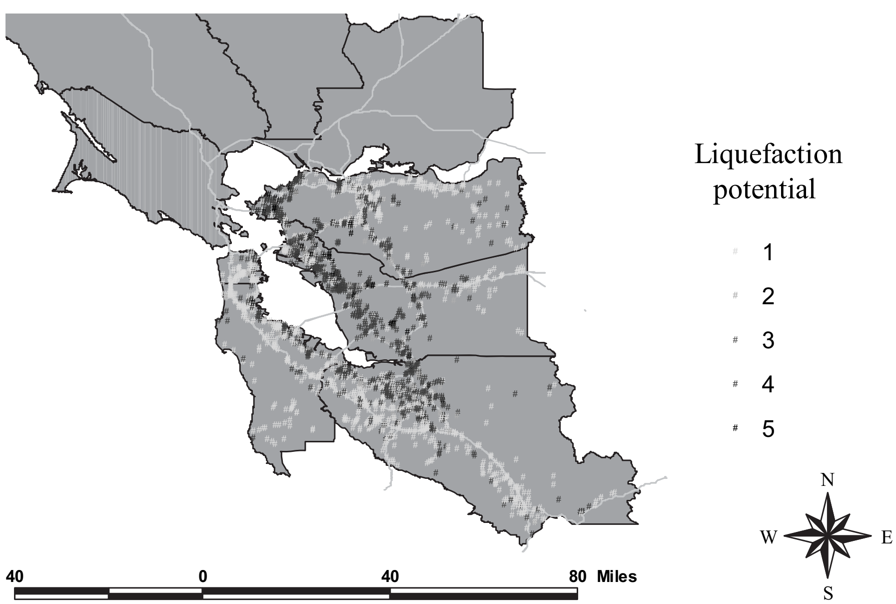

FIGURE 4 Distribution of pre-retrofitted bridge damage due to liquefaction in the San Francisco Bay Area from a $M_w = 7.0$ on the Hayward fault.

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 is most likely a function of the ground deformation assessment methodology. 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 would be necessary to obtain more reliable results, but is beyond the scope of this study.

Analysis for landslides also follows the HAZUS [1999] formulation. The landslide susceptibility map was obtained from the US Geological Survey [USGS, 1997] which identifies 11 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. The mean damage to bridges is evaluated based on the predicted ground displacements similar to the liquefaction approach.

Figure 5 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 of these regions fall outside of the study area.

The direct loss is estimates from repair costs due to damage to bridges. The time delays in traffic for all O-D combinations resulting from closure of damaged bridges are presented in the following section. Repair costs depend on the size of the bridge and the expected damage state of the bridge. The expected damage state for each bridge is evaluated as described earlier in this section. These are the damage states shown in Figs. 2, 4 and 5. The repair cost for a given bridge subjected to event Q_i is given by:

$$l(D \mid Q_i) = Repair\ Cost = Repair\ Cost\ Ratio * Area * Cost \tag{6}$$

where the *Repair Cost Ratio (RCR)* is a function of the damage state of the bridge, which in turn is a dependent on the ground motion at the bridge site. The dependence on A, S_H and S_V that appears for the loss function $l(D \mid Q_i)$ in Eq. (3) is dropped for simplicity. Best estimates of *RCR* values are provided by Basoz and Mander [1999].

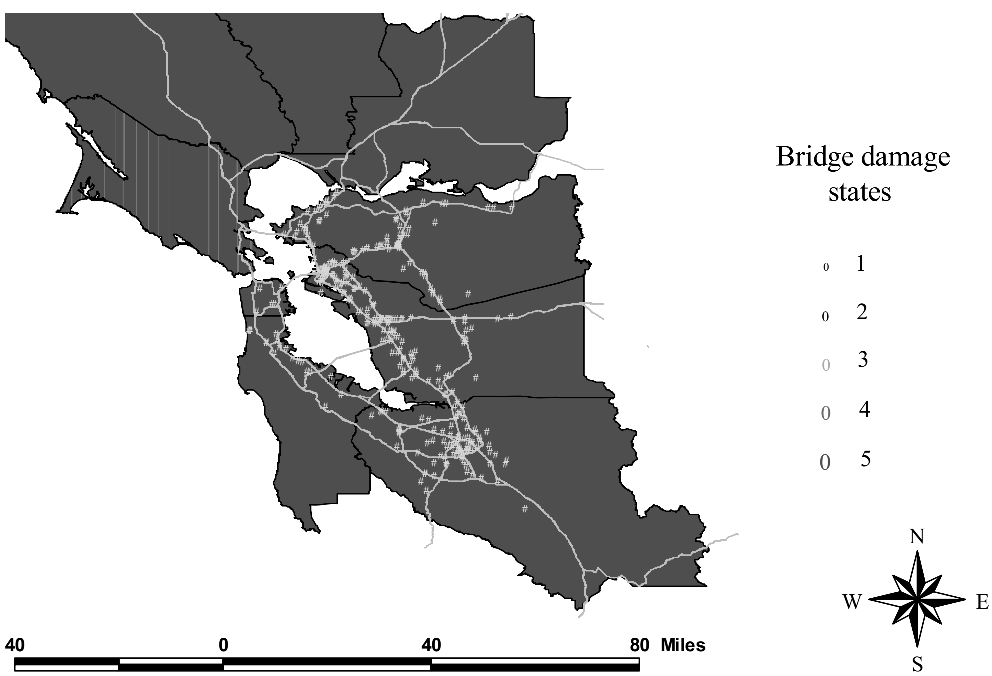

FIGURE 5 Distribution of pre-retrofitted bridge damage due to landslides in the San Francisco Bay Area from a M_w = 7.0 on the Hayward fault.

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)

	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

The area of the bride deck is computed using the following simple formula:

$$Area = bridge\,length * bridge\,(deck)\,width \tag{7}$$

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, January 2000). The repair costs vary from $117.5 per square foot to $165 per square foot of bridge deck depending on the bridge type. These costs, although based on bridge deck area, also account for foundation, column, abutment and approach construction.

Table 1 provides losses corresponding to the repair cost estimates for all the bridges in the study area for the Hayward M_w = 7.0 scenario earthquake. 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 observation is in agreement with the high damage distribution found 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. This result also is in agreement with the geologic setting of the region where relatively few bridges are located at sites susceptible to landslides.

4. 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. For all links information is provided on the number of lanes, speed limits, direction of traffic, off ramps, and on ramps. The MTC data also contains information on the Origin-Destination (O-D) pairs for trips in the San Francisco Bay Area that are needed for travel time evaluation.

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. This process proved to be very difficult and laborious. Dynamic segmentation methods were used to partially automate the bridge assignments to the transportation network. A 90% match was achieved in the bridge and network databases using this approach. The remaining 10% were corrected by hand.

Network analysis of the Bay Area transportation system was performed using the commercial software EMME/2 in order to evaluate travel times for all O-D pairs in the region.

The analysis is conducted to determine pre-earthquake scenario travel times termed *baseline analysis* hereafter. The transportation system is then modified based on information on damaged bridges in the network. Network analysis results in this article are presented for damage due to ground shaking only. Bridges in damage states 3 or greater are considered to be closed for at least the first 72 hours immediately after the earthquake. This assumption is based on extensive discussion with traffic management officials and structural design engineers at CalTrans. Closed links corresponding to bridge closures within the system were identified as shown in Fig. 6. Two different scenarios are considered for post event traffic analysis because traffic demand following an event is likely to change. First, the demand following the event is assumed to be the same as that before the earthquake, termed fixed demand analysis. Second, the analysis is performed by assuming that the demand following the earthquake decreases as was observed following both the Loma Prieta 1989 and Northridge 1995, California earthquakes [e.g., Yee and Leung, 1996a,b]. This assumption is dependent on the behavior of commuters in the region. In contrast to the California experience, traffic demand increased significantly following the Kobe 1995, Japan earthquake. Thus, the results obtained in this study pertain primarily to traffic patterns observed in California. A more detailed description of the variable demand model is given in Fan [2003].

The post-earthquake network analysis is performed for the modified network again using the program EMME/2. Tables 2 and 3 summarize the vehicle hours by type of highway link. The *baseline* estimates correspond to the pre-event conditions and demands. Table 2 presents the vehicle travel times and traffic delays with fixed travel demand. Table 3 summarizes the results for vehicle travel times and traffic delays with variable travel demand.

Comparing Tables 2 and 3, it is interesting to observe that the travel time for some links actually decreases. This decrease is due to the closure of bridges connected to these links and not because traffic has been reduced. For example, Freeway to Freeway (Frwy to Frwy) Ramps appear to have greatly reduced travel times for both fixed and variable travel demand cases. With

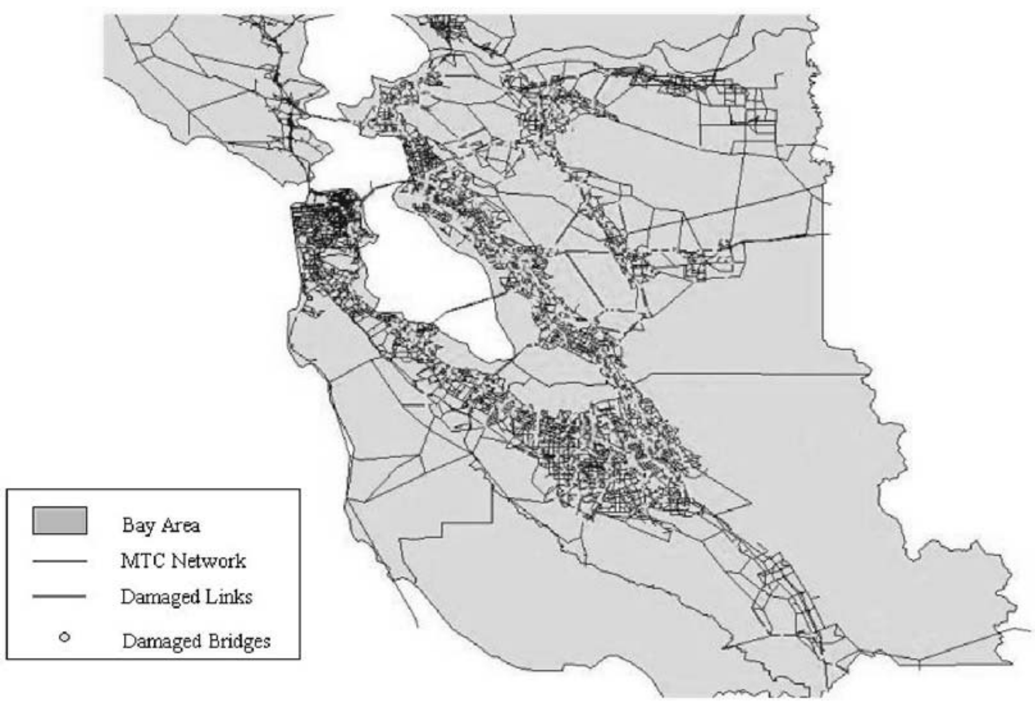

FIGURE 6 Closed highway links for pre-retrofit bridge damage in the San Francisco Bay Area for a scenario earthquake of moment magnitude 7.0 on the Hayward Fault.

TABLE 2 Summary of vehicle hours by link type assuming fixed travel demand

TYPE	Baseline Analysis Travel Times (hrs.)	Post Hayward $M_w = 7.0$ Scenario Event Travel Times (hrs)	Traffic Delays per Link Type (hrs.)
Frwy to Frwy Ramps	260,967	2,285	(258,682)
Freeways	14,868,927	8,336,098	(6,532,829)
Expressways	1,775,829	1,376,278,658	1,374,502,829
Collectors	3,761,980	17,564,050,576	17,560,288,596
On/Off Ramps	1,146,239	88,435	(1,057,804)
Centroid Connectors	858,764	6,744	(852,020)
Major Roads	9,776,532	84,913,386,218	84,903,609,686
Metered Ramps	74,494	52	(74,442)
Golden Gate Bridge	47,866	0	(47,866)
Total	**32,571,596**	**103,862,149,065**	**103,829,577,469**

TABLE 3 Vehicle hours by link type assuming variable travel demand

TYPE	Baseline Analysis	Post Hayward $M_w = 7.0$ Scenario Event	Traffic Delays per Link Type
Frwy to Frwy Ramps	5,775	3,222	(2,553)
Freeways	161,826	62,072	(99,754)
Expressways	30,026	18,092	(11,934)
Collectors	41,677	42,483	806
On/Off Ramps	15,256	11,069	(4,187)
Centroid Connectors	105	35	(70)
Major Roads	133,471	123,335	(10,136)
Metered Ramps	2,126	1,841	(285)
Golden Gate Bridge	524	515	(9)
Total	**390,788**	**262,663**	**(128,125)**

the assumption of fixed travel demand, the total vehicle hours increase by 103,829,577,469 h. For the variable travel demand, the vehicle hours actually decrease by 128,125 h, which is realistic considering the assumption of decreased demand following the earthquake.

5. Conclusions

A method is presented for evaluating the annual expected loss from damage to bridges and resulting travel time delays 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 damaged bridges due to a scenario event. The repair cost is used as a measure of the direct loss from the earthquake. For this purpose, the repair costs are evaluated for a moment magnitude 7.0 scenario earthquake on the Hayward fault in the San Francisco Bay area. From the example analyses, it is observed that damage to bridges and consequent loss is the greatest due to liquefaction. In comparison, landslides appear to have a very small contribution to both damage and repair cost estimates. In general, the contributions of various hazards to repair costs are region dependent. However, liquefaction is likely to govern the damage even though a more robust model for liquefaction displacement assessment and associated fragility functions are needed in order to obtain reliable damage and loss results.

The transportation network was evaluated for changes in vehicle travel times under two assumptions—constant post-event travel demand and variable post-event travel demand. The total vehicle hours increase in post-earthquake networks relative to the baseline network when post-event demand is assumed to be fixed at the pre-event level. In the variable-demand case a lower traffic demand is assumed based on observations in traffic patters following past earthquakes in California. With this assumption, the total vehicle travel hours decrease because the variable demand model assigns fewer trips to the network. For other regions in the world, the traffic demand may increase following an earthquake and the model will need to be adjusted accordingly to account for post-event traffic behavior.

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