Research Progress and Accomplishments

1999 - 2000

A Selection of Papers Chronicling Technical Achievements of the Multidisciplinary Center for Earthquake Engineering Research

▲ *The Multidisciplinary Center for Earthquake Engineering Research*

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation (NSF) in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission is to reduce earthquake losses through research and the application of advanced technologies that improve engineering, pre-earthquake planning and post-earthquake recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

Funded principally by NSF, the State of New York and the Federal Highway Administration (FHWA), the Center derives additional support from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

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Multidisciplinary Center for Earthquake Engineering Research
University at Buffalo, State University of New York

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Foreword

by George C. Lee, Director,
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The research accomplishments of the Multidisciplinary Center for Earthquake Engineering Research are as numerous as they are varied. Since the Center was established by the National Science Foundation (NSF) in 1986, its vision has been to help establish earthquake resilient communities throughout the United States and abroad. Over the past 14 years, our research and education programs have annually supported more than 80 investigators throughout the country and the world, to work toward this goal. Much has been accomplished, most notably in the areas of lifelines and protective systems, but our vision has not yet been fully realized.

Toward this end, we believe that the best way to achieve earthquake resilient communities in the short-term is to invest in two highly focused system-integrated endeavors:

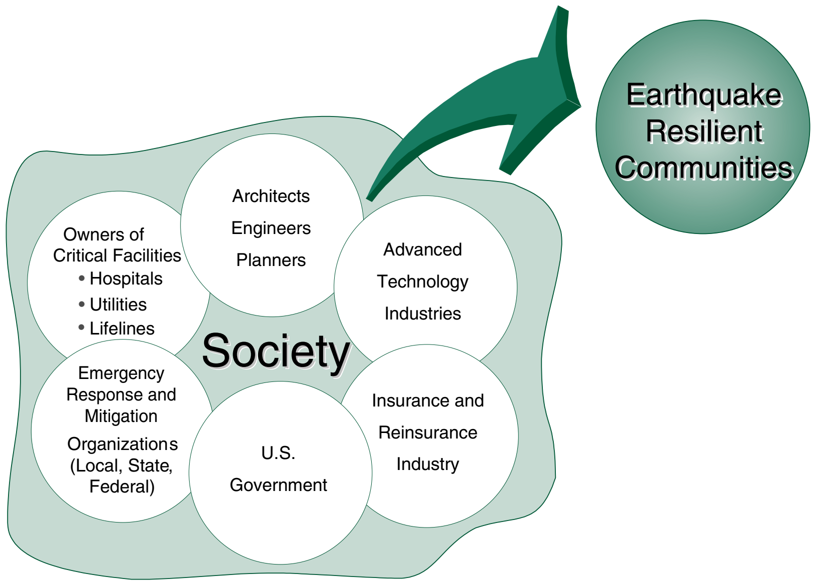
- the rehabilitation of critical infrastructure facilities such as hospitals and lifelines that society will need and expect to be operational following an earthquake; and
- the improvement of emergency response and crisis management capabilities to ensure efficient response and prompt recovery following earthquakes.

Our research is conducted under the sponsorship of two major federal agencies, the National Science Foundation (NSF) Earthquake Engineering Research Centers Program and the Federal Highway Administration (FHWA), and the state of New York. Significant support is also derived from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry. Together these resources are used to implement our research programs.

This *Research Progress and Accomplishments* report is intended to provide the reader with an understanding of our current research efforts. The papers highlight research tasks that are in progress or have recently concluded, and provide those in the earthquake engineering community with a glimpse of the foci and direction that our programs are taking. We anticipate that this information will contribute to the coordination and collaboration effort in earthquake engineering research nationally and globally. The presentation is in descriptive form with preliminary observations and recommendations, and an indication of future efforts is provided.

This past year was marked by two devastating earthquakes in Turkey and Taiwan. MCEER reconnaissance teams visited both these areas, and several of the papers in this report describe their efforts to learn from these tragic events. A few papers describe research that has been completed, most notably the Federal Highway Administration-sponsored project on the seismic vulnerability of new highway construction, while others describe work in progress. The authors identify the sponsors of the research, collaborative partners, related research tasks within MCEER's various programs, links to research and implementation efforts outside MCEER's program, and web site addresses for additional information.

Although MCEER's vision is to achieve earthquake resilient communities, it is the various professionals in earthquake hazard mitigation who will collectively join forces to create them. We can provide relevant tools to these professionals, who include practicing engineers, policy makers, regulators and code officials, facility and building owners, governmental entities, and other stakeholders who have responsibility for loss reduction decision making, and educate them on how to best use or apply these tools. Their decisions can encompass a range of actions, including the adoption of various new technologies, the retrofitting of structures using improved techniques and approaches, and response and recovery activities. This process, which moves from research through knowledge transfer, adoption, and implementation, is illustrated in the figure below. Each paper in this report highlights the end users of the presented research or educational effort.



This report is the second in our annual compilation of research progress and accomplishments. It is available in both printed and electronic form (on our web site in PDF format at *http://mceer.buffalo.edu/publications/default.asp*, under Special Publications).

If you would like more information on any of the studies presented herein, or on other MCEER research or educational activities, you are encouraged to contact us by telephone at (716) 645-3391, facsimile (716) 645-3399, or email at *mceer@acsu.buffalo.edu*.

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Modeling Earthquake Impact on Urban Lifeline Systems: Advances and Integration

by Stephanie E. Chang (Coordinating Author), Adam Rose, Masanobu Shinozuka, Walter D. Svekla and Kathleen J. Tierney

Research Objectives

This research aims to develop and demonstrate an advanced, integrated earthquake loss estimation methodology for urban lifeline systems. The methodology, which evaluates direct and indirect economic losses from lifeline failures, provides a means for assessing both expected losses from future earthquakes and potential loss reduction from mitigation alternatives. This effort builds on and coordinates multidisciplinary contributions from lifeline earthquake engineering, geography, sociology, and economics. An application is demonstrated for the Memphis Light, Gas and Water Division (MLGW) water delivery system.

In recent years, the massive losses caused by major urban earthquakes, combined with the increasing capabilities of computer technologies such as geographic information systems (GIS), have led researchers and practitioners to focus substantial energies on computerized methodologies for estimating expected losses from future earthquake disasters. At the same time, new empirical data on the physical and economic effects of recent earthquakes provide opportunities for re-evaluating, refining, and calibrating loss estimation models. For discussions of current methodologies and issues, see National Research Council (1999) and the 1997 *Earthquake Spectra* special issue on loss estimation (including articles on the FEMA/NIBS HAZUS methodology).

The MCEER loss estimation research effort focuses on economic losses associated with earthquake-induced failures of critical urban lifeline systems, particularly water and electric power systems. It uses a multidisciplinary, coordinated approach to address some of the most salient challenges in the state-of-the-art of earthquake loss estimation: capturing the systems response of engineering and economic systems; calibrating models to limited empirical data; improving our understanding of loss mechanisms, risk factors, and indirect economic loss; acknowledging loss estimate uncertainties; and,

Sponsors

National Science Foundation, Earthquake Engineering Research Centers Program

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Collaborative Partners

Memphis Light, Gas and Water Division (MLGW)

perhaps most fundamentally, integrating engineering and socioeconomic models in a balanced, insightful, and productive way.

This paper describes the methodological approach and initial results of an application to the MLGW water delivery system for Memphis and Shelby County, Tennessee. Other ongoing efforts pertain to the MLGW electric power system and the Los Angeles Department of Water and Power (LADWP) systems. Our ultimate objective is to demonstrate how the methodology can assist end users to assess and compare the potential benefits of different pre- and post-earthquake loss reduction strategies.

Memphis Light, Gas and Water Case Study

Memphis and Shelby County (pop. 900,000) are at risk from earthquakes originating in the New Madrid Seismic Zone (NMSZ) in the Central U.S. The NMSZ produced the largest earthquakes in the recorded history of the U.S. in the winter of 1811-12, including at least three events with magnitude 8.0 or greater. This paper presents initial findings for three scenario earthquakes (magnitudes 6.5, 7.0, and 7.5, respectively) with epicenter at Marked Tree, Arkansas, some 55 km northwest of downtown Memphis, in the southern arm of the NMSZ. Scenario events with epicentral location elsewhere on the NMSZ will be considered in further modeling.

Memphis Light, Gas and Water Division (MLGW) is the primary supplier of water for Shelby County, with the exception of a few unincorporated municipalities. The water source is an underground aquifer accessed by wells. The water delivery system consists of a large low-pressure system and several high-pressure systems located on the outskirts of Memphis city. The network includes about 1,370 km of buried pipes and a number of pumping stations, elevated tanks, and booster pumps.

Methodological Approach

Previous research under the National Center for Earthquake Engineering Research (NCEER) had developed a lifeline loss estimation methodology and demonstrated its application to the MLGW electric power and water systems (Shinozuka et al., eds., 1998; Chang et al., 1996; Rose et al., 1997). While that effort provides a foundation for the current work, numerous significant refinements have been made. Highlights of current advances include:

- **Model integration** - "Seamless" integration of engineering and

Many types of users may benefit from this work. To the research community concerned with earthquake loss modeling and reduction, it provides an advanced methodology for evaluating the economic impacts of lifeline damage in earthquakes. To lifeline agencies and national, state and local governments, this research provides a means for evaluating the economic benefits of potential lifeline loss reduction strategies.

direct economic loss models has been achieved;

- **Multiple earthquake scenarios** - Losses for different potential earthquakes are modeled, and a methodology is available to incorporate these into a probabilistic risk framework (Chang et al., forthcoming);
- **Spatial modeling** - Advanced GIS capabilities have been implemented to refine the spatial resolution of analysis and more effectively use digital spatial data;
- **Temporal modeling** - The time dimension of loss has been better captured through developing a lifeline restoration model that incorporates post-disaster response parameters;
- **Northridge data** - Empirical data on business losses in the Northridge earthquake have been used to refine direct and indirect loss models;
- **Indirect loss modeling** - Computable general equilibrium (CGE) approaches for estimating indirect losses and business resiliency effects have been developed;
- **Uncertainty** - Uncertainties deriving from both engineering and economic models are taken into account.

Figure 1 illustrates the framework for implementing the loss estimation methodology for the MLGW water delivery system. Individual earthquake scenarios are evaluated for events with different magnitudes and locations. For each scenario earthquake, an integrated model (shaded box) is used to estimate damage and loss. Its core consists of an engineering model previously developed by M. Shinozuka and associates to simulate the expected damage and water service outage from major earthquakes (Shinozuka et al., 1994). This model had been implemented in a simulation software program, *Lifeline-W(II)*, for the MLGW case. Here, the *Lifeline-W(II)* model is expanded to a new model (*LLW+E*) that incorporates a direct economic loss component.

The new model uses a Monte Carlo simulation approach to evaluate both physical damage and

Links to Current Research

Program 1: Seismic Evaluation and Retrofit of Lifeline Systems

- *Loss Estimation Methodologies*
- *Memphis Lifeline Systems Analysis*
- *Preliminary part of more comprehensive work for MCEER's demonstration project on Memphis Lifelines*

Program 2: Seismic Retrofit of Hospitals

- *Cost-Benefit Studies*

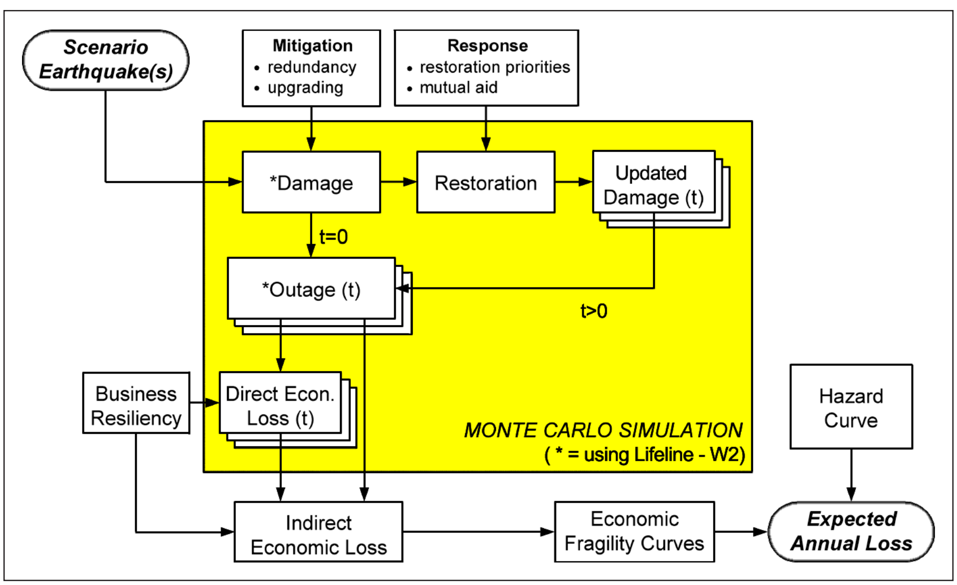


Figure 1. Implementation Framework

"The restoration model specifies a sequence of restoration based on engineering priorities and observations in the Kobe and Northridge disasters."

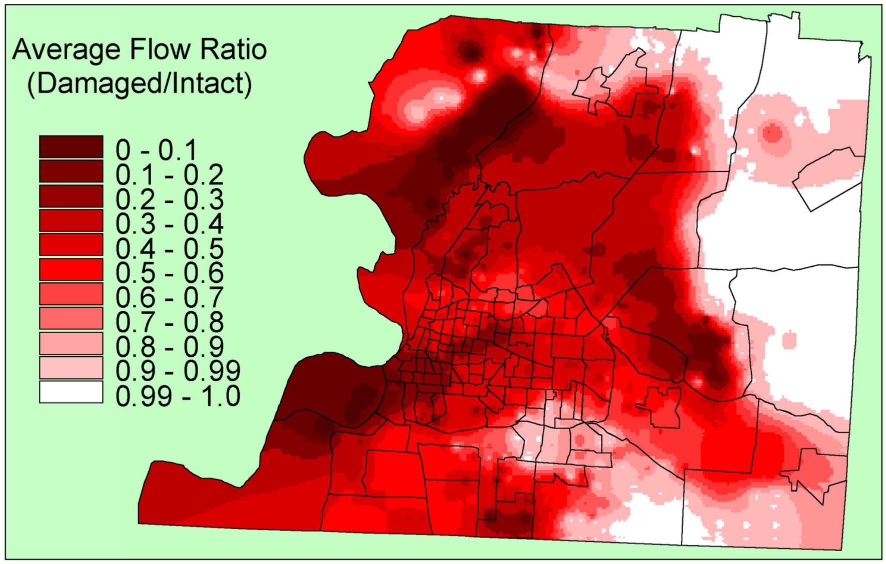
economic loss. The model simulates damage to water system components, water leakage, and initial water outage throughout the system. It then simulates how the situation is improved on a weekly basis as repairs are made. Direct economic loss from business interruption is evaluated probabilistically at weekly intervals and summed over time. This enables economic loss to be estimated probabilistically in a manner consistent with engineering damage estimation. Direct loss estimates, water outage results, and industry resiliency data are input into a CGE model to calibrate and assess indirect economic loss.

Results can be summarized in "economic fragility curves" that indicate the exceedance probability of different levels of economic loss associated with different levels of earthquake severity (e.g., increasing earthquake magnitude, given a fixed epicentral location). The economic fragility curves can then be combined with information on the occurrence probabilities of earthquakes of various severity levels. The ultimate result consists of an estimate of the expected annual loss — in terms of repair costs and economic output loss — from water disruption in future earthquakes. Some of these concepts and frameworks were developed by Shinozuka and Eguchi (1997).

Note that the model is also capable of evaluating the effects of various loss reduction strategies. These include both pre-disaster mitigation measures such as seismically upgrading vulnerable components or increasing network redundancy, as well as post-disaster mitigations such as implementing mutual aid repair crew agreements or restoring damaged facilities according to an optimal restoration pattern. The model can therefore evaluate losses "with" and "without" mitigations to estimate the loss reduction benefits of these actions.

Damage, Outage and Restoration

The MLGW water delivery system is represented in the *LLW+E* model by roughly 960 demand and supply nodes and 1,300 links. The model estimates damage probabilistically using a Monte Carlo simulation approach (Shinozuka et al., 1994). In particular, the damageability of system components such as pipes is represented in terms of fragility curves that indicate the probability of failure for a given level of ground motion input, local soil condition, and component characteristics (e.g., pipe material and diameter). Fragility curves for pumping stations were updated using results in Hwang et al. (1998). For each earthquake scenario, 100 simulation cases of systemwide damage were produced. Each simulation case represents a deterministic damage pattern that is a possible outcome of the earthquake; collectively, they represent the probabilistic damage outcome of the event. Only damage from ground shaking is considered here. Other possible damage sources such as soil liquefaction and electric power disruption are ignored. For each simulation case of scenario damage, the model evaluates the loss of water service by undertaking a complex system flow analysis. The analysis translates pipe damage into water leakage and solves for a new state of system equilibrium for the damaged state. The ratio of water flow in the damaged versus the intact state, evaluated at each of the demand nodes, provides the basic indicator of water outage that is used in the economic loss model.



■ Figure 2. Water Outage in Shelby County, M=7.0 Marked Tree Scenario (Week 0)

Figure 2 shows the initial (week 0) water outage results for the M=7.0 scenario, before any restoration has taken place. Results are averaged over the various simulated cases of the event. In the figure, node-level data on the ratio of water flow in the damaged versus intact conditions are spatially interpolated in GIS to yield an outage surface. Dark shadings indicate areas of greatest water loss. Outage is more severe in the western portion of the county.

Economic loss depends upon not only the water outage that occurs immediately after the earthquake, but how and over what time period water service is restored to the community. Restoration is modeled here using a resource constraint approach, which specifies the number of repairs that can be made in any time period according to the number of repair personnel available. Damage to large pipes requires more worker-days to repair than damage to smaller pipes. Model parameters are based on a survey of current lifeline restoration models and data from the Kobe earthquake (Chang et al., 1999). In addition, the restoration model specifies a sequence of restoration based on engineering priorities and observations in the Kobe and Northridge disasters. Specifically, any damage to large pipes is restored first, in order to bring the transmission "backbone" of the system online before repairing service pipes. The restoration of smaller pipes then occurs in spatial sequence, from census tracts with the lowest damage density (number of pipe breaks per square kilometer) to those with the highest. Initial damage patterns are updated on a weekly basis until repairs have been completed. At each weekly interval, system flow analysis is conducted on the updated network. (Note that alternative restoration patterns can be simulated with our model; for example, employment losses can be minimized by giving priority to those sub-areas that utilize the lowest amounts of water, directly and indirectly, per worker (see Rose et al., 1997)).

Analysis Zones

The extent of economic loss depends not only on water outage, but also on how outage corresponds with the location of economic activity. Loss estimation methodologies have typically used census tracts, of which there are 133 in Shelby County, as the unit of analysis. In contrast, the current analysis defines approximately 3,400 Analysis Zones using GIS overlay and intersection operations integrating two input datasets. The first data set is Service Zones, a contiguous set of 971 polygons for the county, each representing the inferred service area of one node on the water network. The Service Zone polygons were defined by performing a GIS Thiessen polygon operation on the point distribution of water delivery nodes, implementing an assumption that a particular business location will be served by the closest node on the water delivery network. The second dataset pertains to employment, distributed into 515 Traffic Analysis Zone (TAZ) polygons. This information was provided by the Shelby County Planning Department and is based on U.S. Census Bureau data. Defining Analysis Zones in this way reconciles point data on water outage with polygon data on employment. It therefore allows implementation of the loss model at the same spatial resolution as that of the input data and maximizes use of information on the spatial variability of factors contributing to loss.

Business Resiliency

The economic impact of the water loss to businesses is mitigated by their resiliency, or their ability to withstand temporary water disruption. A 50 percent loss of water does not, in other words, necessarily reduce economic output by 50 percent. Until recently, empirical calibration of resiliency has been severely limited by lack of appropriate data, and many loss estimation methodologies use expert opinion data for this purpose. In the previous lifeline loss model developed in Shinozuka et al., eds. (1997), resiliency factors were calibrated on the basis of survey data by K. Tierney and colleagues on Memphis area businesses' dependency on lifelines. Resiliency factors are defined as the remaining percentage output that could still be produced by a specific industry in the event of total water outage. These data are limited, however, because they are hypothetical — businesses had no previous earthquake dislocation experience on which to base their responses.

In the current study, new empirical data from K. Tierney and colleagues' business survey of the Northridge earthquake provide an important source for more accurately calibrating business resiliency (Tierney, 1997; Tierney and Dahlhamer, 1998). The principal difficulty in using data from an actual disaster in this way, however, is that business loss would have been influenced by many sources of disruption besides loss of water. Isolating the effects of water outage from those of building damage, electric power disruption, transportation problems, etc., is critical. A second difficulty consisted of limited sample size. Although the Northridge dataset contained responses from 1,110 businesses, less than one-fifth of them (207) had actually lost water service in Northridge. Moreover, only six businesses indicated that loss of water was the main reason for their business closing temporarily after the earthquake. These data limitations were addressed by dividing the analysis into two steps — first looking at how disruptive water outage was to businesses in different industries, and then evaluating how disruption from all sources impacted business activity.

■ Table 1. Survey-Based Economic Resiliency Factors for Water Outage (1 Week), Selected Industries

Industry	Business Survey	
	Memphis (Hypothetical Disaster)	Northridge (Actual Disaster)
Construction	0.30	0.64
Manufacturing	0.17	0.50
Retail Trade	0.23	0.41
Finance/Insurance/Real Estate	0.21	0.34
Health Services	0.18	0.24

Resiliency factors were developed for 16 industries comprising the private sector economy and for three water outage durations (less than 1 week, 1 week, and 2 or more weeks). Particularly relevant survey data included information on whether or not a business lost water, the duration of this outage, the disruptiveness of this outage, the disruptiveness of numerous other types of damage (e.g., building, transportation), whether or not the business closed for any length of time, and the most important reasons for this closure.

Table 1 compares resiliency factors developed from the Northridge data and the Memphis business survey, respectively, for selected industries. Note that resiliency factors range from 0 (no resiliency) to 1 (complete resiliency, or no dependency on water). The estimated factors differ substantially, with the Memphis hypothetical resiliencies consistently lower than the Northridge actual resiliencies. The most probable explanation is that without having experienced a major earthquake, Memphis businesses underestimated their own ability to cope with an emergency. The analysis reported in this paper used a mathematical average of the Memphis and Northridge resiliency factors in the economic loss model.

Direct Economic Loss

Direct economic loss — defined here as business interruption loss caused by water outage at the site of production — results from a combination of outage pattern, its spatial coincidence with economic activity, and business resiliency to water loss (for details, see Rose et al., 1997, and Chang et al., 1996). A key innovation made here in modeling direct economic loss consisted of probabilistically simulating loss in a Monte Carlo approach rather than estimating it deterministically. Specifically, resiliency factors were applied as a parameter indicating the probability that a business or group of businesses would close if it lost water service. In this simulation, each specified industry (e.g., manufacturing) in each Analysis Zone was modeled as either closed or operating normally in each time period. (Partial closures were also allowed for cases with partial water availability.) This probabilistic approach is important in that it enables consistent treatment of the engineering and economic portions of the overall model.

Indirect Economic Loss

Indirect economic loss is here defined as business interruption

“The analysis is one of the few CGE simulations on any subject that has distinguished direct and indirect effects in detail.”

deriving from interactions between businesses and industries through changes in input demands or output sales, including chain reactions. This study applies Computable General Equilibrium (CGE) methods to assess indirect loss. CGE analysis is the state-of-the-art in regional economic modeling, especially for impact and policy analysis. It represents multi-market simulation models based on the simultaneous optimizing behavior of individual consumers and firms, subject to economic account balances and resource constraints (see, e.g., Shoven and Whalley, 1992). The CGE formulation incorporates many of the best features of other popular model forms, but without many of their limitations.

The basic CGE model represents an excellent framework for analyzing natural hazard impacts and policy responses. CGE models can be finely disaggregated to distinguish the various degrees of vulnerability to hazards across sectors. The production functions are inclusive of all inputs, not just primary factors as in the case of many other economic models, which facilitates identification of materials shortages. At the same time, CGE models allow for the possibility of input substitution, which mimics real world responses beyond the very short-run in minimizing hazard impacts. They also allow for the substitution of imported goods for regionally produced goods. CGE models are non-linear in form, thereby more closely reflecting real world conditions, such as economies of scale and non-linear damage functions. CGE models are more capable of analyzing disjoint change than are model forms based on time series data and which therefore simply extrapolate the past. They can also more readily accommodate engineering data or data based on informed judgment.

Another set of CGE model advantages pertains to the important role of prices and markets. Related to this is explicit consideration of behavioral response, and not just simple optimization but also instances of bounded rationality. This applies not only to consumption but also to mitigation and recovery behavior.

Finally, CGE models are superior to some other alternatives in modeling the role of lifeline infrastructure services. A CGE model can place a valuation on these services, even for public sector outputs that are typically unpriced. This is more than an academic exercise, since “shadow values” might serve as temporary prices to ration these services through the market rather than by administrative decree.

The methodology involves recalibrating the parameters of the CGE model for earthquake simulations to yield direct business disruption losses consistent with empirical results of other MCEER researchers, as referenced above. The parameter adjustments are linked to specific real world examples of business resiliency (e.g., conservation, use of back-up supplies, increased substitutability). Different resiliency measures may result in the same direct output reduction level, but have different implications for indirect impacts. For example, conservation lowers the effective price of water, which stimulates production if the price of the final product is lowered accordingly; however, it leads to a decrease in direct and indirect inputs to providing water, which can have an economy-wide dampening effect. On the other hand, substitution of other inputs for water has a cost-increasing effect, but stimulates direct and indirect demands for other inputs.

The production side of the CGE model used in this paper is composed of a multi-layered, or multi-tiered, constant elasticity of substitution (CES) production function for each sector. We explicitly separate water out as a major aggregate in the top tier of the production function. A summary of adjustment types, linked to the production function layer and parameters to which each relates and the recovery/reconstruction stage (time period) to which each is applicable, is presented in Table 2. The resiliency adjustments listed in Table 2 are incorporated into our analysis by altering the parameters, and, in one case, the variables in the sectoral production functions of the CGE model.

Results of the questionnaire survey by K.Tierney and colleagues for the Northridge earthquake are adapted to specify the resiliency to water disruption in the Memphis economy. Information on what actions businesses took — if any — to remedy the loss of water provided the basis for calibrating parameters pertaining to adjustments listed in Table 2. For example, use of stored or boiled water, or "created supply" (presumably dug a well or captured rain or riverine water) are considered back-up supplies. Use of bottled or hauled water represents the substitution of other inputs for pipeline water. Overall, the proportion of total explained resiliency from the Memphis economy was apportioned to major adjustments in the following manner:

Conservation of water	=	41.9%
Increased substitutability	=	47.7%
Back-up supplies/costless	=	8.1%
Back-up supplies/cost-incurring	=	2.3%
Total of all adjustments	=	100%

■ Table 2. Adjustments to Reduction in Water Availability to Business and Link to Formal Economic Production Function Modeling

Adjustment Type	Parameter	Applicability
1. Conservation of Water	Water Technology	Immediate to Long Run (decreasing)
2. Conservation of Various Inputs	General Technology	Immediate to Long Run (constant)
3. Increased Substitutability of Other Inputs for Water	Water Substitution Elasticity	Very Short Run to Long Run (increasing)
4. Increased Substitutability of Other Inputs for Electricity to Pump Water	Water and Electricity Substitution Elasticities	Immediate to Long Run (increasing)
5. Back-up Supplies	Water Technology, Factor Shares	Immediate to Very Short Run (constant)
6. Water Importance[1]	Water Technology	Immediate to Long Run (constant)
7. Time-of-Day Use	N.A.	Off-hours
8. Change in Technology	Most to All Technology	Long Run (constant)

[1] *Refers to separable aspects of production that do not require water.*

■ Table 3. Loss Results from Monte Carlo Simulation, Marked Tree Earthquakes

Magnitude	6.5	7.0	7.5
Average PGA[1]	0.14 g	0.20 g	0.29 g
Average Number of Pipe Breaks	130	658	4,492
Weeks to Repair	1	2 - 3	12 - 13[2]
Direct Economic Loss[3] - Mean	$42 mil.	$136 mil.	$2,412 mil.
- Standard Deviation	$63 mil.	$99 mil.	n/a[4]

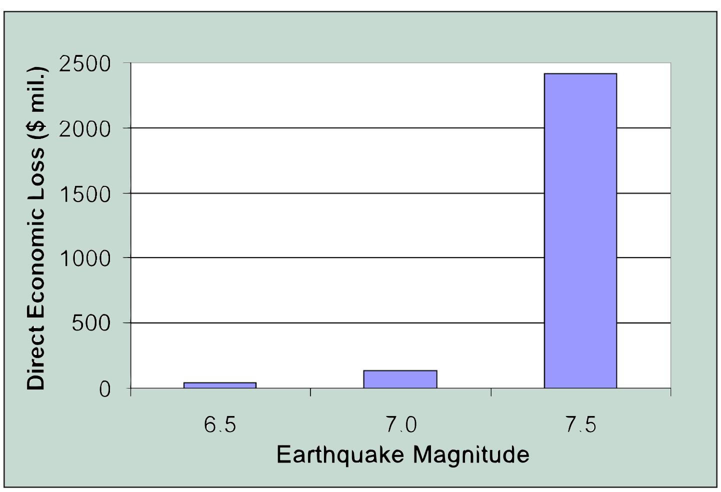
1 Averaged over all links on network
2 Complete water outage in weeks 1 - 4
3 In gross output terms
4 Not available

Overall, the estimation of indirect losses involves a multi-step procedure: (1) Extract the sectoral production functions from the CGE model and adjust parameters and variables in them one at a time to match Chang's direct loss estimates; (2) Reinsert the recalibrated sectoral production functions into the CGE model, reduce water supply to a level consistent with Shinozuka and Chang's estimates, and compute total regional losses; and (3) Subtract direct losses from total losses to determine indirect losses.

Findings

Initial results from applying the above methodology to the MLGW water system have been encouraging and insightful. Figure 3 summarizes direct economic loss results for the magnitude 6.5, 7.0, and 7.5 Marked Tree earthquakes, respectively. Loss values are averaged over 100 Monte Carlo simulations. Table 3 provides more detailed results for these three events.

Figure 3 and Table 3 show that, as expected, losses increase exponentially with magnitude since the three events have identical epicentral locations. The table provides additional insights. First, loss standard deviations are very high relative to mean values, indicating substantial variation from one simulation case to the next for a given scenario. Recall that this variation derives from both engineering and economic model uncertainty. In the case of the M=7.5 event, results are limited by the outcome that in the first four weeks of system repairs, damage is sufficiently great that the system flow model fails to solve, indicating that water outage is likely to be complete throughout the county. In this case, maximum economic loss (defined by resiliency parameters) is assumed. As noted in Table 3, damage (number of pipe breaks) and restoration times also increase exponentially with magnitude.



■ Figure 3. Mean Direct Economic Loss, Earthquakes at Marked Tree

However, closer inspection of the variability in the individual simulation results showed that simulation cases with high dollar loss often had similar numbers of pipe breaks as those with low loss. For the M=6.5 and 7.0 events, losses were poorly correlated with number of pipe breaks but highly correlated with the occurrence of pumping station failure(s). This insight suggests that in the MLGW case, pumping station retrofits would be more effective at reducing losses in moderate earthquakes than wholesale pipe upgrades. On the other hand, M=7.5 event losses appear to be dominated by the overwhelming number of pipe breaks. Even after pumping stations are repaired in the initial week, system-wide failure persists until three more weeks' worth of pipe repairs have been completed.

Results on indirect economic loss are summarized in Table 4. The initial indirect loss results shown here are based on one scenario characterized by a 7.0 magnitude earthquake (average damage and direct loss over 100 simulations), a one-week outage, and resiliency adjustments involving only the substitution of other inputs for water utility services.

In Table 4, the sector labels on the left-hand side refer to the economic producing units of the Memphis CGE model. Direct water disruption for each sector is presented in column 1, and sums to a 20.6 percent decline in water available in Week 1. As noted in column 2, this constraint is binding on all but two sectors as the general equilibrium adjustments work themselves out. As discussed further below, negative indirect effects on Construction and Education are so great as to reduce water demand even below the post-earthquake availability levels. Baseline output is presented in Column 3 and reflects the relative prominence of sectors in Shelby County (Memphis proper) economy and serves as a reference point for the impact simulations. Note that the Water sector (11) gross output represents only 0.113 percent of the regional economy.

Column 4 presents the direct output losses that are estimated in the CGE model before any resiliency adjustment. Chang's estimates of direct output losses, which incorporate the extent of resiliency, are presented in Column 5. Our direct loss estimates are based on input substitution elasticities (the lowest possible values that yielded an equilibrium solution) presented in the next to the last column in Table 4. Note that the CGE direct loss estimates exceed those of Chang in every sector because they omit all resiliency options except normal input substitution. The final column shows the elasticities necessary to incorporate resiliency measures for the CGE model results to be consistent with the Chang estimates.

Our estimates of the indirect and total regional economic impacts of the water lifeline disruption are presented in Columns 6 and 7. Overall, they yield a 5.1 percent indirect reduction in regional gross output and an 19.0 percent total reduction in regional gross output for the week. The former represents \$49.3 million (\$2,563 million ÷ 52) and the latter \$184.6 million.

Some interesting aspects of indirect losses are indicated by Table 4. First, they are slightly more than

"Priorities for continuing work include sensitivity analysis, modeling other New Madrid Seismic Zone earthquakes, and evaluating the effects of pre- and post-disaster loss reduction measures."

Table 4. Partial and General Equilibrium Changes in Output Following a Water Outage in Shelby County (1-week outage following a 7.0 magnitude earthquake)

	Sector	Water Input		Output	Output Change from Water Outage				Elasticity (σ_0)	
		Direct Disruption	Total Unused	Baseline (10^6 1995)	Our Direct w/o Adjust.[2]	Chang's Direct	Indirect	Total[1]	Without Adjustment	With Adjustment
1	Agriculture	-26.7%	-26.7%	128	-21.0%	-11.6%	-11.5%	-23.1%	0.01300	0.01325
2	Mining	-16.5%	-16.5%	20	-9.1%	-8.5%	0.2%	-8.7%	0.01240	0.01241
3	Construction	-25.2%	-33.0%	2782	-18.3%	-8.3%	-24.6%	-32.9%	0.01300	0.01322
4	Food Processing	-19.5%	-19.5%	1999	-17.0%	-15.8%	-0.3%	-16.1%	0.01006	0.01008
5	Manufacturing	-20.1%	-20.1%	8151	-14.5%	-14.0%	-3.0%	-17.0%	0.01200	0.01201
6	Petroleum Refining	-19.5%	-19.5%	511	-17.4%	-15.8%	-0.7%	-16.5%	0.00945	0.00948
7	Transportation	-10.1%	-10.1%	6235	-9.1%	-7.8%	0.2%	-7.6%	0.01150	0.01153
8	Communication	-22.2%	-22.2%	654	-14.7%	-10.8%	-5.5%	-16.3%	0.01300	0.01308
9	Electricity Services	-22.2%	-22.2%	530	-18.5%	-10.8%	-9.5%	-20.3%	0.01200	0.01228
10	Gas Distribution	-22.2%	-22.2%	21	-12.9%	-10.8%	-3.7%	-14.5%	0.01300	0.01304
11	Water & Sanitation	-22.2%	-22.2%	57	-19.1%	-10.8%	-9.2%	-20.0%	0.01300	0.01343
12	Wholesale Trade	-19.7%	-19.7%	4581	-12.7%	-12.7%	-1.7%	-14.4%	0.01300	0.01300
13	Retail Trade	-28.7%	-28.7%	4148	-23.1%	-14.1%	-10.1%	-24.2%	0.01300	0.01324
14	Finance, Insurance & Real Estate	-24.7%	-24.7%	6931	-18.8%	-16.5%	-3.2%	-19.7%	0.01300	0.01306
15	Personal Services	-23.9%	-23.9%	1546	-19.0%	-13.9%	-6.8%	-20.7%	0.01300	0.01316
16	Business & Professional Services	-22.2%	-22.2%	3917	-14.9%	-14.1%	-3.0%	-17.1%	0.01300	0.01302
17	Entertainment Services	-30.8%	-30.8%	293	-25.5%	-15.3%	-11.8%	-27.1%	0.01300	0.01329
18	Health Services	-18.9%	-18.9%	3143	-22.9%	-22.6%	6.8%	-15.8%	0.01050	0.01051
19	Education	-29.1%	-54.0%	1324	-20.7%	-16.1%	-37.9%	-54.0%	0.01300	0.01308
20	Government	-26.9%	-26.9%	3291	-21.6%	-15.7%	-9.1%	-24.8%	0.01200	0.01215
	Total	-20.6%	-20.8%	50263	-16.8%	-13.9%	-5.1%	-19.0%		

[1] *Following CGE simulation*
[2] *From partial equilibrium analysis*

one-third the size of direct losses. In the context of an input-output (I-O) model, this would be a multiplier of about 1.37. The Shelby County overall output multiplier is larger than this, but the CGE model incorporates many other factors that mute the uni-directional and linear nature of the pure interdependence effect of the I-O model. For example, it is able to capture price declines due to decreased intermediate goods demand pressure, various substitutions aside from those relating to water, and various income, substitution and spending considerations on the consumer side. Hence, we note that the two sectors suffering the largest indirect decline are Education (not a necessity in the immediate aftermath of an earthquake) and Construction (a leading indicator of economic activity). Note that once our model factors in post-earthquake recovery and reconstruction, this would offset the Construction decline. In addition, several sectors are characterized by positive or minimally negative indirect effects, most notably basic necessities, such as Food Processing, Petroleum Refining, Transportation, and Health Services.

Note that we have modeled only one resiliency measure, albeit one of the most important ones—increased substitutability of other inputs for water utility services. As discussed earlier, different types of resiliency measures would generate different types of indirect impacts. However, preliminary simulations indicate the differences are small since the vast majority of indirect losses stem from the direct output reduction levels of producing sectors of the Memphis economy, which are basically the same no matter what types of adjustments are modeled.

Overall, our results appear to be reasonable for the economy as a whole, for individual sectors, and for individual impact stages (direct and indirect). The analysis is one of the few CGE simulations on any subject that has distinguished direct and indirect effects in detail. Moreover, we have developed a methodology that enables CGE users to recalibrate their models to make use of empirical data on individual parameters and direct impacts, such as those associated with responses to water lifeline disruptions following an earthquake.

Conclusions

The MLGW water system application demonstrates numerous methodological advances in earthquake loss estimation for lifeline systems, ranging from integrated probabilistic modeling of engineering and economic loss, to refinements based on Northridge data, to development of new Computable General Equilibrium models for indirect loss evaluation. Priorities for continuing work include sensitivity analysis, modeling other New Madrid Seismic Zone earthquakes, and evaluating the effects of pre- and post-disaster loss reduction measures. Ultimately, losses will be summarized in the form of economic fragility curves that indicate the likelihood of exceeding different levels of economic loss, with and without loss reduction actions. These results will be combined with probabilistic hazard information to estimate the expected benefits of mitigations which can then be compared with

"Ultimately, losses will be summarized in the form of economic fragility curves that indicate the likelihood of exceeding different levels of economic loss, with and without loss reduction actions."

their costs. This information can assist lifeline agencies in determining which mitigation options and how much mitigation to undertake. The methodological approach can be implemented for other lifelines, such as electric power systems, and for other seismically vulnerable urban areas.

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Development of Fragility Information for Structures and Nonstructural Components

by Masanobu Shinozuka, Mircea Grigoriu (Coordinating Author), Anthony R. Ingraffea, Sarah L. Billington, Peter Feenstra, Tsu T. Soong, Andrei M. Reinhorn and Emmanuel Maragakis

Research Objectives

Fragility curves are functions which represent the probability that a given structure's response to various seismic (conditions) excitations exceeds performance limit states. As such, fragility curves are a measure of performance in probabilistic terms. The major objectives of MCEER research on fragility information are: (1) developing efficient and accurate methods to calculate fragility curves for structural and nonstructural components and for global assemblies (systems); (2) establishing fragility information as a base for performance-based design, cost and loss assessment, and decision policies; (3) developing optimal strategies for seismic rehabilitation based on cost-benefit analysis; and (4) establishing rational performance limit states based on interaction between engineering and socioeconomic issues.

This research focuses on methods for efficiently and accurately determining fragility information for structural and nonstructural components, and for global assemblies (systems). Fragility curves, giving the probability of exceeding a specific limit state as a function of ground motion intensity, are commonly used to present the fragility information. They can be developed either for a specific system or component, or for a class of systems or components. Fragility curves can also be used to compare different seismic rehabilitation techniques and to optimize the seismic design of structures.

There are two main approaches for generating fragility curves. The first approach is based on damage data obtained from field observations after an earthquake or from experiments. The second approach is based on numerical analysis of the structure, either through detailed time-history analysis or through simplified methods. There is no universally applicable best method for calculating fragility curves. Different methods may be preferred depending on the circumstances. For example, the field data method is particularly useful for characterizing the seismic performance of a collection of similar structures. The numerical analysis method is useful when fragility curves need to be developed for a particular structural system with well-defined limit states.

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In dealing with field data, two-parameter lognormal distribution functions are used to represent fragility curves with all the analytical, interpretational and other advantages associated with this traditional form. In particular, when this form is used, the randomness vs. uncertainty issue can be addressed in a manner as explored in early studies dealing with nuclear power plant equipment (e.g., Holman et al. 1987).

Shinozuka et al. (1999a) further investigated this issue in relation to fragility curves developed for structural types categorized as in ATC-13 (1985). In this investigation, they resurrected the interpretation that each structural category represents a loose collection of sub-categories of structural types that are more similar in structural mechanics behavior, and that the fragility curve for each category is a lognormal distribution function whose median value has a probability distribution. The fragility curve with a realization of the median value represents the randomness of the fragility for a corresponding sub-category of the structural type.

In this sense, the probability distribution of the median is interpreted as arising from the uncertainty. The fragility curve associated with a specific median value represents the randomness of the fragility of a corresponding sub-category of the structural type.

In addition, an analytical expression was derived for the log-standard deviation of the fragility curve for a structural category in terms of the median values and log-standard deviations of constituent sub-categories of structural types. This provided, for the first time, a clear, quantitative insight into this difficult issue of randomness vs. uncertainty involved in the fragility curve.

In connection with damage data to support the development of fragility information for nonstructural components, a comprehensive nonstructural damage database has been developed (Kao et al., 1999). It contains nearly 3,000 entries encompassing more than 50 earthquakes from the 1964 Alaska earthquake to the present. Information from various publications, including books, reports and periodicals, was gathered and recorded, including a description of damage of the nonstructural component, information about the building where the damage occurred, and strong ground motion records, when available.

The database is presented as a living document, which will continue to be updated and evolve. The MCEER nonstructural components database, in Access format, can be downloaded from the publications

Fragility information can be used by design engineers, researchers, reliability experts, insurance experts and administrators of critical systems such as hospitals and highway networks. The information can be used to analyze, evaluate and improve the seismic performance of both structural and nonstructural systems. Optimal design and rehabilitation strategies can be identified. The techniques and computation tools developed as part of this research can also be used in undergraduate and graduate courses in earthquake engineering.

section of MCEER's web site (*http://mceer.buffalo.edu/publications/reports/docs/99-0014/default.html*).

Field and Experimental Data

Suppose that damage data is available from n earthquakes or experiments with characteristic peak ground accelerations a_i, i=1, 2, 3, …,n, with the convention $a_1 \leq a_2 \leq a_3 \leq \ldots < a_n$. Let $n_i > 1$ be the number of structures of a certain class subjected to earthquake i of PGA a_i and $m_i \leq n_i$ be the number of these structures that exceeded a specified limit state. The fraction, $f_i = m_i / n_i$, is an estimate of the probability of failure, or the fragility, of the class of structures considered if subjected to earthquakes of peak ground acceleration a_i. The fragility curve for this class of structures can be obtained by fitting a distribution function to the data set $\{a_i, f_i\}$. Hence, fragility curves are increasing functions of the peak ground acceleration and take values in [0,1].

Field data

This method of generating fragility curves utilizes damage data collected in the field after earthquakes at different sites. The ground motion intensity is determined at the location of each reported structure and the method outlined above can be used to plot the fragility curves. However, more advanced statistical methods are usually employed to determine the parameters of the fragility curve so that the goodness of fit can be tested and statistical confidence intervals estimated. The empirical fragility curves, constructed from the field damage observation, play an indispensable role in the fragility curve development study, because only they can be used to calibrate the fragility curves developed analytically or even experimentally if done under laboratory conditions. The damage data obtained from the 1999 Marmara, Turkey and Chi-Chi, Taiwan earthquakes are extremely valuable for the development of fragility curves in this sense.

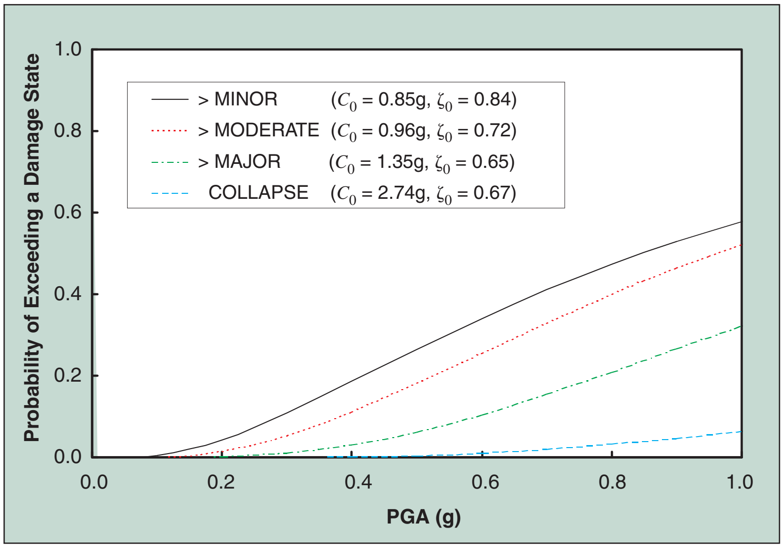
In addition, as shown by Shinozuka et al. (1999b), empirical fragility curves for groups of structures classified in terms of specific attributes (e.g., severity of skewness in the case of bridges) can be developed easily on the basis of the field damage data to demonstrate the effect of the attribute difference on fragility. While analytical avenues are open for this type of study, they would require computational efforts of inhibitive dimension. The empirical distributions would help develop practical approximations based on analysis under these circumstances.

Fragility Curves for Caltrans' Expressway Bridges in Los Angeles County, California (Before Post-earthquake Retrofit)

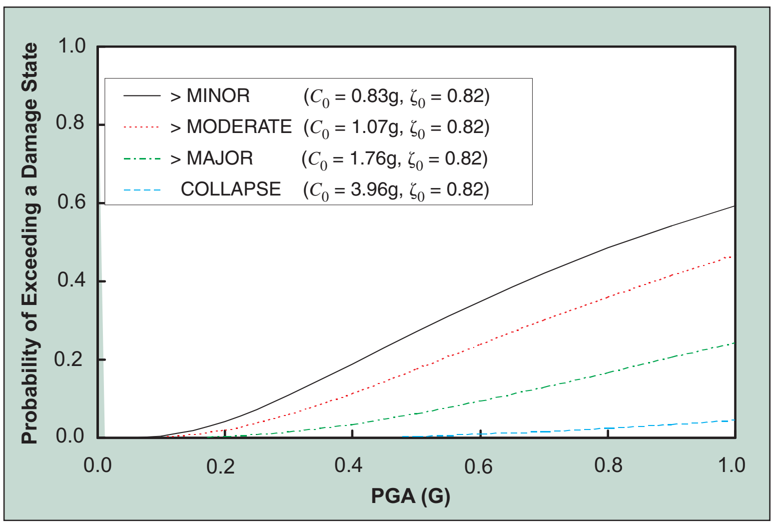
Damage data was collected after the Northridge earthquake for 1,998 of Caltrans' expressway bridges in Los Angeles County, California. Fragility curves were generated by Shinozuka et al. (1999b) for four damage states identified as "at least minor," "at least moderate," "at least major" and "collapse." A two-parameter lognormal distribution function was calibrated to these damage data to develop fragility curves. The parameters of the distribution that must be estimated are

Collaborative Partners

Caltrans
Hanshin Expressway Public Corporation, HEPC
***Gayle Johnson**, EQE International*
***Mohammed Ettouney**, Weidlinger Associates*



■ Figure 1. Fragility curves for Caltrans' bridges (Method 1)



■ Figure 2. Fragility curves for Caltrans' bridges (Method 2)

the median and the log-standard deviation. The peak ground acceleration (PGA) at each bridge site was used to represent the intensity of the seismic ground motion. Two methods were developed to calculate fragility curves and establish confidence intervals on these curves. Method 1 estimates a different median and log-standard deviation for each damage state and group of bridges. In Method 2, a different median is estimated for each damage state and group of bridges, but a single log-standard deviation is estimated for all of the distributions to prevent these fragility curves from intersecting each other. Figures 1 and 2 show fragility curves generated for the four damage states by Methods 1 and 2, respectively. A similar study was done by Basöz et al. (1998).

Fragility Curves for Reinforced Concrete Bridge Columns along Kobe and Ikeda Route, Japan (Before Post-earthquake Retrofit)

A sample of 770 single-support reinforced concrete columns along a 40 km length of viaduct was considered. All of the columns have similar geometry and reinforcement. Figure 3 defines the damage states considered for the columns. Figure 4 shows the fragility curves generated by Method 1 by Shinozuka et al. (1999a, 1999b).

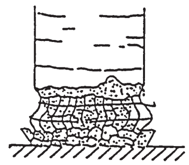
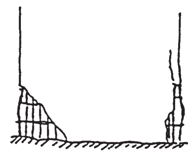
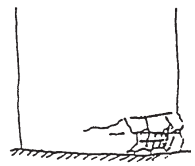
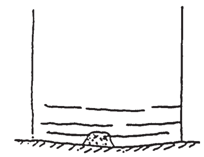
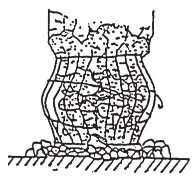
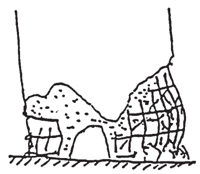
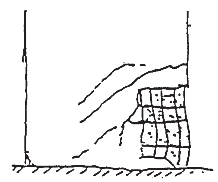
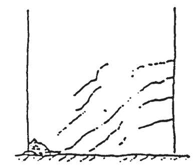
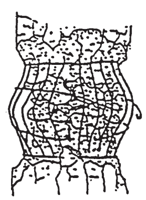
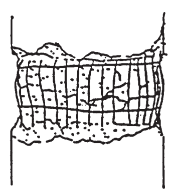
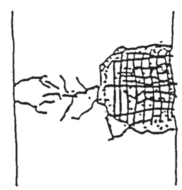
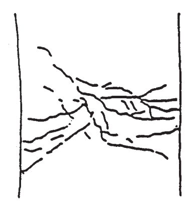
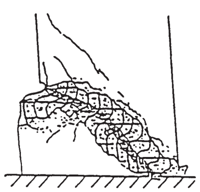
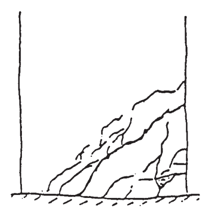
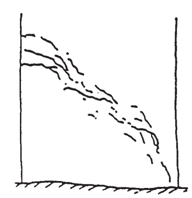
Experimental data

The same approach used for the field data method may be applied to damage data obtained from experiments. In this case, the range of earthquake intensities and the structure type can be controlled as required. However, experiments can be expensive and the amount of damage data available will be limited by the number of experiments that can be carried out. The following three examples illustrate the development of fragility curves using this method:

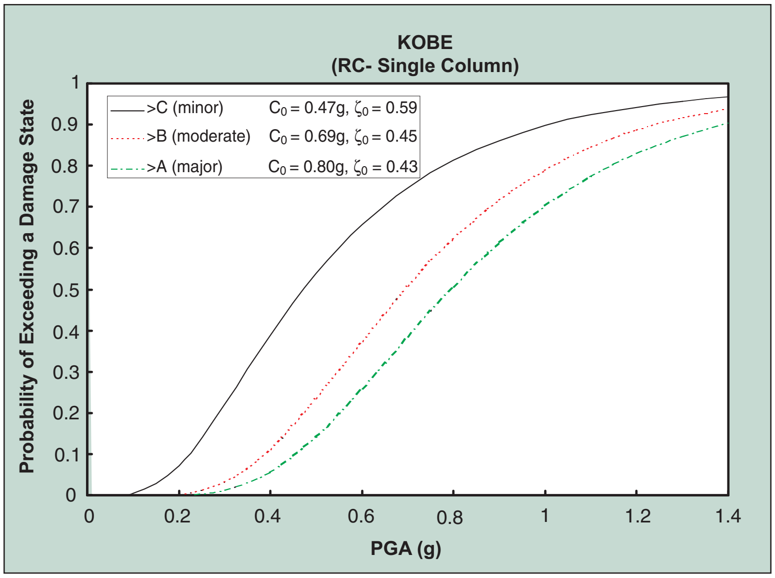
Sliding Fragility Curves of Unrestrained Equipment in Critical Facilities

Seismic design of buildings has been well developed and is being continually updated and improved. Nonstructural components, such as

■ Figure 3. Description of states of damage for Hashin Expressway Corporation's bridge columns

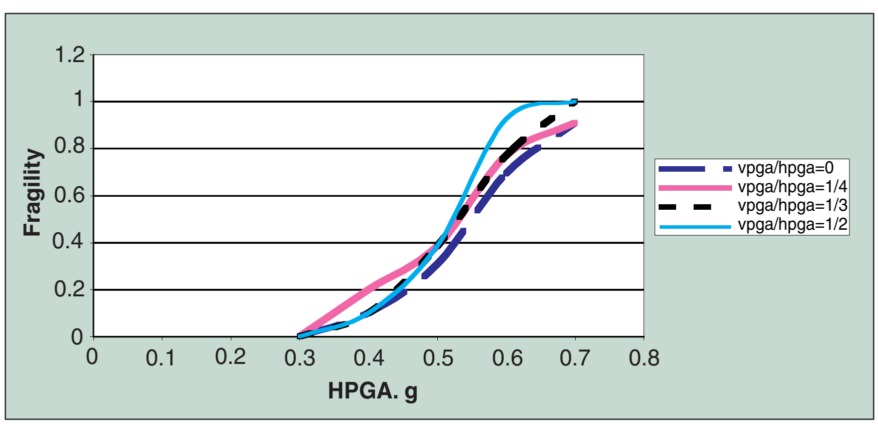
Damage State / Damage Mode	As	A	B	C	D	Remarks
1. Bending damage at ground level	Damage through entire cross section 	Damage mainly at two opposite sides 	Damage mainly at one side 	Light cracking and Partial Spalling 	No Damage	This mode unltimately produces buckling of rebars, spalling and crushing of core concrete
2. Combined bending & shear damage at ground level	Internal Damage 	Damage at two sides 	Damage mainly at one side 	Light cracking and Partial Spalling 	No damage	Bending and shear cracks progress with more wide-spread spalling than model and hoops detached from anchorage
3. Combined bending & shear damage at the level of reduction of longitudinal rebars	Internal Damage 	Internal damage 	Damage mainly at one side 	Partial damage 	No damage	Damage and collapse are observed at about the location (typically 4-5m above ground) of reduction of longitudinal rebars, accompanying buckling of rebars and detached hoops.
4. Shear damage at ground level	Damage through entire cross-section 	Damage through column 	Partial Damage 	Light cracking* 	No Damage	Columns with low aspect ration sheared at 45^0 angle

* No description provided in the original



■ Figure 4. Fragility curves for HEPC's bridge columns (Method 1)

piping systems housed in buildings, are rarely designed with the same degree of consideration. As a result, buildings that remain structurally sound after a strong earthquake often lose their operational capabilities due to damage to their nonstructural components. In certain situations, damage to nonstructural components can pose a greater threat to safety than damage to structural components. The cost of damage to nonstructural components can also exceed the cost of structural damage. For example, of the total damage to one building during the San Fernando earthquake in 1971, over 98% was nonstructural. Moreover, costly damage to nonstructural components could occur in earthquakes of intensities low enough to cause little or no structural damage. This research develops fragility curves for free-standing rigid equipment based on experimental data. To achieve this goal, the sliding motion of a rigid block against the surface of a raised floor was tested on a shaking table using five randomly chosen earthquake time histories. Both horizontal and vertical accelerations were considered in these experiments. Five horizontal peak ground accelerations (HPGA) were considered, namely 0.3 g, 0.4 g, 0.5 g, 0.6 g, and 0.7 g. Four different scale factors were used to represent the vertical peak ground accelerations (VPGA) in terms of HPGA: 0, 1/4, 1/3, and 1/2. Horizontal and vertical acceleration measurements using accelerometers were made at several locations of the shaking table: the raised floor, and the free standing rigid block. The horizontal displacements of the block were measured by the temposonic displacement transducers as well as two permanent markers attached to the left and right side on the surface facing the sliding direction. Eight different relative displacement failure

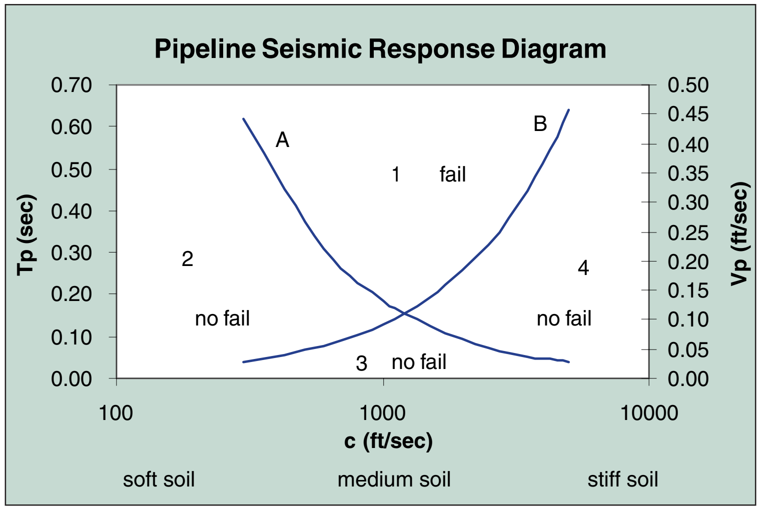


■ Figure 5. Experimental fragility curves for failure threshold = 1 inch thresholds between 0.1 inch and 3 inches were considered, and fragility curves were developed for each of these thresholds. Figure 5 shows the experimental fragility curves for failure threshold of one inch for the four different ratios between vertical and horizontal peak ground accelerations (Chong et al., 2000).

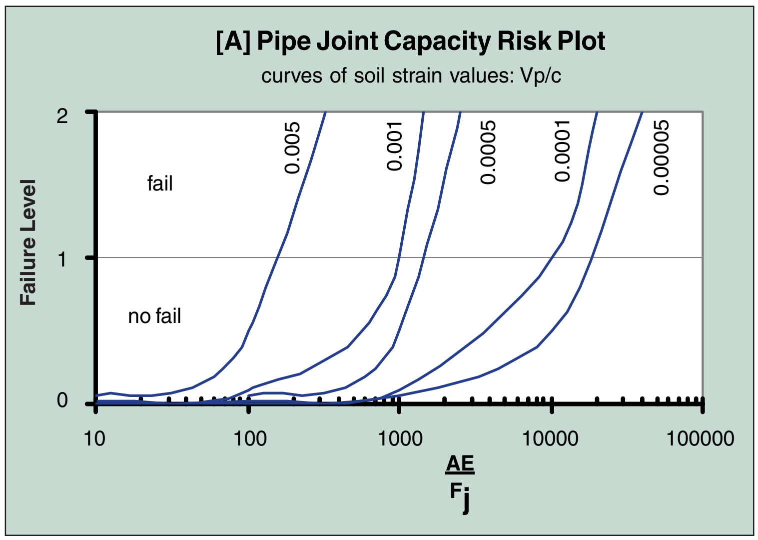
Damage Assessment Curves for Buried Pipe Joints

Pipelines transporting water, gas, or volatile fuels are part of the infrastructure "lifeline" system and are critical to the viability and safety of communities. Disruption to these lifelines can have disastrous results such as the release of natural gas and flammable fuels, or restriction of water required for fire-fighting. Pipelines have been shown to be vulnerable to damage and failure due to seismic motions. The objective of this study is to develop risk assessment charts for pipe joints based on experimental data. Twenty-two separate specimens of various pipe materials and various joint types have been tested under cyclic axial loading. The loading process involved the fabrication of a self-contained loading frame and the use of an MTS 450 kips actuator. Several different failure modes, such as buckling and fracture of the barrel and spigot end, were observed.

Two forms of risk assessment charts have been developed. The first form compares the pipe force capacity with a force level that may be imposed on the pipe due to seismic motion. Two conditions must be satisfied for failure to occur: the level of force from seismic motion must be greater than the pipe force capacity, and the level of force that is able to be transferred from the

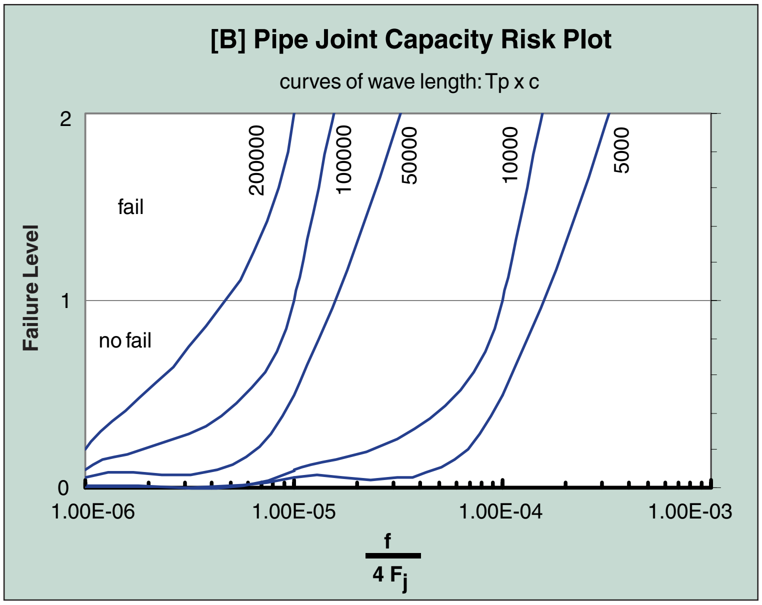


■ Figure 6. Pipeline seismic response diagram



■ Figure 7. Pipe joint capacity plot

soil to the pipe surface by friction must be greater than the pipe force capacity. Given the pipe capacity, the two conditions can be expressed in terms of earthquake and soil parameters such as predominant period of the earthquake (T_p), peak particle velocity (V_p) and the wave propagation velocity (c). Figure 6 is a typical risk assessment plot for one of the joints. The second form of risk assessment chart consists of two separate plots defining two separate considerations as shown in Figures 7 and 8. Figure 7



■ Figure 8. Pipe-soil friction transfer plots

shows the joint force capacity for different curves of imposed soil strains, while Figure 8 is a plot of the friction transfer force for different curves of the earthquake wave lengths. Both plots must have a "fail" condition for the joint to be classified as a "probable fail" condition. These plots are applicable for any pipe material and configuration as well as any site and seismic conditions, and are not specific to any single scenario.

Numerical Analysis

Numerical analysis can be used to generate fragility curves for structures for which no earthquake field data exists, or for which experimentation would be prohibitively expensive. The analyses can be repeated for different ground motions and structural configurations at relatively little cost. However, the results depend on the ground motion and structural models used. Two different levels of numerical analysis have been considered: the simplified capacity spectrum method, and more detailed time-history analysis.

Several material models have been considered for time-history analysis. Two enhanced constitutive models have been developed and implemented in DIANA to improve the characterization of the response of confined concrete and reinforcement under cyclic loads reinforcement (Kwan and Billington, 1999a, 1999b). Two benchmark studies are being conducted to evaluate the accuracy of DIANA in predicting results of shake table experiments. The first benchmark study is a simulation of shake-table experiments of a lightly reinforced concrete frame, and the second is an international benchmark competition to simulate the seismic response of structural concrete shear walls (Report I, 1999).

Spectral Capacity Method for Fragility Evaluation

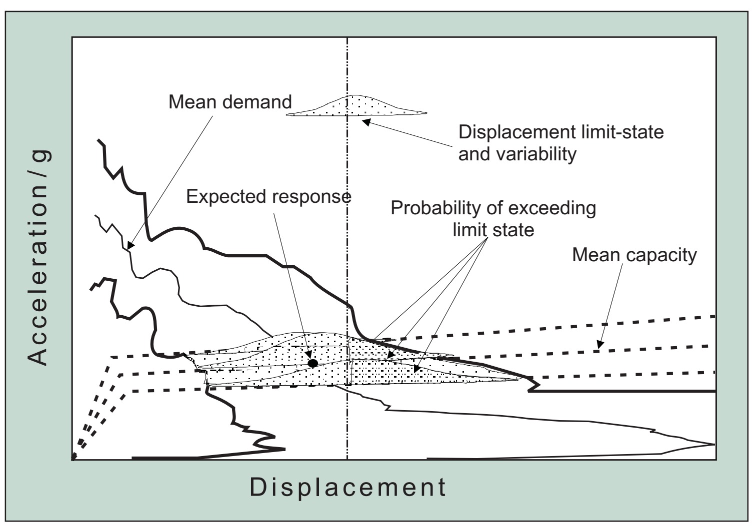
The spectral capacity method (SCM) is a simplified method that estimates the response of a structure from spectrum demand and spectral capacity curves (Barron and Reinhorn, 2000). The *spectrum demand* curve represents the ground motion and is typically derived from the elastic acceleration response spectra of the motion. These spectra are converted to nonlinear spectra (based on rules derived from inelastic spectra analysis) plotted on spectral acceleration, S_a, versus spectral displacement, S_d, axes, similar to ATC-40 representations. The *spectral capacity* curve represents the ability of the structure to deform at various degrees of resistance. The spectral capacity can be approximated from a "pushover" analysis in which monotonically increasing lateral loads are applied to the structure and the deformations are plotted against the load in the (S_d, S_a) coordinates following scaling. The basic idea of the SCM is the assumption that the expected median response is determined by the intersection of the spectral capacity and spectrum demand curves. This intersection is termed the expected response point. If either or both of the curves are random, the response is random. This is conceptually illustrated in Figure 9 by plotting mean plus/minus one standard deviation curves for the capacity and demand. The actual response is distributed in the intersection range. The fragility curves represent the probability-based relation between the expected response and the performance limits.

Various methods were developed to determine the probability that the response exceeds a given limit state. One method has been suggested by Shinozuka et al. (2000) for the case of random ground motion and deterministic structures. The mean and mean plus/minus one standard deviation demand curves are plotted, and the intersection of these curves with the deterministic capacity curve of the structure gives estimates of the mean and mean plus/minus one standard deviation of the response. A lognormal distribution is then fitted to these data points, allowing the fragility to be calculated.

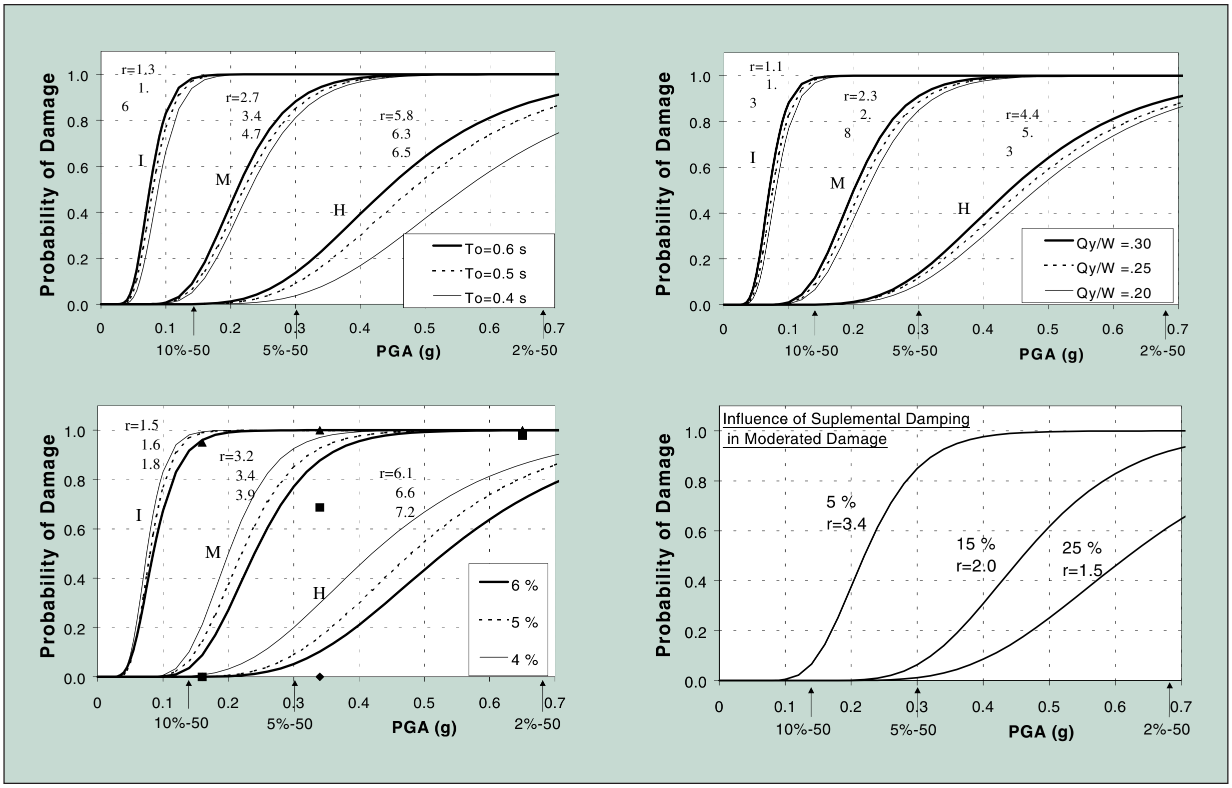
Barron and Reinhorn (2000) developed a second method. In this approach, the structural response is evaluated from inelastic nonlinear response spectrum and spectral capacity curves and the probability distribution function of spectral ordinates is obtained from simplified relationships. These relationships are functions of the structural parameters and allow a direct assessment of the probability of exceeding the limit states, from which the fragility curves can be constructed. This is a consistent methodology that explicitly considers and quantifies uncertainties in both ground motion and structural response. Sensitivity analysis of the fragility curves can be used directly to determine optimum retrofit techniques, or it can be combined with cost estimations to obtain an economically based decision.

The advantage of the SCM is its simplicity and ease of use. No time-consuming time history analyses need be performed. However, it is a heuristic method and will only give approximate answers. Shinozuka used the SCM method to develop fragility curves for a bridge in the Memphis area. Barron and Reinhorn (2000) generated fragility curves for the Patterson building and a bridge, also in Memphis. The influence of the various structural parameters

"Damage to nonstructural components can pose a greater threat to safety than damage to structural components."



■ Figure 9. Probability of exceeding limit-state



■ Figure 10. Fragility sensitivity to change of structural parameters (a) stiffness changes; (b) strength changes; (c) inherent damping estimation; (d) addition of supplemental damping (for moderate limit state only)

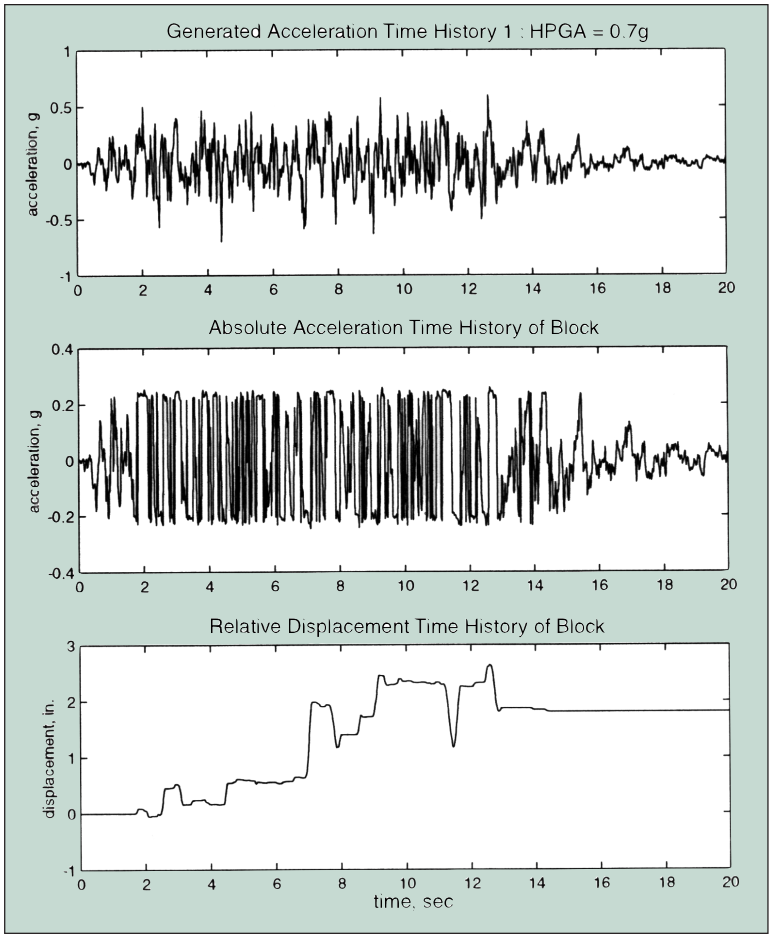
such as the damping ratio, the yield strength level, the initial period, and the post-yielding stiffness ratio was considered in evaluating the probabilistic response of nonlinear systems. The fragility curves obtained from this study were more sensitive to the addition of damping than to the changes in stiffness and strength (see Figure 10), indicating the efficiency of increased damping in structures.

Time History Analysis

Time history analysis is used to simulate the response of a structure to a given ground excitation. It is considered to be the most detailed numerical analysis method. The calculation of fragility curves can be based on the same approach as in the section on *Field and Experimental Data*. The only difference is that the data is obtained by calculation.

Sliding Fragility Curves of Unrestrained Equipment in Critical Facilities

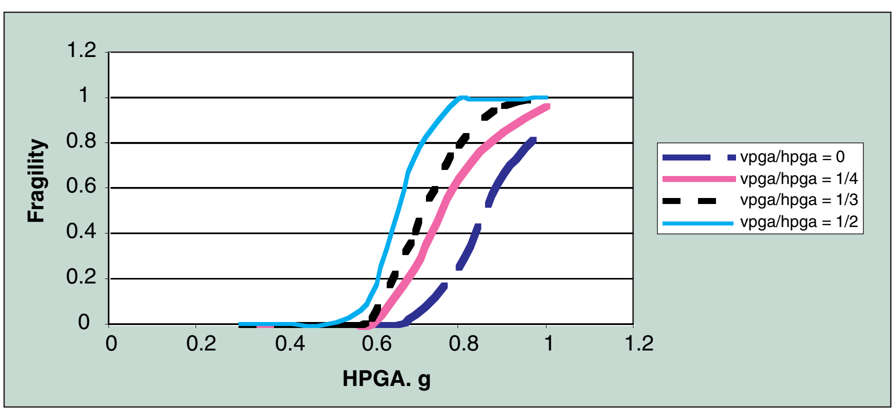
Fragility curves were constructed analytically for the standing-free block described in the section on *Experimental Data* and considered the same eight failure thresholds. Ninety acceleration time histories were generated using SIMQKE, an artificial motion generation program. The time histories were based on a response spectrum from the 1997 NEHRP recommended provisions for seismic regulations of new buildings and other structures. Each of the ninety acceleration time history inputs was scaled to have eight different horizontal peak ground accelerations between 0.3 g and 1.0 g. Each of these eight horizontal time histories was combined with four different vertical acceleration inputs, again scaled to give ratios between VPGA and HPGA of 0, 1/4, 1/3, and 1/2. The total number of time history combinations was 2,880. All of the time history combinations were repeated for five different coefficients of dynamic friction. Figure 11 shows relative displacement and absolute acceleration time histories for HPGA of 0.7 g, VPGA of 0.23 g and coefficient of dynamic friction of 0.21. Fragility curves have also been generated and plotted against the HPGA. Figure 12 shows one of the curves.



■ Figure 11. Analytical Solution I

Fragility Curves for Reinforced Concrete Bridges in the Memphis Area

Two representative bridges with precast prestressed continuous decks in the Memphis, Tennessee area were used for fragility curve development by Shinozuka et al. (1999a, 1999b). Figure 13 shows the plan, elevation and column cross-section of one of the bridges. The strength of the concrete f_c used for the bridges was assumed to be described by a normal distribution, while the yield strength f_y of the reinforcing bars was described by a lognormal distribution. Other parameters that could contribute to variability of structural response were not considered in the analysis. Samples of ten bridges were generated for each bridge. The time histories generated by Hwang and Huo (1996) were used for the



■ Figure 12. Fragility Curves for Ud = 0.3; Failure Threshold = 1 inch

> ***"The damage data obtained from the 1999 Marmara,Turkey and Chi-Chi, Taiwan earthquakes are extremely valuable for the development of fragility curves."***

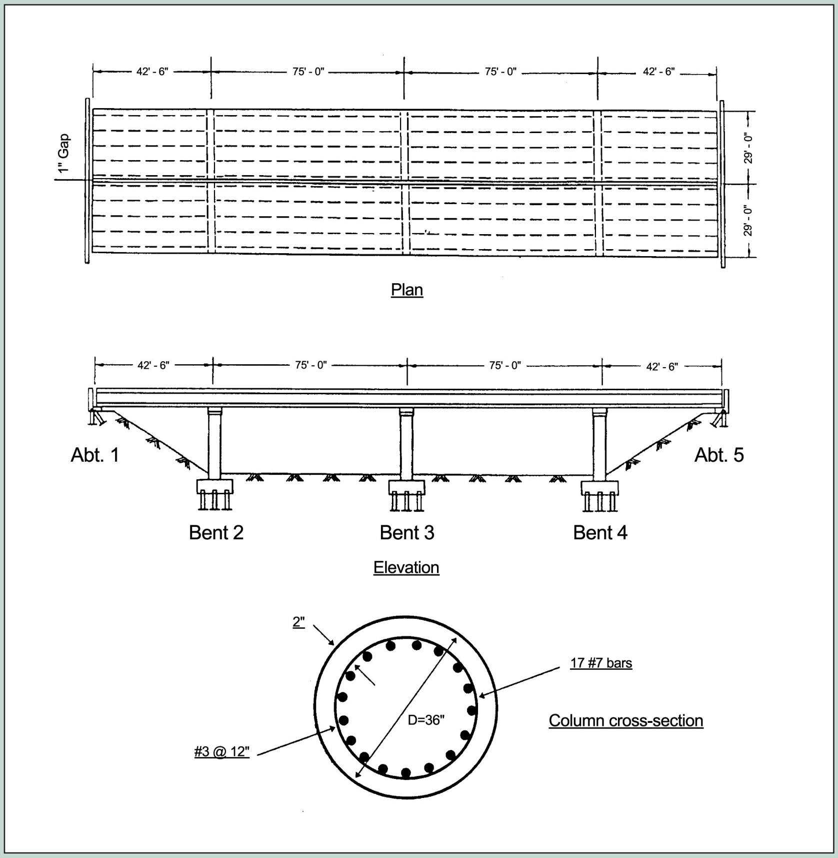


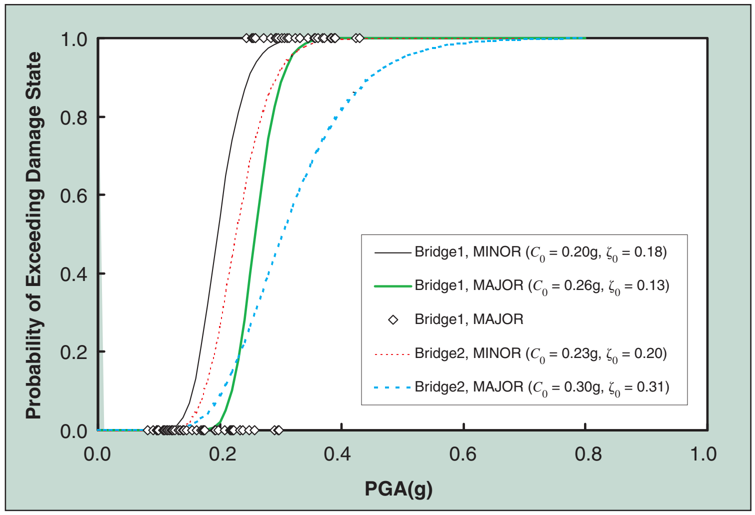
Figure 13. A representative Memphis bridge

ground motion. Ten time histories for each of several moment magnitude and distance combinations were matched with the sample of ten bridges. The SAP 2000 finite element code was used to calculate the state of damage of each bridge. Bilinear hysteretic elements without strength or stiffness degeneration were used. The results from SAP 2000 were validated for the bilinear behavior by analyzing the same problem using ANSYS. Figure 14 shows the fragility curves associated with two states of damage for the two bridges. Tests of goodness of fit and estimation of confidence intervals have been done for the bridges considered in the study. In this study, Shinozuka et al. (1999b) also developed fragility curves using spectral acceleration (SA), peak ground velocity (PGV), spectral velocity (SV) and spectral intensity (SI) as measures of ground motion intensity for comparison, and preliminary observations were made; however, a more elaborate study is currently underway.

Fragility Curves for a Water Tank in a Hospital

A hypothetical 22,000 gallon water tank located on the 20th floor of a hospital in New York City was used to illustrate the development of fragility curves for secondary systems based on the results of time-history analyses. The hospital is a steel frame building with partial moment resistant connections and supported by pile foundations. Figure 15 shows the plaza and the middle tower of the hospital. Figure 16 shows the location of the water tank on a schematic plan of the hospital.

The water tank has dimensions of 20.3 x 16.8 x 4.8 ft. It is supported at its corners by four vertical legs, each of height 6.83 ft. The ground excitation was assumed to be a zero-mean band limited Gaussian white noise (BLWN). Fragility curves were generated for four limit states. The limit states considered were $d > d_{cr}$, where d is drift of the water tank legs and d_{cr} takes the values of 6, 12, 24 and 36% of the height of the legs. The primary structure was assumed to remain linear elastic under the ground motion excitations. The body of the tank was modeled as a rigid body. No feedback from the secondary system to the primary structure was considered. The input to the water tank is modeled by the corresponding floor acceleration spectral density defined by

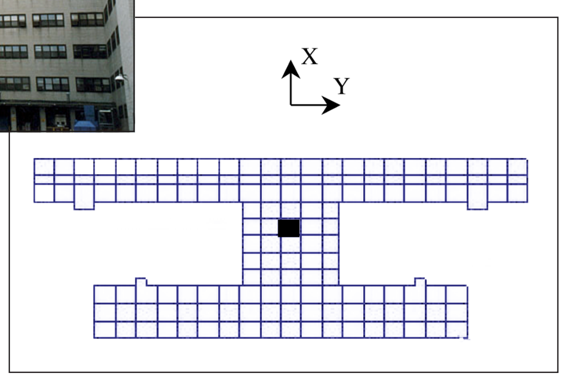


■ Figure 14. Fragility curves for bridge 1 and 2

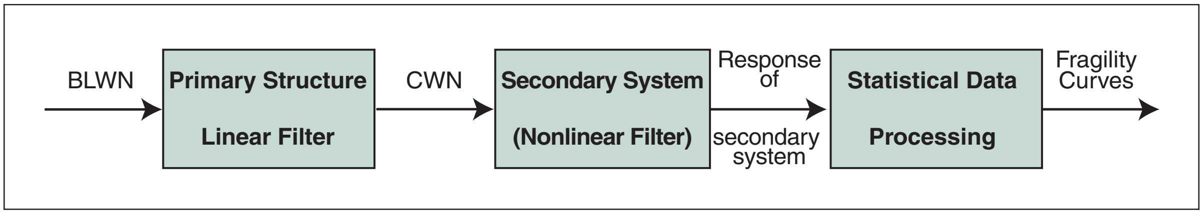
analogy with the pseudo acceleration floor response spectrum. The only source of randomness is the seismic input. Figure 17 shows the solution sequence.

The primary structure was analyzed separately neglecting the interaction with the secondary system. The responses at the attachment points are used as the input to the secondary system. The primary structure is a linear filter so that the power spectral density function for the response at the attachment points can be calculated (Soong and Grigoriu, 1993). The function is then used to generate floor accelerations for the secondary system. 240 realizations of the input were

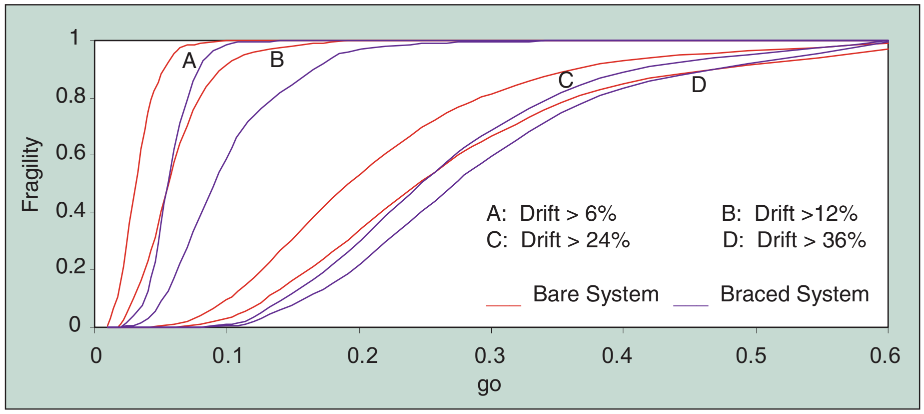
■ Figure 15. Plaza and the middle tower of the hospital



■ Figure 16. Schematic plan of the hospital



■ Figure 17. Solution sequence



■ Figure 18. Fragility curves of the secondary system

generated for twelve values of white noise intensity g_o. The secondary system was studied using DIANA under each of the excitations. The body of the tank was assumed to be rigid so that deformations were concentrated in the four legs. Both geometrical and material nonlinearities were considered in the analysis. The material model of the four legs was von Mises plasticity with strain hardening. The maximum drift of the legs, d, was calculated for each simulation. For a given limit state, d_{cr}, and a specific value of g_o, the fragility $P(d_{cr}, g_o)$ was calculated as the proportion of the samples with maximum drift, d, exceeding d_{cr}.

$$P(d_{cr}, g_o) = N_{ex}(d_{cr}, g_o) / N(g_o),$$

where $N(g_o)$ is the total number of samples generated for the given g_o. A lognormal distribution was then fitted to the points to give the fragility curves. The procedure was repeated after retrofitting the tank with diagonal braces. The fragility curves for the system before and after retrofitting are shown in Figure 18. It is clear that the retrofit improves the seismic performance of the system.

System Fragility

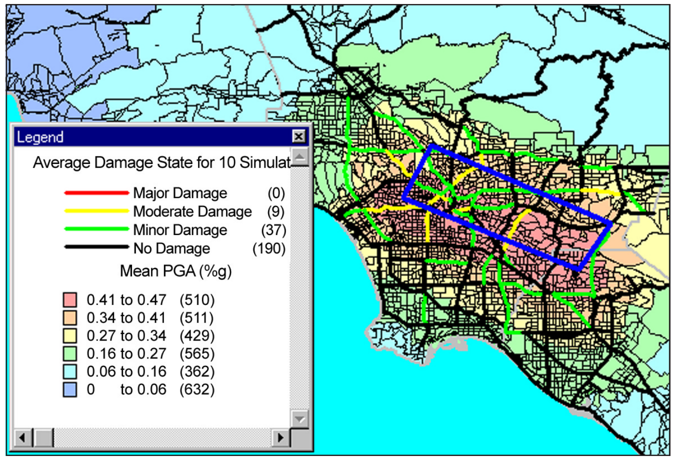
A structural or nonstructural system typically consists of many individual components connected together in a certain way. The fragility of the system depends on (1) the fragility of the individual components and (2) the way in which the components are connected. The fragility of the system can be very different from the fragilities of the components. It is thus essential to evaluate the system fragility in addition to the individual component fragilities.

Seismic Risk Assessment of Los Angeles Area Expressway Network

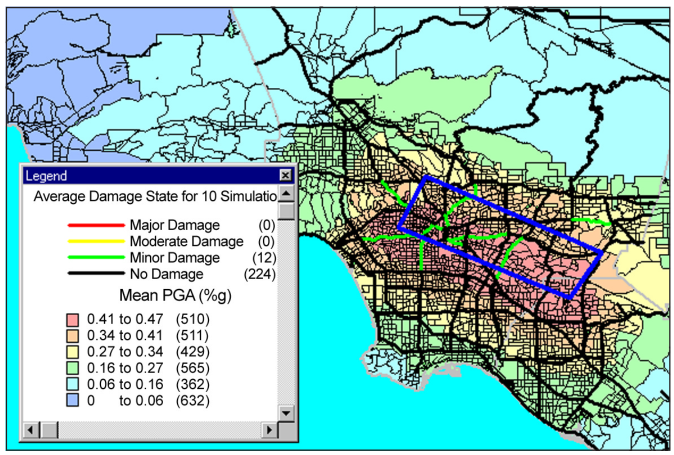
A seismic risk analysis was performed (Shinozuka, et al. 1999b) on the Los Angeles area expressway network under a postulated magnitude 7.1 Elysian Park earthquake. For this purpose, the families of fragility curves for "at least minor," "at least moderate," "at least major" and "collapse" states of damage developed in the section on *Field Data* were used. States of damage for all 2,225 Caltrans' bridges in Los Angeles and Orange County were simulated.

The state of damage simulated for each bridge was quantified using a "bridge damage index" (BDI). The BDI is 0.1, 0.3, 0.75 and 1.0 for the "minor," "moderate," "major" and "collapse" damage states, respectively. The state of link damage was then quantified by making use of a "link damage index" (LDI) which was computed for each link as the square root of the sum of the squares of BDI values assigned to all bridges on the link under consideration. The LDI value was then translated into link traffic flow capacity. In this study, it was considered reasonable to assume that the capacity is 100% (relative to the case with no damaged bridges on the link) if LDI < 0.5 (no link damage), 75% if 0.5 < LDI < 1.0 (minor link damage), 50% if 1.0 < LDI < 1.5 (moderate link damage) and 25% if 1.5 > LDI (major link damage).

In an on-going research project, a computer code "USC-EPEDAT" is being developed to perform the simulation of states of link damage and hence, network damage, efficiently (each simulation takes less than 10 seconds with a 300 MHz or faster PC). Figure 19 depicts the result averaged over 10 simulations. The information contained in Figure 19 can be used to support decision-making for post-earthquake response activities in near real-time. Figure 20 depicts the state of the expressway network damage under the assumption that each bridge has appropriate seismic retrofitting so that the median parameter of the lognormal fragility curve is increased by 50%. Figure 20 clearly indicates that the retrofitting improves the performance



■ Figure 19. Averaged network damage under postulated Elysian Park earthquake (10 simulations)



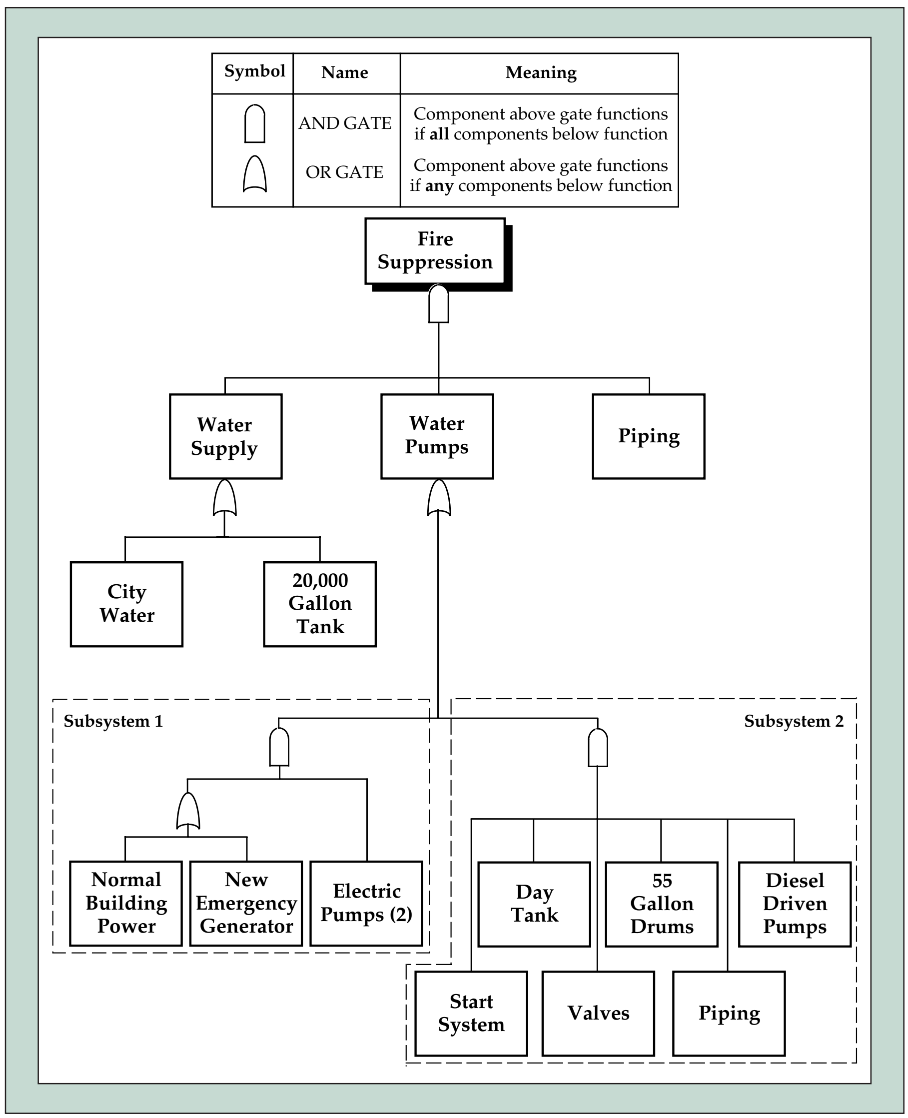
■ Figure 20. Averaged network damage under postulated Elysian Park earthquake (10 simulations on retrofitted network)

"Buildings that remain structurally sound after a strong earthquake often lose their operational capabilities due to damage to their non-structural components."

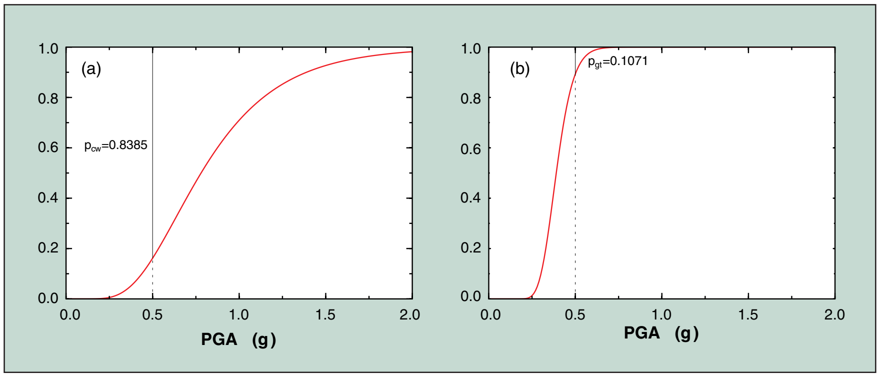
of the network. Such a comparison makes it possible to evaluate the cost-effectiveness of different seismic retrofit strategies by additional cost-benefit analysis.

San Francisco High-rise Fire Suppression System

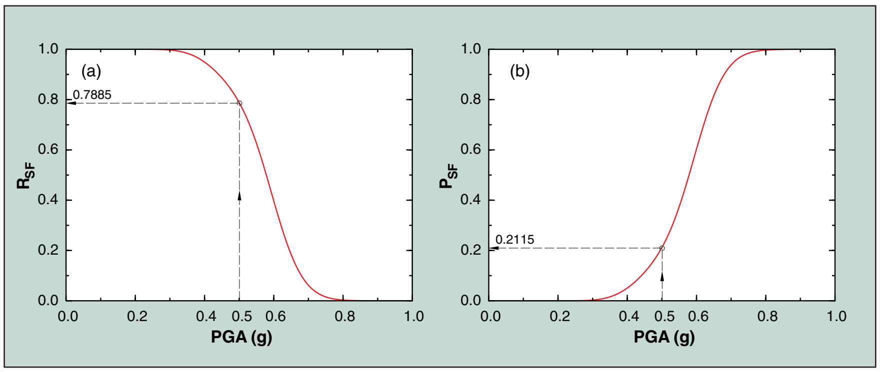
Logic trees are frequently used to represent and analyze structural and nonstructural systems. An example of such a tree is shown in Figure 21 for a San Francisco high-rise fire suppression system (Grigoriu and Waisman, 1998). The tree consists of the components along with "gates" describing the logical connectivity of the components. For example, in Figure 21, the water supply will function if one or both of the city water and the 20,000 gallon tank function. The entire system will function only if all three of the water supply, water pumps and piping function. Equations have been derived for calculating the probability of failure of the system from the probability of failure of the individual



■ Figure 21. Logic tree for San Francisco high-rise fire suppression system



■ Figure 22. Fragility curve for 20,000 gallon tank



■ Figure 23. System fragility curve

components. These equations can be used to generate a fragility curve for the system from the fragility curves of the components (Figures 22 and 23). The logic tree method can also be used for sensitivity analysis to identify the critical components of the system, and to determine confidence intervals for the system fragility (Roth, 1999).

Conclusions

This paper outlines common methods for generating fragility curves, explores some features and limitations of each method, and illustrates the methods by means of examples. The methods are based on field data, experiments, and numerical calculation.

In the future, the techniques described herein will be extended, refined and made more accessible to engineers through the development of suitable computation programs. The statistical data analysis method will be applied to data from the 1999 earthquakes in Taiwan and Turkey. A computer program is planned for the simplified Spectral Capacity Method (SCM), while the more detailed programs for time history analysis will be improved through the addition of sensitivity analysis, adaptive time step algorithms, more robust material models, and parallelization. Another research direction will be in the use of fragility curves for cost-benefit analysis and systems analysis. Alternative ground motion intensity measures to PGA will also be considered.

Web Sites

Nonstructural Damage Database
http://mceer.buffalo.edu/publications/reports/docs/99-0014/default.html

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Damage to Critical Facilities Following the 921 Chi-Chi, Taiwan Earthquake

by Tsu T. Soong (Coordinating Author), George C. Yao and C.C. Lin

Research Objectives

As part of research collaboration between MCEER and the National Center for Research in Earthquake Engineering (NCREE) in Taiwan, a team of MCEER/NCREE researchers undertook a reconnaissance mission shortly after the 921 Chi-Chi earthquake occurred in Taiwan at 1:47 a.m. on September 21, 1999. A major objective of this mission was to assess earthquake-induced damage, to document lessons learned, and to identify short-term strategies for post-earthquake restorations. This paper, a portion of the MCEER/NCREE Reconnaissance Report (MCEER/NCREE, 2000), summarizes preliminary findings on the damaging effects of the earthquake on critical facilities.

Critical facilities include hospitals and health care facilities; schools; police, fire and emergency response stations; key government facilities; and key industries. They provide lifesaving functions and render emergency assistance to communities when a disaster strikes. It is thus particularly important that every effort be made to insure their safety and functionality during and after a disaster. In this paper, damages to some of these facilities due to the 921 Chi-Chi earthquake are assessed, together with their probable causes and impact. Possible corrective actions and research needs in mitigating the effect of a similar future disaster event on these critical facilities are addressed.

It is noted that damage information on many of these facilities is still being collected and processed at the time of this writing. Therefore, they should be considered incomplete and preliminary as reported in this section.

Hospitals

According to available information, there are 4,375 health care facilities within the six-county seismic affected zone, of which 165 are hospitals. Damage to hospitals can be grouped into the following three categories: (1) minor structural damage and minor nonstructural damage, (2) partial

Sponsors

National Science Foundation, Earthquake Engineering Research Centers Program

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Collaborative Partners

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Links to Current Research

MCEER Program 1: Seismic Evaluation and Retrofit of Lifeline Systems
MCEER Program 2: Seismic Retrofit of Hospitals
MCEER Program 3: Emergency Response and Recovery

structural damage but serious non-structural damage, and (3) serious structural damage. In the first category, evacuation of patients and staff was not required and the hospitals were capable of performing emergency care to earthquake victims. In the second, hospitals were rendered non-serviceable and time was required for restoration. This type of damage was prevalent in the areas close to the epicenter. For example, within the critical 48-hour period after the earthquake, close to 1,000 beds were lost for patient care in Nantou county alone. Serious structural damage, or the third category, was also evident in regions close to the epicenter, where major hospitals were closed, requiring either demolition or major repair.

While structural damage was widespread in the six-county affected area, nonstructural damage was found to be a major factor adversely affecting functionality of major hospitals. Common occurrences included fallen interior walls and ceilings, toppling, sliding or collision of medical and non-medical equipment, overturning of water and oxygen tanks, interruption of emergency power, and flooding due to pipe breakage. For a closer scrutiny, several hospitals were chosen for more in-depth site visits. In what follows, damage investigations made on October 5, 1999 at three major hospitals are summarized. The observations described below are based on interior as well as exterior damage inspections and on interviews with hospital officials.

Christian Hospital, Puli

A major facility in Puli and surrounding communities, the Christian Hospital is a 400-bed facility of reinforced concrete (RC) construction consisting of a new (about a year old) section and an old (about 20 years old) section (see Figure 1).

Damage Summary

- New section sustained considerable damage from the main event on 9/21/99. Out of safety concerns primarily due to nonstructural damage (water damage, equipment failure, etc.), the building was evacuated with patients housed in tents on the hospital grounds. The building was immediately inspected and considered safe. Upon interior cleaning, patients were returned to the building.
- The building suffered significant nonstructural damage again from the 9/27/99 M6.8 aftershock. Patients were again evacuated and housed in temporary trailers with considerably reduced capacity (about 50 beds), with overflow transferred to other area hospitals.

This research focused broadly on the damage to numerous critical facilities caused by the 921 Chi-Chi, Taiwan earthquake. It is anticipated that numerous groups including the earthquake research community; seismic code committees; regulatory officials; and administration and technical staff of critical facilities dealing with seismic vulnerability and rehabilitation will have an interest in the issues discussed.

Photographs by T.T. Soong

■ Figure 1. The Christian Hospital sustained considerable damage. Photos show (left) part of the exterior damage to the hospital; and (right) interior damage to partitions and ceilings.

Web Sites

Multidisciplinary Center for Earthquake Engineering Research
http://mceer.buffalo.edu/research/taiwaneq9_99/default.html

- The first floor of the building remained open and was being used for emergency care, patient registration and processing, command post, and other necessary functions (see Figure 2).

Consequences and Impact

- A major part of the hospital was non-serviceable primarily due to nonstructural damage.
- Drastically reduced capacity (10% of original) at a time when demand was the highest.
- Trauma to patients through two relocations.
- Drastically reduced services due to equipment damage.
- The lack of an earthquake emergency management plan probably made the situation worse.

Restoration

Restoration was underway. It was estimated that the interior would be restored and serviceable within two weeks.

Veterans Hospital, Puli

The Veteran's Hospital is another major hospital located in Puli. It is a 450-bed facility with two main reinforced concrete (RC) buildings

Photograph by T.T. Soong

■ Figure 2. The first floor of the Christian Hospital remained open though the hospital suffered extensive interior damage.

Photograph by M. Bruneau

■ Figure 3. An overview model of the Veterans Hospital in Puli. The two white buildings are the newest and both sustained considerable damage.

(the Medical Center and the Administration Center), built about three years ago and several older (about 25 years old) and smaller buildings (see Figures 3 and 4).

Damage Summary

- New buildings sustained considerable damage from the main event. The Medical Building (Bldg. 1) was closed and the patients in the Administration Building (Bldg. 2), along with those in Bldg. 1, were either moved to the older buildings or transferred to other VA hospitals. About 220 patients remained at the hospital.
- Considerable nonstructural damage in Bldgs. 1 and 2, including power failure[1], water damage, and equipment damage. Bldg. 1 also sustained considerable structural damage, probably due to a lack of ductile detailing.

Consequences and Impact

- A major part of the hospital was non-serviceable due to both structural and nonstructural damage.
- Drastically reduced capacity (50% of original) at a time when demand was the highest.
- Trauma to patients due to evacuation.
- Drastically reduced services due to equipment damage.
- As in the case of the Christian Hospital, no earthquake emergency management plan appeared to be in place at the time of the earthquake.

Restoration

Whether Bldg. 1 was to be demolished or repaired remained to be determined. Bldg. 2 was expected to be repaired within two weeks.

Photographs by M. Bruneau

■ Figure 4. The Veterans Hospital sustained both exterior damage (left) and interior damage (right) to the newest buildings of the Medical Center.

Photographs by G.C. Yao

■ Figure 5. Interior damage in the Shiu-Tuan Hospital. Shown are (left) fallen brick inside the hospital and (right) a damaged interior glass brick wall.

Shiu-Tuan Hospital, Tsushan

The Shiu-Tuan Hospital is a 9-story, two year old reinforced concrete (RC) building that has a 400-bed capacity. It is privately owned and is the largest in Nantou county. The structure is situated about 120 m from the Che-Lung-Pu Fault with an uplift of approximately one meter at the site.

Damage Summary

- Structurally intact, it suffered considerable nonstructural damage as in the case of the other two hospitals (see Figures 5 and 6). Interior damage was most severe at the second- and third-floor levels where, unfortunately, some of the major facilities, such as operating and recovery rooms, were located. Patients were moved to open hospital ground and subsequently transferred to other hospitals.
- Hospital closed.

Consequences and Impact

- Trauma to patients due to evacuation and reallocation.
- Hospital closed, making the largest hospital in this vicinity unavailable to patients and earthquake victims.
- Seven patients died due to stoppage of life-support system.

Restoration

Repair was underway and the process was expected to take one to two months. Funds for the repair remained to be found.

Photograph by G.C. Yao

■ Figure 6. Damage to an exterior wall of the Shiu-Tuan Hospital in Nantou county

■ Table 1. Nonstructural Damage in Three Surveyed Hospitals

Cause of Disruption and Evacuation	Christian	Veterans	Shiu-Tuan
Backup Power Outage	X		X
Water Supply Outage	X	X	X
Gas Service Outage		X	X
Elevator Damage		X	X
Communications Failure	X	X	X
Falling Debris	X	X	X
Broken Piping, Water Leakage	X	X	X
HVAC Anchorage Failures	X	X	X
Mechanical Equipment Damage	X	X	X
Toppling of Gas, Liquid Storage Tanks	X	X	X
Medical Equipment Damage	X	X	X
Emergency Evacuation Plan Not in Place	X	X	X

Summary

The damage to the three hospitals and its impact underscores the importance of securing medical equipment and protecting patients and staff from falling debris and overturning objects. As demonstrated in the case studies above, hospitals can be rendered non-serviceable and lives of patients can be lost due to failure of life support equipment in critical care areas. Table 1 is a compilation of nonstructural damage in the three hospitals highlighted in this paper which, incidentally, could have been reduced or even avoided with inexpensive and easily implementable protective measures.

■ Table 2. Extent of Damage to Schools

Type of Institution	Total	Damaged	Damage Ratio (%)
Universities and Colleges	36	33	91.7
Technical Institutions	98	38	38.8
Normal Universities	13	8	61.5
High Schools	242	63	26.0
Middle Schools	715	168	23.5
Elementary Schools	2,557	488	19.1
Schools for the Disadvantaged	20	4	20.0
Total	3,681	802	21.8

Ministry of Education, 1999b

Schools

School buildings sustained severe damage, reaching as far as the city of Taipei, 150 km from the epicenter. As in the 1998 Chia-Yi/Ruei-Li earthquake, the severity of damage to school buildings, as demonstrated in Table 2, again exceeded that of other structures due primarily to the commonality of their weaknesses in construction. The common problems associated with school buildings appeared to be, on the one hand, short-column effects which led to shear failure in columns and, on the other, eccentricity of most school buildings associated with cantilevered corridors at upper floors (see Figure 7). It is estimated that restoration, repair and reconstruction costs associated with school buildings can reach US$ 1.3 billion (Ministry of Education, 1999a).

According to a recent accounting made available by the Ministry of Education, a total of 786 schools were damaged by the earthquake and its aftershocks as listed in Table 3, of which 51 suffered complete collapse. Damage was heavily

Photographs by T.T. Soong

■ Figure 7. Typical damage to schools due to short-column effect and eccentricity

■ Table 3. Damage to Schools

City/County[1]	Universities and Colleges	Technical Institutes and High Schools	Middle Schools	Elementary Schools	Total
Taipei City	8	8	8	43	67
Taipei County	2	1	21	52	76
Yi-Lan County	0	3	1	4	8
Tou-Yuan County	2	1	1	7	11
Hsinchu City	2	0	5	9	16
Hsinchu County	0	1	2	10	13
Miu-Li County	2	4	20	59	85
Taichung City	11	9	19	37	76
Taichung County	3	15	14	39	71
Nantou County	6	11	10	42	69
Chang-Hwa County	3	10	26	46	85
Yu-Lin County	1	6	10	32	49
Chia-Yi City	0	9	7	16	32
Chia-Yi County	2	2	7	35	46
Tainan City	1	0	10	18	29
Tainan County	1	2	0	0	3
Others	3	1	6	39	49
Total	47[2]	83[2]	168	488	786[2]

[1] *Numbers for counties do not include those in cities within the counties.*

[2] *Inconsistencies between Tables 4-2 and 4-3 are probably due to different information sources.*

Ministry of Education, 1999a

■ Table 4. Severity of Elementary and Middle School Damage

County	Total Collapse	Partial Collapse and Nonstructural Damage	Total
Nantou	30	109	139
Taichung	11	32	43
Neighboring Counties	10	41	51

Ministry of Education, 1999a

concentrated in Nantou and Taichung counties as illustrated in Table 4. In Nantou county, for example, 139 out of 186 elementary and middle schools, or approximately 75%, suffered damage serious enough that they had to be closed. This situation not only affected the education of students, but also made them unusable as evacuation and emergency response centers.

Police and Fire Stations

As in the case of schools and other public buildings, police stations and emergency response centers also sustained severe damage in the affected region (for example, see Figures 8 and 9). Damage report forms were sent to these units by the National Center for Research in Earthquake Engineering (NCREE) investigators and those returned to date are summarized in Table 5.

Key Industrial Facilities

Of particular interest to the international business community was impact of the Chi-Chi earthquake on the output at the Hsinchu's Science Based Industrial Park, where about 30 firms produce a significant percentage of the world's semiconductors and silicon wafers. Damage to this facility and its global impact are the focus of this section.

Hsinchu's Industrial Park, situated about 110 km from the epicenter, houses approximately 239 high technology firms that have important links to the world's computer

Photograph by T.T. Soong

■ Figure 9. Heavily damaged Puli Police Station

■ Table 5 Interim Damage Summary Pertaining to Police and Fire Stations

City/County	Severity of Damage				
	Total or Partial Collapse or Overturning	Serious Damage (Requiring Demolition or Retrofit)	Moderate Damage (Requiring Retrofit or Repairable)	Light Damage (Repairable)	No Damage
Nantou County	5	1	1	1	0
Taichung County	--	--	--	--	--
Taichung City	0	0	0	14	0
Miu-Li County	1	0	2	1	4
Chang-Hwa County	0	2	3	0	0
Yu-Lin County	--	--	--	--	--

NCREE, 1999a

and communications industry. Based on the types of products they produce, they can be grouped into the following: Integrated Circuit: 95, Computers and Peripherals: 44, Telecommunications: 36, Electro-optical: 35, Automation: 16, and Bio-technology: 13.

Power to the entire island was interrupted due to damage to the electrical transmission network and switching stations close to the epicenter, due to high-priority user status at the Hsinchu's Industrial Park. Power to the Park was restored to full capacity at 500,000 KV on September 25, 1999, four days after the earthquake. Even so, production loss at the facility was estimated to be around US$ 400 million, most of which incurred at the semiconductor and silicon wafer production facilities.

Overall damage at the facility has been light in comparison with those closer to the epicenter. Again, nonstructural and equipment damage stood out, including fallen ceilings, cracked walls and partitions, shear failure of columns, piping

Photograph by T.T. Soong

■ Figure 8. Total collapse of Puli Town Hall

■ Table 6 Damage Survey at Hsinchu Industrial Park

Forms Returned: 171				
No Damage: 101 Percent of Total: 59%	Damage Reported: 70 Percent of Total: 41%			
	Damage	Light	Moderate	Serious
	Cracks in Walls	55	11	0
	Deformed Floors	8	3	0
	Shear in Columns	5	0	0

NCREE, 1999b

breakage, and equipment damage. Most of this damage was repaired rapidly and the entire industrial complex has been restored to its pre-earthquake production level. Table 6 lists damage survey results based on the returned survey forms to date.

General Observations and Lessons Learned

Seismicity

Heavy damage to critical facilities in areas close to the epicenter was certainly in large part attributable to the unanticipated high level of ground shaking in the region. For example, Nantou and Taichung counties, where most of the damage occurred, are located in seismic zone 2 with a design peak ground acceleration (PGA) specified at 0.23 g. On the other hand, the actual recorded PGAs in the region were in general higher than 0.35 g, and were as high as 0.92 g. Even accounting for an importance factor of 1.25 for public buildings, the design PGA values were considerably below those actually experienced, causing widespread damage to constructed facilities.

Structural Damage

Beyond high seismicity, several important factors contributing to observed structural damage to buildings, including critical facilities, have been identified and include:

- Short-column effects leading to column shear failure.
- Eccentricity due to cantilevered corridors.
- Lack of ductile detailing.
- Column failures due to inadequately spaced stirrups, reinforcements, and splices.
- Soft-story induced failures.
- Unstable foundations and ground uplift.

However, in spite of these common ills, structural damage to critical facilities appeared to be heavier than those in other sectors. It has been speculated that this may be due to the nature of the bidding process associated with the construction of public and government owned buildings, where fixed-price design/built contracts are practiced. As reported in local news broadcasts, this practice invites abuse and encourages contractors to utilize substandard construction materials and circumvent accepted engineering practices in order to complete their projects under budget.

Nonstructural Damage

As highlighted in several parts of this paper, the impact of nonstructural damage on the loss of functionality of critical facilities has been significant, leading to their inability to perform emergency and lifesaving services and, tragically, loss of lives. While seismic codes exist in Taiwan for buildings and bridges, there appears to be an absence of rational seismic provisions for nonstructural components. Ironically, seismic performance of nonstructural components can be substantially improved using rather simple and inexpensive means.

Research Needs and Recommendations

The outstanding issue identified by other team members from MCEER and NCREE related to construction practices associated with public buildings needs to be critically reviewed. Revisions and modifications appear to be necessary in order to insure quality engineering and quality construction in the future.

Also of critical importance is the nonstructural issue. Stringent seismic design and installation guidelines need to be in place to insure not only structural integrity, but also functionality of critical facilities, which require protecting nonstructural components, as well as structures, from seismic damage under strong ground shaking as experienced in the Chi-Chi earthquake. A systematic development of these guidelines involves the following:

- Review and improve current design and installation practices in nonstructural components.
- Develop effective retrofit strategies for nonstructural components in existing critical facilities.
- Develop effective implementational procedures for existing facilities and new constructions.

Endnotes

[1] The emergency generators also failed. They were located on the second floor of a separate building and, due to amplified acceleration on that floor, major components broke loose and rendered them inoperable.

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Highway Bridge Seismic Design: Summary of FHWA/MCEER Project on Seismic Vulnerability of New Highway Construction

by Ian M. Friedland

Research Objectives

The FHWA-sponsored project titled Seismic Vulnerability of New Highway Construction (MCEER Project 112), which was completed in 1998, performed studies on the seismic design and vulnerability analysis of highway bridges, tunnels, and retaining structures. Extensive research was conducted to provide revisions and improvements to current design and detailing approaches and national design specifications for highway bridges. The program included both analytical and experimental studies, and addressed seismic hazard exposure and ground motion input for the U.S. highway system; foundation design and soil behavior; structural importance, analysis, and response; structural design issues and details; and structural design criteria.

In the fall of 1992, MCEER commenced work on a comprehensive research program sponsored by the Federal Highway Administration to evaluate the seismic vulnerability of new and existing highway construction. One part of this two-contract program, Seismic Vulnerability of New Highway Construction (Project 112), resulted in a series of special studies related to seismic design of highway bridges, tunnels, and retaining structures, in order to develop technical information upon which new seismic design approaches and details, and future specifications, could be based. The project was prompted in part because significant progress had been made over the last two decades in several key areas, including improved knowledge of: (1) seismic hazard and risk throughout the United States, (2) geotechnical earthquake engineering, and (3) seismically resistant design. At the time Project 112 was initiated, however, there were still many gaps in basic knowledge, and some of the recently-developed information and data required additional study before they could be applied directly to highway engineering applications nationwide. Consequently, Project 112 resulted in a series of analytical and experimental studies related to the seismic analysis, design, and performance of bridges, tunnels, and foundations.

Sponsors

Federal Highway Administration

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***Ian M. Friedland**, Associate Director for Development, Applied Technology Council; formerly Assistant Director for Bridges and Highways, Multidisciplinary Center for Earthquake Engineering Research*

Key Subcontract Institutions

- *University at Buffalo*
- *Applied Technology Council*
- *Brigham Young University*
- *Dynamic Isolation Systems Inc.*
- *Earth Mechanics Inc.*
- *Geomatrix Consultants Inc.*
- *Imbsen & Associates Inc.*
- *Modjeski and Masters Consulting Engineers*
- *Princeton University*
- *Rensselaer Polytechnic Institute*
- *University of Nevada, Reno*
- *University of Southern California*

The research conducted under Project 112 had a national focus and was intended, in large part, to address differences in seismicity, bridge types, and typical design details between eastern or central U.S. bridges, and those that had been previously studied in California and the western U.S. In particular, unlike the western U.S., design strategies used in the eastern and central U.S. need to reflect the statistical probability that an earthquake significantly larger than the "design" earthquake can occur. In many cases, it was noted that California design practice required significant modification before being implemented in the eastern and central U.S. due to these differences in seismicity and bridge construction type.

A range of special studies were carried out that encompassed research on: seismic hazard; foundation properties, soil properties, and soil response; and the response of structures and systems (see Figure 1). These studies were conducted by a consortium of researchers, coordinated by MCEER. The consortium included a variety of academic institutions and consulting engineering firms, bringing together more than 20 earthquake and bridge engineers and scientists. This consortium provided a balance between researchers and practicing professionals from the eastern, central, and western U.S.

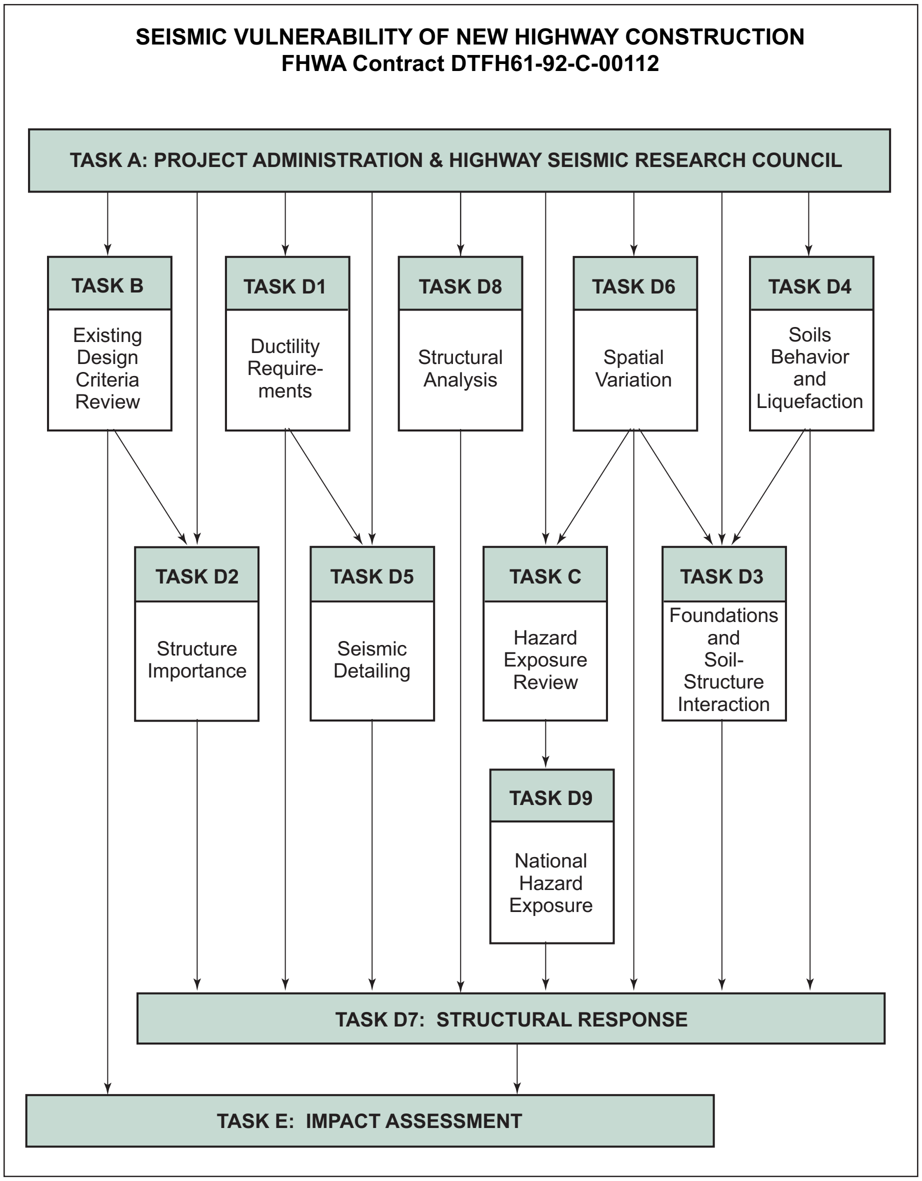
It is anticipated that current specifications for the seismic design of bridges will be revised, and that new seismic design guidelines will be prepared for other highway system components, in part on the basis of this work.

This paper summarizes some of the important results of the research conducted under the program. It draws heavily from a review of the program's research results and expected impacts (Rojahn et al., 1999) and discusses issues raised in the report.

Seismic Hazard Exposure and Ground Motion Input

The research in the area of seismic hazard exposure focused on the evaluation of alternative approaches for portraying and representing the national seismic hazard exposure in the U.S., quantifying and developing an understanding of the effects of spatial variation of ground motion

It is anticipated that the results of this program will be considered in future design specification development work. Specifically, the AASHTO-sponsored National Cooperative Highway Research Program (NCHRP) initiated NCHRP Project 12-49, "Development of Comprehensive Bridge Specifications and Commentary" in the fall of 1998. The objective of NCHRP Project 12-49, which is being conducted by a joint venture between MCEER and the Applied Technology Council, is to develop new bridge seismic design specifications, commentary, and design examples, which can be incorporated into the AASHTO *LRFD Bridge Design Specifications* in the near future. Much of the basis for the specification changes that will be recommended under NCHRP Project 12-49 are expected to be drawn from the results of the work conducted under this FHWA contract.



■ Figure 1. Special Studies Conducted by MCEER under Project 112

Links to Current Research

- *Seismic Vulnerability of Existing Construction (Project 106)*
- *Seismic Vulnerability of the National Highway System (TEA-21 Project)*
- *National Cooperative Highway Research Program (NCHRP) Project 12-49*

on the performance of highway structures, and the development of inelastic design spectra for assessing inelastic deformation demands.

Representation of Seismic Hazard Exposure

Research in the area of seismic hazard exposure representation was conducted in order to:

- explore a number of important issues involved in national representations of seismic ground motions for design of highway facilities;
- recommend future directions for national seismic ground motion representation, especially for use in nationally applicable guidelines and specifications such as the AASHTO seismic design provisions for bridges; and
- identify areas where further development and/or research are needed to define ground motion

Collaborative Partners

Design and Performance Criteria

- *Review Existing Design Criteria and Philosophies,* ***C. Rojahn, R. Mayes, I. Buckle***
- *Impact Assessment and Strawman Guidelines for the Seismic Design of Highway Bridges,* ***C. Rojahn, R. Mayes, I. Buckle***

Seismic Hazard and Exposure

- *Compile and Evaluate Maps and Other Representations, and Summarize Alternative Strategies for Portraying the National Hazard Exposure of the Highway System,* ***M. Power***
- *Recommended Approach for Portraying the National Hazard Exposure,* ***M. Power***

Ductility Requirements

- *Establish Representative Pier Types for Comprehensive Study – Eastern & Western U.S.,* ***J. Kulicki, R. Imbsen***
- *Physical and Analytical Modeling to Derive Overall Inelastic Response of Bridge Piers,* ***J. Mander***
- *Derive Inelastic Design Spectra,* ***R. Imbsen***

Structure Importance

- *Evaluation of Structure Importance,* ***J. Kulicki***

representation for the design of guidelines and specifications.

The ground motion issues that have emerged in recent years as potentially important to the design of highway facilities and that were considered in this work included consideration of the following:

- What should be the basis for the national seismic hazard portrayal of highway facilities, and how should this be implemented in terms of design values?
- Can or should energy or duration be used in a design procedure?
- How should site effects be characterized for design?
- Should vertical ground motions be specified for design?
- Should near-source ground motions be specified for design?

The following summarize the key elements of each issue and conclusions of the research.

Seismic Hazard Portrayal

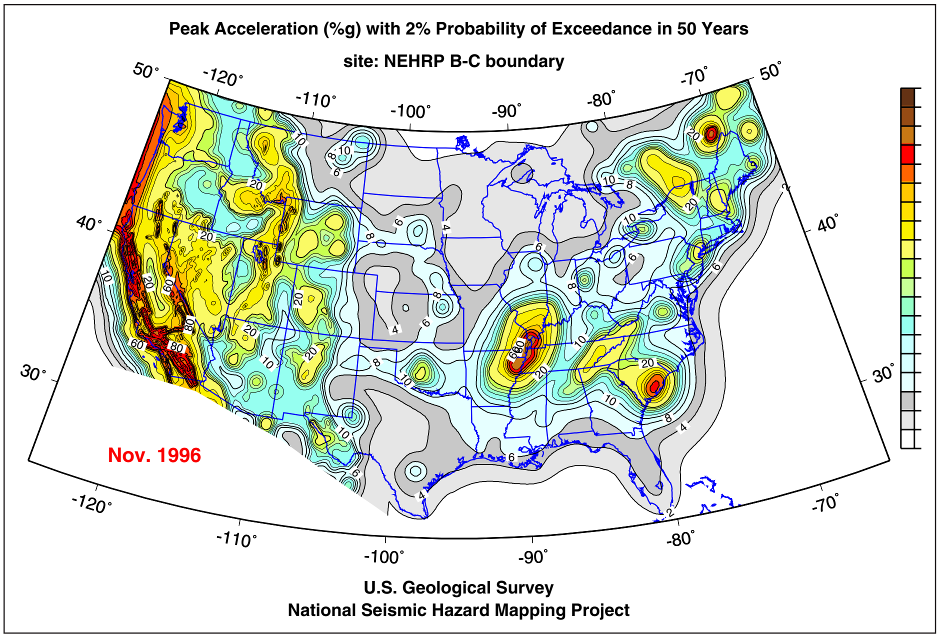
In 1996, the U.S. Geological Survey (USGS) developed new seismic ground shaking maps for the contiguous U.S. These maps depict contours of peak ground acceleration (PGA) and spectral accelerations (SA) at 0.2, 0.3, and 1.0 second (for 5% critical damping) of ground motions on rock for probabilities of exceedance (PE) of 10%, 5%, and 2% in 50 years, corresponding to return periods of approximately 500, 1000, and 2500 years, respectively.

The research considered whether the new USGS maps should replace or update the maps currently in AASHTO, which were developed by the USGS in 1988. The key issue regarding whether the new USGS maps should provide a basis for the national seismic hazard portrayal for highway facilities is the degree to which they provide a scientifically improved representation of seismic ground motion. Based on an analysis of the process of developing the maps, the inputs to the mapping, and the resulting map values, it was concluded that these new maps represent a major step forward in the characterization of national seismic ground motion. The maps are in substantially better agreement with current scientific understanding of seismic sources and ground motion attenuation throughout the U.S. than the current AASHTO maps. It was therefore concluded that the new USGS maps should provide the basis for a new national seismic hazard portrayal for highway facilities.

The issue of an appropriate probability level or return period for design ground motions based on the new USGS maps was also examined. Analyses were presented showing the effect of probability level or return period on ground motions and comparisons of ground motions from the new USGS maps and the current AASHTO maps. The research recommended that, for design of highway facilities against collapse, consideration should be

Technical Report: Seismic Hazard Exposure

- **Proceedings of the FHWA/MCEER Workshop on the National Representation of Seismic Ground Motion for New and Existing Highway Facilities, edited by I.M. Friedland, M.S. Power and R.L. Mayes, NCEER-97-0010.**



U.S. Geological Survey

■ Figure 2. Peak ground accelerations represented as a percentage of g with a 2% probability of exceedance in 50 years

given to adopting probability levels for design ground motions that are lower than the 10% probability of exceedance in 50 years that is currently in AASHTO. This is consistent with proposed revisions to the 1997 NEHRP provisions for buildings, in which the new USGS maps for a probability of exceedance of 2% in 50 years (2,500 year return period) have been adopted as a collapse-prevention design basis. It was determined that, from a deterministic standpoint, the 2%/50 year maps provided a good representation of the acceleration and force levels that had occurred in the 1800s in both the New Madrid seismic zone and in Charleston, South Carolina.

Consideration of Energy or Duration

At the present time, the energy or duration of ground motions is not explicitly recognized in the design process for bridges or buildings, yet many engineers are of the opinion that the performance of a structure may be significantly affected by these parameters, in addition to the response spectral characteristics of the ground motion. As a result, it was concluded that some measure of the energy of ground motions is important to the response of a bridge, but, at present, there is no accepted design procedure to account for energy. It was recommended that research in this area should be continued to develop energy-based design methods that can supplement current elastic-response-spectrum-based design methods. It was also concluded that energy rather than duration is the fundamental parameter affecting structural behavior.

Characterization of Site Effects

At a Site Effects Workshop held in 1992 at the University of Southern California (USC), a revised quantification of site effects on response spectra and revised definitions of

Collaborative Partners (cont.)

Foundations and Soil-Structure Interaction

- *Compile Data and Identify Key Issues,* ***I.P. Lam***
- *Abutment and Pile Footing Studies by Centrifuge Testing,* ***R. Dobry***
- *Develop Analysis and Design Procedures for Abutments,* ***I.P. Lam, G. Martin***
- *Develop Analysis and Design Procedures for Retaining Structures,* ***R. Richards, K. Fishman***
- *Develop Analysis and Design Procedures for Pile Footings,* ***I.P. Lam, G. Martin***
- *Develop Analysis and Design Procedures for Drilled Shafts,* ***I.P. Lam, G. Martin***
- *Develop Analysis and Design Procedures for Spread Footings,* ***G. Gazetas***
- *Performance and Sensitivity Evaluation, and Guideline Development,* ***P. Lam, R. Dobry, G. Martin***

Soil Behavior and Liquefaction

- *Site Response Effects,* ***R. Dobry***
- *Identification of Liquefaction Potential,* ***T.L. Youd***
- *Development of Liquefaction Mitigation Methodologies,* ***G. Martin***
- *Design Recommendations for Site Response and Liquefaction Mitigation,* ***G. Martin***

Collaborative Partners (cont.)

Special Seismic Detailing

- *Capacity Detailing of Columns, Walls, and Piers for Ductility and Shear,* ***J. Mander, R. Imbsen, J. Kulicki, M. Saiidi***
- *Capacity Detailing of Members to Ensure Elastic Behavior,* ***J. Mander, R. Imbsen, J. Kulicki***
- *Detailing for Structural Movements - Bridges,* ***R. Imbsen, J. Kulicki***
- *Detailing for Structural Movements - Tunnels,* ***M. Power***
- *Structural Steel and Steel/Concrete Interface Details,* ***J. Kulicki***

Spatial Variation of Ground Motion

- *Spatial Variation of Ground Motion,* ***M. Shinozuka, G. Deodatis***

Structural Response

- *Effects of Vertical Acceleration on Structural Response,* ***M. Button***

Structural Analysis

- *Review Existing Analytical Methods, and Identify and Recommend Analytical Procedures Appropriate for Each Structure Category and Hazard Exposure,* ***I. Buckle, J. Mander***

site categories were proposed. Subsequently, these revised site factors and site categories were adopted into the 1994 NEHRP provisions and the 1997 Uniform Building Code (UBC). Since the development of these revised site factors, two significant earthquakes occurred (the 1994 Northridge and 1995 Kobe earthquakes) which provided substantial additional data for evaluating site effects on ground motions, and research using these data has been conducted.

The site factors and site categories in the current AASHTO specifications are those that were superseded by the USC Workshop recommendations in the NEHRP Provisions and the UBC. Under this research, the question was whether the USC Workshop recommendations should be utilized in characterizing ground motions for highway facilities design and whether they should be modified to reflect new data and new knowledge since the 1992 Workshop. The most significant differences between the USC Workshop recommendations and the previous site factors (those currently in AASHTO) are: (1) the revised site factors include separate sets of factors for the short-period and long-period parts of the response spectrum, whereas the previous site factors were only for the long-period part; (2) the revised site factors are dependent on rather than independent of intensity of ground shaking, reflecting soil nonlinear response; and (3) the revised site factors are larger (i.e., show a greater soil response amplification) than the previous factors at low levels of shaking, and are appropriate to the lower-seismicity regions in the U.S.

It was found that the post-Northridge and post-Kobe earthquake research conducted to date was supportive of the site factors derived in the 1992 USC Workshop, although revisions to these factors might be considered as further research findings on site effects become available.

Vertical Ground Motions

At present, the AASHTO specifications do not contain explicit requirements to design for vertical accelerations. Ground motion data from many earthquakes in the past 20 years have shown that, in the near-source region, very high short-period vertical spectral accelerations can occur. For near-source moderate-to-large magnitude earthquakes, the rule-of-thumb ratio of 2/3 between vertical and horizontal spectra is a poor descriptor of vertical ground motions. At short periods, the vertical-to-horizontal spectral ratios can substantially exceed unity, whereas at long periods, a ratio of two-thirds may be conservative. It was demonstrated that the profession's current understanding and ability to characterize near-source vertical ground motions is good, especially in the western U.S. where the near-source region is better defined (i.e., near mapped-active faults). It was also demonstrated that high vertical accelerations as may be experienced in the near-source region can significantly impact bridge response and design requirements in some cases. On the basis of these findings, it was concluded that vertical ground motions should be considered in bridge design in higher seismic zones for certain types of bridge construction. However, specific design criteria and procedures still need to be developed for certain bridge types.

Near-source Ground Motions

The characteristics and the effects of near-source ground motions on bridge response were examined. As the distance to an earthquake source decreases, the intensity of ground motions increases, and this increase in ground motion intensity is incorporated in new USGS maps. However, in addition to their higher intensity, near-source ground motions have certain unique characteristics that are not found at greater distances. The most significant characteristic appears to be a large pulse of long-period ground motions when an earthquake rupture propagates toward a site. Furthermore, this pulse is larger in the direction perpendicular to the strike of the fault than in the direction parallel to the strike. This characteristic of near-source ground motions has been observed in many earthquakes, including most recently in the Northridge, Kobe, Turkey and Taiwan earthquakes. Preliminary analyses of bridge response indicate that near-source ground motions may impose unusually large displacement demands on bridge structures. It was therefore concluded that traditional ground motion characterizations (i.e., response spectra) may not be adequate in describing near-source ground motions, because the pulsive character of these motions may be more damaging than indicated by the response spectra of the motions. Recommendations include the need for additional research to evaluate more fully the effects of near-source ground motions on bridge response and to incorporate these effects in code design procedures. Until adequate procedures are developed, consideration should be given to evaluating bridge response using site-specific analyses with representative near-source acceleration time histories.

Spatial Variation of Ground Motion

The objective of the research in this area was to develop procedures for determining spectrum compatible time histories that adequately represent spatial variations in ground motion including the effects of different soil conditions. The procedures were then used to examine the effects of spatial variability on critical response quantities for typical structures.

The methodology used a spectral representation to simulate stochastic vector processes having components corresponding to different locations on the ground surface. An iterative scheme was used to generate time histories compatible with prescribed response spectra, coherency, and duration of motion. Analysis results for eight example bridges were tabulated, showing the relative ductility demand ratio for column flexure due to seismic wave propagation spatial effects. In general, there was about a 10% maximum increase when using

Summary Report: Spatial Variation of Ground Motion

- **Effect of Spatial Variation of Ground Motion on Highway Structures, by M. Shinozuka and G. Deodatis, Agency Final Report.**

■ Figure 3. Research in spatial variation of ground motion included case studies of the SR14/I-5 interchange and other bridges damaged during the Northridge, California earthquake. Further research is needed to define the importance of these effects and to develop simplified design procedures for a broad range of bridge configurations.

Photographs courtesy of I.G. Buckle

linear analysis, and a 25% maximum increase when using nonlinear analysis for bridges up to 1000 feet in length. Results were also tabulated for relative opening and closing at expansion joints for bridges with superstructure hinges. In general, the relative joint opening movement was up to two times when using either linear or nonlinear analysis for bridges up to 1000 feet in length. However, the conducted analyses were too limited in scope on which to base specific guidance for a large variety of bridge types and conditions at this time, and it was recommended that further studies are required before code language could be developed.

Inelastic Design Spectrum

The research in this area had the objective of developing inelastic response spectrum which would allow designers to assess the inelastic deformation demands, ultimately leading to improved seismic performance for new bridge construction. The spectrum are being derived for nationwide use, accommodating different seismic environments and site soil conditions. They are also being developed for design applications, by accounting for scattering and variabilities that exist in real earthquake ground motions and for nonlinear structural response.

Under the current program, the research has not progressed to the point where its results are ready for implementation. When complete, it is likely to have a major impact on seismic design code requirements for bridges, as inelastic spectra will be one of the key elements in a displacement-based or energy-based design procedure. Future work in this area should include procedures for determining inelastic spectra at a specific site. The current state of research provides an approximate method that starts with an elastic spectrum rather than time history; as time histories for the eastern U.S. are currently lacking, this approach will have an obvious appeal.

Foundation Design and Soil Behavior

Research tasks in this area investigated and improved criteria for the design and analysis of major foundation elements including abutments, retaining walls, pile and spread footings, and drilled shafts. In addition, work was performed on soil liquefaction and lateral spread identification and mitigation.

Abutments and Retaining Walls

Research on bridge abutments and retaining walls focused on modeling alternatives, clarifying the process of design for service loads versus seismic loading, and providing simplified approaches for design that incorporate key issues affecting seismic response. The research also attempted to provide a new procedure for determining the seismic displacements of abutments and retaining walls founded on spread footings, which differ from current procedures by addressing mixed-mode behavior (i.e., including rotation due to bearing capacity movement and sliding response). Both experimental and analytical studies were conducted; the experimental studies included sand-box experiments on a shaking table and centrifuge models. Results of this research included:

- Development of a simplified procedure for estimating abutment stiffness. A key element of this approach is determining the portion of the wall that can be relied on to mobilize backfill resistance.
- Extending current AASHTO design procedures to the more general case of translation and rotation of walls and abutments. The results are presented in a manner that will allow the methods to be easily introduced into a future code revision. The new procedures will be of greatest use for free-standing gravity walls and for active mode abutment and wall movements.
- Consideration of passive loading conditions for walls and abutments. Current AASHTO provisions only address active loading conditions. Since passive loading can result in forces that are up to 30 times those for active conditions, there is a strong possibility that many bridges will not develop passive resistance without abutment damage.

Pile and Spread Footings, and Pile Groups

Studies on pile footings, spread footings, and pile groups included experimental and analytical research which was intended to: (a) provide improved understanding of

Technical and Summary Reports: Foundation Design and Soil Behavior

- **Foundations and Soils - Compile Data and Identify Key Issues, by I.P. Lam, Agency Final Report.**
- **Centrifuge Modeling of Cyclic Lateral Response of Pile-Cap Systems and Seat-Type Abutments in Dry Sands, by A. Gadre and R. Dobry, MCEER-98-0010.**
- **Modeling of Bridge Abutments in Seismic Response Analysis of Highway Bridges, I.P. Lam and M. Kapuskar, Agency Final Report.**
- **Seismic Analysis and Design of Bridge Abutments Considering Sliding and Rotation, by K.L. Fishman and R. Richards, Jr., NCEER-97-0009.**
- **Modeling of Pile Footings and Drilled Shafts for Seismic Design, by I.P. Lam, M. Kapuskar and D. Chaudhuri, MCEER-98-0018.**
- **Development of Analysis and Design Procedures for Spread Footings, by G. Gazetas, G. Milonakis and A. Nikolaou, Agency Final Report.**
- **Synthesis Report on Foundation Stiffness and Sensitivity Evaluation on Bridge Response, by I. P. Lam, G.R. Martin, and M. Kapuskar, Agency Final Report.**

Web Sites

MCEER Highway Project
http://mceer.buffalo.edu/research/HighwayPrj/default.html

MCEER Publications
http://mceer.buffalo.edu/publications/default.asp

"Among the major studies conducted under this project was a review, synthesis, and improvement to recent developments in simplified procedures for evaluating the liquefaction resistance of soils, and the compilation and evaluation of case studies and procedures for ground liquefaction mitigation."

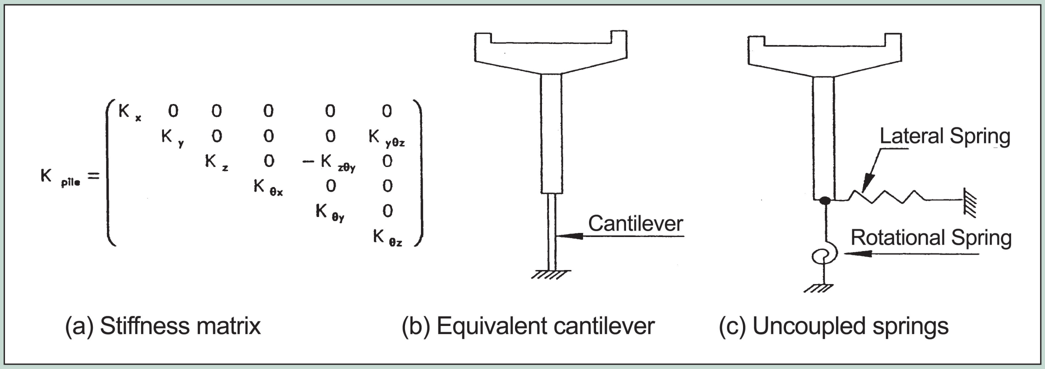
the lateral response of pile-cap foundations; (b) evaluate the influence of modeling parameters on estimated displacement and force demands; (c) recommend methods for characterizing the stiffness of pile footings; (d) quantify the importance of radiation damping and kinematic interaction on response; and (e) evaluate conditions under which uplift becomes significant and how best to model uplift in a design procedure. Results from these studies included the following:

- For pile-cap systems, the research demonstrated that design procedures should use simple additions for the contribution from the base, side and active/ passive ends when estimating the lateral capacity of embedded spread footings in dense sand, along with elastic solutions with an equivalent linear soil shear modulus at shallow depths to estimate the secant stiffness of the footing. This effectively confirms that existing procedures can be used to obtain reasonable approximations of pile-cap foundation response, as long as consideration is given to the levels of deformation and embedment for the system.
- Axial and lateral loading response and stiffness characteristics are important parameters for the design of single piles and pile groups, although such information is not currently addressed in the AASHTO provisions. Axial response often controls rocking response of a pile group. New procedures and simplified stiffness charts are provided for determining the lateral load-deflection characteristics of single piles and groups.
- Nonlinear load-deflection analyses illustrate the sensitivity of results to uncertainties in p-y stiffness, gapping, pile-head fixity, bending stiffness parameters, and embedment effects. The analyses have demonstrated that load-deformation response is more affected by input variations than by the moment within the pile.
- For spread footings without uplift, the research demonstrated that (a) ignoring soil-structure interaction reduces the fundamental period of the system, resulting in higher accelerations; (b) increasing the effectiveness of embedment increases radiation damping and reduces the fundamental period of the system; and (c) neglecting radiation damping has only a minor effect on the system. Uplift of the spread footing results in a softer mode of vibration for the system, with increasing fundamental period as the amount of uplift increases.

Drilled Shafts

Research on drilled shafts was conducted in order to provide information on the influence of modeling procedures on the response of the structure, evaluate the effects of modeling on estimated displacement and force demands on the foundation, and to summarize methods for characterizing the response of drilled shaft foundations, including their limitations. Results of this work included the following:

- Foundation stiffness has been shown as a key parameter and contributor to the dynamic response of the structure, necessitating realistic estimates and appropriate integration into a



■ Figure 4. Researchers reviewed three procedures for representing foundation stiffness in the modeling process: (a) coupled foundation stiffness matrix, (b) equivalent cantilever approach; and (c) uncoupled base-spring model.

detailed structural analysis. The response of a soil-foundation system to load is nonlinear; however, for practical purposes, an equivalent linear representation is normally used.

- Guidance is provided on the development of equivalent linear and nonlinear stiffness values, and the importance and sensitivity of foundation geometry and boundary conditions at the shaft head are identified. A key conclusion is that realistic representation of pile-head fixity can lead to a much more economical design.
- The p-y approach is recognized as the most common method of analyzing the nonlinear response of the shaft to lateral load. Parameters that must be considered include the effects of soil property variation, degradation effects, embedment, gapping, and scour effects.

Liquefaction Processes and Liquefaction Mitigation Methodologies

A significant amount of research was conducted under the MCEER Highway Project on liquefaction processes, screening for liquefaction potential, and the development and/or improvement of liquefaction mitigation methodologies. Much of this work was conducted under a companion FHWA contract on the seismic vulnerability of existing transportation infrastructure (FHWA Contract DTFH61-92-C-00106), but much of it is appropriate for both new design and existing structure evaluation. Among the major studies conducted under this project was a review, synthesis, and improvement to recent developments in simplified procedures for evaluating the liquefaction resistance of soils, and the compilation and evaluation of case studies and procedures for ground liquefaction mitigation. Results of this research included:

- Identification of a consensus simplified procedure for evaluating liquefaction resistance. Minor modifications for the determination of the stress reduction factor used in the calculation of the cyclic stress ratio were recommended, which allow the stress reduction factor to be

"Structural importance, analysis, and response studies provided a synthesis of current systems and details commonly used to provide acceptable seismic performance in various states and regions."

Technical and Summary Reports: Soil Behavior and Liquefaction

- **Site Factors and Site Categories in Seismic Codes, by R. Dobry, R. Ramos and M. Power, MCEER-99-0010.**
- **Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils, edited by T.L. Youd and I.M. Idriss, NCEER-97-0022.**
- **Development of Liquefaction Mitigation Methodologies/Ground Densification Methods, by G. Martin, Agency Final Report.**
- **Design Recommendations for Site Response and Liquefaction, by G. Martin, Agency Final Report.**

calculated to depths greater than 30 meters.

- Identification of the latest procedures for determining cyclic resistance ratios (CRR) using cone penetration test (CPT) procedures. One of the primary advantages of CPT is the consistency and repeatability of the method. Plots for determining the liquefaction resistance directly from CPT data, rather than converting to an equivalent standard penetration test (SPT) N-value, are presented. Procedures are also provided for correcting CPT data based on overburden pressures, fines contents, and for thin layers.
- Plots for determining CRR from shear wave velocity data have been prepared, and procedures for correcting shear wave velocity data due to overburden stress and fines content are explicitly given.
- Methods which have been employed successfully for liquefaction mitigation include deep dynamic compaction, deep vibratory densification, gravel drains, permeation grouting, replacement grouting, soil mixing, and micro blasting. Parameters and limitations for each of these approaches are summarized, including typical treatment depths and applicable soil types.
- Flow charts for assessing ground deformations for pre- and post-treatment conditions were developed. These are accompanied by recommendations for preferred ground improvements methods based on differing site conditions.
- Development of rapid screening procedures for liquefaction susceptibility of soils and foundations.

Structural Importance, Analysis and Response

Studies were conducted in order to provide a definition of structural importance, which is necessary in the development of design and performance criteria, and to evaluate methods of analysis and structural response. Structural importance analysis response studies also provided a synthesis of current systems and details commonly used to provide acceptable seismic performance in various states and regions. Among the findings of these studies were the following:

- Provisions employed by the California Department of Transportation (Caltrans) were generally more rigorous than those used by the majority of states (who primarily used current AASHTO provisions). However, adoption of Caltrans' design provisions nationwide would likely complicate designs and add to construction cost; this may be unjustified for many low-to-moderate seismic hazard states. In addition, if Caltrans' experience is to be adopted nationally, some adjustments are required in order to accommodate bridge types and details commonly used elsewhere.

- Studies that were conducted on the application of advanced modeling methods for concrete bridge components provided a computer program which determines moment-curvature and force-deflection characteristics for reinforced concrete columns; excellent correlation was obtained between analytical and experimental test results for these components.
- A refined model to simulate the hysteretic behavior of confined and unconfined concrete in both cyclic compression and tension was developed. The model includes consideration of the nature of degradation within partial hysteresis looping and the transition between opening and closing cracks.
- A study on energy and fatigue demands on bridge columns resulted in design recommendations for the assessment of fatigue failure in reinforcing steel, based on the results of nonlinear dynamic analyses. This methodology incorporates traditional strength and ductility considerations with the fatigue demands. Based on parametric studies, it was concluded that low cycle fatigue demand is both earthquake and hysteretic model dependent.
- Based on an examination of existing and proposed methods for quantifying bridge importance, a specific method was selected and tested against a database of bridge information commonly available within the FHWA's National Bridge Inventory. One limitation of the study is that it deliberately avoided addressing political and economic issues related to bridge seismic design criteria and highway network considerations.
- Following the Northridge earthquake, concerns were raised as to the role vertical accelerations may have played in causing damage to one or more bridges. In a study conducted to investigate the effects of vertical acceleration on bridge response, preliminary results indicate that vertical components of ground motion could have a significant effect on bridge response for structures within 10 km of the fault, and even within 20 – 30 km for certain conditions. The results of this study will be controversial when publicized; however, a far too limited study was conducted (only six example

Technical Reports: Structural Importance, Analysis and Response

- **Effect of Vertical Ground Motions on the Structural Response of Highway Bridges, by M. Button, C. Cronin and R. Mayes, MCEER-99-0007.**
- **Methodologies for Evaluating the Importance of Highway Bridges, by A. Thomas, S. Eshenaur and J. Kulicki, MCEER-98-0002.**

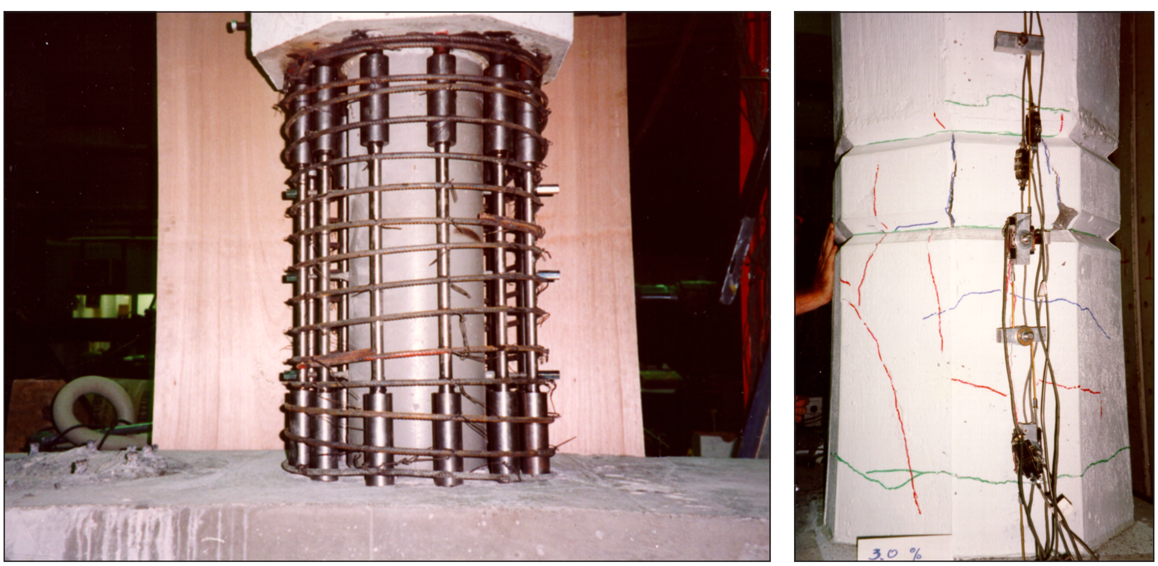
bridges were analyzed) in order to provide definitive guidance at this time.

- In a study which investigated the applicability of simplified analysis methods to various types and configurations of bridges, a number of design and analysis limitations were identified. Parameters evaluated included curvature, span length ratio, pier height, skew and span connectivity. Based on the analyses, a definition for "regular" bridges and for which simplified methods are appropriate was developed. In general, regular bridges must have three or fewer spans, variation of mass distribution between adjacent spans varying by less than 50%, a maximum ratio between adjacent pier stiffnesses in the longitudinal and transverse directions not greater than 4.0, and a subtended angle in plan not greater than 90°.

Structural Design Issues and Details

A number of studies were conducted in order to improve design procedures and structural detailing for highway structures, but the focus was primarily on bridges; one study also examined movement detailing for tunnels. These studies looked at issues of capacity detailing for ductility, elastic behavior, and movements. Among the results of this research were the following:

- A design concept termed Damage Avoidance Design (DAD) was developed which attempts to avoid plastic hinging in columns, thereby avoiding loss of service for important bridges following a major earthquake. The concept evaluated details which provide for rocking of columns and piers, which rotate about their ends but are restrained from collapse through gravity and the optional



Undamaged specimen (prior to testing) *Damaged specimen (after testing)*

Photographs courtesy of J. Mander

■ Figure 5. Researchers developed a new design concept called Control and Repairability of Damage (CARD) for bridge column hinges. The CARD method controls damage while accommodating large earthquake-induced deformations.

use of central unbonded post tensioning in the column core.

- A second design concept termed Control and Repairability of Damage (CARD) was also developed, which provided structural and construction details for reinforced concrete columns that provide replaceable or renewable sacrificial plastic hinge zone components. In this concept, the hinge zones are deliberately weakened and regions outside the hinge zones are detailed to be stronger than the sacrificial (fuse) zone; the remaining elements of the structure then remain elastic during strong earthquakes.
- In a study on transverse reinforcing requirements for concrete bridge columns and pier walls, it was found that the current AASHTO requirements could be lowered by up to 50% while still achieving displacement ductilities of 4 to 7 for bridges in low to moderate seismic zones. An

"Studies in structural design issues and details looked at capacity detailing for ductility, elastic behavior, and movements."

Technical and Summary Reports: Structural Design Issues and Details

- **Application of Simplified Methods of Analysis to the Seismic Design of Bridges, by J.H. Kim, M.R. Button, J.B. Mander and I.G. Buckle, Agency Final Report.**
- **Establish Representative Pier Types for Comprehensive Study: Eastern U.S., by J. Kulicki and Z. Prucz, NCEER-96-0005.**
- **Establish Representative Pier Types for Comprehensive Study: Western U.S., by R.A. Imbsen, R.A. Schamber, and T.A. Osterkamp, NCEER-96-0006.**
- **Seismic Resistance of Bridge Piers Based on Damage Avoidance Design, by J.B. Mander and C.T. Cheng, NCEER-97-0014.**
- **Seismic Design of Bridge Columns Based on Control and Repairability of Damage, by C.T. Cheng and J.B. Mander, NCEER-97-0013.**
- **Capacity Design and Fatigue Analysis of Confined Concrete Columns, by A. Dutta and J.B. Mander, MCEER-98-0007.**
- **Capacity Design of Bridge Piers and the Analysis of Overstrength, by J.B. Mander, A. Dutta, and P. Goel, MCEER-98-0003.**
- **Seismic Energy Based Fatigue Damage Analysis of Bridge Columns: Part I – Evaluation of Seismic Capacity, by G.A. Chang and J.B. Mander, NCEER-94-0006.**
- **Seismic Energy Based Fatigue Damage Analysis of Bridge Columns: Part II – Evaluation of Seismic Demand, by G.A. Chang and J.B. Mander, NCEER-94-0013.**
- **Ductility of Rectangular Reinforced Concrete Bridge Columns with Moderate Confinement, by N. Wehbe, M. Saiidi, D. Sanders and B. Douglas, NCEER-96-0003.**
- **Capacity Detailing of Members to Ensure Elastic Behavior, by R.A. Imbsen, R.A. Schamber, and M. Quest, Agency Final Report.**
- **Capacity Detailing of Members to Ensure Elastic Behavior - Steel Pile-to-Cap Connections, by P. Ritchie and J. M. Kulicki, Agency Final Report.**
- **Structural Steel and Steel/Concrete Interface Details for Bridges, by P. Ritchie, N. Kauhl and J. Kulicki, MCEER-98-0006.**
- **Structural Details to Accommodate Seismic Movements of Highway Bridges and Retaining Walls, R.A. Imbsen, R.A. Schamber, E. Thorkildsen, A. Kartoum, B.T. Martin, T.N. Rosser and J.M. Kulicki, NCEER-97-0007.**
- **Derivation of Inelastic Design Spectrum, by W. D. Liu, R. Imbsen, X. D. Chen and A. Neuenhofer, Agency Final Report.**
- **Summary and Evaluation of Procedures for the Seismic Design of Tunnels., by M. S. Power, D. Rosidi, J. Kaneshiro, S. D. Gilstrap, and S.-J. Chiou, Agency Final Report.**

important aspect of this work was that the end anchorages for transverse steel hoops must be maintained for the reinforcing to be effective; 90° bends on J-hooks were found to be inadequate.

- Research was conducted on moment overstrength capacity in reinforced concrete bridge columns, and a simplified method for determining column overstrength was developed. The upper-bound overstrength factors developed in this task validate prescriptive overstrength factors recommended in ATC-32, but also indicate that some factors in current Caltrans and AASHTO provisions may be too low.
- A synthesis was conducted on details commonly used to accommodate expected movements on bridges and retaining walls in the eastern and western U.S. Based on the synthesis, design and detailing recommendations were made in order to provided the basis for improved bridge design standards. The specific elements considered in this effort included restraining devices, sacrificial elements, passive energy dissipation devices, and isolation bearings. A similar effort was conducted on movement criteria and detailing for tunnels.
- For steel superstructures, a number of issues were considered, including ductility based on cross-section configuration, applicability of eccentrically-braced frames, details which allow for easy repair of steel sections following a moderate to large earthquake, anchor bolt performance under lateral uplift loads, and economical moment connection details between steel superstructures and concrete substructures.

Implementation of Research Results

In the case of highway bridges, seismic design provisions are contained in the two AASHTO bridge specifications: *LRFD Bridge Design Specifications* (2nd Edition, 1998) and Division I-A, Seismic Design, of the *Standard Specifications for Highway Bridges* (16th Edition, 1996). In 1997, AASHTO recognized that there had been many important advances in the knowledge of earthquake hazard, bridge seismic performance, and design and detailing. As a result, AASHTO charged the Transportation Research Board's AASHTO-sponsored National Cooperative Highway Research Program (NCHRP) with conducting a project to update and revise the bridge seismic design specifications contained in the *LRFD Bridge Design Specifications*.

NCHRP Project 12-49, "Comprehensive Specification for the Seismic Design of Bridges," was initiated in

Technical Reports: Implementation of Research Results

- **Impact Assessment of Selected MCEER Highway Project Research on the Seismic Design of Highway Structures, by C. Rojahn, R. Mayes, D.G. Anderson, J.H. Clark, D'Appolonia Engineering, S. Gloyd and R.V. Nutt, MCEER-99-0009.**
- **Seismic Design Criteria for Bridges and Other Structures, by C. Rojahn, R. Mayes, D.G. Anderson, J. Clark, J.H. Hom, R.V. Nutt and M.J. O'Rourke, NCEER-97-0002.**

August 1998. The objective of NCHRP Project 12-49 is to develop new specifications for the seismic design of highway bridges, which can be incorporated into the *LRFD Bridge Design Specifications*. These new specifications will be nationally applicable with provisions for all seismic zones. The results of research currently in progress or recently completed, along with current demonstrated practice, are the principal resources for this project, especially with respect to the research conducted under the FHWA-sponsored MCEER Highway Project.

The design criteria being developed under NCHRP Project 12-49 will address the following: (1) strength-based and displacement-based design philosophies; (2) single- and dual-level performance criteria; (3) acceleration hazard maps and spectral ordinate maps; (4) spatial variation effects; (5) effects of vertical acceleration;(6) site amplification factors; (7) inelastic spectra and use of response modification factors;(8) equivalent static nonlinear analysis methods; (9) modeling of soil-structure interaction and structural discontinuities at expansion joints; (10) duration of the seismic event; and (11) design and detailing requirements for both steel and concrete super- and substructures.

A joint venture of the Applied Technology Council and MCEER was selected by the NCHRP to conduct Project 12-49. In the first phase of the project, the basic philosophy for the new specifications has been developed, along with recommendations regarding representation of seismic hazard for design, and minimum design and performance criteria for typical highway bridges and bridge components. The work conducted previously by MCEER, Caltrans, and others lead directly to the development of this new specification's philosophical framework.

The time schedule for NCHRP Project calls for the completion of a first draft of the specification and commentary by the end of 1999, and subsequent drafts and revisions completed during 2000. The target date for submission of a recommended specification to AASHTO by NCHRP is early 2001.

Conclusion

As a result of a research program sponsored by the Federal Highway Administration, researchers working for the Multidisciplinary Center for Earthquake Engineering Research have developed a number of analytical tools, methods of analysis, structural design details, and specification recommendations appropriate for seismic design of highway systems and structures. The primary focus of this work has been on highway bridges, but some research on tunnels and retaining structures was also performed. The program has also resulted in recommendations regarding the representation of seismic hazard in future design codes, the performance and improvement of soils under seismic shaking, and an improved understanding of the behavior of structural systems and components under seismically-induced forces and displacements. In addition, it is likely that additional recommendations regarding the use of a performance-based design philosophy and dual-level design and performance criteria will be made to AASHTO as a result of this work.

"MCEER has developed a number of analytical tools, methods of analysis, structural design details, and specification recommendations appropriate for seismic design of highway systems and structures."

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Ground Motion Prediction Methodologies for Eastern North America

by Apostolos S. Papageorgiou

Research Objectives

The objectives of this task are both to conduct research on seismic hazards, and to provide relevant input on the expected levels of these hazards to other tasks. Other tasks requiring this input include those dealing with inventory, fragility curves, rehabilitation strategies and demonstration projects. The corresponding input is provided in various formats depending on the intended use: either as peak ground motion parameters and/or response spectral values for given magnitude, epicentral distance and site conditions; or as time histories for scenario earthquakes that are selected based on the disaggregated seismic hazard mapped by the U.S. Geological Survey (Frankel, 1995; Harmsen, et al. 1999) and used in the *NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings* (BSSC, 1998).

Prediction of the seismic hazard in tectonic regions of moderate-to-low seismicity is a difficult task because of the paucity of data that are available regarding such regions. Specifically, the problem of earthquake ground motion prediction in Eastern North America (ENA) is hindered by two factors: (1) the causative structures of seismicity in ENA are largely unknown, and (2) the recorded strong motion database is very limited (if it exists at all), especially for moderate to large magnitude ($M_W \geq 6$) events virtually for all epicentral distances. For these reasons, prediction of strong ground motion in ENA makes the use of well-founded physical models imperative. These models should, among other things, provide the means to make extrapolations to large magnitudes and/or short distances with confidence. [This is in contrast to the western U.S. (WUS), where the abundance of recorded strong motion data makes prediction of ground motion by empirical methods a viable procedure].

Another distinct feature of the tectonic region of ENA is related to its *scattering* and *absorption* characteristics. As pointed out by Aki (1982), because of the extremely low attenuation in ENA as compared to California (an order of magnitude difference in the quality factor Q at around 1 Hz),

Sponsors

National Science Foundation, Earthquake Engineering Research Centers Program

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Links to Current Research

MCEER Program 1: Seismic Evaluation and Retrofit of Lifeline Systems
MCEER Program 2: Seismic Retrofit of Hospitals

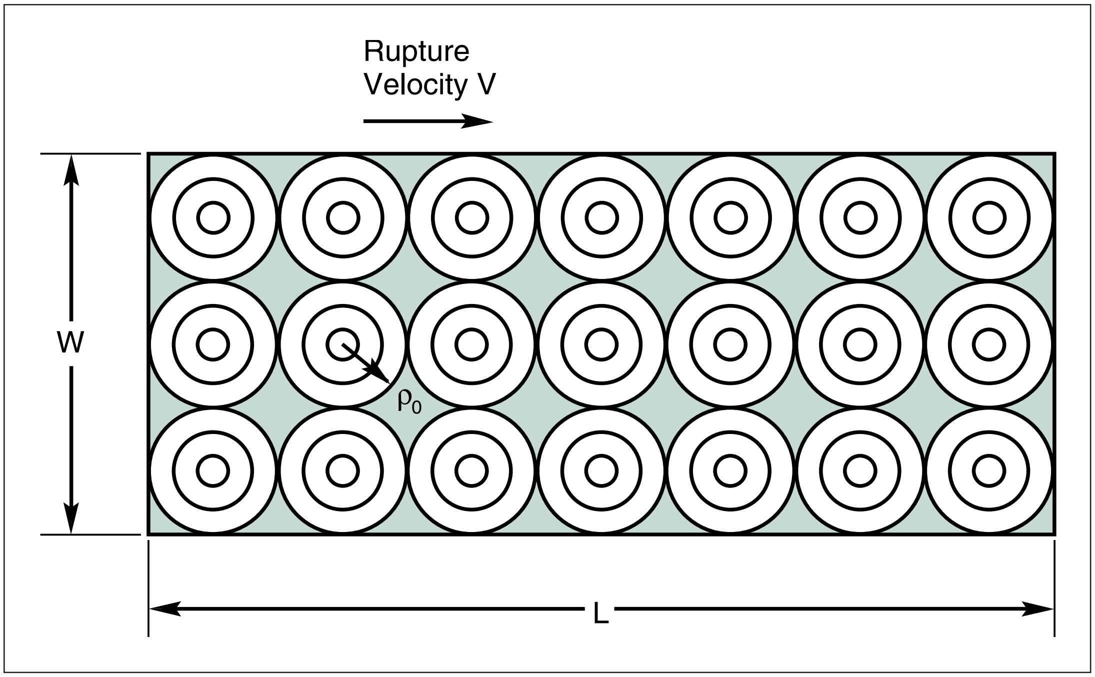
seismic waves traveling along multitudes of paths through the heterogeneous lithosphere of the Earth arrive at an observation site with significant amplitude. This effect tends to make the duration of shaking longer, although the source duration for ENA earthquake sources is shorter. It is therefore very important for ground motion synthesis purposes to study the scattering and absorption characteristics of the lithosphere in ENA.

Strong Motion Synthesis Techniques

Our task is the synthesis of strong ground motion input over the entire frequency range of engineering interest. There are two approaches for modeling earthquake strong motion:

1. The *Stochastic (Engineering) Approach,* according to which, earthquake motion (acceleration) is modeled as Gaussian noise with a spectrum that is either empirical [e.g., band-limited white-noise (e.g., Cornell, 1964; Shinozuka and Sato, 1967), Kanai-Tajimi type of spectrum (e.g., Housner and Jennings, 1964) or variations of it such as the Clough-Penzien type of spectrum (Clough and Penzien, 1993)], or a spectrum that is based on a physical model (such as the *"Specific Barrier Model"*) of the earthquake source. This approach is expedient and therefore cost-effective, and has been extensively used in the past by engineers (using empirical spectra) and recently by seismologists (using spectra derived from physical models of the source). The intent of this approach to strong motion simulation is to capture the essential characteristics of high-frequency motion at an average site from an average earthquake of specified size. Phrasing this differently, the accelerograms artificially generated using the *Engineering Approach* do not represent any specific earthquake, but embody certain average properties of past earthquakes of a given magnitude.
2. The *Kinematic Modeling Approach* was developed by seismologists. In this approach, the rupture process is modeled by postulating a slip function on a fault plane and then using the *Elastodynamic Representation Theorem* to compute the motion. There are several variant forms of this approach depending on whether the *slip function* (i.e., the function that describes the evolution of slip on the fault plane) and/or the

The user community for this research is both academic researchers and practicing engineers who may use the seismic input generated by the synthesis techniques that are developed under this task for a variety of applications. These include ground motions for scenario earthquakes, for developing fragility curves and in specifying ground motion input for critical facilities (such as hospitals) located in the eastern U.S.

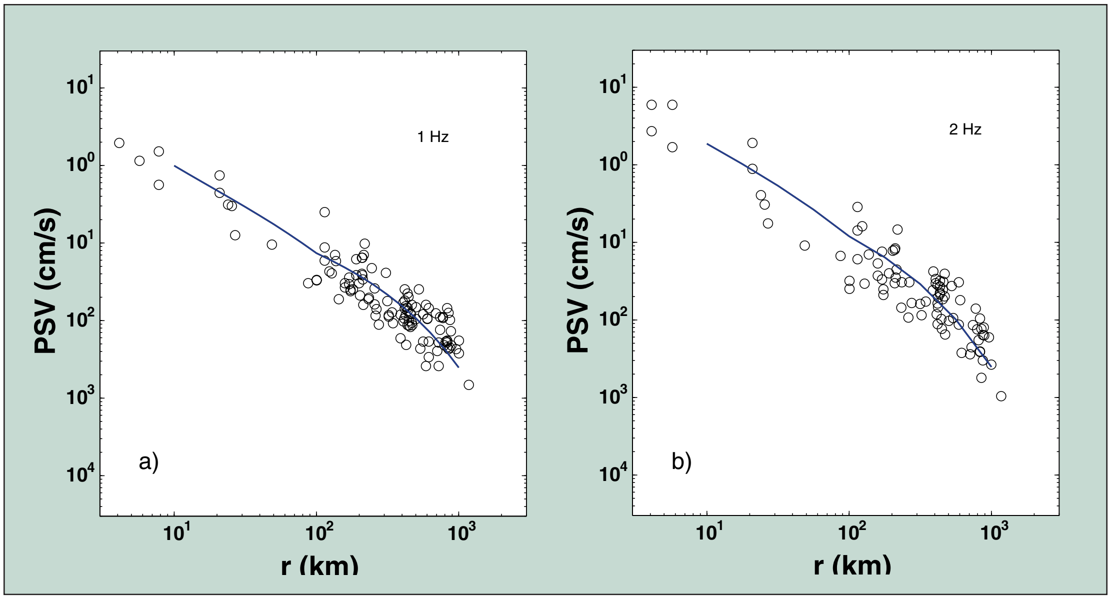


■ Figure 1. The *Specific Barrier Model* consists of an aggregate of circular cracks of equal diameter distributed on a rectangular area

Green functions are synthetic or empirical. The Kinematic Modeling Approach involves the prediction of motions from a fault that has specific dimensions and orientation in a specified geologic setting. As such, this approach more accurately reflects the various wave propagation phenomena and is useful for *site-specific* simulations.

For both approaches, we have adopted the "*Specific Barrier Model*," proposed and developed by Papageorgiou and Aki (1983a, b), to represent the earthquake source. Various source models have been proposed in the literature for ENA [such as the "ω^2-*model*" (Boore and Atkinson, 1987), the "*multiple episode/fractional stress drop model*" by Haddon (1995,1996), and the "*two corner frequency empirical spectral model*" by Atkinson (1993)]. The advantage of the *Specific Barrier Model* is that it provides the most complete, yet parsimonious, self-consistent description of the faulting processes that are responsible for the generation of the high frequencies, and at the same time provides a clear and unambiguous way of how to distribute the seismic moment on the fault plane. The latter requirement is necessary for the implementation of the *Kinematic Modeling Approach* described above.

According to the *Specific Barrier Model*, the seismic source consists of an aggregate of circular cracks (*sub-events*) of equal diameter $2\rho_0$, filling up a rectangular fault plane of length L and width W, as shown in Figure 1. As the rupture front sweeps the fault plane with the *"sweeping velocity" V*, a stress drop $\Delta\sigma$ (referred to as the "*local stress drop"*) takes place in each crack starting from its center or from a point of its periphery and spreading with a *"spreading velocity" v*. The region between the circular cracks represents barriers left

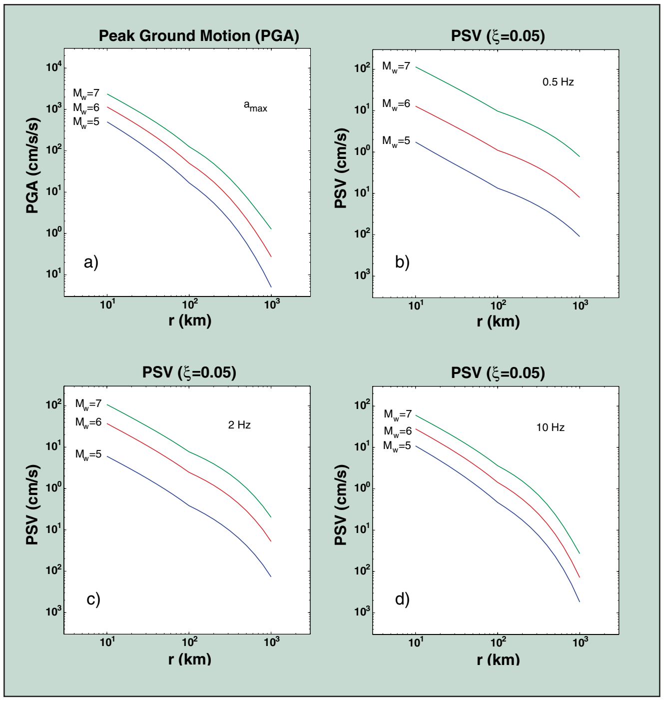


■ Figure 2. Comparison of predicted and observed 5% damped pseudo-velocity response spectra (PSV) for 1 Hz and 2 Hz oscillators

unbroken after the passage of the rupture front. The ruptures of individual cracks are statistically assumed to take place *independently*. Thus, the *Specific Barrier Model* is a hybrid of deterministic and stochastic models and is described by five parameters, namely, *L, W, V (= v), 2*ρ_0 and $\Delta\sigma$. *Rise time* τ (i.e., the time that it takes for a point on the fault plane to complete its slip), which is also a very important source parameter in kinematic modeling, may be estimated as follows: $\tau \approx (1 \sim 2)(v/2\rho_0)$.

After we calibrated the *Specific Barrier Model* using the available strong motion data base (Figure 2), we used the *source spectrum* (i.e., the spectrum of the elastic waves radiated by the source before these have been modified by the propagation path and site effects) of the model (Papageorgiou and Aki, 1985; Papageorgiou, 1988) in combination with *Random Vibration Theory* (or *Stochastic Process Theory*) (e.g.,Boore, 1983) to predict expected peak values of various measures of strong ground motion useful in aseismic design such as peak acceleration a_{max}, peak velocity v_{max}, peak displacement d_{max}, Spectral Acceleration *SA*, Pseudo Spectral Velocity *PSV*, etc., for any combination of magnitude, epicentral distance and site conditions (Figure 3). The amplification functions to account for the different site conditions were selected consistent with the site classes of the *NEHRP Provisions* (Boore and Joyner, 1997). The advantage of the above approach is that the expected peak values mentioned above are obtained without having to resort to the generation of numerous realizations and then average the results. These results should be useful, for example, to all the researchers working on Loss Estimation.

We have used the source spectrum of the *Specific Barrier Model* in the *Stochastic Approach* described above to synthesize realizations

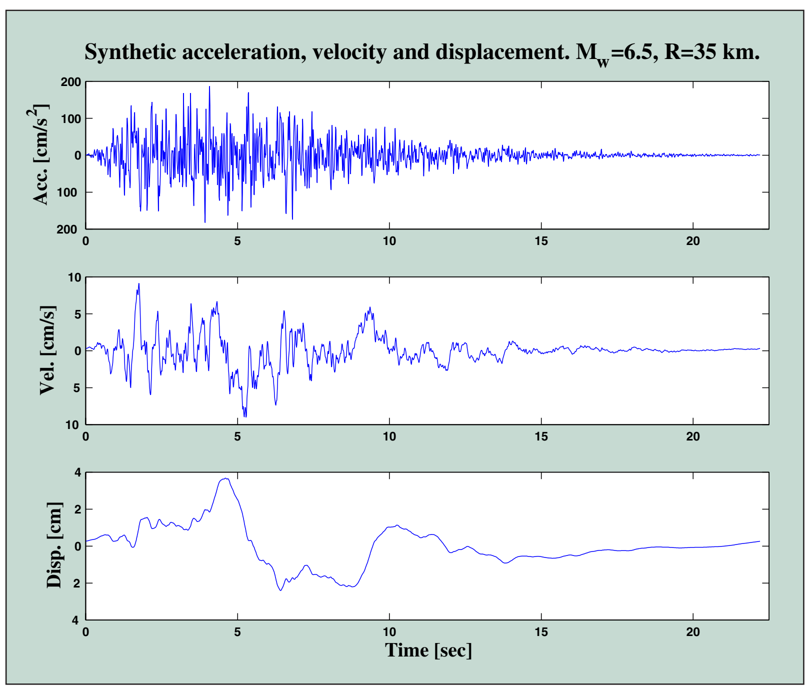


■ Figure 3. Predictions of peak ground acceleration and 5% damped pseudo-velocity response spectra (PSV) at three oscillator frequencies of 0.5 Hz, 2 Hz and 10 Hz, for moment magnitude M_w of 5, 6 and 7

of ground motion for a given magnitude, epicentral distance and site conditions. An example of such a realization is shown in Figure 4 for a M_w *6.5* earthquake event at an epicentral distance $R = 35$ *km* on hard rock.

The stochastic synthesis of accelerograms, as was originally used by engineers or even in its most refined form proposed by seismologists (e.g., Boore, 1983), has the following limitations: (1) The model is based on a point source; (2) the model is not adequate for simulating the long-period *near-field effect* expected in the *near-source region* from the slip on the fault; and (3) the model provides a description of the *temporal* variation of ground motion of a single point of the ground but cannot provide a description of the *spatial* variability of ground motion which is necessary for the analysis of extended structures (e.g., pipelines, tunnels, bridges, dams).

Therefore, in parallel to the above developments, we have initiated work on the *Kinematic Modeling Approach*. Preliminary results for the 1988 Saguenay earthquake are very encouraging. We are currently investigating and testing various models that have been proposed in the field of Stochastic Seismology (Sato and Fehler, 1998) to model scattering effects that are so important in ENA.



■ Figure 4. Synthetic acceleration, velocity and displacement time histories for a moment magnitude M_w 6.5 and epicentral distance R = 35 km

Eventually, a suite of time histories will be synthesized and made directly available for use by consultants (i.e., a suite of "standard" MCEER time histories analogous to those generated for California by the SAC Project).

Conclusions

As part of the development efforts related to the *Kinematic Modeling Approach* discussed above, we have initiated the following subtasks:

1. *Scattering effects of the lithosphere:* Scattering effects are a very important consideration in the synthesis of ground motion in Eastern North America. Our objective is to synthesize results developed in the field of *Stochastic Seismology* with techniques developed in the field of *Applied Stochastic Processes*.
2. *Sub-event Models:* We have made substantial progress in developing closed-form mathematical expressions for the far-field radiation of new kinematic models to represent the sub-events of the *Specific Barrier Model*. These new kinematic models account more realistically for directivity effects.
3. *Validation:* Any simulation method should be validated by comparing synthetic seismograms against recorded ones. We have initiated such validation comparisons using the 1988 Saguenay earthquake event as a case study.
4. *Near-source ground motions:* There are two competing physical effects that affect near-source ground motions in Eastern North America (ENA): earthquake sources in ENA are characterized by higher *local stress drops* and shorter *rise times* as compared to corresponding motions in California. Thus, ENA near-source *"killer pulses"* are expected to be stronger and of higher frequency (i.e., shorter duration). On the other hand, ENA earthquake sources appear to occur at greater depths and thus source-to-station distance (and consequently geometric attenuation) is greater. It is of great practical importance to investigate which of the above two effects dominates.

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Fiber Reinforced Composites for Advanced Seismic Performance of Water Supplies

by Thomas D. O'Rourke (Principal Author), James A. Mason, Ilker Tutuncu and Timothy Bond

Research Objectives

The overall goal of this research is to achieve substantial improvement in seismic reliability of water supply systems through advanced technologies, notably fiber reinforced composites (FRC's) to strengthen the welded slip joints of critical steel trunk lines. The research objectives are: 1) acquisition of full-scale welded slip joint specimens for laboratory testing, 2) development of simplified shell and 3-D FEM analytical models for performance of welded slip joints under compressive load, 3) full-scale testing of welded slip joints without FRC's, 4) refinement and validation of analytical models, 5) full-scale testing of welded slip joints with FRC's, 6) development and validation of analytical models for compressive load performance of FRC-reinforced welded slip joints, and 7) implementation of FRC reinforcement at Los Angeles Department of Water and Power (LADWP) and other water utilities.

In addition, the seismic performance of internal FRC linings will be assessed. This research will take advantage of work already supported by gas utility companies on the chemical and mechanical aging of FRC linings used to rehabilitate cast iron distribution mains. The improved performance of cast iron pipelines strengthened with FRC linings to both transient and permanent ground deformations during an earthquake will be quantified through full-scale tests on industry supplied specimens.

The 1994 Northridge earthquake resulted in the most extensive damage to a U.S. water supply system since the 1906 San Francisco earthquake. Los Angeles Department of Water and Power and Metropolitan Water District (MWD) trunk lines (nominal pipe diameter greater than 600 mm) were damaged at 74 locations, and the LADWP distribution system required repairs at 1,013 locations. An analysis of Northridge earthquake performance shows that approximately 60% of critical trunk line damage in the Los Angeles Department of Water and Power (LADWP) system occurred because of compressive failure at welded slip joints.

Sponsors

National Science Foundation, Earthquake Engineering Research Centers Program
Los Angeles Department of Water and Power

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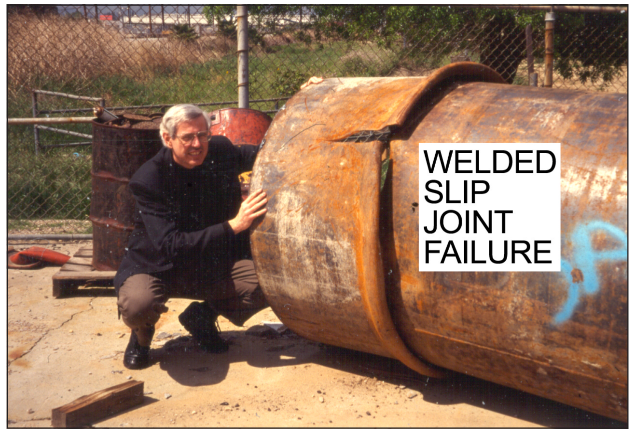
Collaborative Partners

- *LADWP contributed extensive data sets, maps, and information about system facilities. The department has also contributed specially fabricated 305 to 915 mm diameter (12 and 36 in.) steel pipe specimens that were shipped to Cornell University for testing.*
- *EBMUD has agreed to provide technical advice, oversight, and in-house services to validate the FRC technology and improve application procedures in the field.*
- *Taylor Devices, Inc. is providing the use of the 1.5 million lb. load test frame and facilities at their North Tonawanda, New York offices.*
- *Structural Preservation Systems, Inc., Hanover, MD, is providing engineering, FRC materials, and installation personnel.*
- *Master Builders, Inc, Cleveland, Ohio, is providing engineering, FRC materials, and installation personnel.*
- *R.J. Watson, Inc., East Amherst, New York, is providing engineering, FRC materials, and installation personnel.*
- *Fyfe Company, San Diego, California, is providing engineering, FRC materials, and installation personnel.*
- *The research work was*

A welded slip joint is fabricated by inserting the straight end of one pipe into the bell end of another and joining the two sections with a circumferential fillet weld. The bell end is created by the pipe manufacturer by inserting a mandrel in one end of a straight pipe section, and expanding the steel into a flared, or bell casing. Large diameter pipelines can be constructed rapidly and economically in the field by joining the bell and spigot (straight) ends of connecting pipe segments.



■ Figure 1. Compressive failure of the 1,245 mm Granada Trunk Line

Figure 1 shows a compressive failure at a welded slip joint on the Granada Trunk Line, a 1,245 mm (49 in.) diameter steel pipeline with 6.4 mm (1/4 in.) wall thickness that failed during the Northridge earthquake because of lateral ground movement triggered by liquefaction near the intersection of Balboa Boulevard and Rinaldi Street in the San Fernando Valley. Similar compressive failures were observed in trunk lines during the 1971 San Fernando earthquake and in the adjacent 1,727 mm (68 in.) diameter, (9.5 mm (3/8 in.) wall thickness) Rinaldi Trunk Line during the Northridge earthquake. Loss of both the Granada and Rinaldi Trunk Lines cut off water to tens of thousands of customers in the San Fernando Valley for several days.

As illustrated in Figure 2, failure of welded slip joints can be initiated by compressive forces that induce buckling and outward deformation at the location of maximum curvature in the bell casing. Compressive forces sufficient to fail welded slip joints can be generated

The users of research results include: 1) water utilities, such as the Los Angeles Department of Water and Power (LADWP), East Bay Municipal Utility District (EBMUD), Memphis Light, Gas and Water, and many other utilities operating in areas vulnerable to earthquakes; 2) private enterprises, such as engineering firms, construction contractors, and specialists in the design and distribution of advanced materials; and 3) communities that depend on water supply and the engineering and construction services needed to ensure reliable, cost effective service. Research on advanced materials, such as FRC's, not only results in substantial improvements in seismic performance, but also provides advanced materials technology needed for the rehabilitation of U.S. civil infrastructure, under daily conditions of aging and environmental deterioration.

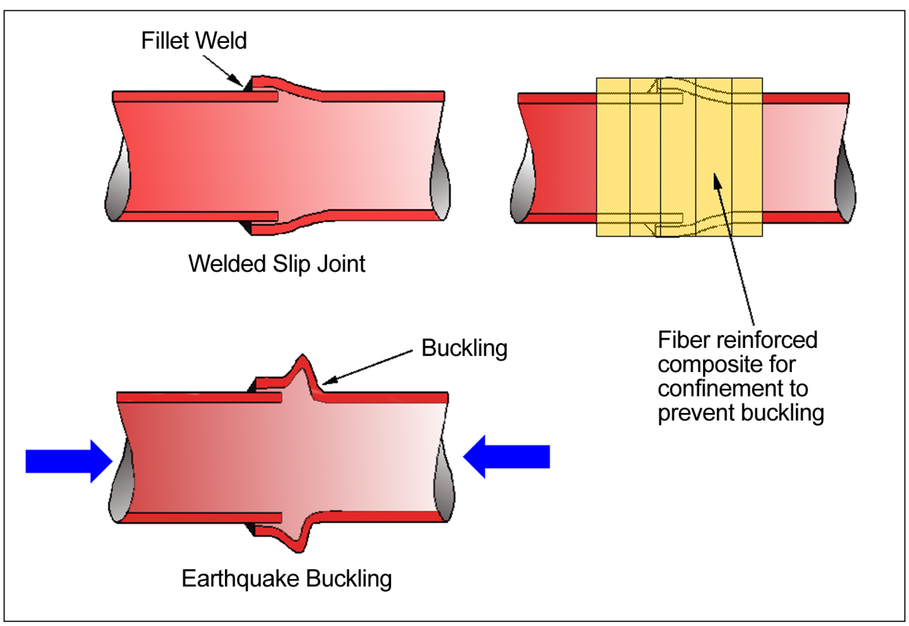
by near source pulses of high particle velocity as well as permanent ground deformation generated by surface faulting, liquefaction, and landslides.

Fiber Reinforced Composite (FRC) wrapping can be used to confine the welded slip joint against outward deformation of the bell, (see Figure 2). This type of reinforcing not only can be used to retrofit existing welded slip joints, but to strengthen new joints during fabrication in the field. As new pipelines are constructed, the pipeline surface at and adjacent to the fillet weld needs to be wrapped to provide corrosion protection. If the wrap used to protect against corrosion can also strengthen the pipeline against compressive failure, then the seismic performance of the critical trunk lines can be enhanced at relatively little additional cost.

Research at MCEER has focused on developing robust analytical models that can emulate buckling in straight pipe and welded slip joint sections. The research also includes a comprehensive laboratory test program to quantify the improvements in axial load capacity achieved with FRC wrap relative to that of unwrapped specimens. The laboratory tests are also used to qualify and validate the analytical models.

A comprehensive study of analytical modeling with DIANA™ and ABAQUS™ was undertaken, and ABAQUS™ was adopted as the finite element method (FEM) package of choice for evaluating welded slip joint and pipeline performance. Benchmark analytical studies were performed with ABAQUS™, and the sensitivity of the solutions to initial imperfections was investigated by bifurcation buckling techniques. The most appropriate element type chosen was a linear, four node, reduced integration shell element. Circumferential weld representation was found to have a significant effect on the finite element solutions, and an appropriate weld representation technique was developed for the analytical work with a technique known as multi-point constraints (MPC). The MPC technique connects nodes around the circumference of the bell to their counterparts on the inserted straight pipe. A rigid weld is then simulated by enforcing identical degrees of freedom in each pair of connecting nodes.

Figure 3 shows profile views of the FEM mesh in the vicinity of a 305 mm (12 in.) diameter welded slip joint before and after the application of axial compressive load. The FEM mesh which was configured to simulate the 610 mm



■ Figure 2. Compressive response of welded slip-joint and FRC reinforcement

Collaborative Partners (cont.)

*coordinated with MCEER-supported studies of the LADWP electric power system supervised by **M. Shinozuka**, University of Southern California.*

- *New York Gas Group, New York City, New York.*
- *In-Situ Form Technologies, Inc. St. Louis, Missouri.*
- *Miller Pipeline Co., Columbus, Ohio.*

Links to Current Research

- *Seismic Reliability Analysis and Retrofit Method for Southern California Power Systems,* ***T.C. Cheng****, University of Southern California.*
- *Rehabilitation Strategies for Lifelines: LADWP Power Systems,* ***S.T. Mau****, New Jersey Institute of Technology,* ***T.C. Cheng*** *and* ***M. Shinozuka****, University of Southern California.*

(24 in.) long experimental specimens, was modeled as a quarter section to take advantage of the symmetrical loading condition and geometry. Based on mesh refinement studies, 7,260 elements were used with 66 equi-dimensional elements along the circumference of each quarter section in the region of refined mesh coverage.

Analytical studies were performed for a prismatic section of pipe with no welded slip joint so that the analytical results could be compared with published solutions and experimental measurements. The buckling limit of a prismatic, or straight, pipe section establishes the maximum capacity of the pipe. The upper bound of performance with FRC wrapping is the buckling limit of the straight pipe. If FRC strengthening of a welded slip joint increases the load carrying capacity to the buckling limit of a straight pipe section, then the FRC technology has been successful in achieving the maximum possible improvement.

Specimens of 305 and 610 mm (12 and 24 in.) diameter welded slip joints were fabricated by LADWP and shipped to the George Winter Structures Laboratory for Structural Engineering Research, at Cornell University. Full cooperation and support from LADWP was established early in the experimental process allowing for immediate feedback between the two parties in project definition and direction. The choice of specimen size (diameter and pipe wall thickness) and joint construction (exterior vs. interior welded slip joint) has had direct input from LADWP to reflect their concerns for existing and future inventory. In addition, close coordination with FRC designers and contractors has progressed in parallel with testing. Laboratory tests have been performed on FRC reinforced as-built specimens that were prepared by two vendor teams participating in the experimental program. The vendor teams are: 1) Structural Preservation Systems, Inc, Baltimore, MD, and Master Builders, Inc., Cleveland OH, and 2) Fyfe, Inc., La Jolla, CA, and R.J. Watson, Inc., Buffalo, NY.

The types of tests that have been performed on 305 mm (12 in.) diameter pipe are: 1) compression of a prismatic section, 2) compression of unreinforced welded slip-joints, and 3) compression of FRC-reinforced welded slip-joints. As previously discussed, the performance of the prismatic section establishes the baseline, i.e., the maximum, for comparison with all other test results.

The experimental testing facilities consisted of a custom designed MTS load frame, with a load capacity of 2,700 kN (600 kips). Data was acquired by a personal computer controlling several data acquisition systems. Axial forces

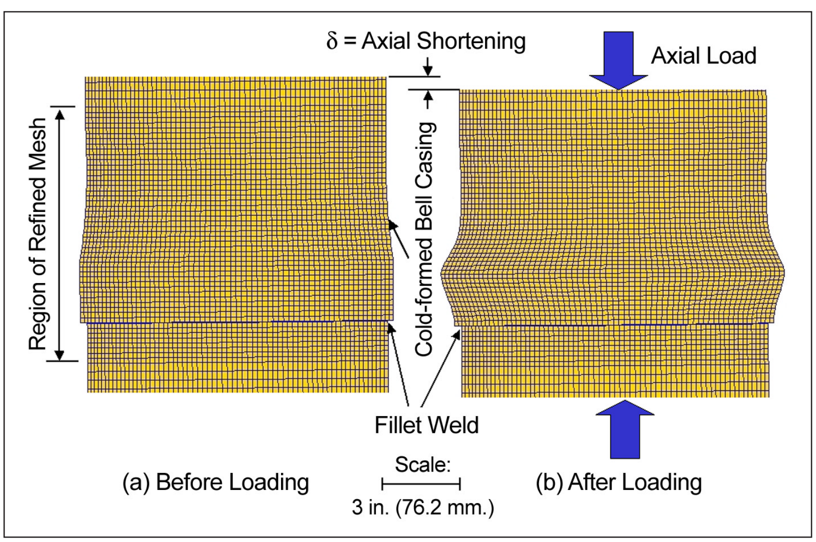


Figure 3. Finite element mesh of welded slip-joint

■ Figure 4. Prismatic pipe specimen in load frame

were cycled on sections of strain-gaged pipe at levels needed to seat the specimen, and at approximately 30 and 60 percent maximum capacity. The pipe then was loaded to the yield capacity and cycled, after which axial load was applied as far as the hydraulic ram could move [100 mm (4 in.)].

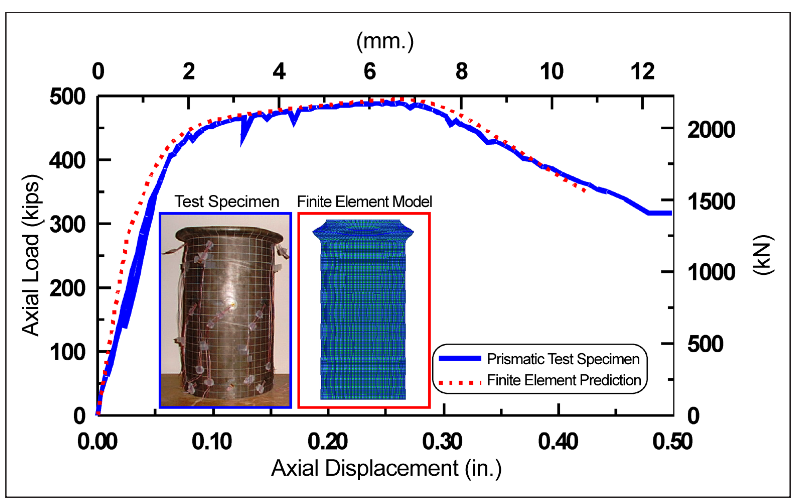
Figure 4 shows the prismatic section in the test frame. For this test a total of 48-strain gage rosettes were bonded to the pipe, 24 on the outside and 24 on the inside matching the location and orientation of the associated gage on the outside.

Many researchers (e.g., Donnell and Wan, 1950) have shown that initial imperfections due to the manufacturing and handling have a strong influence on the buckling limit. Imperfections were measured systematically across the prismatic pipe specimen on a 25 mm (1 in.) grid, utilizing a digital dial gage. The periodicity of the imperfections was analyzed with fast Fourier transform functions, and the imperfection spectra generated was used to model the imperfection amplitude and wavelengths. The maximum imperfection amplitude was approximately three percent of the pipe wall thickness. Close agreement between the experimentally observed buckling pattern and numerically simulated pattern was achieved.

Figure 5 shows the axial load vs. displacement plots for the prismatic test specimen and the numerical simulation. There is a remarkably close agreement between the experimental and analytical results. The peak predicted and measured loads are 2,200 and 2,175 kN (495 and 489 kips), respectively, which are two to three percent greater than the theoretical yield load of the specimen. As shown by the inset images, there is close agreement with respect to the location of buckling in the experimental and analytical results.

Figure 6 shows the axial load vs. displacement plots for a welded slip joint specimen and the numerical simulation. Again, there is remarkably close agreement between the

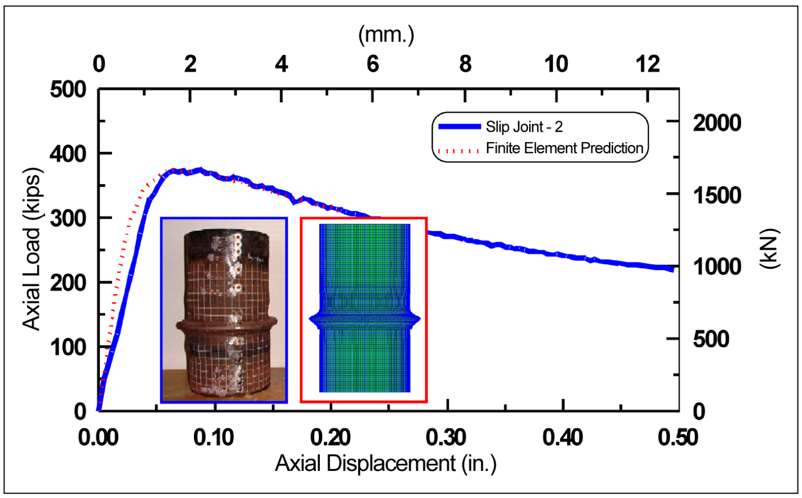
"Research at MCEER has focused on developing robust analytical models that can emulate buckling in straight pipe and welded slip joint sections."



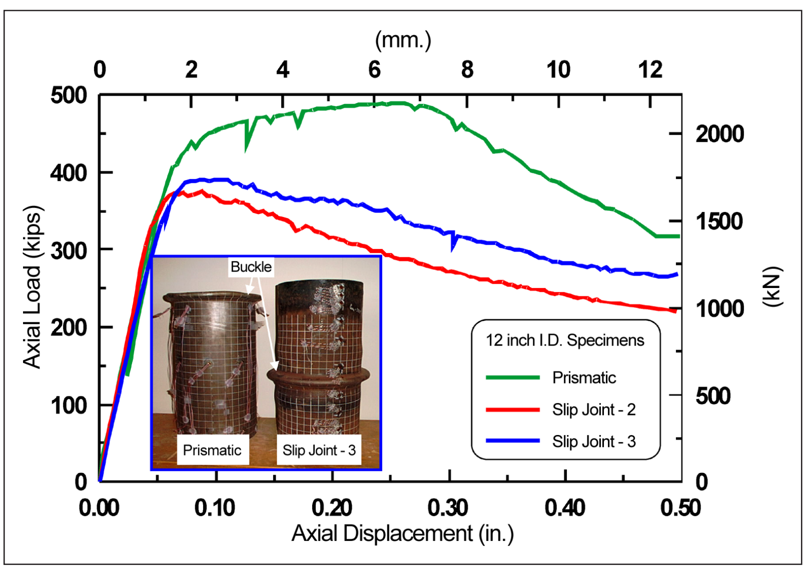
■ Figure 5. Comparison of test and FEM results for prismatic pipe force vs. displacement relationships and patterns of buckling.

Figure 7 shows the axial load vs. displacement plots of the prismatic and the welded slip joint specimens. The maximum loads carried by the welded slip joints were 1,670 and 1,740 kN (375 and 390 kips), which are between 77 and 79 percent of the buckling limit of the prismatic pipe section.

Figure 8 shows the axial load vs. displacement plots for the welded slip joint specimen, Slip Joint 3, and the FRC wrapped slip joint specimens prepared by the SPS/MB (FRC Wrapped-2) and Fyfe/Watson (FRC Wrapped-1) teams. In each case, the FRC wrap resulted in an increased capacity of approximately 25 percent. When the wrapped specimen results are compared with those of the prismatic section, it can be seen that FRC strengthening achieves a compressive capacity virtually equal to the buckling limit of a straight pipe section. Moreover, as the inset images in Figure 7 and Figure 8 show, the FRC wrapped specimen "FRC Wrapped–2" failed by buckling at the same location and manner as the prismatic specimen.



■ Figure 6. Comparison of test and FEM results for a welded slip-joint

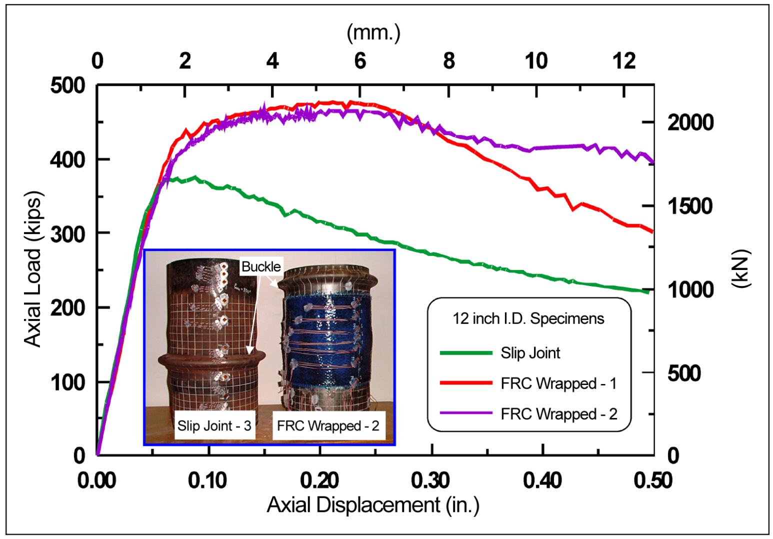


■ Figure 7. Comparison of prismatic and welded slip-joint performance

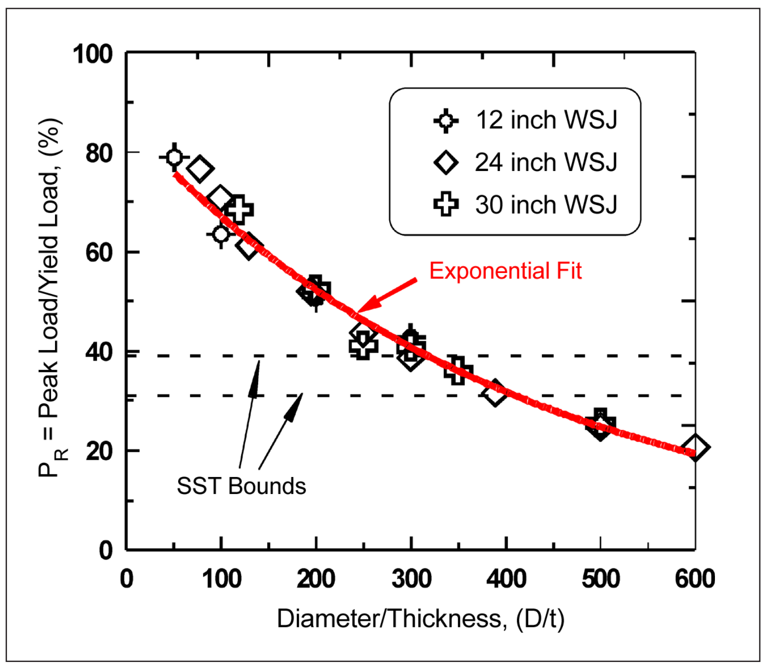
The close agreement between the analytical and experimental results indicates that the model developed in the research work is robust and sufficiently reliable for evaluating the response of welded slip joints with different geometries. Figure 9 shows the analytical results of welded slip joint axial load capacity, expressed as P_R, the ratio of maximum to theoretical yield load, plotted relative to pipe diameter-to-thickness ratio, D/t. The results for various pipe diameters are plotted. The yield load is simply the product of the steel compressive yield stress and cross-sectional area of the pipe. As discussed previously, the yield load is very close to the buckling capacity of a prismatic pipe section so that it may be taken as the maximum achievable capacity of the pipe.

The analytical results in Figure 9 allow one to scale the current findings to larger D/t ratios, representative of larger diameter pipe. For example, the Granada and Rinaldi Trunk Lines described previously, have D/t ratios 160 to 180. Welded slip joints in this D/t range would be expected to mobilize only about 50 percent of the maximum axial capacity of the pipe. Hence, FRC strengthening can result in nearly a 100 percent increase in compressive load capacity of a pipe with these geometric characteristics.

The FEM results are also plotted relative to the results from a simplified shell model developed by Tawfik and O'Rourke (1985). Although the simplified shell model provides a good representation for D/t ≥ 300, it tends to underpredict the axial compressive capacity for the D/t range most frequently encountered in water supply trunk lines (75 ≤ D/t ≤ 200).



■ Figure 8. Comparison of welded slip-joint and FRC reinforced test specimen performance



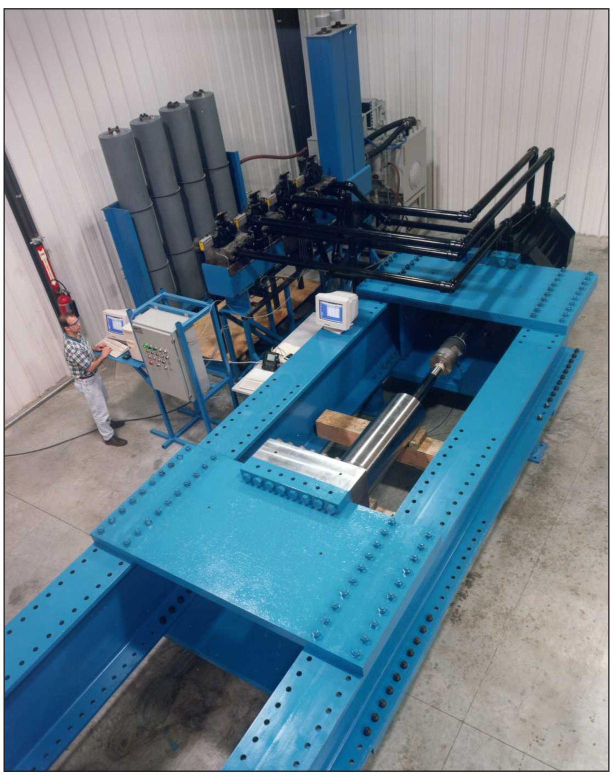
■ Figure 9. Welded slip joint capacity as a function of diameter-to-wall thickness ratio

Conclusions and Future Research Needs

The full-scale tests being performed at Cornell University are focused on the effectiveness of FRC strengthening for steel pipeline with welded slip joints. The experimental and numerical simulation work in progress will clarify: 1) influence of diameter to pipe wall thickness (D/t) on overall performance, 2) surface irregularities and their effects on performance, 3) local buckling deformation of exterior welded joints verses interior welded joints, and 4) different vendor FRC designs and installation procedures. As-constructed welded slip joints (bell housing and spigot) are tested to investigate the reduction of axial compressive capacity due to the joint. Participating vendors wrap the joint regions of test specimens with proprietary FRC materials. All specimens are tested to large plastic strains that investigate the failure process through successive local buckling modes.

The experimental program includes tests of pipes ranging in diameter from 305 to 914 mm with D/t ratios from 48 to 250. Both static and dynamic tests are in progress, and an experimental evaluation of performance under compressive and tensile forces will be made. At the request of LADWP, an assessment will be made of the performance of slip joints with exterior and interior fillet welds at a D/t ratio identical to that of the new 2.44 m (96 in.) diameter City Trunk Line currently in design.

Large diameter pipes (762 and 914 mm) will be tested at the Taylor Devices facilities in North Tonawanda, New York. Taylor Devices will donate the use of its equipment at no charge, except for time required by Taylor personnel to assist in test preparation. This represents exceptional cost and time savings relative to previous plans for fabricating the appropriate testing equipment at Cornell. It also represents an excellent example of industry cooperation in the MCEER research effort. The capacity of the load frame at their facilities is roughly 6,700 kN (1500 kips). This load can be applied in either compression or tension. The test machine is capable of rapid loading with velocities similar to those recorded during the Northridge earthquake. Figure 10 shows the frame being used for testing a large seismic damping device.



■ Figure 10. 1.5 million lb. load frame at the Taylor Devices Testing Facility

A similar approach with internally applied FRCs for improving the seismic performance of gas and water distribution mains is being pursued. In this case, MCEER researchers are taking advantage of research already in progress and funded by the New York Gas Group (NYGAS) at Cornell. This work involves mechanical and chemical aging tests on full-scale specimens of cast iron (CI) distribution pipe prepared and lined with FRCs under the supervision of gas utility personnel and contractors specializing in FRC lining technologies. Specimens of cast iron gas mains, provided by the New York Gas Group, have been lined with the FRCs and tested under conditions in which the cast iron pipe has ruptured with the internal lining intact. The tests involved the simulation of vertical offsets and relative rotations of fractured pipe lengths consistent with the type of deformation experienced in liquefied ground. The lining was able to sustain low-pressure service without disruption.

Because this research involves the qualification of FRC linings for damaged pipe under cyclic and permanent deformations, the results can be readily adapted to evaluate the seismic performance of FRC-reinforced distribution mains. Additional tests are planned to load the FRC-lined pipes to failure and to assess dynamic deformations consistent with near field strong motion records. Cooperation in this testing has been obtained from the New York Gas Group, In-situ Form Technologies Inc., St. Louis, Missouri and the Miller Pipeline Co., Columbus, Ohio.

To evaluate the impact of FRC technology, improvements in system reliability will be evaluated by means of probabilistic hydraulic network simulations. These analyses will be used to quantify the effects on system performance of pipe and welded slip joints strengthened by FRCs. The systems analyses will take advantage of the inventory development and GIS modeling of the Los Angeles water supply being performed concurrently with the FRC research.

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The Marmara, Turkey Earthquake: Using Advanced Technology to Conduct Earthquake Reconnaissance

by Ronald T. Eguchi (Coordinating Author), Charles K. Huyck, Bijan Houshmand, Babak Mansouri, Masanobu Shinozuka, Fumio Yamazaki, Masashi Matsuoka and Suha Ülgen

Research Objectives

1. To conduct high level reconnaissance using satellite imagery, Differential Global Positioning Systems (GPS), and in-field GPS-GIS interfaces
2. To validate damage information contained in early U.S. State Department Damage Maps
3. To serve as a model case study for exploring the use of remotely sensed data for post-earthquake damage assessment.
4. To reinforce the collaborative activities between MCEER and EDM

The Marmara earthquake occurred during a time of unprecedented technological development. Post-disaster information and data that once took months to generate were developed within a matter of days in this event. Furthermore, the ability to comprehensively understand the meaning of these data was significantly enhanced because of the use of sophisticated database management programs and geographical relational algorithms, e.g., geographic information systems, (GIS). In the most general sense, we were able to literally map the effects of the earthquake in "real time."

One area that has benefited immensely from this technology explosion is earth observation and mapping (see Figure 1). From over a dozen different platforms, we are able to view and quantify with surprising precision the different properties of the earth's surface. Topographic features are clearly seen from low earth-orbiting optical satellites. Urban areas are also visible in these images. In addition, using an analysis technique called "interferometry," it is possible to detect minute changes in the earth's surface by comparing a series of radar images taken at different times. It is from the perspective of testing the use of advanced technologies for post-earthquake reconnaissance that we provide our analysis of the Marmara earthquake.

The following discussion offers a preliminary report on a joint reconnaissance effort between MCEER and the Earthquake Disaster Mitigation (EDM) Research Center in Miki, Japan. This reconnaissance took place

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National Science Foundation, Earthquake Engineering Research Center Program

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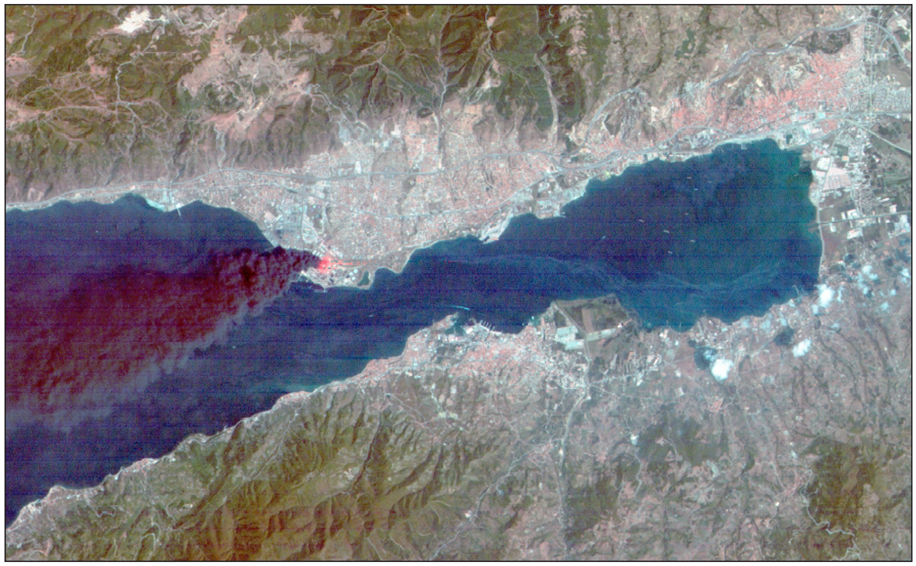


Image provided to EQE International by the European Space Agency under a cooperative research agreement established for this earthquake. Image details: RGB mapping of 721, replacing the red band with the far infrared band. A Gaussian filter was applied to maximize visibility of the smoke.

■ Figure 1. Landsat 5 Image of İzmit Bay taken on August 19, 1999. Note the fire and smoke plume originating from the Tüpraş Refinery, seen at the center of the figure.

approximately one and a half months – between September 28th through October 4th - after the disastrous main shock of the Marmara earthquake. The team leaders were Ronald T. Eguchi of ImageCat, Inc. (formerly of EQE International), who led the MCEER team and Professor Fumio Yamazaki of Tokyo University, who led the EDM team. The collaboration with EDM has been ongoing since the 1994 Northridge earthquake in the U.S. and the Kobe earthquake in Japan (1995). Both Centers have committed substantial resources to explore the use of advanced technologies for natural disaster management. The investigation of the Marmara earthquake represents the latest collaboration between these two organizations.

The following sections discuss the purpose of the trip and the meetings that were held, the new technologies that were used during this reconnaissance trip, a "thumbnail" sketch of specific in-field studies

The data collected during this reconnaissance will benefit various user groups. First, this information will help researchers validate new damage detection models based on remote sensing technologies. Second, the lessons learned during this trip will help to improve earthquake reconnaissance techniques and procedures by encouraging the use of new and advanced technologies. Of particular significance is the contribution that advanced GIS-GPS interface systems have in recording damage information in real-time. Finally, the results of this research will ultimately help future emergency responders by providing more reliable methods of assessing post-earthquake damage. Assessing damage sooner will allow responders to act more quickly and more effectively in deploying limited resources.

that were conducted, and finally, the usefulness of these advanced technologies in assessing damage from this devastating event.

Itinerary

The itinerary for the trip was established several weeks before departing for Turkey. The trip consisted of meetings with Turkish researchers and investigators, and brief field visits to several of the hardest hit areas. The details of the field visits are discussed in more detail later in this section. Provided below are brief summaries of the meetings that were held during the first two days of this trip. Table 1 summarizes the itinerary for this trip.

During our visit with Professor Mustafa Erdik at the Kandilli Observatory and Earthquake Research Center of Boğaziçi University, the research team was able to ask general questions about the extent of damage to western Turkey. We found that although the earthquake was initially named after one of the cities closest to the main shock (i.e., İzmit), damage in this area was not as severe as other areas further away from the epicenter. We were told that Gölcük (located on the southern side of İzmit Bay and roughly 80 kilometers east of İstanbul) and Adapazarı (located roughly 125 kilometers east of İstanbul) had experienced far more damage than the town of İzmit.

We were also shown preliminary ground motion records from this event, learning that the peak ground acceleration in Adapazarı reached about 40 percent g. At the time of our visit, a number of portable instruments were being installed in order to record ground motions from large aftershocks. Before leaving this facility, the MCEER/EDM team was given a tour of the Kandilli Observatory Laboratory where we viewed other ground motion data that was being collected.

At TÜBİTAK (Turkish Scientific and Technical Research Institute) Marmara Research Center, several different meetings were held. The first meeting was with the Earth Sciences Research Institute where the team met with Dr. M. Namık Yalçın, the Director of the Earth Sciences Institute at TÜBİTAK Marmara Research Center, and Dr. Semih Ergintav, a member of the Earth Sciences Research Institute. The purpose of this meeting was to determine the availability of GPS information for the earthquake. The team was particularly interested in collecting data on post-earthquake displacements for towns that were hardest hit by this earthquake. This information would be used to compare permanent ground displacements calculated using Synthetic Aperture Radar (SAR) with those derived from the continuous GPS network. We understood that a continuous GPS system was in

Links to Current Research

Program 3: Emergency Response and Recovery

Table 1. Itinerary

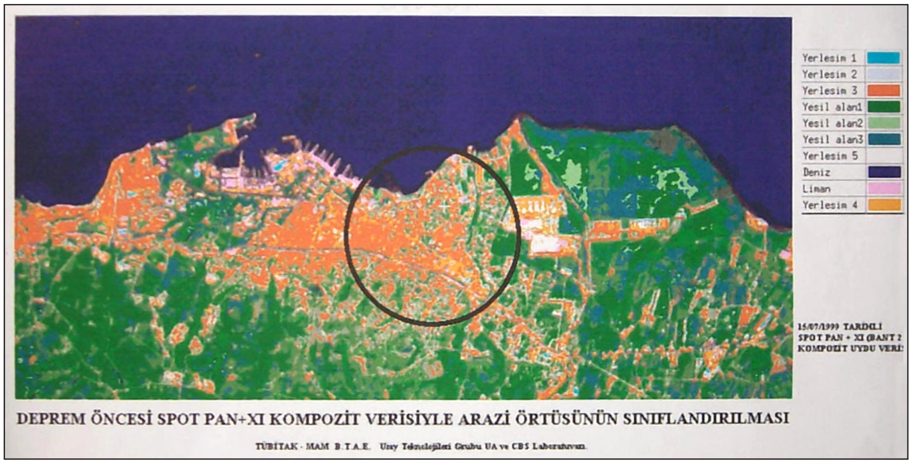
Date	Meeting/Visit
9/30/99	• Mustafa Erdik, Kandilli Observatory and Earthquake Research Institute, Boğaziçi University • Field Visit to Avcılar
10/1/99	• TÜBİTAK Marmara Research Center: Earth Sciences Research Institute • TÜBİTAK Marmara Research Center: Space Technologies Group • Field Visit to Seymen • Field Visit to Gölcük
10/2/99	• Field Visit to Adapazarı
10/3/99	• Field Visit to Seymen • Field Visit to Gölcük

Web Sites

Multidisciplinary Center for Earthquake Engineering Research
http://mceer.buffalo.edu/research/turkeyeq/default.html

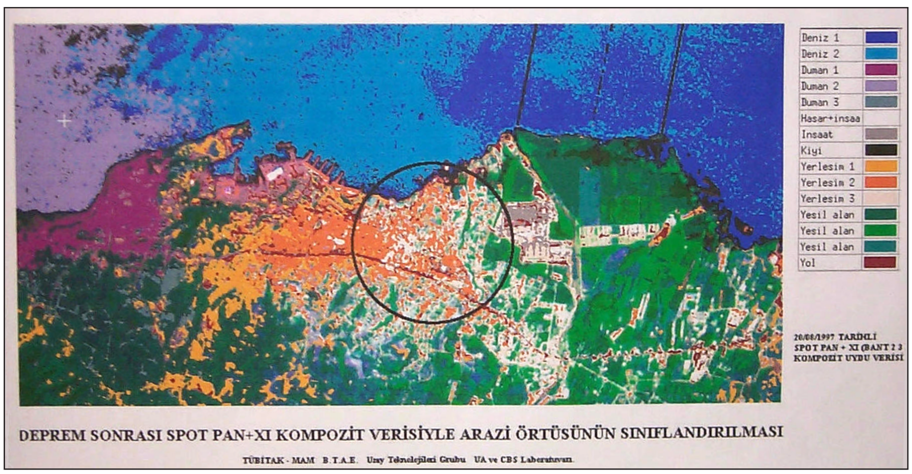
Boğaziçi University, Kandilli Observatory and Earthquake Research Institute
http://www.koeri.boun.edu.tr

Earthquake Disaster Mitigation Research Center
http://www.miki.riken.go.jp



TÜBİTAK

■ Figure 2. Landuse Map developed from SPOT image after earthquake (July 7, 1999). The different colors/shades represent various levels of development or open areas. The circle surrounds the town of Gölcük. Note that the harbor is located just to the left of the circle.



TÜBİTAK

■ Figure 3. Image of Gölcük created after the earthquake. (SPOT image taken on 8/20/99). Note that the white or light areas identify city blocks where significant damage to buildings occurred.

place at the time of the earthquake and that displacements at several sites were being monitored. We also understood that the primary interest in these data was to map the co-seismic slip of the fault, and not the relative tectonic movement of the region. The results of this work were presented at the Annual American Geophysical Union meeting that was held in San Francisco in December 1999.

The second meeting was held with the Space Technologies Group at TÜBİTAK. The investigation team met with Dr. Hülya Yıldırım, the Director of Remote Sensing and Geographic Information Systems at the Marmara Research Center. Before the earthquake, this group was involved with numerous environmental and agricultural studies. One study involved the preparation of watershed maps for the five provinces surrounding İzmit, which is in the province of Kocaeli. After the August 1999 earthquake, this group was assigned the responsibility of producing GIS maps that documented damage in the İzmit area. While lacking any prior earthquake experience, this group immediately began integrating available GIS maps with satellite imagery to identify those urban regions that were most affected by this event.

One analysis, which was based on a comparison of pre- and post-earthquake SPOT[1] images, showed large areas in Gölcük that were clearly affected by the earthquake. Several of these images are shown in Figures 2 and 3. In addition, other satellite-derived images showed extensive areas along the shore near Gölcük that were inundated as a result of ground subsidence caused by liquefaction. Figure 4 shows an aerial view of the inundation area.

Photograph by D. Andrews

■ Figure 4. Aerial view of earthquake damage in Gölcük. This area was affected by ground subsidence caused by liquefaction.

Field Investigations

During this trip, the MCEER/EDM team was able to survey earthquake damage in four areas: Avcılar, Seymen, Gölcük and Adapazarı. Where possible, we applied GPS technology linked with GIS systems to record damage information. In addition, satellite imagery and aerial photographs were available for some areas. The following sections discuss the data that were collected, the technologies that were used in recording this information, and the analyses that have been performed – since our return – to interpret the effects of this earthquake. Before discussing these field investigations, we discuss very briefly the technologies that were used on this trip.

New Technologies

Radar Images. The MCEER/EDM team was fortunate to obtain numerous satellite images of the İzmit area prior to its departure. Through a cooperative research agreement with the European Space Agency (ESA), EQE International received a series of radar images, both before and after the earthquake, via the ERS-1 and ERS-2 satellites. A tabulation of these data is listed in Table 2. As will be discussed later, several of these scenes (i.e., images) are being used to create interferograms that will hopefully identify areas of significant damage.

The project team also received post-earthquake Radarsat images of western Turkey. These, however, were received after the team returned from Turkey. We have yet to process this information.

Optical Satellite Images. In addition to the radar data, ESA also provided Landsat 5 images taken several days after the earthquake. Figure 1 shows a Landsat 5 image of the İzmit Bay region. Visible in this image is the fire that occurred at the Tüpraş Oil Refinery, approximately 70 kilometers southeast of İstanbul.

■ Table 2. ESA Synthetic Aperture Radar (SAR) Data and Images

Date (mm/dd/yy)	Track	Frame	Orbit	Product
06/07/95	336	2781	20364	RAW or SLC
06/08/95	336	2781	00691	RAW or SLC
10/15/98	336	2781	18226	RAW or SLC
12/24/98	336	2781	19228	RAW or SLC
03/04/99	336	2781	20230	RAW or SLC or PRI
03/20/99	064	2781	20459	RAW or SLC
04/05/99	293	2781+2 nodes	20688	PRI
04/24/99*	064	2781	20960	RAW or SLC
08/12/99	157	819-4 nodes	42229	RAW or SLC or PRI
08/13/99	157	819-4 nodes	22556	RAW or SLC or PRI
08/17/99	**EARTHQUAKE**			
08/23/99	293	2781+2 nodes	22692	PRI
08/25/99	336	2781	42408	RAW or SLC or PRI
08/26/99	336	2781	22735	RAW or SLC or PRI
09/10/99*	064	2781	42637	RAW or SLC
09/11/99	064	2781	22964	RAW or SLC
09/16/99	157	819-4 nodes	42730	RAW or SLC
09/17/99	157	819-4 nodes	23057	RAW or SLC

Note: RAW refers to unprocessed data; SLC is single look complex; and PRI is precision averaging. Asterisks refer to scenes that were used to create interferograms for this event.

ESA

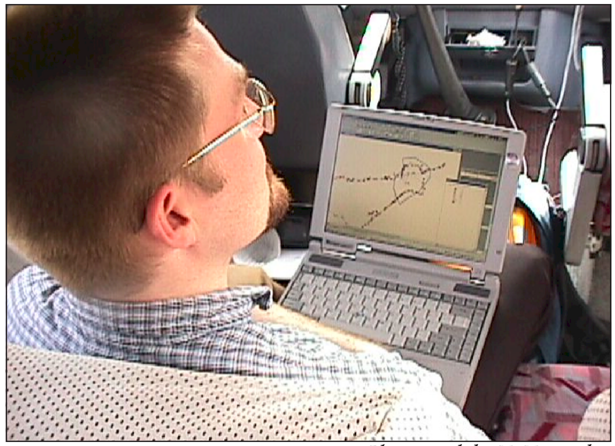
Photograph by R. Eguchi

■ Figure 5. Vehicle used to collect damage/GPS data in Avcılar and Adapazarı. Note the antennae being held by front passenger.

Aerial Photographs. Some aerial photos were taken of the affected areas; these, however, have yet to be widely distributed. One photo was published in a local İstanbul newspaper. The photo was scanned by one of our collaborators in Turkey (IMAGINS) and was used during our field survey of the Avcılar area. This is discussed further in the next section.

Global Positioning Systems. Two separate GPS systems were used in the field during this investigation. The first was a high-precision single-frequency 12-channel NovAtel GPS receiver. This system was generally used while driving through the different study areas, see Figure 5. A second system – a handheld Magellan unit – was used when field studies were conducted on foot.

Real-time GPS-GIS Interface. One of the major improvements in documenting the effects of this earthquake was the use of a real-time GPS-GIS system. Using the GPS systems mentioned above, the MCEER/EDM team was able to associate damage information, including photographs, with accurate geographical coordinates. Where there was real-time Differential GPS broadcast data (FM-RDS), which was the case in Avcılar, the positional accuracy was one meter or less. When using the handheld Magellan unit, the accuracy level dropped to plus or minus 30 meters. Figure 6 shows the equipment setup for this GPS-GIS interface. One of the advantages to using this system was that the investigation team was able to create reasonably accurate road maps when none were available. These maps were created by plotting GPS coordinates (while in transit) directly onto Landsat 5 imagery. The interface between the NovAtel GPS receiver and the MapInfo GIS software was provided by GeoTracker from Blue Marble Geographics.



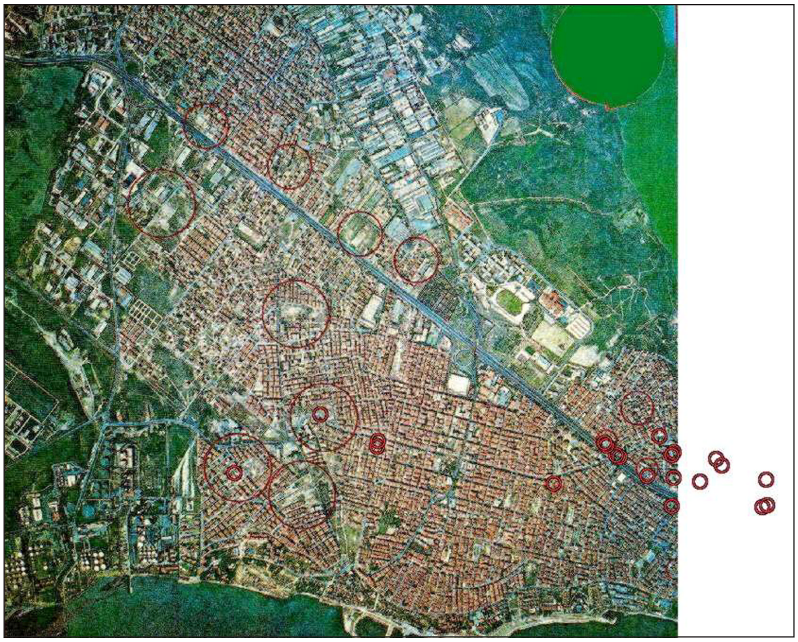
Photograph by M. Matsuoka

■ Figure 6. Real-time GPS-GIS setup for in-field data collection and processing.

Avcılar

Avcılar is located in the south-western part of İstanbul bordering the Marmara Sea. Although located roughly 80 kilometers from the epicenter of the August 17, 1999 earthquake, there was substantial – but isolated – damage to multi-story residential buildings. At the time of our visit, most of the severely damaged structures had already been demolished. Since there was very little to record, other than the location of these demolished buildings, the team opted to use this time as an opportunity to refine and calibrate our GPS-GIS data collection system.

Figure 7 shows an aerial photo of the part of Avcılar that we focused on. Visible on this photograph – scanned from a newspaper article – is the shoreline facing the Marmara Sea, at the bottom of the figure.



IMAGINS

■ Figure 7. Aerial photograph of the city of Avcılar. Shown on this figure are sites (identified by small circles) visited by the MCEER/EDM team in September 1999.

In this part of Avcılar, there were about a dozen buildings that experienced significant damage, resulting in complete collapse of the structure, or substantial damage requiring demolition of the building. While traveling to each of these sites, the investigation team utilized the real-time Differential GPS-GIS system. With accuracy levels within one meter, we were able to record the precise location of each of the demolished buildings. This information will be used to assess whether these particular sites can be recognized from either satellite imagery or aerial photos. Most other structures in this area experienced little, if any damage.

Seymen

Seymen is located on the southern side of İzmit Bay, just east of Gölcük (40º 42' N latitude and 29º 54' E longitude). This particular area was of interest to the MCEER/EDM team because 1) damage to buildings (the area is composed of entirely residential apartment buildings) varied widely ranging from slight to complete collapse; 2) the area was unoccupied at the time of our visits, and 3) the buildings were situated in large, open areas. From the standpoint of detecting damage from spaceborne systems, this area would be ideal. Figures 8 through 10 show some of the buildings where detailed data were collected by the investigation team.

As part of an ongoing research project, researchers at the University of Southern California (Mansouri and Shinozuka) are exploring ways in which SAR data can be used to characterize earthquake damage to buildings. Simulation algorithms are being developed that will model such failures as tilting, first floor collapse and complete building failure (i.e., massive pancaking). During this reconnaissance trip, Mansouri collected detailed measurements on several of the buildings that had collapsed during the earthquake. All of the

Photograph by R. Eguchi

■ Figure 8. Isolated building in Seymen. This building experienced first floor collapse and well as damage to the top floor. This building should be visible from aerial photos; it may be detectable using radar pre- and post-event images.

buildings were constructed of reinforced concrete with rectangular footprints and had tiled roofs. Because of the orientation of these buildings (two rows of six buildings each) and because of the large spaces between buildings, this site was considered an ideal one from the standpoint of testing or validating their analytical models.

As indicated earlier, SAR images of this area – both before and after the earthquake – have been obtained from ESA and RADARSAT. Pre- and post-event SAR data is preferred for detecting damage after catastrophic events. Using SAR data, it is possible to create images at night or through cloud cover. Also, because of its ability to facilitate change detection analysis, SAR technology is considered the most effective technology in attempting to "quantify" the effects of large disasters.

Over the next year, Mansouri and Shinozuka will be calibrating their simulation algorithms by testing them against the Seymen data. Some of the questions that they will attempt to answer are: (1) what damage conditions or failure modes are detectable using coarse resolution SAR data, (2) can damage be accurately simulated using these new simulation algorithms, and (3) how can these findings be extended to assess damage to larger areas.

Adapazarı

The town of Adapazarı is located about 125 kilometers east of İstanbul. The town sits on a recent lakebed, and suffered extensive liquefaction during this earthquake. This was one of the most heavily damaged areas in this event; damage

Photograph by R. Eguchi

■ Figure 9. Near complete collapse of a five-story concrete structure. Should be visible from both aerial photos and SAR imagery.

Photograph by R. Eguchi

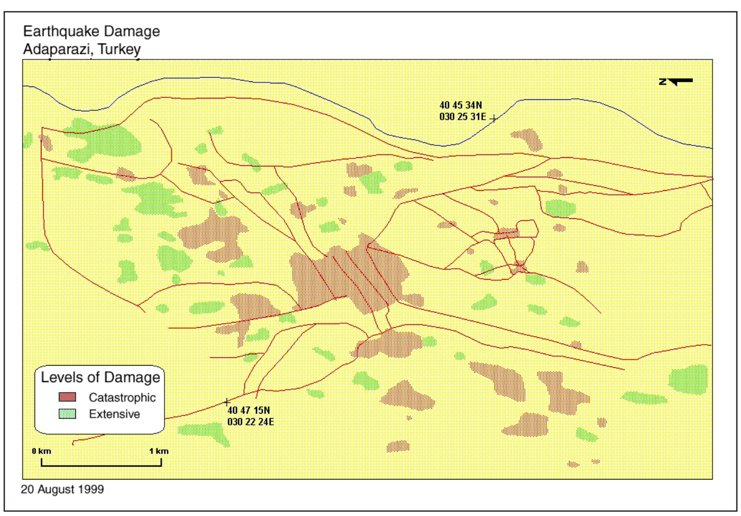
■ Figure 10. Severe damage to multi-story apartment buildings. Lower floors have "pancaked" and building is not tilted. May be visible from aerial photos; collapse of lower floors may be detectable from radar imagery.

to multi-story apartment buildings was severe, many commercial structures were also seriously damaged.

The MCEER/EDM team spent an entire day in Adapazarı attempting to collect damage information from local authorities. Despite the fact that the requests were made almost two months after the earthquake, there was still very little data available on number of damaged buildings, whether structures were safe or unsafe, and how many people had perished in this earthquake. Because of this, the investigation team decided to conduct its own survey of Adapazarı.

One of the primary objectives of this trip was to collect enough information to validate a series of earthquake damage maps that were produced by the U.S. State Department shortly after the earthquake. These maps appeared on the Internet on the Kandilli Observatory website. In total, the U.S. State Department produced five maps: Yalova, Seymen, Derence, Adapazarı and West Gölcük.

One example of the type of map distributed by the State Department is seen in Figure 11 for the Adapazarı area. The map identifies areas of catastrophic and extensive damage. This map was put on the Internet on August 20, 1999, three days after the earthquake. According to officials at the State Department, high-resolution satellite images were used to classify the town into these two damage categories. Our purpose in validating these maps was to create a "ground truth" database that could eventually be used to calibrate a series of interferograms developed from this earthquake.



U.S. State Department

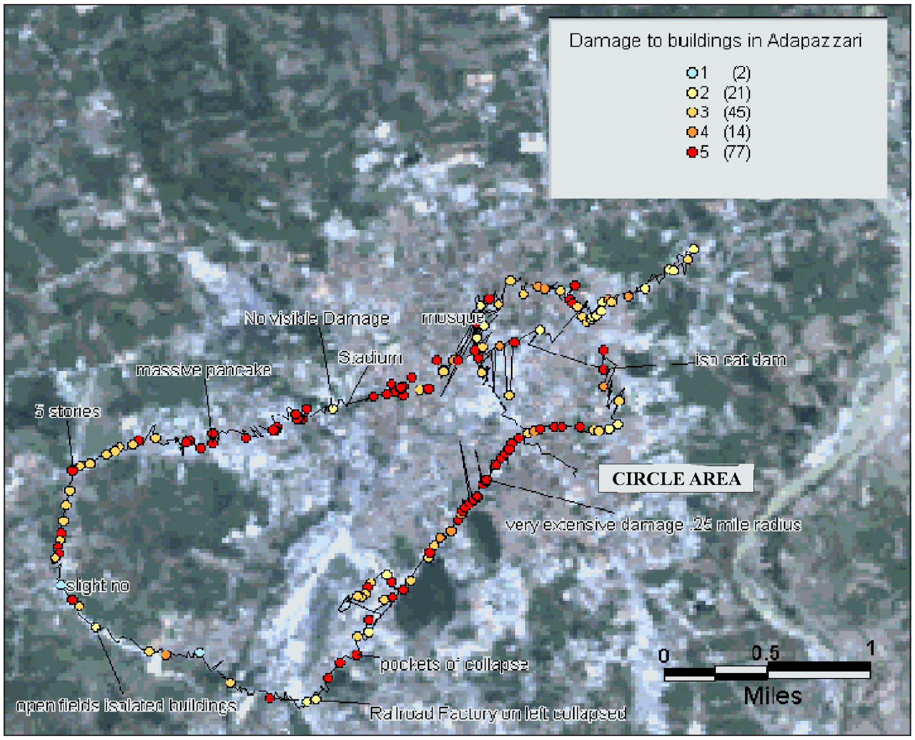
Figure 11. Earthquake damage map produced by the U.S. State Department for the Adapazarı region (August 20, 1999) - uncorrected.

Unfortunately, the scale and projection of these maps was a little misleading. When compared directly with Landsat images – which were in a valid geographical projection – many of the obvious features (roads, rivers, and city boundaries) – did not match. The State Department maps appeared to present a distorted image of the affected areas.

Since returning from Turkey, EQE spent considerable time trying to "warp" the images so that the State Department maps actually coincided with the major land features and roadways of the region. As it turns out, it is possible to approximately fit these maps to the correct projections by overlaying the maps onto available Landsat images and "warping" the map to match obvious landmarks (e.g., roads, rivers, major intersections, etc.) The next section discusses how the MCEER/EDM team attempted to validate the damage maps.

Figure 12 shows a Landsat 5 image of the Adapazarı area. Shown on this same figure is the route taken by the investigation team on October 2nd. It is interesting to note that at the time of our visit, there appeared to be no publicly available maps of the city.[2] Therefore, our only means of tracking our route was to plot the latitude/longitude of the van – as determined from the portable GPS system – directly onto a Landsat image of Adapazarı. Although it took some time to set up, this system was invaluable in assigning geographical coordinates to specific damage sites.

The route, shown in Figure 12 as a black line, began near the Mosque



■ Figure 12. Landsat 5 image showing Adapazarı (light area in center of figure) and the route taken by the MCEER/EDM team on October 2, 1999 (route shown as a continuous black line). Also seen are individual damage assignments that were made along the route. Note: A damage index of 1 is associated with an observation of slight to no damage; an index of 5 reflects catastrophic damage.

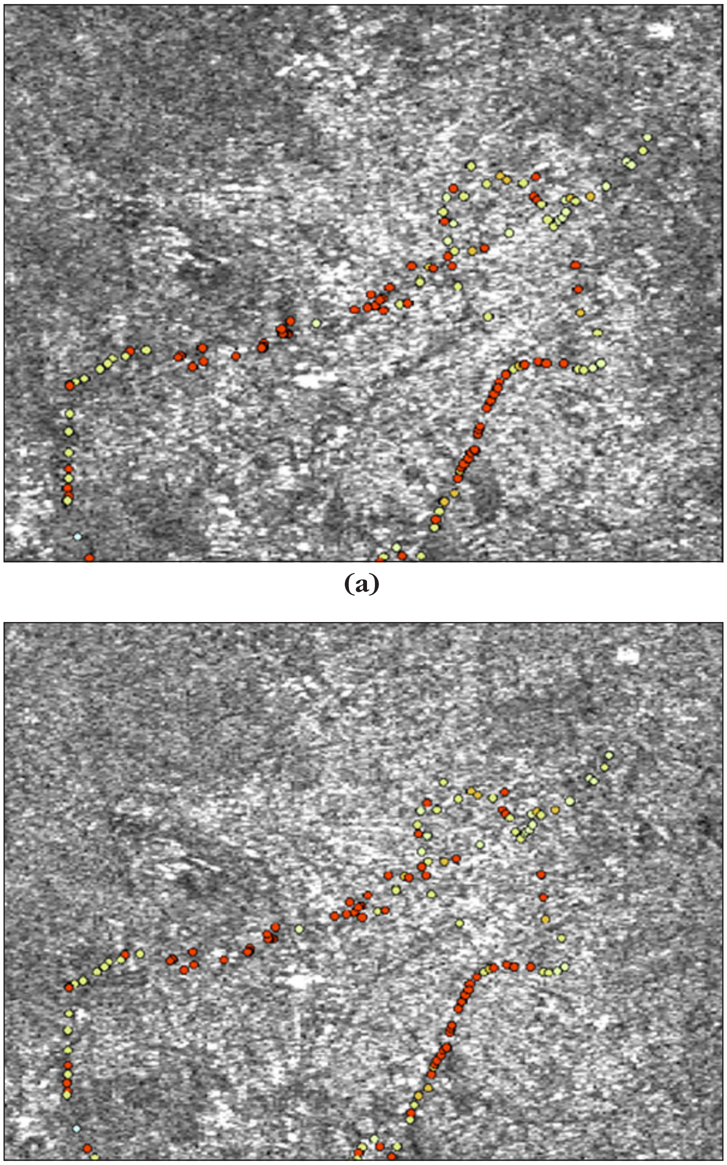
"As part of an ongoing research project, researchers at the University of Southern California are exploring ways in which SAR data can be used to characterize earthquake damage to buildings."

(center of the figure) and proceeded in a counterclockwise direction. Also noted on Figure 12 are color-coded circles that represent various levels of site damage (on a city block level), ranging from none or slight to catastrophic damage. Unlike the Avcılar survey, we did not have access to Differential GPS. Therefore, some wavering of the route trace is noted. In theory, the coordinates that are registered are within a block of the actual location.

To help select the best route to take, we enlisted the services of a government worker who was familiar with many of the city's reconstruction projects. With her help, we were able to map out a route that took us through the most heavily damaged areas, as well as other areas (generally outside of town) which did not suffer much damage. Most importantly, this route took us in and out of those areas that were classified as catastrophic and extensive damage by the U.S. State Department.

In addition to assigning damage levels to each block, we attempted to record this information via (1) digital still cameras, and (2) digital video camera.[3] Also recorded via laptop computer were written comments regarding our damage observations at specific sites. Some of these comments appear on Figure 12. Note on the figure, the area designated as "Circle Area." This was one of the most devastated areas in the city.

Figure 13 shows two ERS radar images of the Adapazarı area, taken before and after the earthquake. As in Figure 12, the team's route is seen



■ Figure 13. Intensity images of Adapazarı based on before and after earthquake SAR data (Data Source: ESA). The light areas correspond to built-up areas, which generally demonstrate a higher degree of reflectance or brightness. A median and Frost filter were applied to reduce white noise and maintain edges.

in these figures as a string of small circles. Unlike the previous image, which was optical, the images in Figure 13 were derived from processed SAR data and show up as pixels of varying intensity. Each pixel in the raw data set represents a rectangular area of approximately 4 meters by 21 meters, depending on the terrain. Since each of these images was taken from the same satellite track, the view or position of the image is similar.

To process these data, EQE imported the single-look complex images into the ENVI (the Environment for Visualizing Images) software, a special imaging processing program designed specifically for remotely sensed data. The single-look complex images provide the highest resolution possible using a SAR imaging system. The resolution or pixel size is dependent on a number of factors including radar hardware parameters. For our data set, the pixel size is about 4 meters in the azimuthal direction (i.e., the direction of the radar platform) and 21 meters in the cross direction. In order to reduce the inherent noise in the radar image (e.g., speckle noise), we applied an averaging filter in the azimuthal direction. This process is normally referred to as multi-look averaging. This reduction in noise, however, comes at the expense of reduced spatial resolution. The end product, after this processing, is a 21 meter by 21 meter pixel.

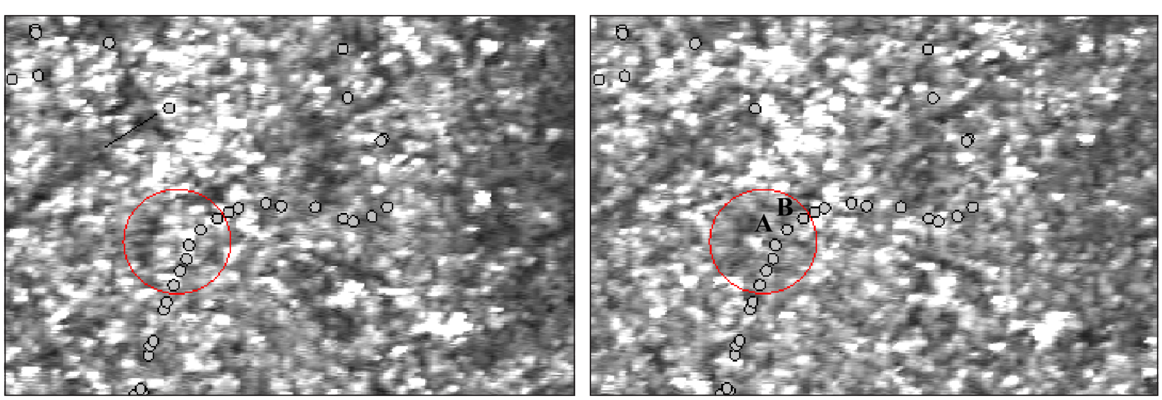
We anticipate that with this resolution, it will be difficult to recognize from these images physical structures having dimensions of less that 20 meters. Therefore, unless a structure takes up several pixels, it may be difficult to assess any change between before- and after-earthquake images. We are also investigating a "correlation" approach to detect pixel level changes; however, these analyses are not complete at this time.

The two images that are shown in Figure 13 were taken almost five months apart. The first image was taken in late spring (4/24/99); the second image was taken less than one month after the August 17th earthquake (9/10/99). Generally, there would be image differences caused by seasonal change. However, for this area, temperature differences within that time span are expected to be mild (55 °F in late spring to 70+ °F in summer); average monthly rainfall between these two periods is also expected to vary only slightly.

In general, pixel intensity will depend upon vegetation level, the density of buildings and their shapes, moisture levels, season, etc. Brighter areas are those that reflect more of the radar energy sent down from the sensor. In Figures 13a and 13b, the brighter areas are associated with the built-up area of Adapazarı. Both images were exported to MapInfo where they were georeferenced to the Landsat 5 data. Since the resolution of these images is fairly coarse, we generally see only the major features of the region, e.g., major roadways and streets and some very large buildings. A cursory examination of both images does show some differences between the two figures. In order to view these changes in detail, we must concentrate on smaller portions of these images.

In order to identify any significant changes between the two images, we had to isolate part of the previous figures and concentrate on those areas that the team spent some time investigating while in the field. Once such area is the "Circle Area" which shows up at the tail end of the route (see Figure 12 for approximate location). To examine the changes between the two images, we drew a circle of 0.25-mile radius around this area. Comparison of the two images reveals that the after-earthquake image (Figure 14b) contains fewer bright spots. As was explained before, many of the buildings in this area had either completely failed (total collapse) or were severely damaged (many tilted buildings). It is expected that this type of damage would result in more scattering and thus, duller images.

Figure 15 shows two photographs of damage in the "Circle Area." The first photograph (Figure 15a) is taken looking west along the main road. The second photograph is taken from the same location,



(a) (b)

■ Figure 14. Close-up of "Circle Area" in Adapazarı (see Figure 12 for location). Note the designations (a) and (b) in Figure 14b which refer to photographs (a) and (b) in Figure 15. North is up. Raw data supplied by ESA.

(a) **(b)**

Photographs by R. Eguchi

■ Figure 15 . Damage to apartment buildings in the "Circle Area" of Adapazarı. Left image is view (a) in Figure 14b. Right image is view (b) in Figure 14b.

looking northeast. Note that many of the damaged buildings have been torn down and the debris hauled away (Figure 15a). Since the second image was taken about one month after the earthquake, it is possible that the bare ground was being imaged at that time. At any rate, the second image was able to pick up this change.

In the next several months, we will be examining these data in more detail. In addition to the "Circle Area," we hope to examine other sites where we have collected field data on the earthquake. One useful source is a digital video that was taken on the second trip to Adapazarı in November. By examining these images in more detail, and perhaps, by creating a series of correlation or coherence maps, we can begin to explain the meaning of these image changes. In addition, we hope to return to Turkey to collect other data that may help to quantify the extent of damage to this town.

Summary

Although largely untested in earthquakes, all of the new technologies employed during our reconnaissance proved to be invaluable in documenting the effects from this earthquake. Listed below are some of the lessons learned while performing this investigation.

1. The Landsat images proved to be invaluable in calibrating on-ground data, such as the locations of major roads, the boundaries of urban regions, and in some cases, the location of large buildings, i.e., buildings with large footprints. Because the resolution was fairly coarse (30 meters), it was difficult to use these data to detect or quantify earthquake damage. These images, however, were easily processed and were available soon after earthquake.
2. The ERS-1 and ERS-2 data proved to be useful once the MCEER/

EDM team left the field and returned home. Although these data were available before the trip, it was difficult to process this information because of map registration problems, and because the data contained more than just image data. We are now beginning to work with these data to explore how useful they are in detecting damage through interferometric techniques. We speculate that correlation or coherence maps developed from an analysis of pre- and post-earthquake images will result in the best use of these data and could possibly detect areas where significant damage (e.g., collapsed buildings) has occurred.

3. The use of GPS equipment was essential in documenting the activities of the team. Precise coordinates were established for important damage sites. This information was crucial in relating satellite imagery data to on-ground observations. Also, when connected to the portable laptop computer, many critical analyses were possible in real-time. There was also a significant difference in results when Differential GPS was available. In Avcılar, geographical coordinates were accurate to within one meter. In Adapazarı, where Differential GPS measurements were not possible, coordinates were accurate to within 30 meters. This difference could be critical when attempting to document damage to individual buildings.
4. Having access to in-field GIS software made the documentation process extremely efficient. Many of the records – such as the Adapazarı survey – would not have been possible had it not been for the GPS-GIS setup. The actual survey that was discussed in the previous section took less than 4 hours. If paper maps or other manual methods of documenting damage had been employed, it would have taken at least several days to accomplish what was done in half a day using these new mapping technologies.
5. One important piece of equipment – which was used by investigation team members for the first time – was a digital camera. The advantages to using such a camera is that the images that are taken are immediately viewable, they can be downloaded immediately for transmission to some other site, and when connected to a GPS unit (which was not done on this trip), could produce more reliable documentation of an event.

Endnotes

[1] SPOT is a French company that provides satellite imagery data throughout the world. SPOT stands for Satellite Pour l'Observation de la Terra.

[2] As it turns out, one of the guides that we used during this half-day trek had a tourist map of the city, which she kindly turned over to us as we departed.

[3] A digital video camera was used on a second trip to Adapazarı on November 20, 1999.

Acknowledgments

The MCEER/EDM team would like to acknowledge the Multidisciplinary Center for Earthquake Engineering Research for its generous support of this investigation. In addition, we would like to thank the following individuals and organizations for their help in making this a unique and productive trip. Without this support, many of the activities mentioned above would not have been possible. They are: Dr. Betlem Rosich, ESA/ESRIN; Mr. Serkan Bozkurt, IMAGINS; Mr. Turgay Türker, Türker Engineering; Professor Mustafa Erdik, Kandilli Observatory and Earthquake Research Institute; Dr. M. Namık Yalçın, Dr. Semih Ergintav, and Dr. Hülya Yıldırım, TÜBİTAK; Mr. İsmail Barış, Mayor of Gölcük; Mr. Larry Roeder, U.S. State Department; and Dr. Charles Scawthorn and Ms. Hope A. Seligson, EQE International.

Restoration Activities Following the Marmara, Turkey Earthquake of August 17, 1999

by Gary R. Webb

Sponsors

National Science Foundation, Earthquake Engineering Research Centers Program

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Research Objectives

The primary objective of the research is to provide detailed information on various social aspects of the Marmara earthquake. In particular, the research focuses on activities aimed at restoring basic social functions to the impacted region during the early recovery phase of the disaster. This paper examines three of those functions: (1) housing, (2) education, and (3) health care. The paper concludes by discussing numerous future research needs that stem from this earthquake in the areas of disaster preparedness, emergency response, social recovery, and mitigation.

By any standard or definition, the earthquake that struck northwestern Turkey on August 17, 1999 was a major disaster. Measuring 7.4 on the Richter scale, the earthquake was centered near the cities of İzmit, Gölcük, and Adapazarı. It damaged or destroyed over 200,000 buildings, left hundreds of thousands of people homeless, and, according to official estimates, resulted in the deaths of nearly 17,000 people. The earthquake also had a major impact on large industrial facilities in the region, and estimates of its economic impacts vary between 5 billion and 10 billion U.S. dollars. While preliminary estimates of the economic costs associated with the earthquake vary widely, actual costs will likely be substantial given the sheer magnitude of the event. Because the earthquake occurred in a largely urban and industrialized area, it resulted in widespread physical damage and severe social and economic disruptions.

This paper describes activities that were initiated to restore social routines to the impacted region during the early recovery phase of the disaster. Three basic social functions are described: (1) housing, (2) education, and (3) health care. The first part of this paper describes some of the major housing issues that arose following the earthquake, including difficulties associated with estimating the number of homeless and the establishment of large "tent cities." The second section addresses the issue of restoring education, particularly in Gölcük, and discusses the challenge of determining when it was appropriate to resume school and deciding how

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to best do that. The third section describes how some hospitals in the region were impacted and how they responded following the earthquake.

Housing and the Earthquake

During the MCEER team's trip to Turkey (September 28 to October 5, about six weeks after the earthquake occurred), the most prominent and salient social aspect of the event was housing. Because the earthquake was so physically destructive, it displaced an enormous number of people from their homes, all of whom needed alternative living arrangements. As will be discussed below, however, for various reasons it is difficult to know exactly how many people were left without homes in the earthquake's aftermath.

Following major disasters like the one in Turkey, the provision of temporary sheltering and housing is typically a priority in early attempts to restore normal social functioning. While in the first few hours and days after a major event the focus is likely to be on immediate response activities such as search and rescue and the delivery of emergency medical services, the sheltering and housing process also typically begins fairly quickly. In terms of characterizing the social aspects of disasters, housing is a crucial component of the entire process.

Estimating the Number of Homeless

The task of estimating the number of tent cities that were established after the earthquake and the number of people living in them proved to be a major challenge. Some estimates suggest that the earthquake destroyed or badly damaged 120,000 housing units, leaving as many as 600,000 people without homes. Other estimates suggest that approximately 120,000 people are living in 200 tent cities throughout the region. In either case, the number of people left homeless in this disaster is very large, and it will be important to generate more accurate estimates as plans are developed for more permanent living arrangements.

The need for more accurate estimates is heightened due to the fact that winter can be bitter in the impacted region. Because most of the tents in which people were living at the time of the team's visit were not adequate for extreme winter

Because this research focuses broadly on the social aspects of the Marmara earthquake, it is anticipated that numerous groups will have an interest in the issues discussed. Researchers in the United States, for example, can use the material presented here as a basis for making cross-cultural comparisons of social responses to disaster. The research will also be useful to policy makers and other officials who must make crucial decisions about disaster response priorities and recovery alternatives. Emergency management officials and relief workers from voluntary associations, government agencies, and non-government organizations will also benefit from the research findings.

weather, plans were being discussed to bring in stronger winter tents and some pre-fabricated buildings. Therefore, as officials began making housing arrangements, they could have benefited from an accurate estimate of the number of people living in tent cities.

In many U.S. disasters, it is not uncommon for officials to drastically over-estimate public housing needs because they sometimes do not recognize that many of those who are displaced go to live with friends or relatives whose homes were not destroyed. It is likely that similar patterns occurred in response to the Turkey earthquake and that these patterns may have complicated census-taking efforts. For example, in the mountains surrounding Gölcük and Adapazarı, two cities that were very heavily damaged, there are many small villages from which people migrated to live in the larger cities. And many people from other parts of the country that may be much further away have migrated to these more urbanized and industrialized cities to find work. Following the earthquake, it was not known how many people returned to their places of origin to live with friends or relatives and exactly how many people remained in the two cities. It may have been easier for people from the surrounding mountain villages to return home, whereas people from more distant places in Turkey may have been less likely to leave the area after the earthquake.

In either case, officials do know that there has been some migration, but they do not know how much. For example, a health official in Adapazarı indicated that prior to the earthquake, approximately 200,000 people lived in the center of the city. After the earthquake, this official estimated that only about 50,000 to 70,000 remained in the city. Similarly, an official in Gölcük, which had a population of about 75,000 prior to the earthquake, indicated that about half that many remained in the city after the earthquake.

In addition to internal migration patterns and survivors' reliance on existing social networks of support, there are other reasons why it is difficult to officially estimate the number of people left homeless by the earthquake. For example, another major impediment to obtaining an accurate census is that many people (exactly how many is not known) whose homes were not badly damaged are nevertheless reluctant to reenter their buildings. Since the earthquake occurred, there have been several major aftershocks that have instilled hesitancy on the part of survivors.

Additionally, some officials indicated that although several groups and organizations are developing counts for various purposes, they are not coordinating those efforts closely enough. For example, some groups are taking counts in order to make arrangements for the delivery of mental health services, and others may be trying to order appropriate amounts of certain supplies. With so much activity going on, however, it is very difficult for these various groups to collaborate with each other and coordinate their efforts. The result, then, is that various groups and organizations are taking counts for their own purposes, and these numbers are not being shared.

In most disaster situations, research has shown that both inter- and intra-organizational coordination are

Links to Current Research

Program 2: Seismic Retrofit of Hospitals
Program 3: Emergency Response and Recovery

Web Sites

Multidisciplinary Center for Earthquake Engineering Research
http://mceer.buffalo.edu/research/turkeyeq/default.html

often difficult to achieve because circumstances change rapidly and because numerous organizations (many of which have no mandate or responsibility for emergencies) become involved in the overall community response (Dynes 1970). In situations where various organizations are not familiar with one another and lack established patterns of interaction and coordination, it is not uncommon for these kinds of problems and issues to arise.

Three Types of Tent Cities

Although it was not possible at the time of the team's visit to know exactly how many tent cities existed and how many people were living in them, it was possible to describe the tent cities and how residents adjusted to living in them. Basically, displaced people in the impacted area who have not sought shelter in other locations were living in three different types of tent cities: (1) those organized by the military, (2) those organized by non-government organizations and private corporations, and (3) those that are informally organized. In reality, it is difficult to classify individual tent cities because there is some overlap among these general types. For example, a tent city organized and run by the military may also offer some services to residents that are performed by a voluntary or non-government organization. Similarly, a tent city organized by a private corporation may integrate non-government organizations into its service delivery system and rely on military personnel to provide security. In a very general sense, however, it is useful to organize the numerous tent cities into these three general types.

In terms of size, the largest tent cities seem to be those that are organized either by the military or by private corporations or non-government organizations. At one of the military-run tent cities in Gölcük, for example, 3,000 people are living in tents that cover a large land area (shown in Figure 1). Another tent city in Gölcük set up by a large manufacturer in the area houses approximately 3,700 people. Informal tent cities, which are comprised mainly of neighborhood groups living outside in tents near their homes (which may or may not be badly damaged), are scattered throughout the region and tend to be comparatively small (see Figure 2). It was difficult at the time of the visit to ascertain the proportion of people living in the various types of tent cities for the same reasons discussed above. For example, the crisis response center in Gölcük reported the existence of 12 tent cities in Gölcük, but one administrator knew of at least 21 different tent cities. A more accurate count may improve the efficiency and effectiveness of the delivery of needed supplies, and it may ultimately help in the arrangement of

Photograph by G. Webb

■ Figure 1. A military-run tent city in Gölcük adequate provisions for the future, particularly for winter.

A more accurate census of tent cities and people living in them would also make it possible to compare the different types along several dimensions. For example, on the one hand, a clear benefit of the informally organized tent cities is that they allow primary social groups (i.e., families, extended families, and close friends) to live near each other and rely on each other for social support. While administrators of the other two types of tent cities have tried to keep these groupings intact, they are less able to do so as these tent cities increase dramatically in size and as space becomes less plentiful in them. On the other hand, the larger military- and volunteer-run tent cities may be able to offer a wider range of services to residents, including large kitchens, pharmacies, counseling services, entertainment, and kindergarten for small children. For example, at one of the large military-run tent cities in Gölcük, a civic group from İstanbul (which had no prior involvement in disasters) established a kindergarten for young people.

This involvement of non-emergency organizations in providing services after the earthquake is similar to what occurs in many U.S. disasters, and it is an issue that should be explored further through cross-cultural and cross-societal comparisons of disaster responses. If there are important differences in the type and quality of services offered at the various types of tent cities, and if there are certain benefits and limitations to each of them, they should be used as lessons for future disasters when mass numbers of people must be temporarily relocated.

Photograph by G. Webb

■ Figure 2. An informal tent city

Adjusting to Daily Living in the Tent Cities

Following major disasters like the one in Turkey, the establishment of tent cities serves several important functions: it provides necessary shelter from the elements; it re-establishes and reaffirms community and collective solidarity; and it begins to provide a stable base from which people can start to restore their daily routines. In some of the large military- and volunteer-run tent cities, for example, meals are served at certain times each day, residents engage in routine religious rituals and perform basic routines like doing laundry, young people play soccer and attend kindergarten, and some adults leave each morning to go to work. Just across the street from one of the tent cities, a market has emerged that provides residents a place to go to purchase basic items. And local bus companies have altered their routes to provide transportation from the tent cities to various points throughout the city. All of these examples illustrate the point that when social routines are severely disrupted, individuals, groups, and organizations improvise and adapt in

Photograph by G. Webb

■ Figure 3. A "renovated tent"

Photograph by G. Webb

■ Figure 4. A tent under construction

creative ways as they attempt to restore normalcy to the social order (Bosworth and Kreps 1986; Kreps and Bosworth 1993; Quarantelli 1996; Webb 1998).

One of the most important issues that individuals and families face under these circumstances is the challenge of making a temporary living arrangement into a home that provides all its members with safety and comfort. In a social psychological sense, this means rebuilding or re-establishing an attachment to place that provides security and stability in daily interactions. When a major disaster disrupts a group's attachment to place, its members interact to develop a new definition of the situation that gives meaning to their experiences and guides them through their interactions with others.

One of the most noticeable things about life in a large tent city is that residents have almost no privacy. In this kind of living arrangement, virtually every aspect of an individual's life is on public display. To minimize or alleviate that problem, residents often adapt in some very creative ways. For example, occupants of a tent will make additions that divide it into two separate spheres: a front area where they can sit and talk with others, and a back area where they sleep and prepare for the day. Figure 3 nicely illustrates how this is accomplished. In Figure 4, a tent is shown that is "under construction," and Figure 5 shows a finished product that actually resembles a small house.

In a sociological sense, these innovations are very meaningful because, although there are important cultural differences, the separation of public and private spheres is a crucial component of social life. In their interactions with others,

Photograph by G. Webb

■ Figure 5. A finished product

Photograph by G. Webb

■ Figure 6. A "street sign" in a tent city

individuals make decisions about what things to openly present in the front stage region and what things to display only in the back stage region (Goffman 1959). In a very basic sense, for example, housing units in many cultures are designed with a living area intended to be on display to guests and a sleeping area that is typically not openly displayed. By making these kinds of additions to their tents, many of which are fairly elaborate, residents of the tent cities are redefining a fundamental aspect of their social lives.

Residents are also engaged in the process of building new social relationships and a sense of community. For example, as shown in Figure 6, the residents of a particular row of tents in a very large tent city in Gölcük gave themselves a street name and erected a sign bearing the words "Save Me Street" (translated). This example nicely illustrates how under conditions of extreme stress people rely on each other and the relationships they have to give meaning to their experiences. Similarly, in other cases, community members often spray paint graffiti after disasters to express either messages of hope and collective solidarity, discontent with the official response, or simply convey basic information. As shown in Figure 7, residents of one tent city stretched large white banners across a fence surrounding a playground and painted various things on them, including the slogan "Let's not Forget Gölcük."

These expressions of solidarity and hope may account for some of the debate about the delivery of mental health services following major disasters (Quarantelli 1985). In many U.S. disasters it is often assumed that these services will be widely needed, but in many cases survivors do not seek out that kind of assistance. At some of the tent cities in Turkey, there have also been some concerns that residents are not utilizing mental health services to the degree that they should. There may be two reasons why disaster survivors do not always seek mental health services after a major event: first, they may find comfort and support in their interactions with significant others who have

"Some estimates suggest that the earthquake destroyed or badly damaged 120,000 housing units, leaving as many as 600,000 people without homes."

Photograph by G. Webb

■ Figure 7. Graffiti in Gölcük

> ***"When a community has been severely disrupted, its members rely on existing social relationships and newly formed ones in coping with the emergency and beginning to restore normalcy to their lives."***

also experienced the event; and second, some of the mental health consequences may not necessarily be negative. As some of the examples above show, when a community has been severely disrupted, its members rely on existing social relationships and newly formed ones in coping with the emergency and beginning to restore normalcy to their lives. Sometimes disasters may enhance, if only temporarily, the collective solidarity felt by members of a community because they all share a common experience. Clearly, there is a need for more research on the mental health consequences of disasters, and the earthquake in Turkey provides a setting where important cross-cultural and cross-societal comparisons can be made.

Restoration of Education After the Earthquake

Another basic social institution that is often disrupted in a disaster and that must be restored, is education. In addition to providing young people knowledge they need to become adult members of a society, schools also serve the crucial function of keeping a substantial portion of a population occupied and on a rigorous daily schedule. When that schedule is interrupted, a certain amount of ambiguity and confusion is created, so officials typically try to resume school as quickly as possible. Their concern is often not only to get students back in school for learning purposes, but also to give structure and meaning to young people's lives in a period of confusion and disruption. The restoration of daily activities, including school for children, is a crucial part of community response to and recovery from a disaster.

The earthquake in Turkey occurred almost one month before schools across the country were originally scheduled to begin on September 15. Schools in many areas did begin as scheduled, but when a major aftershock occurred on that same day, all school openings were indefinitely postponed. Ultimately, schools in areas such as İstanbul that did not sustain heavy damage began operations on Monday, October 4. Even that caused some controversy because many parents in those areas did not understand why their children were being held out of school for so long. In more heavily damaged regions, such as Gölcük, it was hoped that school could begin in early November, significantly later than originally planned.

There are several reasons why the opening of schools in Gölcük was delayed for such a lengthy period of time. First, some of the school buildings themselves sustained heavy damage, so pre-fabricated structures or large tents would be needed to conduct classes. Second, many teachers, students, and parents expressed major concerns about reentering even those school buildings that had not been badly damaged in the earthquake. Finally, in Gölcük it was not known how many students in the area would be returning to school. As was discussed above in relation to housing issues, migration patterns strongly affected the population of students in the most severely impacted areas, and that made it difficult to estimate the number of returning students for whom plans should be made. Many students were believed to have returned with their families to either villages in the surrounding mountains from which they came or to more distant parts of the country to live with relatives or close friends. A school official in Gölcük, for example, estimated that only 10,000 of the area's 28,000 students would return to school.

To facilitate the opening of schools in the most heavily damaged regions, the Turkish government commissioned one of the major universities to become involved. According to some of those involved in the project, the commission has two major goals: first, to get an accurate estimate of the number of students who will be returning to school; and, second, to conduct focus groups with teachers, students, and parents to better understand their anxiety about reentering school buildings that were not damaged.

Some school officials, however, indicated that this approach may not be the most efficient and effective way to go about restoring school to the most badly damaged areas. For example, one official suggested that it may be more productive to establish schools throughout the region in large tents and see how many students report. If the demand were to exceed the number of tent schools established, then additional ones could be set up. This case illustrates that a major disaster can disrupt even the most basic social institutions and that key participants often have differing perspectives on how to respond. In some disasters, such as the recent earthquake in Taiwan, schools resume fairly quickly, but there are certainly times when a prompt restoration is not possible. Thus, there are important lessons to be learned from the recent earthquakes in terms of understanding barriers to the restoration of basic social institutions and identifying strategies that are particularly effective.

Health Care Facilities and the Earthquake

Another basic social function that is sometimes disrupted in major disasters is health care. These disruptions occur either because the number of fatalities and injuries exceeds the health care system's capacity to respond or the health care system itself sustains physical damage which affects its ability to deliver services. In either case, this is another area in which the social system often becomes very flexible and adaptive in meeting heightened emergency demands.

In both İzmit and Adapazarı, several hospital buildings experienced major physical damage during the earthquake. At a hospital in İzmit, for example, two buildings and the pedestrian walkway connecting them sustained serious damage from the shaking. Immediately after the earthquake, medical staff were forced to evacuate the building and move existing patients outside. As people began bringing the injured to the hospital's emergency department, it quickly became congested and overcrowded. To alleviate the crowding, hospital staff began assembling the injured in a school yard across the street, sorting and tagging them by severity of injury, and transporting them to other regional facilities. Similarly, existing patients who could not

"Schools serve the crucial function of keeping a substantial portion of a population occupied and on a rigorous daily schedule."

simply be discharged early were also transferred to other facilities.

What is most interesting about this particular hospital is that even five weeks after the earthquake, staff still had not yet reentered the buildings. On two occasions they tried to reenter, but when major aftershocks occurred, they returned outside. Because they were forced to set up operations in tents in the parking lot (shown in Figure 8), the hospital has been unable to resume its normal functioning. For example, minor injuries are treated, basic exams are conducted, and medications are dispensed, but it is not possible to perform major medical procedures. This case shows that even emergency relevant organizations such as hospitals can themselves be impacted by disasters, and, when they are, they must become flexible and adaptive under the circumstances.

Similarly, a major hospital in Adapazarı sustained extensive physical damage to its buildings. In particular, two of the facility's five buildings were damaged, forcing staff members to move existing patients outside. As was the case in the previous example, existing patients and new arrivals were assembled outside, sorted and tagged by severity of injury, and transferred to other regional hospitals or field hospitals set up by international relief organizations. According to one official, this process created some confusion at the hospital because staff members were not able to document all of the victims who were seen and transferred. The receiving hospitals later created detailed lists and sent them back to this facility, but the delay in that process created some confusion as concerned people came to the hospital looking for their friends or relatives. This official also indicated that for a short period of time there was a shortage of trained medical staff in the immediate aftermath of the earthquake. That problem was resolved, however, as volunteers quickly began arriving. The same official pointed out that this staff shortage existed in Adapazarı even before the earthquake.

While staff members have reentered the facility in Adapazarı, the hospital still had not resumed its normal functioning at the time the research team visited. For example, major medical procedures still were not being performed at the hospital, and staff from other cities who came to volunteer were still living in tents in the parking lot. At the time the team visited, the hospital in Adapazarı had focused its activities on providing broader public health services. For example, officials began producing and distributing brochures and pamphlets that describe how to treat water, prepare food, and avoid bacterial diseases. In addition, local health officials have been involved in monitoring the city's supply of clean water, much of which was being hauled in by tankers from a nearby lake. One official

Photograph by G. Webb

■ Figure 8. A hospital in İzmit

gladly reported that there have been no major outbreaks of bacterial diseases in the region, in large part because of the activities undertaken by staff members at the hospital.

These examples of hospitals in Turkey highlight two important points. First, they clearly show that health care facilities, which are usually assumed to be operational in mass emergency situations, can sometimes experience physical impacts themselves. And, second, when hospitals are impacted by disasters, their basic structures and functions are often altered to meet heightened demands created by the emergency. Although these alterations and innovations are often functional and adaptive, they may sometimes be dysfunctional and maladaptive. In either case, it cannot be assumed that hospitals will always be operational in the aftermath of a major disaster event. In fact, surprisingly little research has been done that documents exactly how prepared hospitals are for disasters and how they actually function when disasters do occur. Clearly, this is an area where much more research is needed, and the earthquake in Turkey provides a situation where cross-cultural and cross-societal comparisons can be made in describing and understanding how hospitals function under stress.

Future Research Needs

This section draws out some of the future research needs that were mentioned in the previous sections and presents others that were not explicitly stated. There are several areas in which the earthquake in Turkey provides a setting in which interesting cross-cultural and cross-societal comparisons can be made along several dimensions. First, at a very basic and descriptive level, it would be useful to do further research on the various organizations that have become involved in the response to and recovery from the earthquake. As was described in the previous sections, various organizations, many of which have no defined disaster responsibilities, have become involved, and many of those that do have disaster responsibilities, such as hospitals, have significantly altered their basic structures and functions. This kind of organizational innovation and adaptation has often been documented in studies of U.S. disasters, so there is a unique opportunity to make comparisons with the situation in Turkey. These studies can either document how specific types of organizations, such as hospitals, responded to the earthquake or focus on the issue of inter-organizational coordination between various types of organizations. This kind of research can be readily translated into lessons learned and ultimately usefully integrated into the practice of emergency management.

The broader issue of social recovery is another area in which important cross-cultural comparisons can be made. Several studies have looked at the process of household (Bolin 1994) and business recovery (Dahlhamer and Tierney 1998; Tierney and Dahlhamer 1998; Webb, Tierney and Dahlhamer forthcoming) in the U.S., so the earthquake in Turkey presents an opportunity for comparative research. There are several important

"Existing patients and new arrivals were assembled outside, sorted and tagged by severity of injury, and transferred to other regional hospitals or field hospitals set up by international relief organizations."

"Ultimately, the lessons learned from this earthquake should be translated into measures that either reduce the impacts of future disasters or improve societal responses to them."

areas in which the earthquake in Turkey can improve our broader understanding of community recovery as a social process (Nigg 1995). For example, future studies might document the impact of this event on the collective memory of the people who experienced it and assess the degree to which it may or may not affect subsequent mitigation decisions aimed at reducing the impacts of future disasters. Along those same lines, it will be interesting to measure the local, regional, national, and international economic impacts of the earthquake and monitor the progress of economic recovery. As one example of this, officials in Gölcük have already expressed differing views of how best to promote economic recovery—some want to rebuild the existing downtown business district, while others want to relocate it away from the sea and closer to the mountains. These kinds of perspectives and debates will likely intensify in the coming months, and that process should be studied.

In addition to studying the process of economic recovery, there is a tremendous amount to be learned from studying the transition of earthquake survivors from temporary to permanent housing. On a practical level, there are valuable lessons to be learned from this case as officials try to place tens or even hundreds of thousands of people in more permanent living arrangements. And, on a conceptual level, it will be important to understand how individuals, families, and groups construct meaning in their daily lives in the tent cities and beyond and how they re-establish their attachment to place under conditions of such extreme uncertainty.

Future research should also be done to explore the many political implications of the earthquake (Sylves 1998). For example, some commentators have suggested that the earthquake has promoted a certain critical sentiment among Turkish citizens and that for the first time they are speaking out against their government and criticizing its response to the disaster. Others have suggested that the sympathetic outpouring of international relief reflects improved relations between Turkey and other nations. Whether these changes were induced by the earthquake or simply accelerated by it, the political dimensions of this disaster will also be important to consider.

Finally, the recent earthquake in Turkey also provides a setting in which to assess the applicability and utility of advanced damage assessment technologies and loss estimation methodologies (see the MCEER reconnaissance report on the earthquake, Scawthorn 2000). Moreover, there is a need for research that describes what technologies have been employed in responding to and recovering from the earthquake, assesses their utility, and identifies areas in which technologies can be improved to enhance response capabilities.

Whether the knowledge gained from that research is used to promote disaster preparedness, enhance emergency response, facilitate social recovery, or suggest certain mitigation measures, there is a tremendous amount to be learned from this event. Ultimately, the lessons learned from this earthquake should be translated into measures that either reduce the impacts of future disasters or improve societal responses to them.

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Human and Institutional Perspectives of the 921 Chi-Chi, Taiwan Earthquake

by George C. Lee and Chin-Hsiung Loh

Research Objectives

MCEER and the National Center for Research on Earthquake Engineering (NCREE) have had a cooperative agreement to carry out fundamental earthquake engineering research in areas of mutual interest since 1992. Shortly after the devastating Chi-Chi earthquake of September 21, 1999, the Directors of the two Centers planned a joint MCEER-NCREE workshop to identify important short-term strategies and actions for post-earthquake restoration and identify research needs. In April 2000, a second workshop was held between NCREE, MCEER, the Pacific Earthquake Engineering Research (PEER) Center at the University of California, Berkeley, and the Office of National Science and Technology Hazard Mitigation of the Taiwan government, to develop a highly focused Center-to-Center research program. The program will incorporate the vast amount of reconnaissance information gathered in Taiwan and apply it to specific problem-focused research already underway at the four Centers. This plan, together with observations of the authors with respect to the societal and government responses, is offered herein.

On Tuesday, September 21, 1999, a devastating earthquake struck the central region of Taiwan. This earthquake became known as the 921 earthquake or the "Ji-Ji" or "Chi-Chi" earthquake. The magnitude of the 921 earthquake was M_S = 7.6 (Richter scale) or M_L = 7.3 (the system used in Taiwan). There were ten aftershocks greater than magnitude 6. Of these, an M_L = 6.8 occurred about 30 hours and 120 hours after the main shock, respectively. An M_L = 5.3 aftershock was recorded as late as 260 hours later causing collapses of already damaged structures. As of October 8, the death toll was more than 2,350. Over 8,700 people were injured, and dozens remained missing. Approximately 10,000 buildings/homes collapsed and over 7,000 more were damaged.

For the past eight years, MCEER and the National Center for Research on Earthquake Engineering (NCREE) have had a research collaboration agreement to carry out fundamental earthquake engineering research in areas

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of mutual interest. A number of joint studies in the general area of seismic response control are in progress and last year, two additional research projects were added (remote sensing applications, and protective systems for bridges).

Photograph by M. Bruneau

■ Figure 1. Surface faulting caused major damage to the Shih-kang Dam

Under the umbrella of continuing cooperative research, the authors discussed the best way to join forces following the 921 earthquake. They decided to hold an MCEER-NCREE workshop, which took place on October 3-5, 1999 in Taiwan. The purpose of the workshop was to identify important short-term strategies/actions for post-earthquake restoration and research needs, including specific cooperative projects for investigators from both centers to work as teams based on the 921 experience. Many reports have since been published by NCREE on a variety of technical areas (in Chinese) and MCEER has a reconnaissance report in press at this time (Lee and Loh, 2000), which focuses on both technical and societal issues.

This growing body of knowledge and its vast potential prompted MCEER to examine whether or not our research results, which are carried out in concert with achieving our vision of creating earthquake resilient communities, could help in Taiwan; and if so, how it could best be accomplished. To explore this possibility in greater detail, a second workshop was organized in April 2000 in Taiwan and included two more centers, the Pacific Earthquake Engineering Research (PEER) Center at the University of California, Berkeley, and the Office of National Science and Technology Hazard Mitigation of the Taiwan government. The Directors from each of the four Centers held discussions to further define and clarify how to bring their collective strengths together to make this vision a reality. The result was the establishment of a three-year Center-to-Center research program. The specific research projects to

Post-earthquake information is valuable for the enhancement and validation of existing models, methods and practices. It is anticipated that the results of this research effort will be used by earthquake hazard mitigation experts for this purpose, and will ultimately strengthen our existing knowledge base in a wide variety of areas. On the Taiwan side, one focus will be to validate HAZ-Taiwan, to develop more accurate loss estimation methodologies. For both the U.S. and Taiwan, new knowledge gained will be applicable to code improvements and implementation in both countries.

be carried out under this program are described later in this paper.

The first part of this paper summarizes the observations and reflections of the authors shortly after the earthquake with respect to the societal and government responses of the 921 earthquake. The authors are of the opinion that this earthquake not only destroyed a segment of Taiwan's physical landscape, but also made a significant impact on the society and government. Taiwan, like the U.S., is lucky because it hasn't experienced a major destructive earthquake with large death tolls in recent memory. This 921 earthquake presents a reminder and an opportunity for the people and government in Taiwan to begin a serious effort to establish more resilient communities against future earthquakes. The second part of the paper describes the new Center-to-Center research program.

Initial Observations and Reflections

The Public

Earthquake ground motions are felt by people living throughout Taiwan. Thus, the term "earthquake" is a familiar one. However, an earthquake of the magnitude of 921 has not happened in recent history. To many people, an earthquake amounted to the swaying of buildings and the development of cracks on a wall. Occasionally, the roof of some houses collapsed. The building code in Taiwan provides for reasonable design guidelines (the most recent update to the guidelines was made in 1997). Based on historical data and measurements made by strong motion instrumentation programs, the Taichung/Nantou area is classified as a region of moderate intensity with a design peak horizontal acceleration of 0.23 g. The 921 earthquake generated a horizontal force of more than four times this maximum design criterion. It is thus easy to see why so many buildings and bridges collapsed. Psychologically, the public in the area was accustomed to earthquakes, but not one of such destructive magnitude, occurring in built-up areas.

The public showed tremendous spirit as they worked together to save lives and help each other with the basic needs to survive in the days following the earthquake. After a day or two, many began to complain that the government was too slow in its rescue and relief efforts. As a few more days passed and people were forced to accept the loss of a loved one whose body had not yet been located, these complaints of ineptitude and inefficiency were understandably intensified. Nonetheless, it seemed that the government was actually quite swift and effectual in its response

Photograph by M. Bruneau

Figure 2. Damage to buildings and bridges was widespread throughout the epicentral area

Web Sites

Multidisciplinary Center for Earthquake Engineering Research
http://mceer.buffalo.edu/research/taiwaneq9_99/default.html

National Center for Research on Earthquake Engineering
http://www.ncree.gov.tw

Pacific Earthquake Engineering Research Center
http://peer.berkeley.edu/index.html

"An effective institutional structure for earthquake hazard mitigation is needed to develop well-prepared communities."

to the event, given its magnitude. At the same time, many people praised the efforts of military personnel and international emergency response teams, even though such help was limited in its effectiveness by the scarcity of critical information such as local area maps, building blueprints, and other such data. The disaster management effort at the regional and local level was clearly unprepared for this disaster.

In speaking with a variety of individuals, one can see that this earthquake has had an enormous impact on the way the public views the importance of building safety and location of both workplace and residences. In the short three-day visit, questions regarding these issues were the most frequently raised by the general public. Now is the time in Taiwan to emphasize public education about earthquake hazards and mitigation measures. A well-educated public will affect improvements in policy regarding mitigation and preparedness for earthquake and other natural hazards. In the past, real estate properties for many are the means to become rich. The landslides, the disappearance of the lake (reservoir), and the interrupted skylines in the city caused by the 921 earthquake had elevated the awareness of the public to treasure the small island shared by 22 million people. One may expect that environmental conservation and protection will be emphasized. Activities such as illegal pumping of fresh ground water for growing seafood (sinking land surface level) will be condemned by the public.

Photograph by M. Bruneau

■ Figure 3. Newly constructed buildings suffered severe damage

The Government

On the national level, the government seems to have responded well. It was certainly not possible to satisfy all those affected by the earthquake. However, many of the complaints stemmed from lack of preparedness rather than lack of emergency action. Within hours of the initial main impact, the national government announced policies for relief, short-term restoration and an organized interagency structure for efficient execution of rescue efforts. By September 28th (one week later), there were 17 major policies implemented, including hotlines, information and health centers, temporary housing, disaster relief funds and materials, and others.

However, a lack of earthquake disaster preparedness at both the national and local levels was evident. To varying degrees, this state of affairs exists everywhere in the world with respect to unexpected natural disasters. Because the occurrence of devastating earthquakes is probabilistic in nature, the consequences of such events are often not taken seriously by either the government or its constituents. In recent decades, the professional communities and government in Taiwan have made significant progress to mitigate earthquake hazards by, for example, funding the Strong Motion Instrumentation Programs at the Central Weather Bureau of the Ministry of Transportation and Communication, and funding earthquake and earthquake engineering research projects by the National Science Council, including the establishment of NCREE. The Ministry of the Interior and the various structural engineering professional organizations have also been active in updating building codes, and the Ministry of Education has been investing in human resources development and earthquake engineering facilities at the universities. Additionally, a National Science and Technology Program for hazard mitigation was established several years ago to coordinate the development of national hazard mitigation strategies.

All these efforts have been carried out by many talented researchers and administrators. They now beg the question, "What difference did these programs make in the communities where the earthquake struck?" Other than building code improvements for recently-built structures, very little can be said about how the investment of tax money improved the preparedness and resiliency of the communities. It seems that a systems approach involving multiple agencies and professionals at all levels from national to local must be designed and implemented. An effective institutional structure for earthquake hazard mitigation is needed to develop well-prepared communities. It is important, however, to distinguish between a comprehensive block diagram of relevant components (which is easy to draw) and a properly functioning hierarchy of agencies (which makes decisions at each level in a manner consistent with the overall system objectives).

Lessons Learned and Recommendations for Possible Actions

An earthquake resilient community should have three elements at its core:

- Properly developed codes for the physical infrastructure and high quality professional practice in planning, design, construction and maintenance.
- An informed and participating public.
- An institutional infrastructure system prepared for mitigation and response.

All three of these points require long-term sustained commitment from both the government and its citizens.

The 921 earthquake offers a chance to learn from "real world experience." Many issues related to earthquake engineering, from both the research and practical sides, have been addressed in other reports co-authored by investigators from both NCREE and MCEER. Several reconnaissance teams have also issued technical observation reports (for examples, the NSF-supported reconnaissance team, the EERI reconnaissance team, and others). In this section, the authors

"Within hours of the initial main impact, the national government announced policies for relief, short-term restoration and an organized interagency structure for efficient execution of rescue efforts."

"A well-educated public will affect improvements in policy regarding mitigation and preparedness for earthquake and other natural hazards."

reflect on their observations of the damage from the 921 earthquake and its effect on the local people, their community and government infrastructure, and the level of public knowledge on issues of earthquake hazard preparedness. Other reconnaissance reports have paid special attention to earthquake engineering research opportunities and the importance of long-term professional practice dealing with the physical world. The following observations are made from the total perspective involving human, institutional, and physical infrastructure system. They are offered for the public and the government in Taiwan as they face the restoration challenge after the 921 earthquake.

1. If the epicenter of the 921 earthquake had been located just 50 miles either north or south of the Taichung/Nantou area, the devastation to Taiwan's economy and the quality of life would have been much worse. To the north, the high-tech industrial park in Hsin-Chu and the political and economic center Taipei would have been struck; to the south, the center of heavy industry and manufacturing KaoHsiung could have been destroyed or seriously damaged. Eventually, these areas will be hit with a major earthquake. The opportunity exists today to carry out careful loss estimation and risk assessment studies for these areas. Ground motion information, geotechnical and structural design information all exist in sufficient quantities to conduct credible analyses of possible earthquake scenarios. These results could have a significant impact on the general public, elected officials and other decision-makers and stakeholders in Taiwan. Many individuals and organizations have gained financially from the booming real estate market of the past several decades – these groups will surely be supportive of such studies while the 921 earthquake is fresh in the population's collective memory. This type of study would allow for some quantification of the vulnerability of critical regions in Taiwan and could serve as the focus for a sustained effort in public education.

   Many individuals directly impacted by the earthquake require psychological help, for which the government has implemented a program. Often, survivors of critical events (drunk driving car crash, recovery from a terminal disease, and other traumatic events) become the best crusaders. These individuals may be provided with adequate understanding of the issues involving earthquake preparedness so that they can contribute to the public education task.

2. There is an immediate need for reliable methods to evaluate the extent of damage to a structure so that proper decisions can be made with regard to its retrofit/repair/replacement. More than 7,000 damaged buildings remain standing in and around the epicenter and they all need critical assessment of the damage sustained. This is a significant opportunity to begin accumulating the knowledge about "building damage" by developing an "expert system" or standardized system of measures

for non-destructive building evaluation. Of high priority is the evaluation of essential infrastructure buildings such as command centers, hospitals, manufacturing complexes and critical lifeline systems such as water, electrical power networks and bridges. An additional research effort to explore advanced technologies for deployment and implementation of emergency response, communication and rescue is also appropriate at this point, based on the lessons learned. There are many other long-term research opportunities in earthquake engineering that will not be addressed in this article.

3. The current emergency management and restoration organizational structure should be replaced gradually by a long-term institutional infrastructure which involves agencies at all government levels concerning all types of hazards. But beyond a simple box diagram of the hierarchy, such a system requires thoughtful implementation. One very important element is the appointment of the proper individuals at key positions in the various agencies (an Emergency Response Corps - the ERC). In an emergency situation, these individuals of the ERC are the connecting nodes of the system of agencies. They must be well versed in and loyal to the overall strategic and tactical aims of the system because they may be called upon to make decisions on short notice without the ability to consult either their superiors or their subordinates. These individuals would need to meet regularly, say twice a year, to review the emergency operating plan that should exist, and to update their coordinated efforts in mitigation and emergency preparedness. An institutional infrastructure for multiple hazard mitigation and response may be organized differently consistent with a country's own system and culture. The system in the United States (Congressional hearings and actions, the NEHRP agencies, the lead agency FEMA and its regional office, etc., and how they function) can be used as a starting point for development.

In general, a functioning institutional infrastructure system is much more difficult to establish than to reconstruct the physical infrastructure system. The latter may be targeted for completion in three or five years if resources are available. Emergency response and short-term actions require a top-down approach. But for long-term re-establishment, the top-down approach must be coupled with the bottom-up efforts of the participation of a well-educated public. In the opinion of the authors, the central government responded swiftly and in an organized manner with reasonable policies to help the affected people. However, preparedness at the local and regional levels was very inadequate, due to the lack of emergency awareness and relief plans. A

"A functioning institutional infrastructure system is much more difficult to establish than to reconstruct the physical infrastructure system."

Photograph by T.T. Soong

■ Figure 4. Reliable methods to evaluate the extent of damage are needed workable system to empower local government and a strategic system that ties together local and national government agencies during times of crisis is needed to avoid potential bottlenecks that could impede the implementation of Taiwan's five-year reconstruction plan. Addressing these issues is one of the major challenges ahead for post-921 revitalization.

4. One of the most pressing issues in short-term restoration is that of construction quality. This has always been an ill-defined factor that makes the evaluation of existing damaged facilities more difficult. It also becomes a factor of importance in the time immediately following an earthquake, as reconstruction begins. Other issues such as public education, research, institutional effectiveness and building code improvements are longer-term efforts. However, working with the real estate and construction industry can and should begin immediately with the restoration efforts. A workshop might be organized to review the current practice in building inspections (see item 2 above) and construction monitoring. Additional guidelines or recommendations would be issued as necessary. Building inspection and construction quality assurance should be examined from the overall perspective of planning, design, construction, decision-making processes (in the case of public works) and cost.

Photograph by M. Bruneau

■ Figure 5. Failure of non-ductile details was frequently observed

5. The short-term and long-term research needs identified by the 921 earthquake indicate that most of the research programs of MCEER and NCREE, particularly those involving current and potential joint MCEER-NCREE research efforts in: (a) loss estimation and risk assessment, (b) developing evaluation and retrofit strategies for critical facilities (water and electric power networks, medical facilities and bridges) and (c) application of advanced technologies in structural response mitigation and emergency responses, can benefit from the real world experience of the 921 earthquake. At the same time, these efforts can make a contribution to the state-of-the-art of earthquake engineering practice both in Taiwan and U.S. We look forward to a success story resulting from this center-to-center cooperation enhanced by the 921 earthquake.

Opportunities for Collaborative Research Projects

As noted in the introductory section, MCEER and NCREE have had a long-term cooperative agreement since 1992. Over the past several years, many workshops and discussions have been carried out to identify joint research and information exchange between the two Centers. At the time of the 921 earthquake, some of these research activities were already underway.

A special workshop was held shortly after the 921 earthquake during the first week of October 1999 in Taipei, organized by the directors of the two Centers. In view of the observations made following the devastating earthquake, workshop participants reexamined current research efforts, and priority was given to those issues that may answer questions related to Taiwan's short-term restoration efforts. These projects include:

1. Seismic retrofit (retrofit strategy) of transformer-bushing systems: system evaluation and analysis, develop retrofit options.
2. Seismic response, system identification, non-destructive evaluation and response modification technologies for hospitals, manufacturing facilities, and other facilities; bridges; and lifeline systems (electric power).
3. GIS-integrated technologies (including optical and RADAR-based remote sensing) for damage assessment from a system viewpoint.
4. 3-D time domain characterization of ground acceleration at a point and experimental validation of Tong-Lee kinematic formulation.

More recently, a Center-to-Center cooperative research program was initiated, including MCEER, NCREE and two additional Centers, the Pacific Earthquake Engineering Research Center (PEER) at the University of California at Berkeley in the U.S., and the Office of National Science and Technology Hazard Mitigation in Taiwan. The proposed three-year effort aims to take advantage of areas of overlapping interest and strengths of the four Centers, and to capitalize on the extensive results collected by the research team in Taiwan's reconnaissance efforts. Two major areas of emphasis were identified:

- The analysis of new information to enhance model validation, and to develop a better understanding that will lead to a new, more accurate knowledge base.
- Code improvements and implementation specific to Taiwan developed by earthquake hazard mitigation professionals.

These types of efforts are already underway and funded through the research programs of the four Centers. The proposed focus of the Center-to-Center research program is as follows:

1. Ground motion attenuation, site effects, spatial variation and validation.

Photograph by M. Bruneau

■ Figure 6. Damage to the Veteran's Hospital in Puli reduced its capacity to about 50% at a time when demand was highest.

2. Development of retrofit strategies for buildings shown to be vulnerable by the Chi-Chi earthquake. This includes two parts: development of specific retrofit ideas for 1-3 story and 8-12 story buildings; and development of evaluation and retrofit strategies for hospitals and selected manufacturing facilities including contents. This effort is an extension of existing projects on structural control technologies.
3. Development of evaluation and retrofit strategies for electric power (extension of existing project) water systems; and system analysis of electric power and water systems (extension of existing project).
4. HAZUS and HAZ-Taiwan Program (with Chi-Chi earthquake data, develop new system-related loss estimation methods for HAZ-Taiwan).
5. Social and economic issues.

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Education and Educational Outreach: Using the Center Approach for Effective Knowledge Transfer

by Andrea S. Dargush and George C. Lee,
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Research Objectives

The vision of the MCEER education program is to educate potential users through formal and nontraditional programs. Users include but are not limited to researchers, students, practicing professionals, public officials, organizational decision-makers and other beneficiaries of new discoveries and applications in earthquake studies. The objective is to increase awareness, improve safety and advance earthquake loss reduction activities in government, private industry, and the public at large.

In 1986, the National Science Foundation established the National Center for Earthquake Engineering Research (NCEER) to carry out systems integrated studies in earthquake hazard mitigation that would yield results that could not be accomplished by using the individual investigators approach. The success of NCEER for 10 years has resulted in an expansion of the center approach in earthquake engineering research. In 1997, NSF awarded three earthquake engineering research centers. NCEER continued its efforts with a name change to MCEER in 1998.

One of the most important efforts in pursuing the "center approach" is the organized earthquake engineering educational effort, which would be difficult to carry out with individual investigators.This paper not only summarizes the NCEER/MCEER programs of the past 14 years, but also examines formal degree programs and other types of nontraditional efforts. In accordance with the nature of the effort, both successful and challenging efforts will be highlighted. Special emphasis will also be given to organized efforts that require a center approach for development and implementation. Among the activities to be highlighted in this paper are:

- K-12 efforts
- Undergraduate participation
- Master of Engineering program in earthquake engineering
- Professional and public education

Effective transfer of knowledge is influenced by many external variables which affect the eventual application of research findings. Experts in this

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Collaborative Partners

MCEER works with various organizations to enhance the impact of its educational activities. These partners include:

- *Earthquake Information Providers Group (EqIP)*
- *Federal Emergency Management Agency (FEMA)*
- *IRIS (Institutions in Research in Seismology)*
- *Mid-America Earthquake Center (MAE)*
- *Pacific Earthquake Engineering Center (PEER)*

area of communication agree that one of the most effective vehicles for knowledge utilization is through social interaction (Lagorio et al., 1991), involving researchers and users from many different disciplines to maximize exchange of information on respective needs, potential applications and their limitations. The principal assumptions are that the greater the systematic organization and coordination between information user and researcher, the more likely the knowledge will be used. Further, the greater the number and variety of end user communities, the more likely the user is to be innovative and to use new ideas.

Because MCEER serves a wide range of end users with varying needs and educational and professional backgrounds, it is imperative that the educational efforts of the Center build on the collective strengths of its researchers, packaging knowledge in various ways to optimally educate these individuals. MCEER's systems approach to research and education thus provides an ideal platform to develop and carry out its education and educational outreach activities, which are highlighted in Table 1. Because of the importance of having a center-wide platform, a five-member committee on education-research interface was established and chaired by the Center's director. The five members are Research Committee members from the Center's core institutions: University at Buffalo, Cornell University, University of Delaware, University of Southern California and University of Nevada/Reno.

All educational activities are overseen by this committee and are coordinated by the Assistant Director for Education and Research Administration. Representatives from these institutions also play an advisory role in identifying future activities. As efforts to electronically link the affiliated institutions together continue, more educational activities common to the core universities are expected.

Achievements and New Undertakings

K-12 Education

The Center began its K-12 activities in 1988, with a series of workshops to raise the awareness of teachers and administrators about earthquake hazard and the risk posed to a school population by a damaging earthquake. Basic concepts of earth science and engineering were presented, accompanied by necessary emergency response and social counseling procedures.

The end users of MCEER education and educational outreach activities span a wide range of audiences, beginning with K-12 students, teachers and parents, university students, and extending to government officials, public and private business executives, practicing professionals, and researchers advancing the state of existing knowledge. In summary, the public-at-large can be considered to be MCEER's end user community.

A highlight of these activities was realized in 1997, when an earthquake education program to promote awareness and preparedness was held in Anchorage, Alaska. In spite of its high seismic hazards, no unilateral mitigation/response plan for schools existed within the district before this initiative.

A comprehensive listing of existing earthquake educational materials was initiated in 1989. The *Bibliography of Earthquake Education Materials* (Ross, 1989) has been widely distributed and has been revised several times. The latest revision of the document – which includes both paper and electronic reference material citations – will include an evaluative component. A panel of educators will assess materials for effectiveness and grade-appropriateness. When completed, the document will also be produced on CD-ROM to facilitate more expedient searching and retrieval.

Single-day seminars for teachers have also been held over the years, to expose them to basic concepts, available materials and resources, and potential instructional ideas. This effort will be expanded in 2000, through the creation of an annual summer Teachers Institute, which will add to the normal seminar content by exposing them to earthquake research and thus stimulating ideas for creative educational approaches. It is well documented that teachers, like other professionals, benefit from continuing education and that exposure to research enhances appreciation of the scientific method (Voss, 1999).

An important aspect of K-12 Educational activities is the inclusion of underrepresented minorities. A critical objective of NSF is to promote interest among precollege

"It is well documented that teachers, like other professionals, benefit from continuing education and that exposure to research enhances appreciation of the scientific method."

■ Table 1. MCEER's Traditional Technology Transfer Activities

Activity/Product	Focus	Target Audience						
		1	2	3	4	5	6	7
Technical Reports	MCEER research topics	x	x	x				x
Newsletters	MCEER research updates, activities	x	x	x	x	x	x	x
Workshops	State-of-knowledge exchange	x	x					x
Conferences	Review, application of research	x	x	x				x
Seminars, Briefings	Current issues of technical interest		x	x	x			x
Short Courses	Professionally relevant research and applications		x	x				
Computer Programs; Software	Design analysis, vulnerability assessments, ground motion data access	x	x					x
Public Awareness	Hazard and risk education		x	x	x	x	x	
Educational Materials	Teaching tools from an earthquake perspective	x			x	x	x	x
Web-based Information	Timely information, links, references	x	x	x	x	x	x	x

1 Academia 2 Practice 3 Policy 4 Informed Lay Audience 5 General 6 Precollege 7 University Students

Links to Current Research

MCEER educational activities are natural extensions of its ongoing research activities. For example:

- *The work the Center has done in the area of structural control provides an engaging focal topic for many groups from K-12 to practice, because of its innovative approach.*
- *People at many levels are interested in the application of pre-existing technologies, for example, in the area of defense, to the solution of earthquake engineering design problems.*
- *Relating earthquake problems from a multidisciplinary perspective stimulates interest in individuals beyond limited technical contexts.*
- *The Center's studies in Emergency Response will lead to an educational effort to assist emergency responders in the effective use of decision support systems.*
- *Work on retrofit technologies for improved pipeline performance are of interest to the utility community.*
- *MCEER's hospital project will be developing important guidelines on the performance of buildings and critical nonstructural components which will be very useful to hospital administrators.*

students in Science, Mathematics, Engineering and Technology (SMET). MCEER embraces this objective and endeavors to encourage this interest among individuals who do not traditionally enter these fields. This is carried out through outreach to such groups as BEAM (Buffalo-area Engineering Activities for Minorities), ASCE Future Cities Program, the Girl Scouts and Boy Scouts of America, Urban League, and others.

While not a precollege project, a particular effort to involve minorities was carried out under the auspices of MCEER's New York City-area Consortium for Earthquake-loss Mitigation (NYCEM) project. An element of the study required field validation of building inventory data being used in an earthquake loss estimation of New York City, under FEMA sponsorship. MCEER contributed funding to the activity to support the City University of New York (CUNY), a minority-serving institution, to allow CUNY students to carry out the needed field survey. This effort was successfully carried out under the guidance of Professor George Mylonakis of CUNY.

Undergraduate Activities

Undergraduates have always been a part of the MCEER educational process. Because most MCEER researchers are also teaching faculty, they integrate many of their findings and approaches into traditional undergraduate and graduate studies. Students are then exposed to state-of-the-art knowledge and research developments through such course offerings as structures, mechanics, and others.

To further enhance student exposure to MCEER research, the Center has entered a collaborative enterprise with its sister Earthquake Engineering Research Centers (EERCs), the Mid-America Earthquake Center (MAE) and the Pacific Earthquake Engineering Research Center (PEER), to organize the *Tricenter Research Experiences for Undergraduates (REU)* program. The program invites undergraduate students from U.S. universities to engage in EERC faculty-supervised research activities. The multi-year program will conclude annually with an REU symposium, which will require all participating students to make presentations on their research and will offer lectures on issues key to developing engineers – ethics and communications.

Graduate Activities

Graduate education has traditionally been a prominent element of MCEER educational activities. Faculty members have supported numerous graduate students to assist in their MCEER-sponsored activities. Hundreds of students have matriculated with the help of MCEER faculty involvement and advisement, and have progressed to significant positions at universities, public agencies and private businesses. Many of their technical efforts have been documented in the NCEER/MCEER Technical Report Series.

Masters of Engineering Program in Earthquake Engineering

In 1998, encouraged and partially supported by MCEER, the Department of Civil, Structural and Environmental Engineering at the University of Buffalo developed a

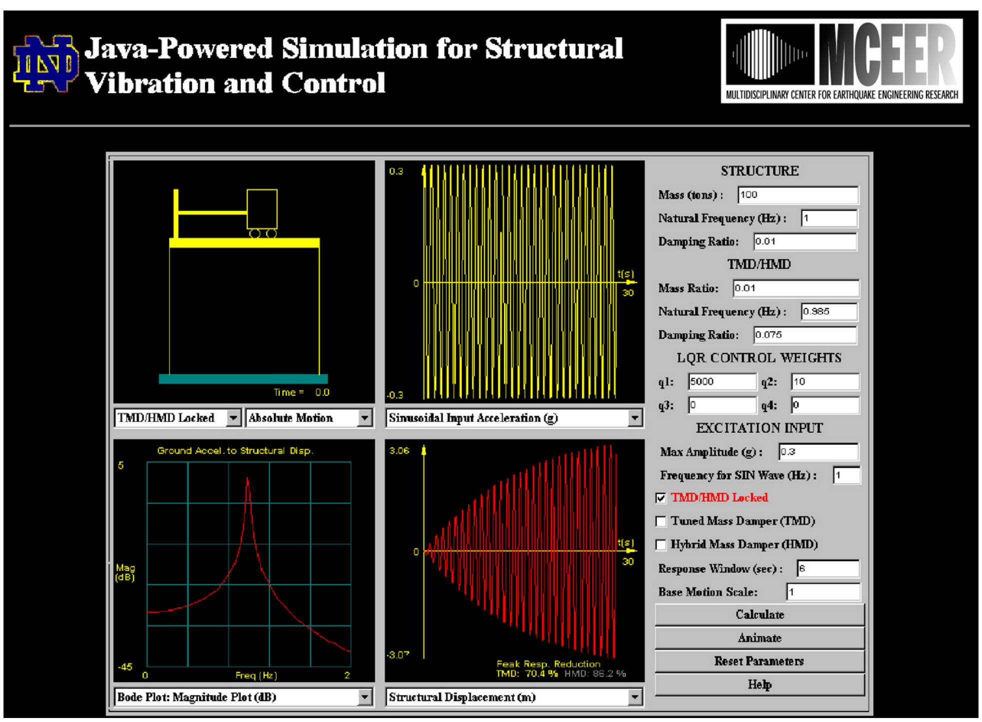
Master's of Engineering Program in Earthquake Engineering. The intent of this specialized degree is to provide post-graduate training for students wishing to improve their knowledge base in earthquake engineering. It is a design and practice-oriented program suitable for students planning to pursue a professional career in consulting, industry or government service. In addition to traditional courses in structural dynamics, plastic analysis and design, concrete and steel structures and construction estimating, a seminar on social and economic aspects of earthquake engineering is part of the curriculum. This course, offered for the first time in Spring 2000, featured speakers from many different disciplines and professions, many of whom were linked to the class remotely. More information on this course, developed by Professor Ernest Sternberg, as well as the degree program itself, may be found in *Graduate Professional Education in Earthquake Engineering: An Integrated Approach* in this report.

Virtual Laboratory Tools for Earthquake Engineering Experiments

Professor B.F. Spencer carried out a separately funded MCEER education project at Notre Dame University to develop learning tools to be used in the Masters of Engineering courses in structural dynamics. A suite of Virtual Laboratory earthquake engineering experiments were developed using Java to provide an interactive means of instruction on structural performance under seismic conditions. Two modules were developed, consistent with MCEER's emphasis on advanced technologies, to enact simulations under varying conditions. The first module, "Structural Control using Tuned Mass Dampers (TMD) and Hybrid Mass Dampers

Links to Current Research (cont.)

- *The incorporation of MCEER research findings into undergraduate and graduate curricula remains a constant educational vehicle, and has led in many instances to rewarding undergraduate experiences, new courses and new degree programs. This important interface between research and education is critical to the Center's success and is increasingly encouraged.*



■ Figure 1. The Virtual Laboratory for Earthquake Engineering provides an interactive framework for students and others to gain fundamental understanding of a wide range of topics in earthquake engineering

MCEER's professional and continuing education program focuses on informing professionals about new technologies and their potential for application.

(HMD)," considers a single-degree-of-freedom building model subjected to various historical earthquake records. The module allows users to change system parameters and design TMD and HMD for structural response modification. A snapshot of this module can be seen in Figure 1.

The second module, "Base Isolation," considers a two-degree-of-freedom building model with base isolation, which can be animated by various historical isolation earthquake records. Again, users may change system parameters and design base isolators to modify structural performance.

Both modules were mounted on the Notre Dame web site, and hotlinked to MCEER's web site to provide wide access to the modules. They may be found at the following URL's: *http://www.nd.edu/~quake/java/animation.html*, and *http://www.nd.edu/~quake/java/isolation/animation.html*.

Each module is accompanied by technical background information for the user, as well as suggested exercises and references. They are intended to provide students with a greater understanding and appreciation of simulation techniques. This is especially useful for students at institutions without sophisticated experimental facilities. These activities may be expanded as MCEER's research program in User Networks for Seismic Assessment and Retrofit of Critical Facilities becomes better developed. They may also provide insight into how such activities might be designed at a larger scale, such as through the new NSF initiative, Network for Earthquake Engineering Simulation.

Student Leadership Council

As part of its charge from the NSF EEC Division, MCEER has established its own EERC Student Leadership Council (SLC). Because MCEER is a multi-institutional organization, SLC subcouncils are established at institutions with greater numbers of MCEER students. The balance of students at remaining universities will be incorporated into an at-large chapter, allowing them equal access to the SLC activities.

The SLC is designed to increase interaction between EERC-funded faculty and associated students, enhancing student exposure to research and the concurrent process. It is also intended to encourage networking with students at other EERC–affiliate institutions and to improve needed skills in communication and other areas. Increased interactions between SLC students and members of MCEER's industry partnership program will provide students and practitioners with a valuable interface.

Professional and Public Education

Professional and Continuing Education

Throughout its lifetime, NCEER/MCEER has had constant interaction with engineering professionals. It became apparent that as new technologies were developed for use in seismic design and construction, there was an increasing need for professionals to become better informed about the technologies and their potential for application.

In 1996, NCEER launched a formal short course program for practicing engineers, called PACE (Professional and Continuing Education). The initial three courses focused on passive energy dissipation systems and their use in the design of building for seismic and wind retrofit.

The course was supplemented by an MCEER monograph (Constantinou et al., 1998) on the same subject, which presented technical information in a fashion that would be easily understood by the professional non-expert. The monograph continues to be in high demand and is an excellent educational tool.

The course itself was well-received in areas where local engineers had a better appreciation for the potential of the technology. This became an important lesson to learn. While MCEER research had great potential for knowledge transfer, it needed to be carefully tailored to the needs, expectations, and educational background of the audience.

The second topic to be featured in the PACE program was a pilot course on the seismic retrofitting of highway bridges, which was based on research and a resulting manual (FHWA, 1995) done under the Center's Federal Highway Administration contract. Because this information was immediately relevant to state transportation engineers, it was a very well attended event.

In NCEER's transition to MCEER, course delivery has been slowed, but the Center has continued its momentum to develop new courses which can help practicing engineers stay abreast of new design and code developments. More specific, corporate-driven courses are likely to be offered as MCEER's industrial partnership program grows. A major direction is the application of advanced technologies in performance-based engineering.

Public Education Activities

MCEER education and outreach to the public-at-large serves as a foundation to many of the program's other activities. In communicating information about seismic hazards, risk and mitigation approaches, it must be carefully formulated. Messages need to be represented clearly and credibly, presented in many formats to appeal to different learning styles, and easily accessible (Nathe et al., 1999). The audiences may include average homeowners, public officials, concerned citizens, and students - all with a different need to know. To reach them, MCEER's efforts in this area have used many vehicles to convey information - popular press, museum exhibits, public briefings and fact sheets.

MCEER Web Site and Information Service

Perhaps our most dynamic mechanism for conveying timely information and reference assistance is the MCEER web site. Developed and maintained by the MCEER Information Service, the web site is a key repository of many of MCEER's activities and products. Technical reports may be partially viewed and ordered, and the Center's two newsletters are mounted there. In addition, countless links and references, "frequently-asked-questions," and educational exercises make it a comprehensive source of information (see Figure 2). It is a highly visited site, with nearly 300 outside visitors each day. It is now undergoing additional

The MCEER Information Service hosts EqNet, the web site of the Earthquake Information Provider's Group, which provides one-stop access to earthquake information resources and links to quality earthquake information web sites.

Web Sites

Multidisciplinary Center for Earthquake Engineering Research
http://mceer.buffalo.edu

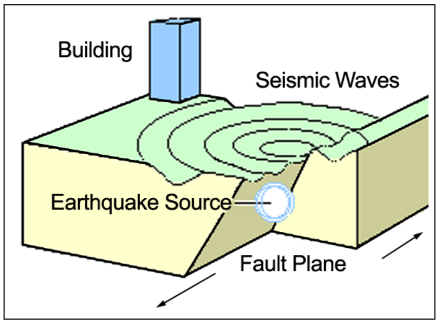
New York City Consortium for Earthquake-loss Mitigation (NYCEM)
http://nycem.org

Virtual Laboratory Tools for Earthquake Engineering Experiments
http://www.nd.edu/~quake/java/animation.html
http://www.nd.edu/~quake/java/isolation/animation.html.

EQNet
http://www.eqnet.org

Other limited access web sites:

- *MCEER investigators and students can test new software to evaluate the structural sensitivity of buildings subjected to seismic ground motion.*
- *MCEER Research Experiences for Undergraduates Program*
- *MCEER-wide Student Leadership Council members*



■ Figure 2. Basic illustration of earthquake ground motion

enhancements to make it even more accessible - particularly to users in the disabled community.

Beyond its management of the web site, the Information Service has a national and international reputation for excellence in key earthquake reference acquisitions and in thorough reference assistance. The searchable Quakeline® database of earthquake-related publications is the only one its kind, featuring fugitive reference citations on earthquake engineering and related subjects that might not be otherwise catalogued or archived.

Because of their expertise, the Information Service was selected by the National Science Foundation to lead an effort to unify the information provision activities of many other natural disaster organizations. The program, called EqIP (Earthquake Information Providers group), seeks to improve access to useful earthquake information and reduce redundancies through a global web site, EqNet. EqNet functions as sort of a clearinghouse - a gateway to the numerous other organization web sites which exist. EqIP's members include federal agencies, universities, not for profit agencies, and private research organizations.

New Endeavors

Among the new emphases MCEER plans to pursue in the coming years is the increased utilization of advanced communications technologies for information sharing and exchange. It is our goal to be able to link MCEER-affiliated institutions into one network that will allow both researchers and students access to teaching and research going on throughout the consortium. Students involved in disaster studies need increased exposure to knowledge of other disciplines that address earthquake problems. Remote learning capabilities, when used responsibly and effectively, can help make this type of holistic learning experience a reality.

As a cooperative effort, MCEER is working with the Mid-America Center and the Pacific Earthquake Engineering Center to develop graduate school modules in earthquake-related studies. Each center will build on their own respective technical expertise to formulate six- to eight-week stand-alone modules that can then be exchanged with other institutions. As more modules are developed it is hoped that a complete program will be developed that might serve as a template for a national earthquake-engineering curriculum that would be made widely available. The first modules are to be completed in 2000.

Conclusions

It has been satisfying to watch the Center's educational program become more robust and responsive to the needs of information-seekers. This has only been possible due to the collective technical strength contributed by its many researchers and the systematically-integrated approach which MCEER/NCEER has historically used for both research and education. The great challenge we face in trying to communicate rather abstract concepts of risk and mitigation cannot be handled effectively by a single investigator.

As MCEER research continues to bear fruit and the interaction between research and education increases, the educational outcomes for the public will be enriched. Education programs with an impact are essential for MCEER to achieve its vision of disaster resilient communities.

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Graduate Professional Education in Earthquake Engineering: An Integrated Approach

by Andrei M. Reinhorn, Shahid Ahmad and Ernest Sternberg

Research Objectives

The master of engineering (M.Eng.) program at the University at Buffalo is a comprehensive educational endeavor dedicated to training professionals in specialty fields (structures, geotechnical, environmental or construction engineering) while providing a wide view of the profession, including management, economics and socioeconomic aspects. The newest addition to the curriculum is training in earthquake engineering, which is inspired by the needs of and research work conducted at MCEER. A required comprehensive team project provides the student with the opportunity to observe the integration of the various specialties and subjects, while strengthening the individual specialty focus. In this program, the variety and uniqueness of subjects related to earthquake engineering and structural dynamics help produce unparalleled professionals.

The earthquake engineering program at the University at Buffalo developed over the last two decades from a single course presentation to a comprehensive program offering Master of Science (M.S.), Master of Engineering (M.Eng.), Doctor of Philosophy (Ph.D.) degrees, and most recently, a combined Bachelor/Master of Engineering (B.S./M.Eng.) degree. The focus of this education program is to prepare professionals who can lead design and decision processes to develop earthquake-safe communities. Moreover, the program is intended to prepare professionals who can further develop themselves as technologies advance throughout their careers.

The catalyst for the development of these degree programs was the National Center for Earthquake Engineering Research from 1986-1996, and the renewed MCEER from 1997. The program began from the need to train students for their research work and then expanded to include the transfer of the newest research developments. Most recently, due to the multidisciplinary aspect of the earthquake engineering problem and new understanding of societal problems, the program has further expanded its horizons to include an introductory seminar

Sponsors

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University at Buffalo, State University of New York

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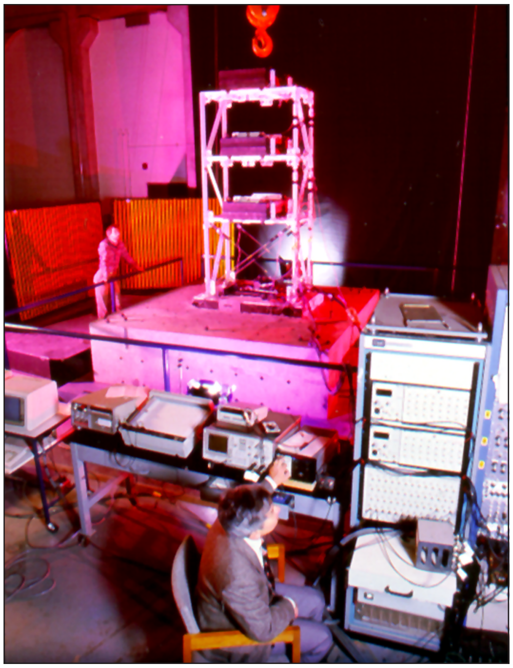
on socioeconomic aspects of disasters with a focus on earthquakes, as described later in this paper. With strong support from MCEER and private contributions, the program has developed, under the guidance of the third author, a multidisciplinary seminar using teleconferencing and expertise from prominent specialists from around the country and the University at Buffalo. Moreover, the program provides expertise for short continuing education courses, seminars and consultations.

This paper describes the content of the earthquake engineering education program and emphasizes the new multidisciplinary seminar developed in the last year. The program may serve as a prototype for other programs or provide a possibility for exchange of content with other institutions.

Educational Program Overview

The educational program is based on several core courses, taught *every year*, that introduce the students to the basic sources and effects of earthquakes on structures and foundations. These courses are taught based on the principles of structural dynamics and wave propagation, i.e.: (1) structural dynamics and earthquake engineering sequence of two courses, (2) structural systems and construction technology with economics content, (3) geotechnical aspects and foundation design. In addition, a variety of specialty courses are taught *every other year*, allowing limited specialization for M.S. and M.Eng. students and a more thorough education for the B.S./M.Eng. and Ph.D. students. The specialty courses include: (1) random vibrations, (2) advanced topics in engineering seismology, (3) plastic analysis and design, (4) advanced topics in reinforced concrete, steel and timber design, (5) aseismic base isolations, (6) structural control - damping systems (active and passive), (7) experimental methods in structural dynamics and (8) advanced topics in structure analysis (finite elements and boundary elements). Several topics, such as base-isolation design, structural control and structural experimentation, are unique to this program. These topics have been developed as result of the research of the faculty and students. In fact, in most of the classes, the students are exposed to combined analytical and experimental methods using shaking table (see Figure 1) testing, in particular in the experimentation course. The latest development in the program is the addition of the seminar on socio-economic aspects of disasters.

The users of this educational program are full-time students and distance learning engineers, enrolled on limited basis. With the development of networking technology, user groups can be extended to professionals already in practice.



■ Figure 1. Shaking table experiment used in Structural Control and Experimentation courses

The program leading to the M.Eng. degree is more rigidly structured and emphasizes the practical aspects of engineering subjects. The current and future suggested curriculum is shown in Table 1. The highlights of the M.Eng. program are (1) exposing the students to multidisciplinary aspects of the design and construction process along with the socioeconomic concerns through the seminar highlighted below, and (2) the preparation of a major group project exposing the students to all construction and management issues.

The model of the group project is a version of the project concept developed for the last twenty-five years at Cornell University by the late Professor Peter Gergely (former member of the Executive Committee of NCEER). The project is performed jointly by groups of students, specialists in different areas (structures, construction, foundation, earthquake engineering, management, architectural engineering), working together to design and "deliver" a turnkey project for a bridge or a large building (sports complex, airport building, or other large structures). Students are supervised during the year by several faculty and during critical studio sessions by practicing consultants.

It should be noted that recently, a direct B.S./M.Eng. path was approved by the University at Buffalo administration, which allows

Web Sites

Course Designation

CIE 505, Social and Economic Aspects of Disaster

Seminar Web Page

http://mceer.buffalo.edu/courses/cie505/default.html

■ Table 1. Requirements for the M.Eng. degree

Fall Semester	Spring Semester
Required	*Required*
CIE 519 Structural Dynamics & Earthquake Eng I	CIE 619 Structural Dynamics & Earthquake Eng II
CIE 527 Design and Construction of Structural Systems	CIE 505E Earthquake Engineering Seminar
CIE 557 Engineering Project (3 credits)	CIE 558 Engineering Project (3 credits)
Electives (select two from the following):	*Electives (select two from the following):*
CIE 524 High Performance Steel Structures	CIE 521 Plastic Analysis & Design
CIE 525 High Performance Concrete Structures	CIE 534 Earthquake Engr & Found Dynamics
CIE 526 Finite Elements	CIE 616 Experimental Methods in Structural Engr
CIE 520 Random Vibrations	CIE 625 Aseismic Base Isolation
	CIE 626 Structural Control

exceptional senior students to enroll and take specialty courses in their last undergraduate year, thus completing a larger sequence of courses than the graduate only program. The first group of students is about to graduate and their performance and feedback will be valuable to the earthquake engineering educators.

Social and Economic Aspects of Disaster: Focus on Earthquakes - A Graduate Seminar

During the Spring 2000 semester, and with MCEER support, the University of Buffalo's Department of Civil, Structural, and Environmental Engineering offered to students an innovative new graduate professional learning opportunity: a multidisciplinary seminar on natural disasters, with a focus on earthquakes. The objective was to give them a broad background of the complex institutional frameworks and diverse methods they would have to work with as earthquake engineers. To achieve this objective, the seminar made heavy use of remotely-sited lecturers from around the U.S. They made presentations to students and responded to student questions through interactive video technology.

First-year enrollment was limited to a small number of students in keeping with the experimental nature of the seminar. Ten masters' students were registered: five from the M.Eng. program in earthquake engineering, four from urban planning, and one from architecture. In addition, the interactive video lectures were routinely publicized, bringing in several guests (faculty and graduate students) each session.

The seminar sought to combine the advantages of teleconferencing technology—which brought leading earthquake and disaster specialists to the classroom from remote locations—with the values of on-site workshop learning led by the instructor. Of the seminar's 14 sessions, four were conducted by the instructor, two by on-site guest faculty from the University at Buffalo, and the remaining eight by guest lecturers appearing through interactive video.

The remotely-sited video guests allowed students to interact directly with some of the leading figures in multidisciplinary aspects of earthquake engineering, including Howard Kunreuther (University of Pennsylvania) on cost-benefit analysis and Kathleen Tierney (University of Delaware) on organizational aspects of disasters. One guest was not an individual faculty member but an organization: the New York State

■ Figure 2. Nine members of the New York State Emergency Management Organization gave short presentations and a real-time virtual tour of their emergency operations center via interactive video

Seminar Schedule & Guest Lecturers 2000

"Earthquakes as Compared to Other Disasters," Ernest Sternberg, School of Architecture and Planning, University of Buffalo, State University of New York

"Disaster Planning," Ernest Sternberg, School of Architecture and Planning, University of Buffalo, State University of New York

"Earthquake Effects on Hospitals," Chris Tokas, California Office of Statewide Health Planning and Development

"Information Sources for Earthquake Research," Laura Taddeo, MCEER Information Service

"Hazard Assessment through HAZUS," Mike Tantala, Department of Civil Engineering, Princeton University

"Risk-Cost-Benefit Analysis," Howard Kunreuther, Wharton School, University of Pennsylvania

"Individual Behavior in Buildings During Emergencies," Ed Steinfeld, School of Architecture and Planning, University of Buffalo, State University of New York

"Administrative and Organizational Issues in Disaster," Kathleen Tierney, Disaster Research Center, University of Delaware

"Mitigation Techniques and Code Making," Rob Olshanksy, University of Illinois at Urbana-Champaign

"Politics and Policies for Disaster Mitigation," NYS Emergency Management Office personnel

"Information Technology Applications for Disaster Management," Ron Eguchi, ImageCat, Inc., formerly of EQE International

Special Project Day to Prepare Final Project Report, Ernest Sternberg, School of Architecture and Planning, University of Buffalo, State University of New York

"Ethics of Disaster Planning and Engineering," Ernest Sternberg, School of Architecture and Planning, University of Buffalo, State University of New York

Final project presentation

Emergency Management Organization. On April 2, nine members of its staff gave short presentations on various aspects of the agency's functioning and included a real-time virtual tour of its emergency operations center, with students asking questions from Buffalo as the camera was walked around the facility in Albany (see Figure 2). For each of these sessions, students had to prepare through assigned readings and required questioning and participation.

Seminar Project

The seminar sought to balance, on the one hand, the interactions with remotely-sited guests on multiple topics with, on the other hand, one focused on-site project developed directly with the instructor. The project is an inventory of hospital evacuations in the U.S. from 1970 to 1999. Using multiple databases and telephone interviews, students prepared a unique resource: a list of hospital evacuations, causes of evacuation,

Cooperation within the University at Buffalo

The implementation of the seminar required collaboration not just with remotely sited guests, but also among divisions of the University at Buffalo. The seminar was formally offered by the Department of Civil, Structural, and Environmental Engineering, in the School of Engineering and Applied Science, and supported by MCEER. However, since the seminar was purposefully meant to incorporate diverse perspectives, the coordinating instructor was a faculty member in the Department of Planning of the School of Architecture and Planning. The seminar also received extensive technical assistance from the distance learning operations of the University's Millard Fillmore College.

duration, numbers evacuated, and casualties, if any. The results will give hospital administrators and policy makers evidence by which to judge how much priority to give to internal disaster plans and to disaster mitigation in the facility.

The focus on hospitals gave students a central theme throughout the seminar, a theme on which they could ask questions of, and draw insights from, speakers representing many points of view. The project also gave students a preliminary introduction to methods of social and economic research. The final report may be issued as an MCEER publication or submitted to an academic journal.

Future Directions

The plans for Spring 2001 are to make the seminar simultaneously available at several universities affiliated with MCEER. Complex arrangements will have to be worked out on incentives for guest instructors, students' registration for credits at home institutions, fees to cooperating institutions, and technical assistance for bridging several campuses.

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