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A PEER Highway Demonstration Project

Earthquake Risk Assessment for Transportation Systems: Analysis of Pre-Retrofitted System

by

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Transportation systems are spatially distributed systems whereby components of the system are exposed to different ground motions due to the same earthquake event. Consideration of the spatial dependence of individual components, connectivity, and flow through the network are key factors in the development of an earthquake risk assessment model for such systems.

Most recently, Werner et al. (1999) and Basoz and Kiremidjian (1996) considered 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 the major components such as the bridges, the connectivity between a predefined origin-destination (O-D) set, and the time delays from bridge closures. The 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 the components of the system are not included. In a paper by Chang et al. (2000) a simple risk measure for transportation systems is proposed to represent the effectiveness of retrofit strategies by considering the difference in damaged highway links before and after retrofitting. The proposed risk measure can be a useful tool but should be expanded to consider actual travel times because damaged links do not necessarily reflect the actual costs associated with travel delays, which is a function of the network redundancy.

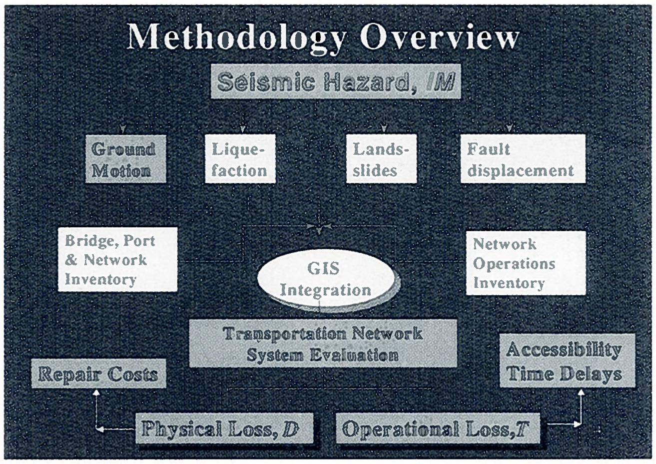

Figure 1. Risk assessment methodology for highway network systems

In the current study a framework for risk assessment of a transportation system is postulated that considers the direct cost of damage and costs due to time delays in the damaged system. The study was conducted by PEER faculty participants Anne S. Kiremidjian and James Moore, and graduate student researchers Yueyue Fan, Ayse Hortacsu, Kelly Burnell, and Jeremiah LeGrue. The model is first formulated for a scenario event and then expanded for a suitable ensemble of earthquake events to capture the total hazard and risk to the system.

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Model Formulation

For the purposes of this project, 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 M_i, the expected loss from the system can be estimated as

$$E[Loss \mid M_i] = \sum_{All\ components} \int \int l(D \mid IM,M_i) f_D(d \mid IM,M_i) f_{IM}(im \mid M_i) dim\, dd + \int l(T \mid D,M_i) f_D(d \mid M_i) dd \quad (1)$$

where

$l(D \mid IM,M_i)$ = cost of repair of individual components of the system at damage D due to intensity IM from an event M_i, where $0 \leq D \leq 1.0$,

$f_D(d \mid IM,M_i)$ = probability density of damage D given intensity IM from an event M_i,

$f_{IM}(im \mid M_i)$ = probability density of hazard intensity IM for event M_i,

$l(T \mid D,M_i)$ = costs associated with time delays T due to detours of route closures or reduced traffic capacity per event M_i.

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

$$E[Loss] = \sum_{all\ events} E[Loss \mid M_i] \nu_i \quad (2)$$

Equations 1 and 2 are consistent with the general equation used by PEER (Cornell and Krawinkler 2000) to characterize the performance of a structure or, as in this case, a system. If we define the total cost to be the decision variable DV in the PEER equation, Equation 2 reflects the expected value of that decision variable. Similar relationships have been developed for estimating the standard deviation of the costs. Evaluation of the decision probability distribution $\lambda(DV)$ will require very high computational capabilities, such as those by supercomputer, to perform the large number of simulations needed for this process.

Figure 1 shows the major components of the overall methodology. Four types of hazards from earthquakes are identified in that figure — ground motion, liquefaction, landslides, and fault displacements. The hazard intensity measure IM for such a system consists of the hazard from ground shaking denoted as $IM(A)$ and hazard due to ground deformations $IM(G)$, such as amount of lateral spreading or settlement from liquefaction, ground displacements due to landslides, or surface ruptures from direct fault displacements or local ground fissuring. The main distinction between the hazard evaluation of a network system and a building is that the hazard has to be evaluated at the multitude of the system component locations. This process is greatly facilitated with the use of geographic information systems (GIS) that enables the storing of such information in a spatial manner that permits overlay of network system data onto the hazard information, creating a link between the hazard and the network component within the same platform.

The damage to individual components of the network is expressed in terms of fragility functions, here denoted simplistically as $f_D(d \mid IM,M_i)$. In general, a distinct fragility function is required for each component in the network. Furthermore, separate fragility functions are needed to estimate the damage from ground shaking and from ground deformation. Given the large number and diversity in designs of bridges, pavement segments, and tunnels that exist in a highway network, it has become customary to group these components into generic classes that capture the gross characteristics of the various components. As computational power increases and our ability to efficiently and effectively evaluate damage on a structure-by-structure basis improve, such classification and generic fragility functions will not be necessary. Currently, various researchers within PEER are developing fragility functions for different bridge classes. For the purposes of applying the methodology presented in this article, the fragility functions developed for implementation in the 1999 HAZUS software will be utilized (Basoz and Mander 1999).

The direct loss functions $l(D \mid IM, M_i)$ in equations 1 and 2 include losses due to damage from ground shaking and ground deformations, and represent the cost of repair of damaged components. For a given event M_i, losses due to time delays $l(T \mid D, M_i)$ arise from delays in commuter and freight traffic. The time delays result from closure of particular routes because of excessive damage to key components such as bridges, or due to reduced flow capacity (either from imposed lower speed limit or closure of a number of available traffic lanes) due to minor or moderate damage. The increase in travel times is the difference in the travel times for specified origins and destinations (O-D) for commuter and freight traffic under normal operating conditions and travel times after an earthquake with reduced capacity or closure of certain links and nodes in the system.

Application Area Description

One of the main objectives of this project is to apply the methodology to an existing highway transportation system. During the first PEER Transportation Risk Analysis

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Workshop, held in 1998, the workshop participants recommended that the application area be the San Francisco Bay region. The rationale for the selection was that the region has a very complex transportation network with limited redundancy. In particular, it is very likely that the major bridges in the region will be subjected to ground motions of similar severity due to their proximity to major faults in the area. All the long-span bridges, the San Francisco-Oakland Bay Bridge, the Golden Gate, San Mateo, Dumbarton, and San Rafael, are flanked by the San Andreas fault to the west and the Hayward fault or its extension to the east.

In addition to the San Andreas and Hayward faults, the Calaveras and the San Gregorio-Palo Colorado faults are also capable of significant earthquakes that can cause damage to the system. For the purposes of the demonstration project, however, only events on the San Andreas and the Hayward faults were considered. These include moment magnitude events of 7.5 and 8.0 on the San Andreas fault and 7.0 and 7.5 on the Hayward fault. The rupture length was estimated using the Wells and Coppersmith (1994) relationship for strike-slip faults, and the rupture location is assumed to be such that it flanks the entire network system. Ground motions for the region were estimated using Boore et al. (1997) attenuation function for peak ground and spectral accelerations. The ground motions reflect the local soil conditions classified as B, C, D, and E (Boore et al. 1997). Ground motions within 15 km of the fault were estimated using the Campbell (1997) attenuation function. Currently, the team is evaluating the liquefaction potential and ground deformations for the scenario events. Figure 2 shows the distribution of ground motion for the magnitude 7.5 event on the San Andreas fault. The commercial software *ARC/INFO™* was used for the purposes of storing and displaying the ground motion information.

Data on bridge locations and engineering characteristics were obtained from the California Department of Transportation (Caltrans). The data were verified and corrected by Basoz [Basoz and Kiremidjian (1997)]. A total of 2,640 bridges were included in the study. These were classified according to the NIBS (1999) scheme, which utilizes the National Bridge Inventory (NBI) physical attributes. The site ground motions for each bridge were determined by overlaying the bridge location onto the ground motion map. The expected damage state for each bridge was estimated using the NIBS fragility functions. Five damage states are defined in Basoz and Mander (1999) for highway system components. These are none, slight/minor, moderate, extensive and complete. Table 1 lists the number of pre-retrofit bridges in each damage state for the four scenario earthquake events. For the analysis of the transportation network it was assumed that if a bridge is in damage state 3 or greater, the bridge is closed to all traffic, and if the bridge is in damage state 1 or 2, it is open at full capacity. Partial closures or reduction of speed limits was not considered for this initial evaluation. These will be investigated in subsequent analyses. Figure 2 shows the distribution of pre-retrofit bridge damage with the distribution of ground motion.

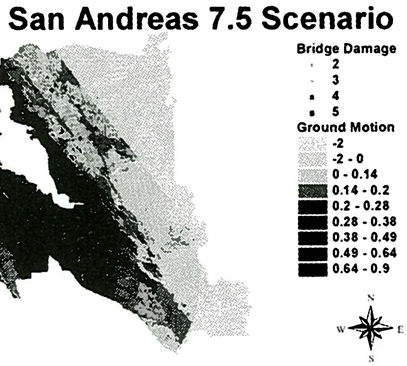

Figure 2. Distribution of pre-retrofit damaged bridges in the San Francisco Bay Area for a scenario earthquake of moment magnitude 7.5 on the San Andreas fault

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). A significant effort was devoted to importing the highway network information within the *ARC/INFO™* GIS. The bridge data were then linked to the highway network and corrected to match bridge locations with network locations. Baseline analysis was conducted on the transportation network pre-earthquake scenario. The post-earthquake scenario for a magnitude 7.5 event on the San Andreas fault was modeled in EMME/2, a transportation systems network analysis software. Based on this initial analysis closed links within the system

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Table 1. Distribution of pre-retrofit bridge damage for different scenario earthquakes

Damage State	Hayward 7.0 # of bridges	Hayward 7.5 # of bridges	San Andreas7.5 # of bridges	San Andreas 8.0 # of bridges
1	1732	1350	1589	1334
2	585	778	658	634
3 closed	221	280	249	413
4 closed	91	182	110	201
5 closed	21	50	35	59

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were identified, shown in Figure 3. Table 2a summarizes the number of links, the link and lane lengths, and the number of vehicles affected by the closures. These results should be considered as preliminary because most of the work is still in progress. Table 2b presents the results for the number of vehicle miles, average speed, average commuter traffic volume, and the maximum volume effects of the earthquake. The baseline calculations correspond to the pre-event conditions and demands. The post-event analysis results are listed under the SA (San Andreas) 7.5 column.

At present, a preliminary estimate on the cost of replacing and repairing the bridges in the Bay Area in the event of an earthquake has been obtained. For that purpose an estimate of the total square foot area of each damaged bridge has been computed using basic information available in the bridge database and using California repair costs per square foot. Table 3 lists the total repair or replacement cost for each scenario event. These numbers are very preliminary and should be used only for illustrative purposes rather than as absolute terms. They are based on generic regional replacement costs and do not reflect bridge specific repair and replacement costs.

The research team is currently obtaining more realistic cost estimates as provided by Caltrans engineers. Furthermore, the retrofitted strength of bridges has not been taken into consideration. The bridge database is currently being augmented to reflect the bridges that have been retrofitted over the past ten years. The effect of this information will be that bridge damage will be reduced, and as a result repair costs will decrease. In addition, the network performance will change, reducing the difference in pre- and post-event numbers listed in Tables 2a and 2b.

San Andreas 7.5 Scenario

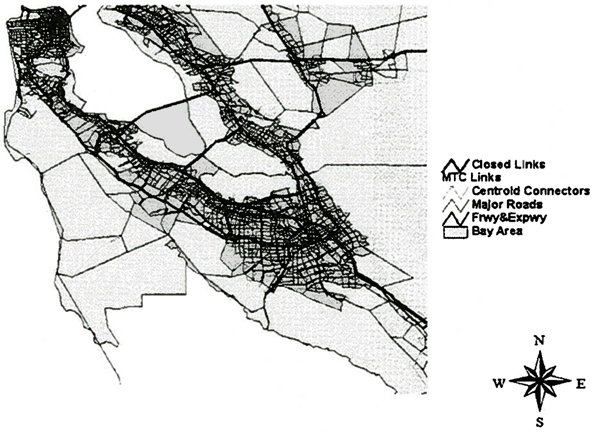

Figure 3. Closed highway links for pre-retrofit bridge damage in the San Francisco Bay Area for a scenario earthquake of moment magnitude 7.5 on the San Andreas fault

Costs due to traffic delays are still under investigation.

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Table 2a. Effect of pre-retrofit bridge closure on the highway transportation system in District 4, California

Link Type	No. of Links		Link Length(mi)		Lane Length		Vehicle Hours	
	Base	SA 7.5	Base	SA 7.5	Base	SA 7.5	Base	SA 7.5
1	178	92	87.09	42.44	140.95	64.84	2,420	1,490
2	2013	1495	1327.39	1025.35	3592.97	2771.98	116,589	119,347
3	829	709	432.15	391.64	862.36	785.79	11,951	19,820
4	6931	6857	4426.28	4385.49	5304.06	5250.76	17,156	59,094
5	1852	1489	528.13	415.67	567	442.64	8,632	11,353
6	4892	4892	1921.57	1921.57	5764.65	5764.65	5,385	5,385
7	9741	9595	4680.06	4613.54	8113.71	7983.87	59,894	147,671
8	78	47	29.89	18.24	31.09	19.44	485	419
9	8	8	3.99	3.99	11.97	11.97	3,389	9,195
Total	26522	25184	13436.5	12817.9	24388.8	23095.9	225,901	373,774

Notes: Link Type 1 = freeway to freeway ramp, Link Type 2 = freeway, Link Type 3 = expressway, Link Type 4 = collector, Link Type 5 = on or off ramp, Link Type 6 = centroid connector (a virtual link connecting travel demand to physical links in the vicinity of a traffic analysis zone), Link Type 7 = major road, Link Type 8 = metered ramp, and Link Type 9 = Golden Gate Bridge

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Table 2b. Effect of pre-retrofit bridge closure on the highway transportation system in District 4, California

Link Type	Vehicle Miles		Average Speed		Average Volumes		Max Volumes	
	Base	SA 7.5	Base	SA 7.5	Base	SA 7.5	Base	SA 7.5
1	103,774	56,683	43	38	1192	1336	7719	9923
2	4,740,782	3,043,641	41	26	3572	2968	11266	14542
3	538,111	722,303	45	36	1245	1844	4555	7192
4	458,204	1,032,831	27	17	104	236	3438	4173
5	234,930	201,356	27	18	445	484	4362	6199
6	537,591	537,163	100	100	280	280	6897	9463
7	1,779,913	3,229,454	30	22	380	700	4344	6577
8	11,718	6,758	24	16	392	370	1869	1806
9	44,576	56,282	13	6	11172	14106	11174	14433
Total	8,449,598	8,886,470	37	24	629	693	11266	14542

Table 3. Preliminary scenario pre-retrofit bridge repair/replacement cost totals

Scenario	*Number of Damaged Bridges*	*Total Repair/Replacement Cost*
Hayward 7.0	974	$168,234,741
Hayward 7.5	1321	$273,477,856
San Andreas 7.5	1045	$201,759,360
San Andreas 8.0	1277	$299,843,314

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Network for Earthquake Engineering Simulation: Sites at Berkeley, UCLA, Davis, and Oregon

The National Science Foundation (NSF) George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) is a project funded under the NSF Major Research Equipment Program. Congress has authorized NEES for a five-year construction period, from fall 1999 through fall 2004, for a total of $81.9M. The goal of NEES is to provide a national, networked collaboratory of geographically distributed, shared-use, next-generation experimental research equipment sites, with teleobservation and teleoperation capabilities, that will transform the environment for earthquake engineering research and education through collaborative and integrated experimentation, computation, theory, databases, and model-based simulation to improve the seismic design and performance of U.S. civil and mechanical infrastructure systems.

NSF recently announced funding of ten NEES equipment sites, four of which are at participating universities of the Pacific Earthquake Engineering Research Center. The four sites include a reaction wall facility at UC Berkeley, a mobile field laboratory at UCLA, a centrifuge at UC Davis, and a tsunami wave tank at the University of Oregon. For more information about the NEES program, see **http://www.nsf.gov.**

UC Berkeley Reconfigurable Reaction Wall-based Earthquake Simulator Facility

At UC Berkeley, the Reconfigurable Reaction Wall earthquake simulator facility will support the development of a new generation of hybrid testing methods. Such testing methods smoothly integrate physical and numerical simulations conducted at different locations using the Internet. The facility leverages the capabilities of existing testing facilities located at the University of California, Berkeley, Richmond Field Station. It builds on an existing 60x20-ft strong floor and an existing 4-million-lb axial compression-tension machine by adding a reconfigurable 42-ft-high strong wall, a set of dynamic and static actuators, a new multichannel digital control system, and equipment and Internet connections to enable teleparticipation. Faculty investigators at Berkeley are Jack Moehle, Stephen Mahin, Božidar Stojadinović, and Khalid Mosalam (Civil and Environmental Engineering); and John Canny (Computer Sciences). For more information see **http://www.eerc.berkeley.edu/~nees.**

Field Testing and Monitoring of Structural Performance at UCLA

UCLA will develop mobile equipment for field testing of structural and geotechnical systems. This equipment will fill a critical need for measuring the linear and nonlinear dynamic response of full-scale structures with a high degree of spatial and temporal resolution. The equipment will consist of state-of-the-art vibration sources, a wireless data acquisition system, a CPT truck and in-situ soil vibration sensors, and networking equipment to allow for *real-time* data acquisition, processing, and World Wide Web broadcasting of experimental results. Most experiments with the equipment will consist of forced-vibration testing and earthquake aftershock monitoring of full-scale structures. Large arrays of sensors will be placed in structures and the surrounding foundation soils. The data obtained will be at levels of detail that have not been previously possible and will lead to a better understanding of linear and nonlinear response mechanisms. Faculty investigators at UCLA are John Wallace, Jonathan Stewart, Joel Conte, Patrick Fox (Civil and Environmental Engineering); and Deborah Estrin (Computer Science).

UC Davis Geotechnical Centrifuge Facility

At UC Davis, the advanced centrifuge facilities will provide the NEES with capabilities necessary for producing comprehensive and accurate data for the development and rigorous testing of model-based simulation methods in geotechnical engineering. The project is working to implement advanced instrumentation, digital video, robotics, and geophysical testing to greatly increase the quality and quantity of data that can be collected from experiments. A specific aim is to improve the capacity of the existing centrifuge facility, in part by adding a biaxial shaking table capability in the centrifuge. These improvements will allow extraction of more detailed and more accurate information from experiments and simulations. Faculty investigators at UC Davis are Bruce Kutte, Ross Boulanger, and Boris Jeremic (Civil Engineering); Stephen Velinsky (Mechanical Engineering); Bernd Hamman and Kwan Liu Ma (Computer Sciences); and Ben Yoo (Electrical and Computer Engineering).

Oregon State University Multidirectional Wave Basin Facility for Remote Tsunami Research

Oregon State University will extend and enhance an existing multidirectional wave basin at the O. H. Hinsdale Wave Research Laboratory to create a Tsunami Basin that will be the only facility of its kind in the world, from three perspectives. First, it will be the largest and most advanced tsunami testing facility of its kind, fulfilling the NEES goal to provide next-generation experimental research equipment. Second, a comprehensive Information Architecture supporting remote users will be developed by experienced usability engineers to ensure a positive impact on researcher effectiveness and productivity. Third, a Tsunami Experiment Databank will be established so that the broader research community can study the results of tsunami experiments, reducing the need for experimentation and providing data for validating numerical models. The basin dimensions (approximately 27m x 50m x 2m) and wave-generation capabilities (2m maximum stroke and 2m/s maximum velocity) closely match the tsunami community's vision of an "ideal basin." Faculty investigators at Oregon are Solomon Yim, Cherri Pancke, and Charles Sollitt.

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