Research Progress and Accomplishments

2003-2004

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

MCEER

MULTIDISCIPLINARY CENTER FOR EARTHQUAKE ENGINEERING RESEARCH

A National Center of Excellence in Advanced Technology Applications

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 Michel Bruneau, Director
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As MCEER enters its 18th year as a national earthquake engineering center, it finds itself at a strategic juncture with a promising future. Strong from the leadership of its past directors, and in particular of George C. Lee, MCEER has pioneered multidisciplinary earthquake engineering research and a culture of coordinated large-scale integrated research projects. These, in turn, have led to many advances in knowledge and accomplishments that have had a tangible impact on practice.

This sixth volume of *Research Progress and Accomplishments* highlights many of these advances, starting with an overview of the multidisciplinary center approach in earthquake engineering that MCEER has pioneered. The 14 papers that follow provide selected detailed examples of how MCEER research is fulfilling its vision to achieve earthquake resilient communities through its activities.

The papers are presented in groups according to major areas of activity. First are the "Overarching Center-wide Cross Program Research Activities," whose outcomes provide support to and further integrate the other three major research areas. These studies include the development of earthquake simulation tools (Papageorgiou); development of an Internet-based geographic information system management process (O'Rourke); and an analysis of economic resilience to earthquakes (Rose).

The "Seismic Evaluation and Retrofit of Lifeline Systems" research focuses on the development of analytical, experimental and empirical procedures to evaluate and enhance the seismic resilience of lifeline systems. These studies include the development of improved models of the post-earthquake restoration processes for electric power and water supply systems (Davidson); the development of advanced systems analysis tools to evaluate the joint performance of water supply and electric power networks before and after an earthquake (Shinozuka et al.); and a state-of-the-art disaster loss modeling procedure, that emphasizes understanding how mitigating lifeline infrastructure systems can improve the disaster resilience of a community (Chang).

The "Seismic Retrofit of Acute Care Facilities" research aims to quantify the influence of various seismic response modification technologies to protect structural and nonstructural systems and components in acute care facilities from the effects of earthquakes. The results will be used to provide meaningful input to integrated decision support tools. Studies include development of new materials and technologies for the seismic retrofit of a wide variety of structures and nonstructural components (Filiatrault et al.); development of an integrated decision-assisting model to help executives and engineers make informed choices about alternative approaches to improving seismic safety (Alesch and Petak); and formulation and application of an evolution theory design approach to aseismic design and retrofit and organizational decision support (Dargush).

The "Emergency Response and Recovery" research deals primarily with developing post-event response and recovery strategies to enhance resilience through improving the rapidity with which impacts are identified, resources are mobilized and critical systems are restored when earthquakes strike, as well as through improving the effectiveness of community recovery strategies that are used following earthquake disasters. Studies include the investigation of the relationship between technological and natural disasters (Tierney); and the development of tools and techniques for post-earthquake urban damage detection based on remote sensing images (Eguchi).

Education and outreach activities focus on providing an interface between ongoing research activities and end users. In this regard, a series of web-based education modules on earthquake engineering have been developed and are available on the Internet (Spencer).

Research in the "Seismic Vulnerability of the Highway System" concentrates on developing formal loss estimation technologies and methodologies; analysis, design, detailing and retrofitting technologies for special bridges; response modification technologies; and soil and foundation behavior and ground motion studies for large bridges. Studies include the development of an analytical methodology to evaluate the effectiveness of vibro-stone column and dynamic compaction techniques (Thevanayagam); and the development of decision support software for improving traffic flow after major disasters, which has recently been expanded to include Tri-Center collaboration (Werner).

The papers included in this volume also showcase the type of multidisciplinary multi-institution innovative research for which MCEER is recognized in the engineering community. This tradition of being able to spearhead and/or embrace innovative ideas and nurture them from initial fundamental research to implementation through the efforts of high caliber affiliated researchers and strategic partners, provides the platform from which MCEER is now working to build the Center's future successes beyond the term of its current 10 year funding cycle as part of the NSF Engineering Education and Centers division. MCEER's outlook on the future is positive. The Center is looking forward to continuing to serve the NEHRP mission for many years to come, as well as to tackle new challenges by expanding its research activities, through teamwork efforts of MCEER's researchers, partners and management.

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 at (716) 645-3399, or email at *mceer@mceermail.buffalo.edu*. This report 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).

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Progress and Accomplishments of the Center Approach in Earthquake Engineering Research

by George C. Lee, Director Emeritus
Multidisciplinary Center for Earthquake Engineering Research

Vision

The ultimate vision of the Multidisciplinary Center for Earthquake Engineering Research (MCEER) is to help establish earthquake resilient communities.

Mission

The overall goal of MCEER is to enhance the seismic resilience of communities through improved engineering and management tools for critical infrastructure systems (water supply, electric power, and hospitals) and emergency management functions. Seismic resilience (technical, organizational, social, and economic) is characterized by reduced probability of system failure, reduced consequences due to failure, and reduced time to system restoration.

Major Sponsors

National Science Foundation, Earthquake Engineering Research Centers Program

State of New York

University at Buffalo, State University of New York

Federal Highway Administration

Federal Emergency Management Agency

In 1985, the National Science Foundation (NSF) realized there was a need to facilitate coordination and cooperation among the various research efforts in earthquake engineering across the United States. As a result, NSF initiated a national competition to establish this "Center Approach," which included university-based earthquake engineering research, as well as education and outreach activities. This was a major milestone in the development of earthquake engineering research in the U.S. A new knowledge base in earthquake engineering, contributed by teams of researchers with different expertise, has since been advanced which has had a positive impact on educating the present and future earthquake engineering workforce.

The first center to be established under this competition was the National Center for Earthquake Engineering Research (NCEER), which has now become MCEER. For ten years, NCEER was the only earthquake engineering research center in the United States supported by NSF. In addition, it received significant financial support from the State of New York and the administration of the University at Buffalo. This sustained funding for a decade allowed NCEER to develop multidisciplinary team efforts with expert participants recruited from many institutions (Figure 1). Simultaneously, NCEER established many cooperative research efforts with institutions worldwide to share information, experience and facilities in earthquake engineering research and education, which are still in place today (Figure 2).

As a result of NCEER's success during its first ten years and the recommendation of the earthquake engineering research community, NSF expanded its "Center Approach" by carrying out a second round of national competitions for Earthquake Engineering Research Centers (EERCs) in 1996. Two new centers received funding – the Mid-American Earthquake Center (MAE) and the Pacific Earthquake Engineering Research Center (PEER). In 1997, NCEER became the Multidisciplinary Center for Earthquake Engineering Research (MCEER).

Three Phases of MCEER Development

One can view the evolution of NCEER/MCEER from a system's perspective, in which the Center's fundamental mission involves research, education and outreach.

Phase 1

The initial period of NCEER development concentrated on 'components research' in targeted engineering systems. Emphasis was placed on developing a fundamental knowledge base for evaluating and ensuring the seismic performance of selected building and lifeline systems.

Among the many accomplishments and developments, two

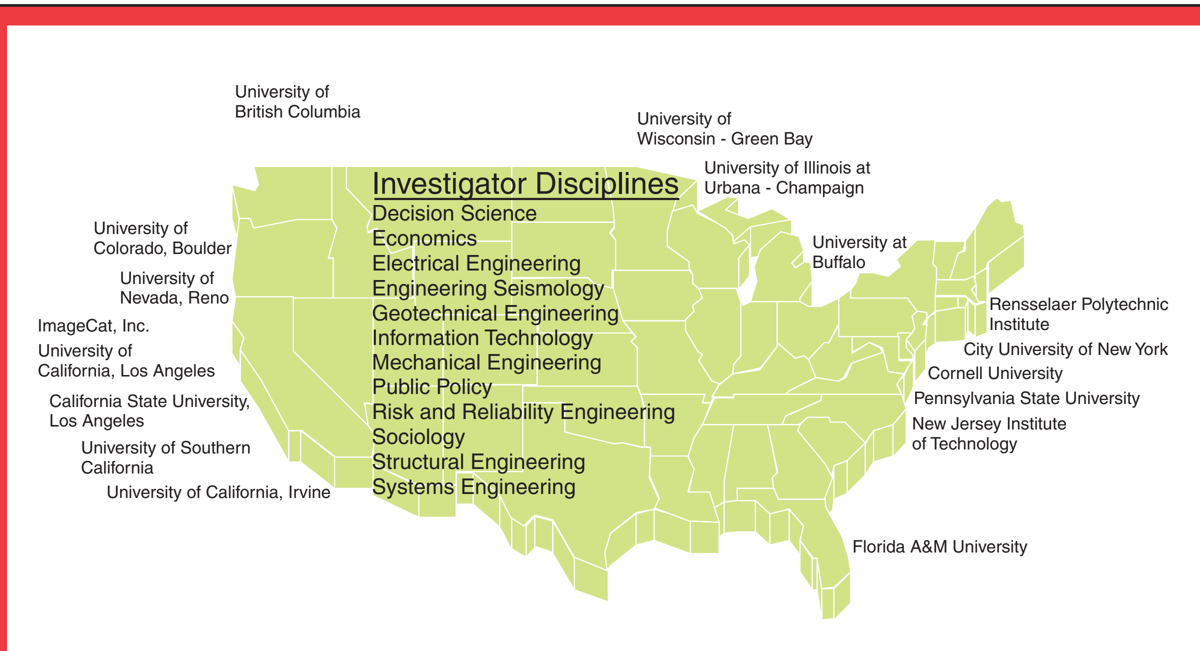


Figure 1. Institutions and Investigator Disciplines Currently Participating in MCEER Research Activities

■ Figure 2. Countries with Joint Activities and Formal Agreements with NCEER/MCEER

in particular may be noted. First, the Center pioneered and established the culture and practice of multiple institution collaboration by engaging the best minds and cooperating on the use of the best facilities. Second, the Center enhanced the rapid development of the emerging field of structural control.

Phase 2

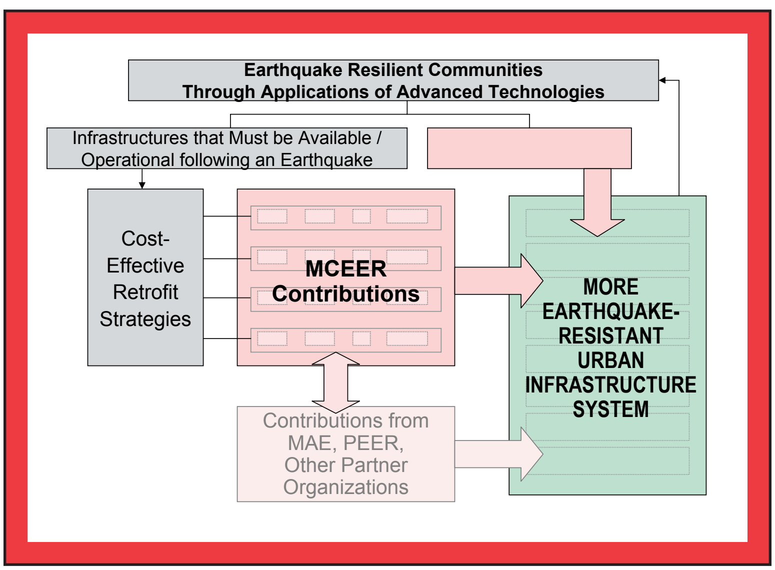
The second phase of expansion emphasized the development of a knowledge base and efficient mechanisms for sharing and transmitting this information to both the research community and earthquake vulnerable communities. MCEER has emphasized the development of retrofitting strategies for existing structures (and the development of loss estimation methods) and the simultaneous consideration of mitigation measures with response and recovery strategies. This shift in emphasis to aid in the establishment of earthquake resilient communities enabled the Center to seriously explore transdisciplinary cooperation between the fields of engineering and social science. This is evidenced by the partnership between multidisciplinary groups at MCEER and Los Angeles Department of Water and Power (LADWP) on water and electric power systems, the partnership with the Federal Highway Administration (FHWA) and Caltrans on decision-support software for improving traffic flow after major disasters, and the partnership with California and New York healthcare facilities to development cost-effective retrofit strategies and emergency operations support software.

Phase 3

The third (current) phase focuses on achieving community resilience (Figure 3) in partnership with a variety of other organizations. It can be characterized by three additional distinctions. The first is an exploration of the appropriate quantitative measures for estimating earthquake resiliency in a system or a community. This effort is motivated by the need for self-assessment of our progress toward realizing the Center's vision and mission. It is hoped that the development of such metrics will provide a gauge for progress at the national level (effectiveness of National Earthquake Hazards Reduction Program (NEHRP)).

The second is the expansion of the Center's collaborative efforts with other EERCs in the United States and abroad. This is reflected in the major role that MCEER plays in Tri-Center research activities on transportation network studies, its role in aiding the development of and collaborating with the Asian-Pacific Network of Centers of Earthquake Engineering Research (ANCER), and its full support and participation in the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) endeavor.

The third is to develop and document many important research results into the forms of design, retrofit and operating guidelines, by engaging practicing professionals working synergistically together. Over the years, the Center approach has facilitated the rapid advancement of knowledge in selected thrust areas. As a Center, it has the important mission to shorten the time required to implement new knowledge into improved engineering and management tools.



■ Figure 3. Contribution of MCEER to Achieve Earthquake Resilient Communities through its Integrated Systems Approach

Earthquake Engineering Perspective

From the viewpoint of earthquake engineering, one may paraphrase the three phases of NCEER/MCEER development into research themes – overarching areas in which progress was made only because of the Center infrastructure.

- *New technology-based earthquake engineering*: Based on state-of-the-art experimental facilities and interfaces with many technology-based disciplines (e.g., aerospace, mechanical, control systems, computer engineering, etc.), development and application of advanced technologies in earthquake hazard mitigation and disaster response are rapidly becoming major research thrust areas in earthquake engineering around the world. MCEER can claim a leadership role in advancing several important research fronts (e.g., earthquake response control technologies and remote sensing technologies) in this regard.

- *Nonstructural systems earthquake engineering*: An emphasis on systems (of components) performance, fragility-based engineering investigations and functionality of critical systems has helped MCEER pave the way toward developing new knowledge to ensure the post-earthquake operability of electric power systems, water supply systems, highway networks and healthcare facilities. This advancement in systems-integrated consideration of structural and essential nonstructural components in the seismic performance and functionality of critical facilities is a significant milestone in earthquake engineering research.
- *Multidisciplinary earthquake engineering*: Earthquake hazard mitigation and response activities are truly multidisciplinary activities and are the responsibility of a collection of different organizations consisting of a variety of professional expertise. The Center approach of MCEER successfully integrated essential knowledge areas (see Figure 1), resulting in the development of useful tools for the professional community that otherwise would have been difficult to achieve. Examples of MCEER contributions include earthquake damage assessment and loss estimation methodologies, hazard mitigation and disaster response decision-support technologies, and various seismic design and retrofit engineering guidelines.
- *Development and implementation of codes and standards*: The Center research team has collectively made many key contributions to the country's most advanced building codes and seismic guidelines over the years. Examples include next generation performance-based seismic design procedures (ATC-58), seismic design and retrofit guidelines for bridges and highway systems (NCHRP 12-49 and FHWA-sponsored retrofit manuals), provisions for passive energy dissipation systems (2000/2003 NEHRP provisions and FEMA 273/274), and seismic design code for new construction in New York City.

The above highlights are important examples of MCEER's achievements as a research center. They are the beginning, rather than the end of new horizons in earthquake engineering research. MCEER is well-positioned today to continue its Center approach, with well-established cornerstones in experimental and analytical-based investigations, education, technical publications, industry outreach, and in obtaining first hand information on lessons learned from recent major earthquakes through its national and international partnerships and collaborative efforts.

Looking Ahead

While MCEER can rightfully claim many significant accomplishments and contributions in the field of earthquake engineering, its success as a Center must include the realization of its far-reaching vision of integrating research, education and outreach into an accessible and operational platform for continued development toward establishing earthquake resilient communities.

While great strides have been made in building team efforts that combine experts from various disciplines in engineering and the social sciences, the Center is ready to expand its leadership role to emphasize the research-education interface. This added focus can be fostered by the development of innovative multidisciplinary educational programs that will prepare future generations of earthquake engineering professionals and enrich the toolset available to engineers currently in practice.

To add this emphasis to the continuing focus on research will require the sustained commitment of the participatory academic institutions. In the long run, these educational institutions will be the ones to continue MCEER's mission through the training of new professionals who will, in turn, continue to meet the challenge of establishing earthquake resilient communities.

The final evaluation of MCEER must ultimately hinge on how successful it is in developing and implementing this research-education interface, for only by channeling the invaluable information gained through research into education and outreach programs can progress be made toward the realization of truly earthquake resilient communities in the future.

Analysis and Simulation of Earthquake Strong Ground Motion for Earthquake Engineering Applications

by Apostolos S. Papageorgiou

Research Objectives

The objectives of this task are 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: as peak ground motion parameters and/or response spectral values for a 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 and used in the NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings (BSSC, 1998).

We have developed the capability to synthesize/simulate earthquake strong motion over the entire frequency range, and for any source-receiver distance of engineering interest. The same models that are used to simulate strong ground motion can also be used to predict various measures of ground motion (e.g., a_{max}, v_{max}, d_{max}, *SA, PSV*, etc.) that are important for earthquake engineering design. The synthesis/simulation and prediction techniques of strong ground motion that we developed properly account for site effects and are valid for sites both near an extended fault/source as well as at far-field.

Originally, our goal was to focus our prediction efforts on Eastern North America (ENA). However, responding to the growing needs of MCEER researchers, we expanded the scope of our work to include the entire continental United States. Specifically, we calibrated our models to provide earthquake ground motion modeling and prediction capabilities for three types of tectonic regimes that characterize the continental United States: *active* tectonic regime (e.g., California), *extensional* tectonic regime (e.g., Nevada), and *low seismicity* tectonic regime (ENA).

The 'tools' that we developed are very practical (so that they can be used with ease by earthquake engineers), yet they are grounded on solid physical models that properly account for all the important aspects of seismic wave generation at the source, as well as propagation path and site effects.

Sponsors

National Science Foundation, Earthquake Engineering Research Centers Program

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Previous Summaries

2000-2001:
Papageorgiou et al.,
http://mceer.buffalo.edu/publications/resaccom/0001/rpa_pdfs/01papag.pdf

1999-2000:
Papageorgiou,
http://mceer.buffalo.edu/publications/resaccom/9900/default.asp#Contents

In parallel to the above efforts, we have performed basic research that focused in the areas of earthquake source radiation and local site effects. Specifically, we have developed mathematical models that can be used, for instance, to mathematically represent the sub-events that compose large earthquake events, and we have investigated and compared various methods (e.g., "*coda wave*" methods, the "*standard spectral ratio*" method, the "*H/V ratio*" method) that have been proposed to quantify local site effects.

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, or 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 (e.g., Aki and Richards, 1980). There are several variants 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 *Green functions* are synthetic or empirical. The *Kinematic Modeling Approach* involves 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.

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.

Stochastic (Engineering) Approach

Recognizing that the *Stochastic Approach* for synthesizing earthquake strong motion time histories is the most expedient method, ground motion synthesis efforts were initiated following this approach. We developed computer programs that may be used to:

1. Estimate the mean/expected values of peak ground motion parameters (i.e., peak acceleration, peak velocity and peak displacement), and spectral response amplitudes, based on *Random Vibration Theory* (e.g., Rice, 1944, 1945; Cartwright and Longuet-Higgins, 1956; Shinozuka and Yang, 1971; Soong and Grigoriu, 1993);
2. Simulate ground motions using the Stochastic (Engineering) Approach briefly described above (e.g., Shinozuka and Jan, 1972; Shinozuka and Deodatis, 1991; Boore, 1983; Grigoriu, 1995);
3. Simulate ground motion time histories that are compatible with prescribed response spectra using the *Spectral Representation Method* (Shinozuka and Deodatis, 1991; Deodatis, 1996).

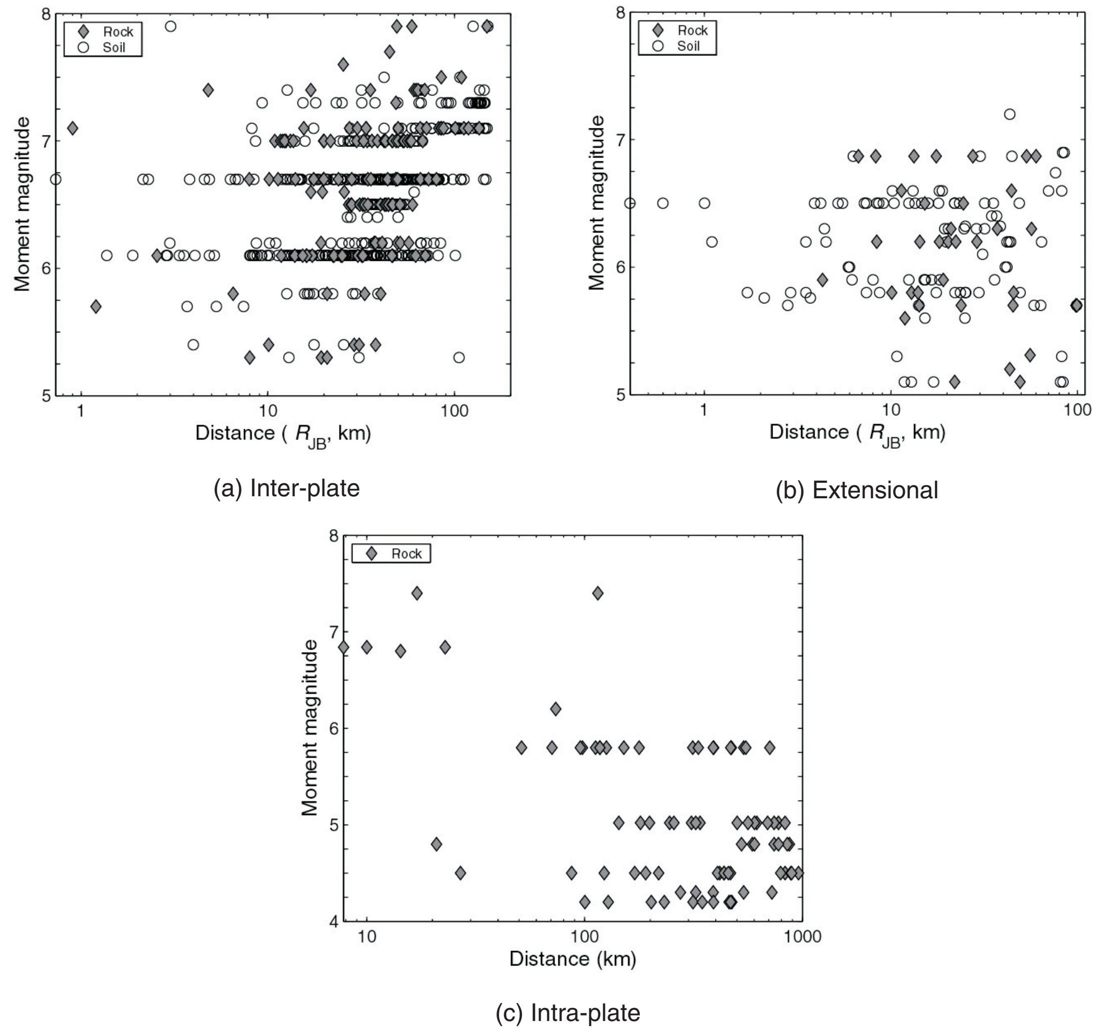
Various earthquake source models that have been proposed in the published literature [such as the *Specific Barrier Model* (Papageorgiou and Aki, 1983a,b; 1985; 1988) and the *ω^2-model* (Brune, 1970; Frankel et al., 1996)] have been implemented (and are provided as options) in the above mentioned computer codes. Site effects are taken into account in the simulated ground motions by using the site classifications of the 1997 NEHRP Provisions (BSSC, 1998).

Of all the source models, we favor the *Specific Barrier Model* because 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 synthesizing *near-fault* (i.e., in the vicinity of an extended source/fault) ground motions.

We calibrated the *Specific Barrier Model* using three different extensive databases of recorded earthquake strong motions reflecting the characteristics of three types of tectonic regimes that characterize the continental United States: (1) *active* tectonic regime (e.g., California), (2) *extensional* tectonic regime (e.g., Nevada), and (3) *low seismicity* tectonic regime (ENA). Thus, the *"scaling law"* of the source spectra (i.e., how the spectral content of the seismic waves radiated by the source varies with earthquake magnitude) was established for each one of the above tectonic regimes. Such a "scaling law" is necessary for the prediction/simulation of ground motion at any site of any one of the above tectonic regimes.

Links to Current Research

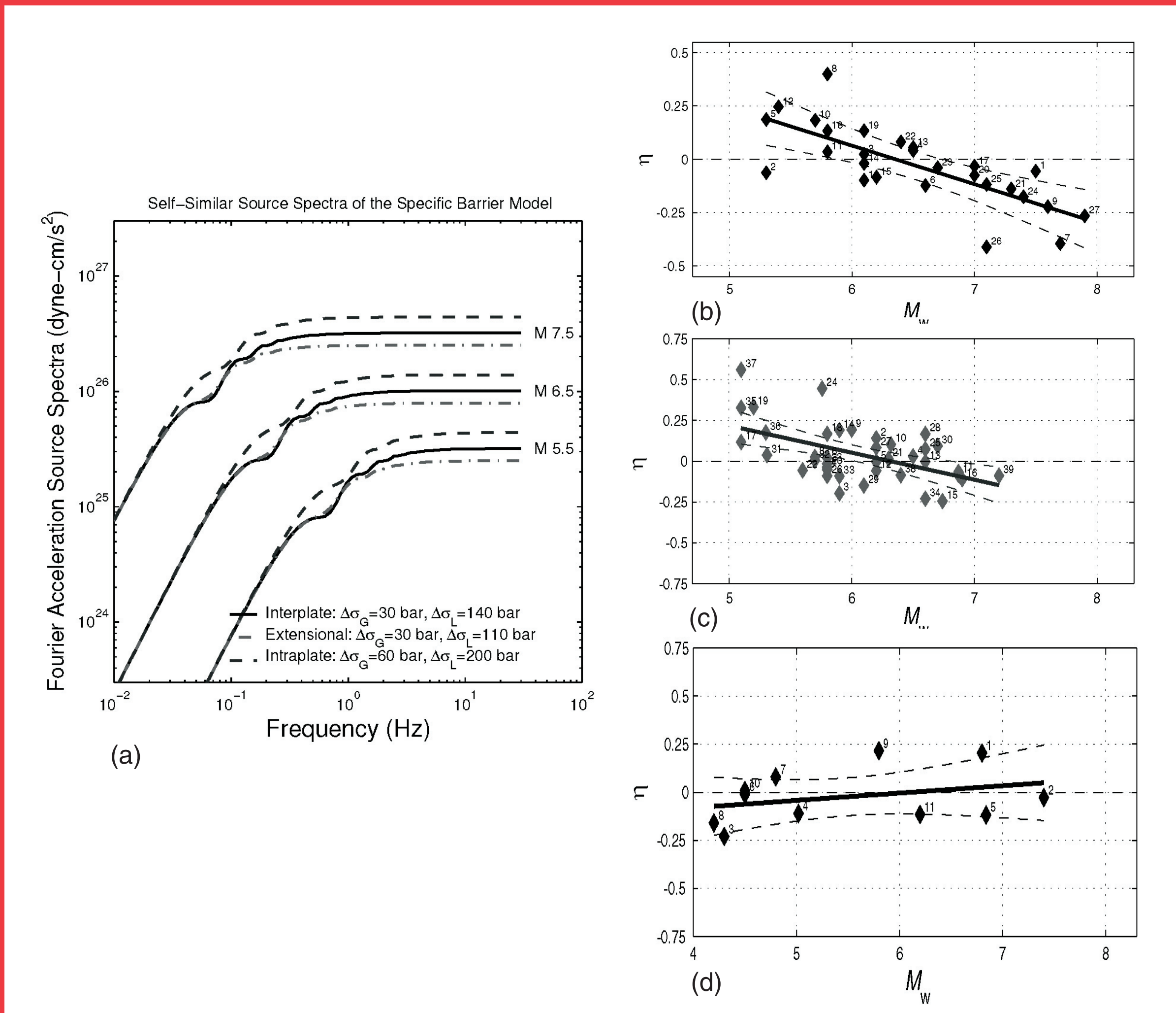
The practical tools and models used to simulate strong ground motion and predict various measures of ground motion developed in this task are used by researchers in the other thrust areas to develop scenario earthquakes, fragility curves, and ground motion input.



Halldorsson, 2004, PhD Thesis in preparation

■ Figure 1. Magnitude-Distance Characteristics of the Strong Motion Datasets

Figure 1 displays the 'Magnitude-Distance' space of the above datasets, while Figures 2, 3 and 4 summarize the results of the fitting of the Specific Barrier Model to the datasets of each one of the tectonic regions. Specifically, Figures 2 and 3 show the source spectra of the Specific Barrier Model fitted to the data of each one of the tectonic regions assuming "*self-similarity*" (Figure 2a) and disregarding self-similarity (Figure 3a). [According to the assumption of self-similarity, all earthquake events may be specified by a single parameter, say seismic moment M_0, and that small events are similar to large ones. Self-similarity implies "*geometric similarity*," i.e., length L, width W and slip Δu_0 all scale as $\sim M_0^{1/3}$, and "*physical similarity*," i.e., all nondimensional products of source parameters are the same, while the rupture velocity is constant and all parameters with the

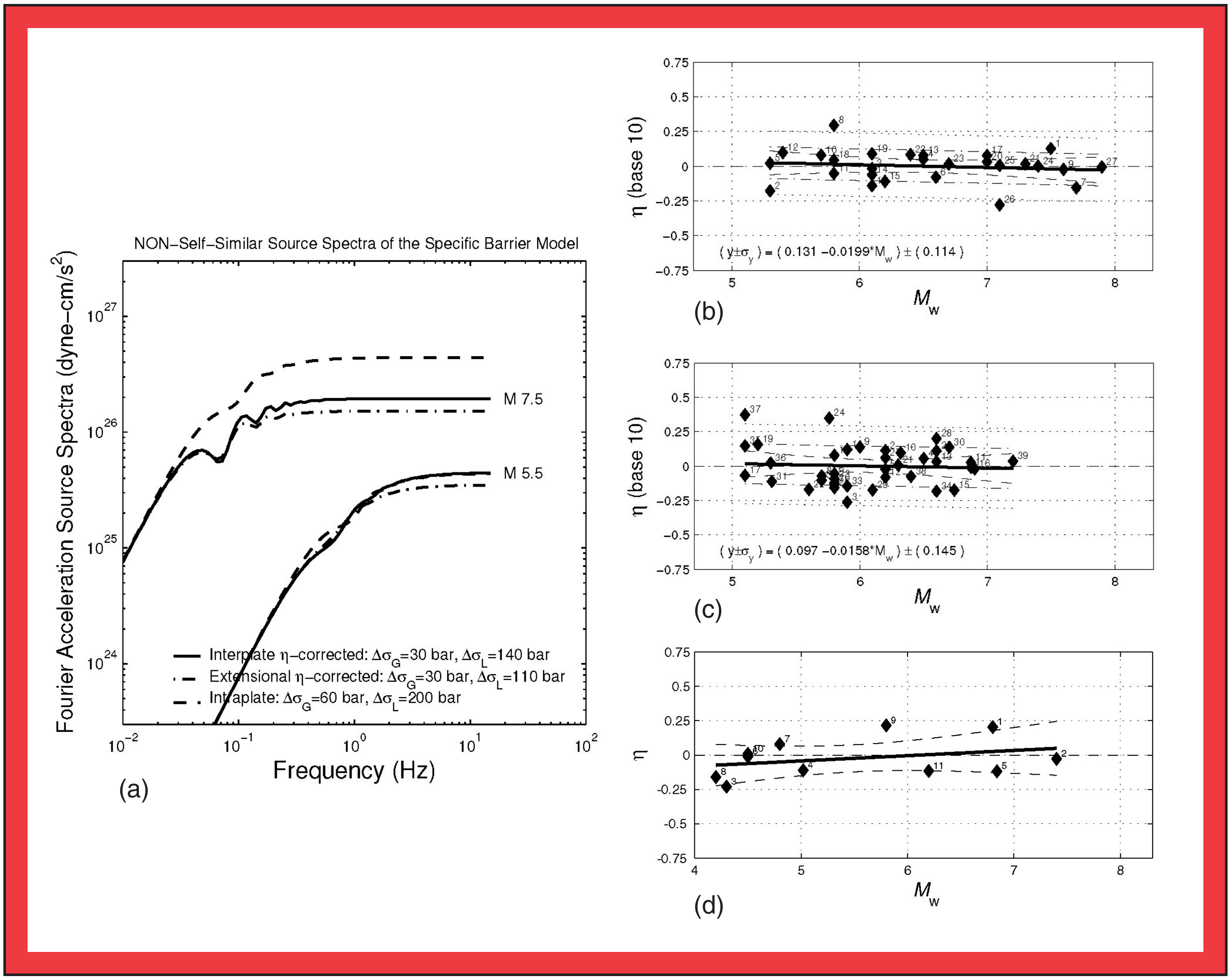


Halldorsson, 2004, PhD Thesis in preparation

■ Figure 2. (a) *Self-similar* far-field S-wave source spectra of the Specific Barrier Model as inferred from the regression to the data for each of the tectonic regimes. The inter-event residuals for (b) the inter-plate, (c) extensional and (d) intra-plate regimes are also shown. The inter-event trends apparent in the plots for the inter-plate and extensional regimes indicate a deviation from self-similar source scaling.

dimension of time scale as ~$M_0^{1/3}$ (Aki 1967).] Figures 2b,c,d and 3b,c,d display the corresponding *inter-event* residuals. Clearly, the data reveal that the assumption of self-similarity does not hold in the strict sense for the active and extensional tectonic regimes (notice the linear variation of the inter-event residuals with M_w). Finally, Figure 4 displays the behavior of the residuals for each one of the tectonic regimes. The purpose of plots such as Figure 4 is to reveal any significant biases in the fitting, or any trends with earthquake magnitude and/or source-station distance. The behavior of the residuals shown in Figure 4 confirms that the fitting of the Specific Barrier Model to the data is satisfactory.

As we pointed out above, the *Specific Barrier Model* makes it



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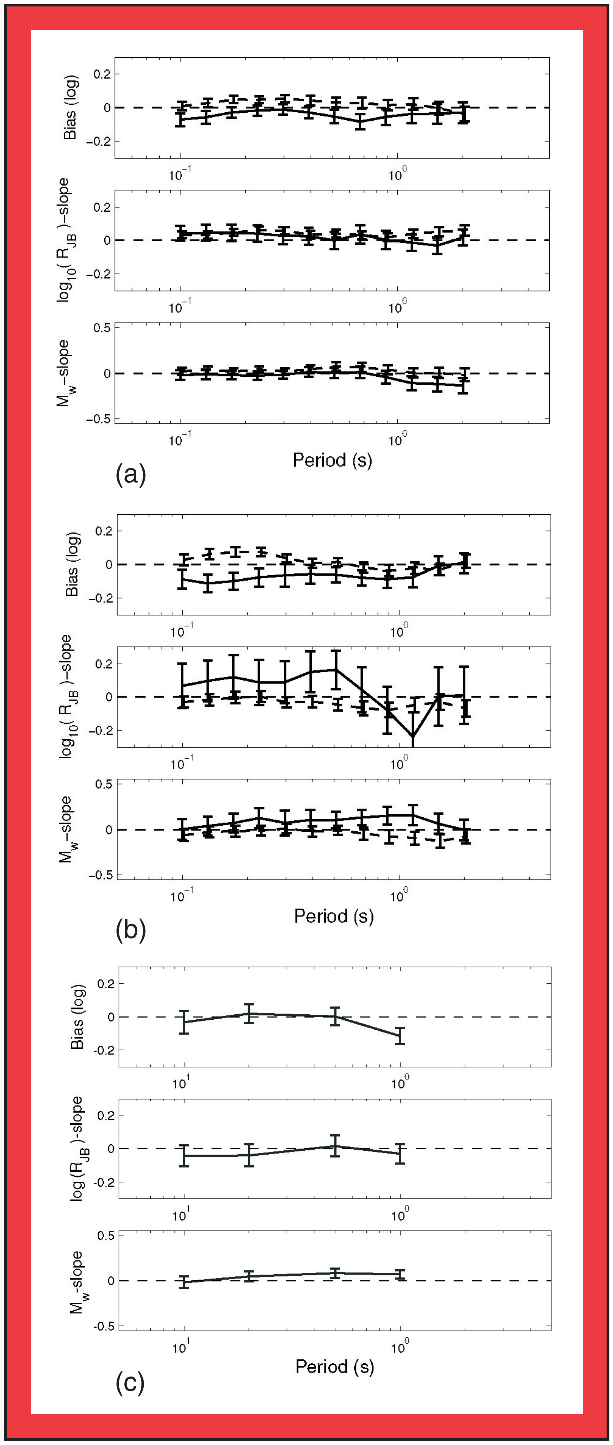
■ Figure 3. This figure shows the same information as Figure 2, except that in this case, the "non-self-similar" far-field S-wave source spectra of the Specific Barrier Model are shown for the inter-plate and extensional regimes. The corresponding inter-event residuals are displayed in (b), (c), and (d). It is evident that for all tectonic regions, the inter-event residuals do not exhibit any significant trends.

possible to simulate, in a consistent and physically plausible manner, *near-fault* ground motions. This feature of the model is especially significant for relatively densely populated urban areas located in the midst of tectonically active regions such as the Los Angeles (LA) Basin. For instance, it has been estimated that, for a profile of sites crossing the LA Basin, the 10%-in-50 yr exceedance level (which is typically used in design) is generally dominated by $M_W \geq 6.75$ events within ~20 km of the site (Field et al., 2000). The fault-normal component (i.e., the component normal to the *strike* of the fault; "*strike*" is the direction defined by the intersection of the fault plane with the free surface of the earth) of ground velocity recorded at a station in the vicinity of a fault and located in the forward (relative to the propagating rupture front) direction is characterized by a pulse of intermediate to long period. Such near-fault velocity pulses have intense amplitude (*A* ~ 100 cm/sec) and are the result of *directivity* (for appropriate source mechanisms, such pulses may be the result of the combined effects of *directivity* and *permanent translation*; for a complete and detailed discussion see Mavroeidis and Papageorgiou, 2003). Figure 5 displays near-fault strong ground motion records with 'distinct' velocity pulses.

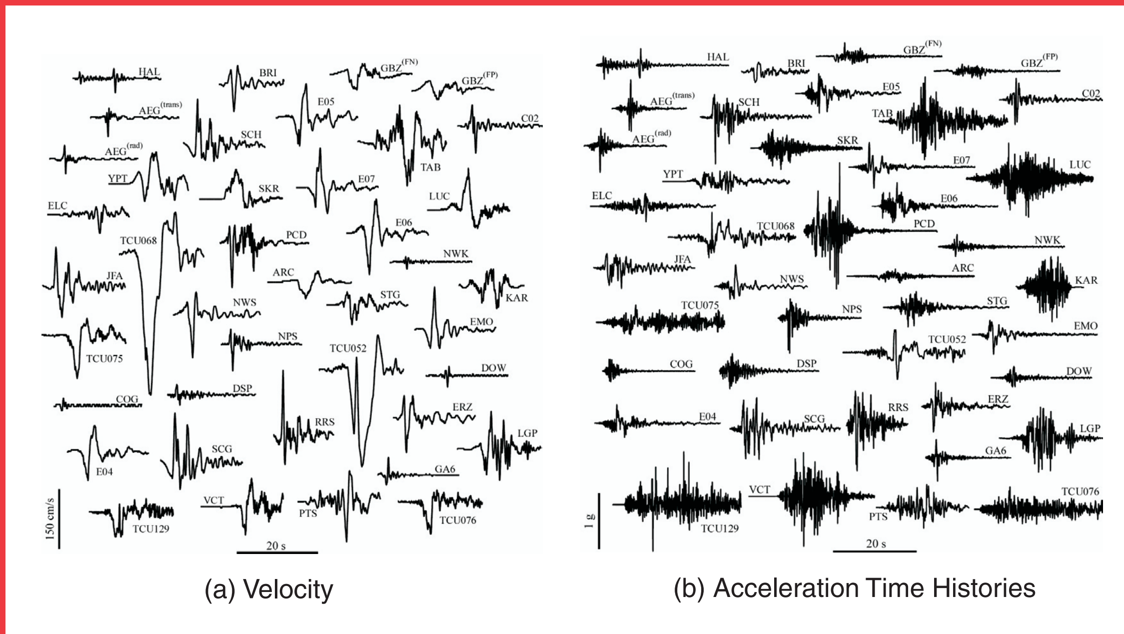
We have proposed a simple, yet effective, analytical model to mathematically represent such near-fault directivity pulses. The model adequately describes the impulsive character of near-fault ground motions both qualitatively and quantitatively. In addition, it can be used to analytically reproduce empirical observations that are based on available near-source records. The input parameters of the model have an unambiguous physical meaning. The proposed analytical model has been calibrated using a large number of actual near-field ground motion records. It successfully simulates the entire set of available near-fault displacement, velocity and, in many cases, acceleration time histories, as well as the corresponding deformation, velocity and acceleration response spectra. Figure 6 shows a sample of synthetic waveforms (red trace) fitted to actual near-fault records (gray trace) along with the corresponding 5% damped elastic response spectra.

The same mathematical model has been exploited for the investigation of the elastic and inelastic response of the single-degree-of-freedom (SDOF) system to near-fault seismic excitations (Mavroeidis et al., 2004). A parametric analysis of the dynamic response of the SDOF system as a function of the input parameters of



Halldorsson, 2004, PhD Thesis in preparation

■ Figure 4. Summary of the behavior of residuals for (a) the inter-plate, (b) the extensional, and (c) the intra-plate tectonic regions based on the "*non-self-similar*" source scaling. The figures display as a function of oscillator period the (i) mean residual bias (top), and the slope of a straight line fitted through the residuals plotted vs. (ii) log-distance (middle) or vs. (iii) magnitude (bottom). In all cases, the residuals are near zero and exhibit no significant trends.

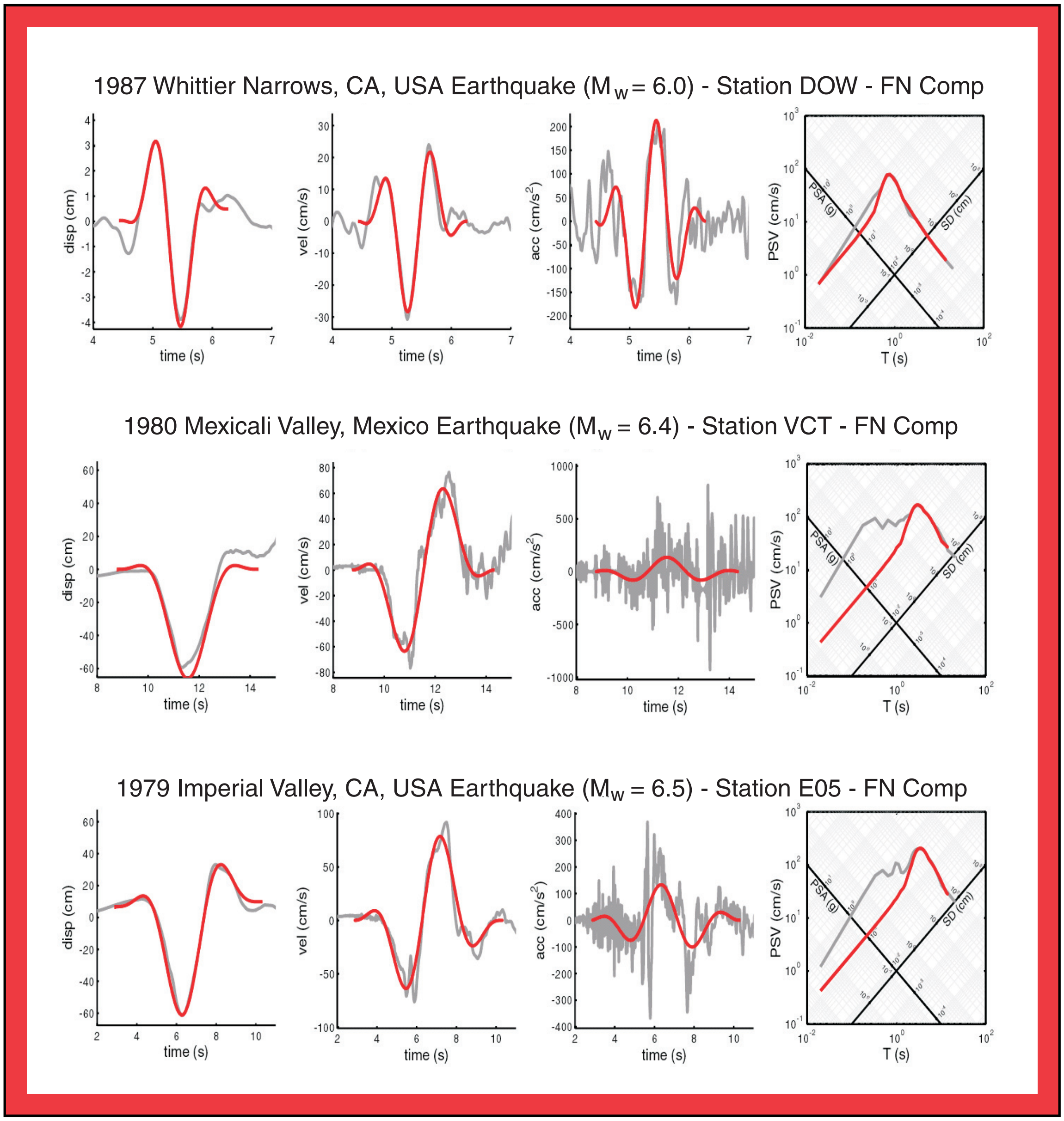


■ Figure 5. Near-Fault Strong Ground Motion Records with 'Distinct' Velocity Pulses (see Table 1 in Mavroeidis and Papageorgiou, 2003)

the mathematical model was performed to gain insight regarding the near-fault ground motion characteristics that significantly affect the elastic and inelastic structural performance.

A parameter of the mathematical representation of near-fault motions, referred to as "*pulse duration*" (T_P), emerges as a key parameter of the problem under investigation. Specifically, T_P is employed to normalize the elastic and inelastic response spectra of actual near-fault strong ground motion records. Such normalization makes feasible the specification of design spectra and reduction factors appropriate for near-fault ground motions. The "pulse duration" (T_P) is related to an important parameter of the rupture process referred to as "*rise time*" (τ) that is controlled by the dimension of the sub-events ("*barrier interval*" $2\rho_0$) that compose the main-shock. From the variation of T_P vs "*moment magnitude*" (M_w) (Figure 7a) and the scaling of the sub-event size ($2\rho_0$) with M_w (Figure 7b), we inferred that $\tau \sim (1/2)T_P$. [The "*rise time*" (τ) is the time that it takes for a representative point of the fault plane to complete its slip.]

Parameters T_P and A can be utilized to effectively normalize the elastic and inelastic response spectra of SDOF systems subjected to actual near-fault records. Such normalization makes feasible the specification of normalized design spectra for near-fault ground motion excitations of different earthquake magnitude ranges. The Veletsos-Newmark-Hall equations for reduction factors can be used for near-fault ground motions provided that normalized response spectra are used along with appropriately selected values of $(T_n/T_P)_a$, $(T_n/T_P)_b$, and $(T_n/T_P)_c$. Average elastic spectra for near

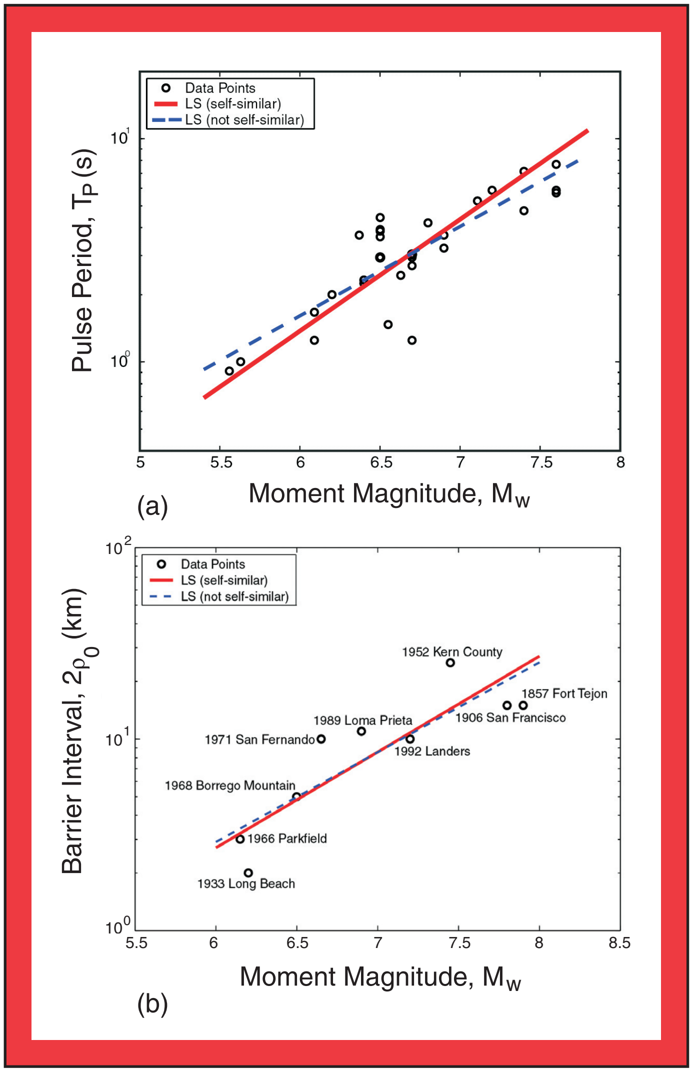


Mavroeidis et al., 2004

■ Figure 6. Sample of synthetic waveforms (red trace) fitted to actual near-fault records (gray trace). Ground motion time histories (displacement, velocity and acceleration series), as well as the corresponding 5% damped elastic response spectra, are illustrated.

fault ground motions (along with appropriate reduction factors for various values of ductility) have been proposed by Mavroeidis et al. (2004).

Analytical modeling makes it feasible to make educated conjectures about the character of near-fault pulses for tectonic regions (such as Eastern North America) for which such recordings are very few or completely lacking. For example, for Eastern North America (ENA), various investigators (e.g., Halldorsson and Papageorgiou, 2004) have concluded that the value of the stress parameter (local stress drop) that controls the high



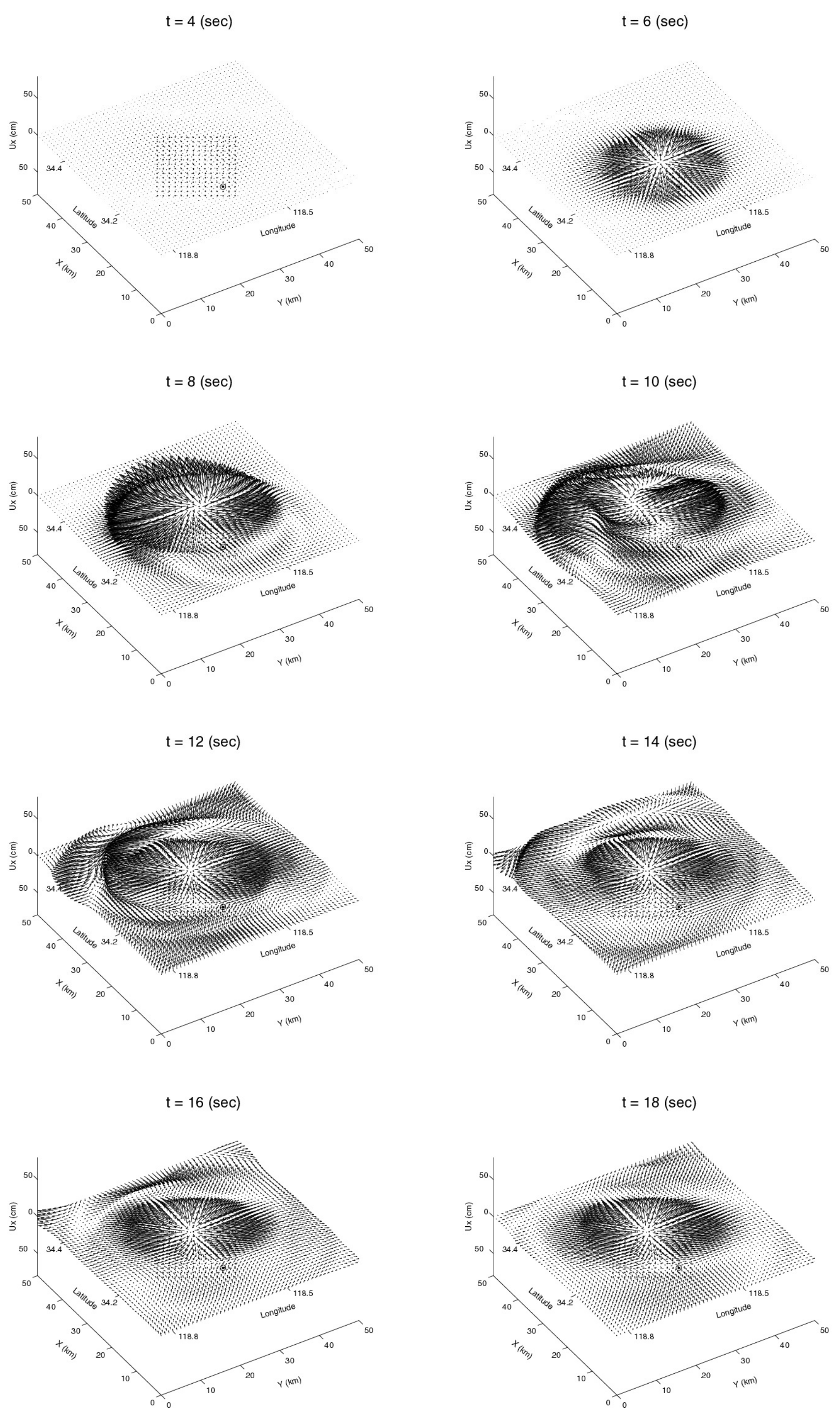
(a) Mavroeidis and Papageorgiou, 2003; (b) Mavroeidis et al., 2004

■ Figure 7. (a) Variation of pulse period (T_P) with moment magnitude (M_w): empirical relationships obtained by least squares fit with and without the assumption of self-similarity based on forward directivity pulses only. (b) Variation of the barrier interval ($2\rho_0$) with moment magnitude (M_w) for major earthquakes in California.

frequency amplitudes of source spectra of intra-plate sources is higher when compared to that of inter-plate sources. Furthermore, it has been conjectured that the rise-time of intra-plate sources may be shorter when compared to that of inter-plate events of comparable size. In view of these observations, one would expect the near-fault velocity pulses to be "*sharper*" (i.e., to have larger amplitude and shorter duration) when compared to the corresponding pulses of inter-plate events of comparable magnitude. Halldorsson et al. (2003) explored the above hypothesis by investigating the very limited relevant strong motion database, and concluded that the above conjecture appears to be valid. This result, however, is very tentative and requires more data to be firmly established or refuted.

Kinematic Modeling Approach

In the 1990's [when MCEER was known as the National Center for Earthquake Engineering Research Center (NCEER)] we had developed a computer code implementing a method, referred to as the "*Discrete Wave-number Method,*" originally proposed and developed by Bouchon and Aki (1977) and Bouchon (1979). The method is a very efficient computational technique that can be used to compute the wave-field [i.e., displacements and differential motions (i.e., strains)] generated by a seismic source (such as a shear fault) in layered homogeneous isotropic elastic half-space (for a discussion of the method see Spudich and Archuleta, 1987; Bouchon, 2003). We have used the code to compute the wave field generated by the 1994 Northridge earthquake (Zhang and Papageorgiou, 1995, 1996; Papageorgiou, 1997). [Figure 8, which displays snapshots of the horizontal component of displacement of the 1994 Northridge, California earthquake (taken from Papageorgiou 1997; originally presented by Zhang and Papageorgiou, 1995), was generated using our computer code.] Recently,

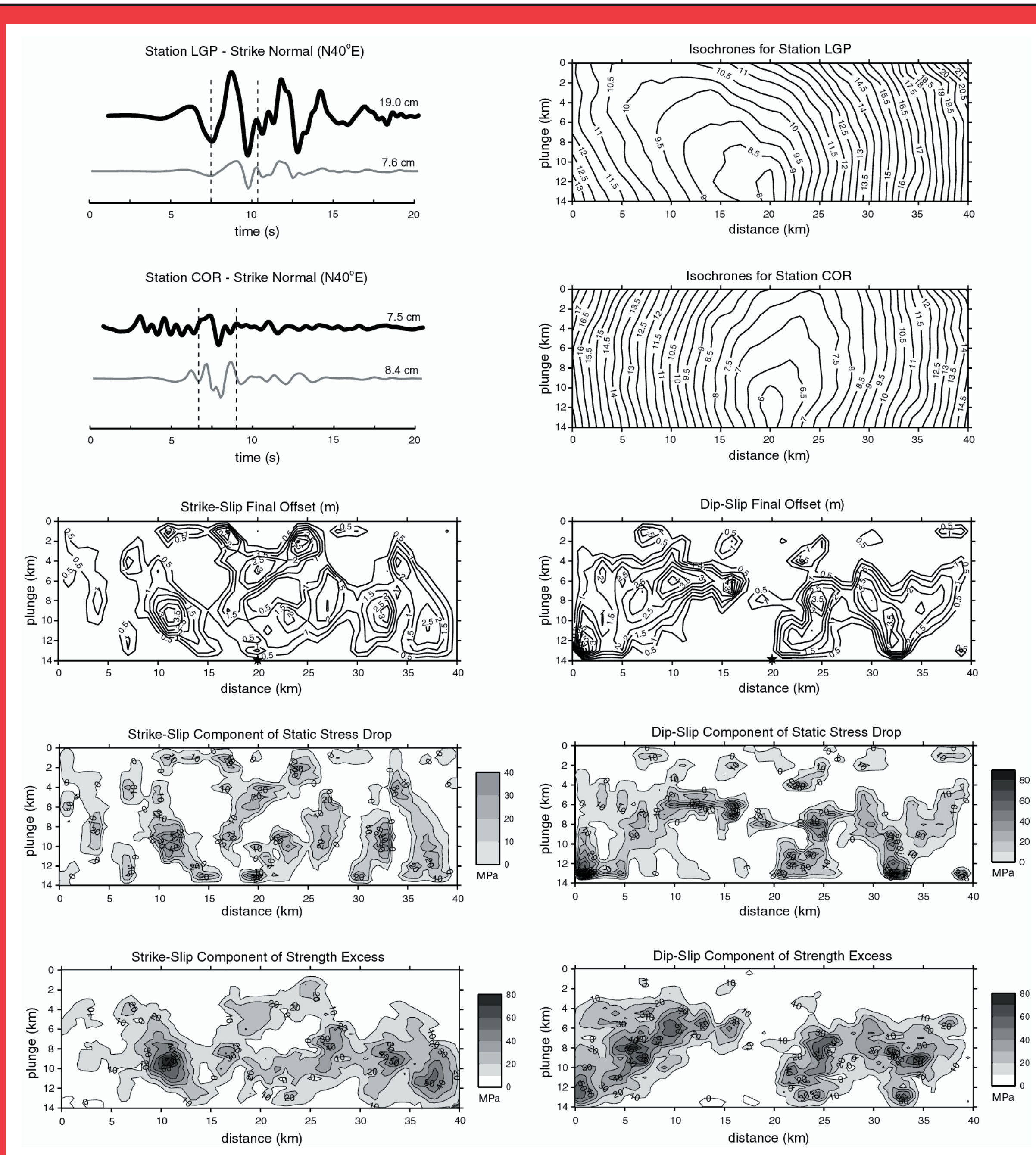


Papageorgiou, 1997

■ Figure 8. Snapshots of the Horizontal Component of Displacement of the 1994 Northridge, California Earthquake using the Rupture Model of Wald et al. (1996)

Bouchon (1997) extended the "Discrete Wave-number Method" to compute the evolution of stress on the causative fault plane of an earthquake.

In order to investigate the relation of the near-fault velocity pulse waveform to the slip and stress spatio-temporal history over the fault plane, we proposed to investigate



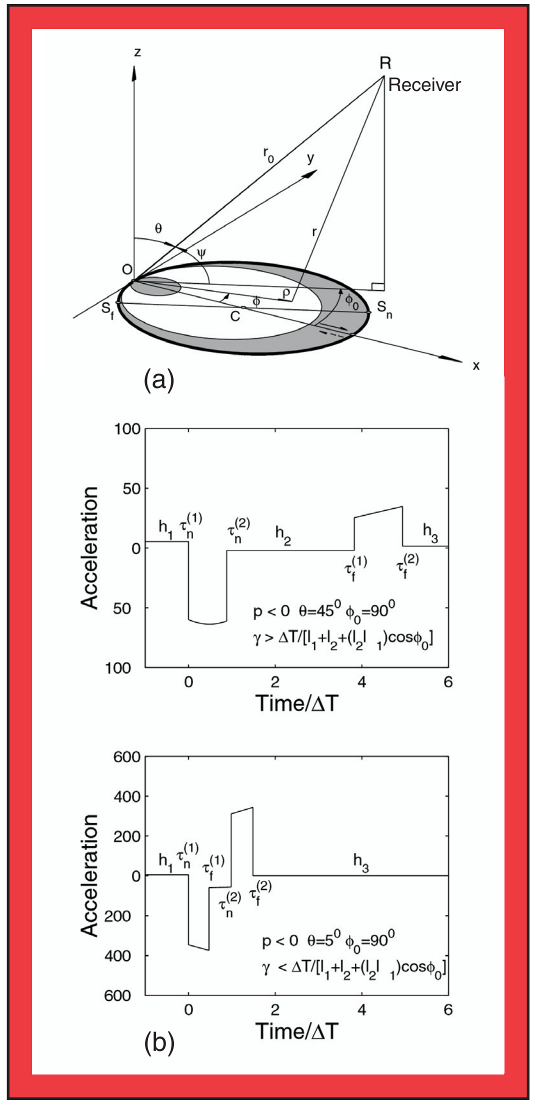
Mavroeidis, 2004

■ Figure 9. Recorded (black trace) and synthetic (gray trace) near-fault ground motion time histories and S-wave isochrones for selected stations that recorded the 1989 Loma Prieta earthquake. Tomographic images of the *static slip offset*, static stress drop, and *strength excess* along the strike and dip directions are also illustrated.

events that produced near-fault strong motion recordings and for which reliable tomographic images of the evolution of slip have been inferred by inversion. In order to accomplish the above-stated goal, we implemented (Mavroeidis, 2004) Bouchon's (1997) method for the computation of the spatio-temporal evolution of various measures of stress change (e.g., *strength excess*, *dynamic stress drop*, *static stress drop*) over the fault plane, and we related the slip distribution and the above measures of stress change to the near-fault velocity pulses using the concept of "*isochrone*" curves. Figure 9, taken from Mavroeidis (2004), displays tomographic images of the static slip offset, static stress drop, and strength excess over the fault plane along with recorded (black trace) and synthetic (gray trace) near-fault ground motion time histories and *S*-wave isochrones for selected stations that recorded the 1989 Loma Prieta earthquake. Images such as Figure 9 reveal the factors that contribute to (and therefore control) the generation of near-fault intense pulses.

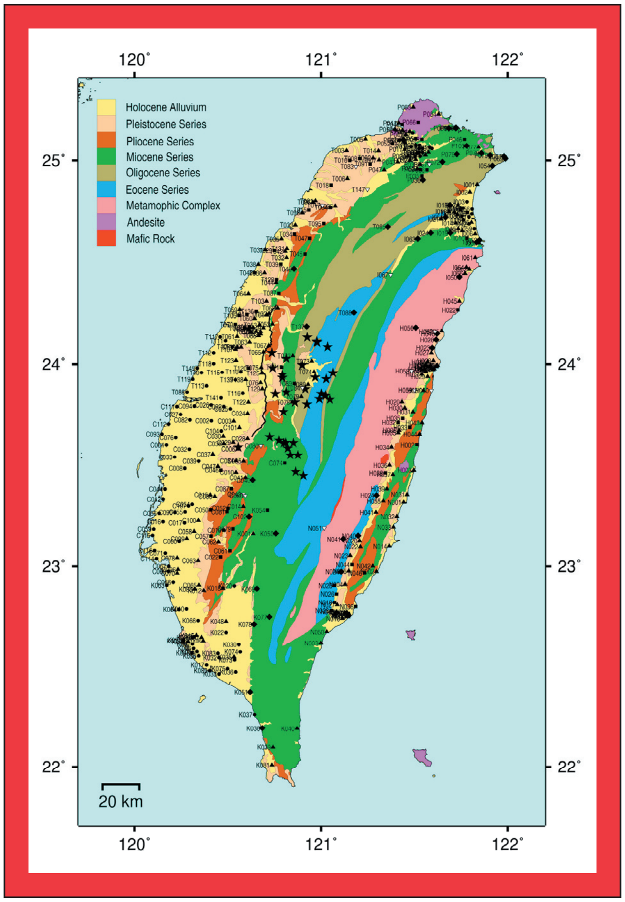
Mathematical Models of Sub-events

In a series of papers (Dong and Papageorgiou, 2002a,b; 2003; 2004), we have developed *closed-form* mathematical expressions regarding the seismic radiation of a general family of crack models. Such models can be used to represent sub-events of a main earthquake event in source models such as the "*Specific Barrier Model*." Such mathematical models are very useful because, among other things, they provide a quantitative relation between important source parameters [such as "*stress drop*" $\Delta\sigma$, rupture front geometry (curvature) and kinematics (rupture velocity variations)] and the radiated seismic field. For example, such models quantify the directivity effects of rupture front kinematics on the radiated acceleration pulses at near-field, and thus complement the model that we proposed (and summarized above) for the near-fault velocity pulses. Figure 10 shows the acceleration pulses (Figure 10b) radiated by an asymmetrical circular crack model (Figure 10a) when the rupture propagation is decelerated and eventually arrested at the periphery of the crack.



Dong and Papageorgiou, 2002b

■ Figure 10. (a) Three-dimensional perspective of an asymmetrical circular crack model. The gray area near the periphery of the crack represents a zone over which the rupture front decelerates until it stops completely at the edge of the crack. (b) The acceleration pulses radiated when the rupture front enters into the '*deceleration zone.*'



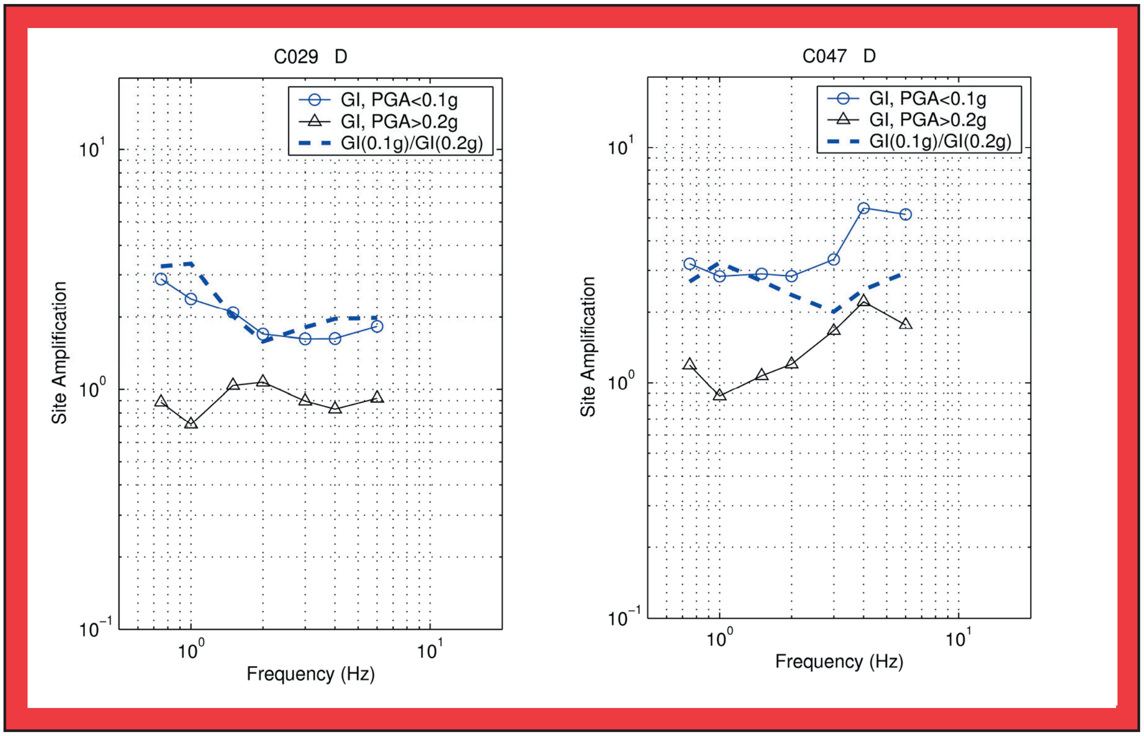
Zhang 2004, PhD Thesis in preparation

Figure 11. Distribution of the stations of the seismic network of Taiwan Strong Motion Instrumentation Program (TSMIP) that recorded the 1999 Chi-Chi earthquake and its most significant aftershocks (indicated by stars) on a geological map of the island of Taiwan.

Site Effects

The unprecedented recorded database generated by the 1999 Chi-Chi, Taiwan, earthquake and its aftershocks provides a unique opportunity to investigate site effects on earthquake ground motion. We analyzed *strong motion* data [recorded by the seismic network of Taiwan Strong Motion Instrumentation Program (TSMIP) during the main event and 33 aftershocks of 1999 Chi-Chi, Taiwan, earthquake (M_L 7.6)] (Figure 11) and *short period* data [recorded by the network of Central Weather Bureau Seismic Network equipped with 3-component Teledyne-Geotech S-13 seismometers; this data set consists of 5,499 records generated by 108 events ($2.90 < M_L < 4.97$)] (Zhang and Papageorgiou, 2004a). The strong motion data were grouped according to peak ground acceleration (PGA). Site amplification was inferred using three techniques: (1) Generalized Inversion of S-waves; (2) H/V method (i.e., the ratio of the spectral amplitudes of the horizontal and vertical components of motion); (3) Coda-wave inversion. Coda waves from both short period and strong motion data were used. As reference sites for the generalized inversion, we selected stations that have been classified as belonging to site class B. The site amplification estimates obtained using the abovementioned three different techniques are reasonably close to each other for weak motions (< 0.1 g). The presence of nonlinearity, due to the intensity of ground motion, was clearly identified at several stations that recorded both strong (> 0.2 g) as well as weak (< 0.1 g) motions (Figure 12). Finally, we correlated site amplification with geologic formation (i.e., classification based on geologic age), and NEHRP classification, and we concluded that the latter classification provides the smaller scatter.

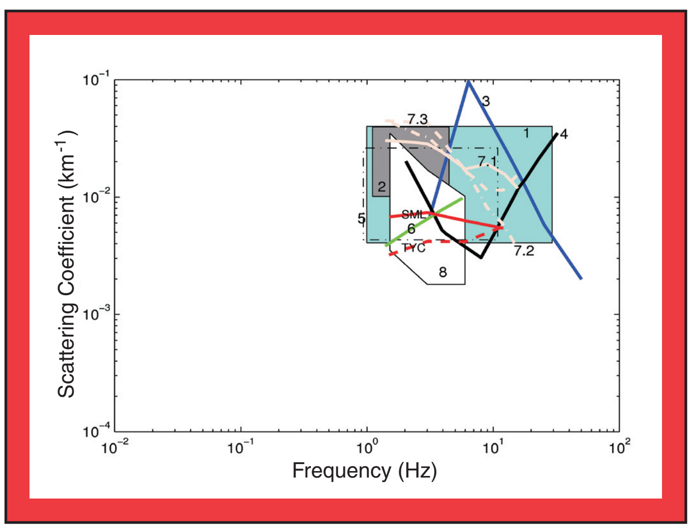
Using the short period data, we also investigated the attenuation characteristics of Taiwan (Zhang and Papageorgiou, 2004b). Specifically, using the "*coda decay curve,*" we estimated the coda attenuation Q_c, and while using the "*Coda Normalization Method*" we estimated the *S*-wave attenuation Q_S. Furthermore, we used the



Zhang 2004, PhD Thesis in preparation

■ Figure 12. Comparison at two stations (classified as NEHRP class D) of the site amplification factor from weak (< 0.1 g) and strong motions (> 0.2 g). Notice that the amplification factors of the weak motions are roughly a factor of ~2 larger than the amplification factors of the strong motions, suggesting the presence of nonlinear effects.

"*Multiple Lapse Time Window*" (MLTW) method to resolve the total attenuation Q_t into scattering Q_s and intrinsic Q_i attenuation, as well as the *scattering coefficient* g_0 (for a description of the above methods of data analysis, we refer the reader to Sato and Fehler, 1998). Based on the results of our analysis, we observed that the coda attenuation Q_c is close to the intrinsic attenuation Q_i, which agrees with the results of previous investigations. The total attenuation Q_t, is close to that obtained from the *Coda Normalization Method*. The scattering coefficient is estimated to be ~ 4-8 $\cdot 10^{-3}$ km^{-1}, consistent with (yet closer to the lower side of) estimates of this parameter for other tectonically active regions (Figure 13). Attenuation and scattering characteristics (and corresponding parameters) of a region are necessary input in the simulation of realistic Green's functions of



Zhang 2004, PhD Thesis in preparation;
modified from Figure 3.10 of Sato and Fehler, 1998

■ Figure 13. Comparison of the scattering coefficient g_0 (indicated by the red continuous and dashed lines), as inferred at two stations, CML and SML in Taiwan, with that of other tectonically active regions.

Related Web Sites

Engineering Seismology Laboratory:
http://civil.eng.buffalo.edu/engseislab/

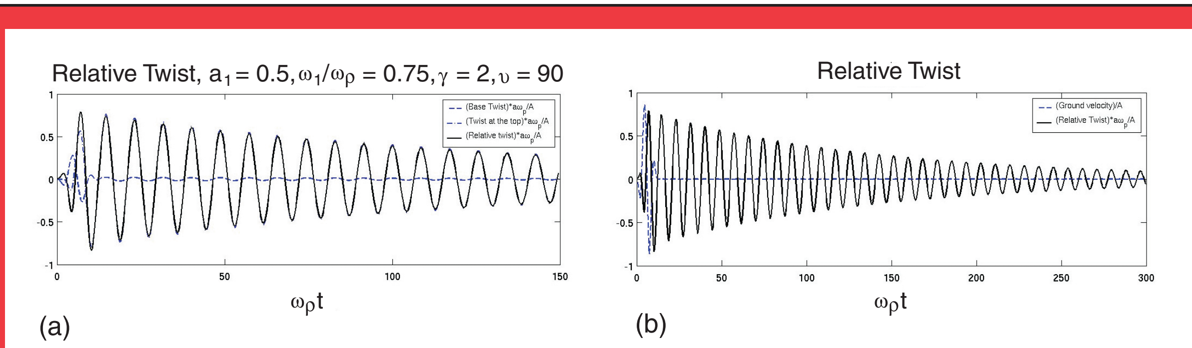
USGS National Seismic Hazards Project of the Earthquake Hazards Program:
http://geohazards.cr.usgs.gov/eq/

the lithosphere, which, in turn, are necessary for the synthesis of earthquake ground motion.

Conclusions and Future Research

We have developed simple, yet effective, models for analyzing and simulating strong ground motion for earthquake engineering applications. Using the "*Stochastic (Engineering) Approach*," the simulated time series may account for near-fault effects, if necessary. However, the simulation techniques that we have developed so far do not account for the long period surface waves (usually T ~ 3 sec and longer) that are generated in a sedimentary basin, (i) from the conversion of body waves at the edges of the basin, if the seismic source is located outside the basin (e.g., 1952 Kern County; 1971 San Fernando; 1990 Upland; 1992 Landers; 1994 Northridge; 1999 Hector Mine), or (ii) from channeling of seismic energy in the waveguide of the sediments in the form of surface waves, if the source is located in the basin (e.g., 1979 Imperial Valley earthquake). Such waves affect the long-period structures, such as long-span bridges, and high-rise buildings. From the above list of earthquakes, it is evident that basin-edge-generated surface waves are an important consideration for long-period structures located in the LA Basin.

We would like to expand the capability of our simulation techniques and incorporate such waves in the synthetic motions for sites where the conditions are conducive for such waves. The technique that we propose to use is based on the physics of surface wave propagation and incorporates the *dispersion characteristics* of the sedimentary deposit (i.e., *group* and *phase* velocities). Incorporation of such waves, with the appropriate arrival time, in the synthetic motions will render the simulated time-series *non-stationary* with respect to their frequency content. In the past, earthquake engineers proposed simulation techniques of non-stationary processes (e.g., Grigoriu et al., 1988). We would like to explore how our



Meza-Fajardo 2004, MSc Thesis in preparation

■ Figure 14. The response of a structure (modeled as a cylindrical shaft and supported on an elastic, homogeneous and isotropic half-space) to near fault pulses. The right panel (a) displays the absolute and relative (to the foundation) twist of the top of the structure along with the twist of the structure at the foundation level. At the left panel (b), the relative (to the foundation) twist of the top of the structure is displayed again, along with the free-field near-fault pulse that represents the excitation.

technique, that is motivated by the physics of the process, relates to the abovementioned phenomenological techniques.

Finally, using the models of ground motion that we have developed, we are currently investigating the response of structures (including soil-structure-interaction effects) to near-fault ground motions and basin-generated surface waves. Specifically, reasoning that the near-fault intense pulses may be associated with intense rotational motions about a vertical axis (Bouchon and Aki, 1982; Zhang and Papageorgiou, 1996; Gomberg, 1997; Mavroeidis, 2004), we are currently investigating the torsional response of structures to such motions (Figure 14; Meza-Fajardo and Papageorgiou, 2004). Similarly, recognizing that the basin-generated surface waves may be detrimental for long period structures, we have developed an analytical model of a suspension bridge tower-pier system and are currently investigating its response to such waves (Dong and Papageorgiou, 2004; manuscript in preparation).

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Advanced Web-based GIS Management Technology

by Arthur J. Lembo, Amanda Bonneau and Thomas D. O'Rourke

Research Objectives

The objective of this research is to develop an Internet-based geographic information system (GIS) management process for earthquake engineering. Research and development activities combine Internet map server (IMS) and geographical information system (GIS) technologies to create web-accessible databases and data management procedures for geographically distributed networks, such as water supplies, electric power, transportation, and regional complexes of acute care facilities. Applications of the technology are illustrated with respect to hospital sites and regional geotechnical characteristics. Additional applications are discussed for lifeline systems, emergency response and recovery, and educational tools at the graduate, undergraduate, K-12, and local community levels.

Sponsors

National Science Foundation, Earthquake Engineering Research Centers Program

Research Team

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Geographical information systems (GIS) are well suited for database collection and management related to geographically dispersed networks. Access to and management of GIS through the Internet allows for effective, multi-user development and applications of databases for lifeline and hospital systems; a platform for the dynamic assembly of data and rapid response during post-earthquake reconnaissance and emergency operations: and a broadly used medium for education at the university, K-12, and local community levels.

GIS technology for earthquake engineering is well established, with research focused on assessing the seismic damage of underground infrastructure (O'Rourke et al., 2004; Shinozuka et al., 2003a; Toprak et al., 1999), liquefaction modeling (Bardet and Hu, 2003; Bardet et al., 1999) reconnaissance and recovery (Eguchi et al., 2003); evaluating electrical power systems (Shinozuka et al., 2003b), water supply networks (O'Rourke et al., 2001), and earthquake warning systems (Jia et al., 2003). Conversely, other GIS practitioners have made extensive use of Internet Map Server (IMS) technology (Peng, 1997; Jones, 2000; Singh, 1999; Lembo, 1999). Studies show an exponential growth rate in the use of Internet GIS between 1996–2000 (Peterson, 2003; Peterson, 1999), with integration of

Previous Summaries

2000-2001:
O'Rourke et al.,
http://mceer.buffalo.edu/publications/resaccom/0001/rpa_pdfs/14orourkegis-4.pdf

1997-1999:
O'Rourke et al.,
http://mceer.buffalo.edu/publications/resaccom/9799/Ch5orour.pdf

web based services (Evans, 1999), and online cartographic production (Peterson, 1997).

This paper describes MCEER activities to combine GIS and IMS technology for earthquake engineering. The strategy adopted by MCEER is to internalize map server technology with the user's desk or laptop GIS so that access, queries, and database management can be performed directly over the Internet for maximum operational efficiency. The technology approach being developed by MCEER is described, as are its applications to hospitals, lifelines, post-earthquake reconnaissance and emergency response, and education.

Hospital and Geotechnical Databases

A detailed survey was conducted of 186 hospital facilities in northern and southern California, covering 1,072 buildings, which represent 43% of the total number of acute care facilities in the state (Lew et. al, 2004). The survey was a collaborative effort undertaken by MCEER researchers at Cornell University and RPI, MACTEC Engineering and Consulting, Inc., Los Angeles, and the California Office of Statewide Planning and Development (OSHPD). Information was collected and summarized regarding facility name; location; buildings per site; number of licensed and general acute care (GAC) beds; structural performance category (SPC) ratings; liquefaction, landslide, tsunami/seiche, surface faulting, seismically induced flooding potential, and seismic motion hazards; and building characteristics. The information was used for a statistical assessment of the hospital sites and systematic evaluation of the main geotechnical factors that will affect hospital performance in future earthquakes. The study shows that approximately 20% of the hospital sites investigated are vulnerable to soil liquefaction. Liquefaction potential, in terms of vertical ground movement and lateral spread, are summarized for 32 different sites.

MCEER researchers have taken advantage of the unique opportunities for data mining with the OSHPD hospital site information by creating a web-based center for subsurface data and borehole information in GIS format. Bore-

> Primary users of the research will include researchers who need to obtain earthquake engineering related data for acute care facilities in California. The information can be queried through the Internet Map Server, or copied and downloaded to a local computer for more in-depth analysis. The technology used allows for rapid implementation that will be helpful in assisting post-disaster damage detection and restoration through making up-to-date information immediately understandable and accessible through the Internet. This research will also provide educational tools to be used at the graduate, undergraduate, K-12, and local community levels.

hole and subsurface information are being collected and digitized from the hospital site engineering geologic reports. This information is then linked to GIS maps of hospital sites and boring locations in two steps. First, the borehole data are scanned and made accessible through the web by hyperlink to borehole log images. Links can also be created to the geotechnical reports in pdf format. This first step allows for relatively rapid creation of the website and dissemination of information at a rudimentary level. The second step involves transferring the borehole data into relational database software. The relational database will connect with the web-based GIS so users can click on borehole and query data and use them for analysis purposes.

In developing an architecture and process for web-based GIS data management, MCEER researchers have been in contact with investigators at the University of Southern California (USC), Southern California Earthquake Center (SCEC), California Geologic Survey (CGS), US Geologic Survey (USGS), Pacific Earthquake Engineering Research Center (PEER) and COSMOS. There are many existing databases and GIS platforms used by these organizations, and several activities are underway with input from a large user community. These activities involve the PEER/COSMOS Project on Archiving and Web Dissemination of Geotechnical Data (*http://geoinfo.usc.edu/gvdc*) and the Geotechnical Information ITR Project at USC (*http://geoinfo.usc.edu/itr*).

To promote open access and continuing integration of data sets from multiple users, the central hub concept described by Stepp et al. (2001) has been expanded to multiple sites. In the MCEER approach, web servers at various user/developer sites contain data, metadata, and/or indices that permit access through various linked databases from various contributors. Whereas access to the web server, or hub, is achieved conventionally through an intermediate portal with a map server, the MCEER approach uses software that combines the map server with the desktop (or laptop) GIS for direct contact and query of geotechnical information.

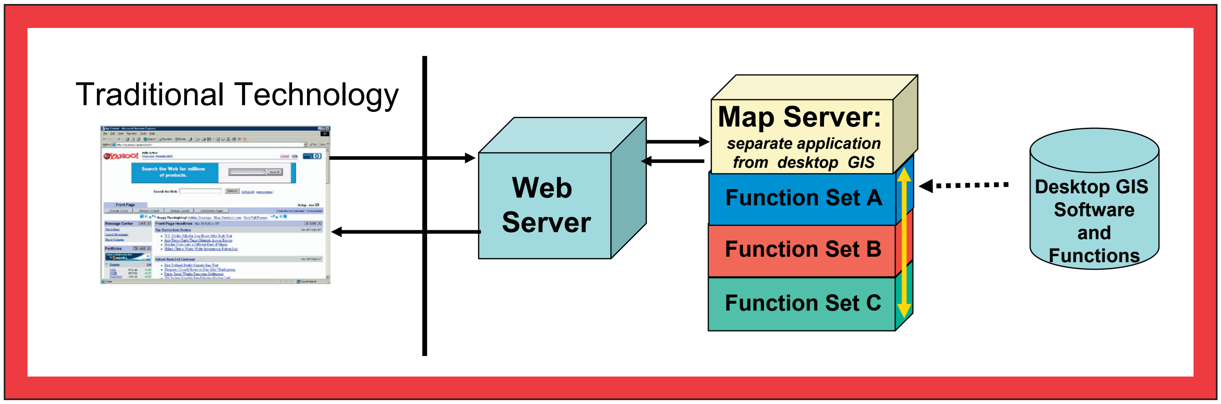
Web-based GIS Management

The ideal characteristics of a geographical central repository are the ability to store large amounts of data and support multiple graphics per site. The GIS must support spatial query functionality such that the data are accessible and easily manipulated by users. The data repository must be easy to maintain and update. Finally, access to the GIS website should require as little additional software as possible, preferably only an Internet browser.

While there are numerous ways to publish geographic information on the Internet (Peng and Ming, 2003), commercially available GIS software primarily focuses on two distinct methods. The first option we refer to as External Map Server Technology (EMST). As shown in Figure 1, this conventional IMS approach requires a separate map server that is only loosely connected with the GIS. In addition, only those services developed within

Links to Current Research

The development of an Internet-based GIS database for acute care facilities and other geographically disperse data can be integrated into research being carried out in all three thrust areas.

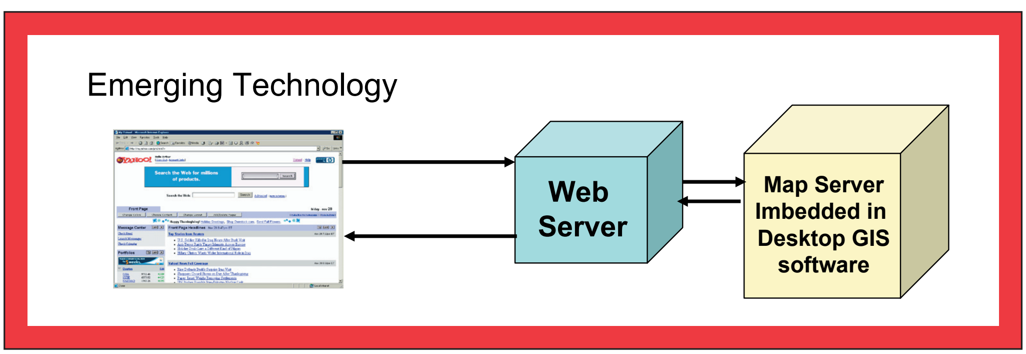


■ Figure 1. Conventional External Map Server Technology (EMST) approach uses a GIS loosely connected to a separate map server technology. In some instances, the GIS is not connected to the map server at all.

the map server are available to Internet developers. Users are not actually working with the native GIS software, but rather with a middleware product whose level of connectivity with the desktop GIS varies.

Recent architectural developments use the desktop GIS as an engine to create IMS applications. Similar to Figure 1, the desktop GIS software merely produces a file the map server can then read. Therefore, the application still requires the purchase of separate middleware, and all GIS functions must be written for the map server. Only those functions exposed within the map server would be available to the IMS developer. While particular queries or functions can be utilized in the desktop GIS, they are not available in the IMS application. The functions must be re-written using the separate map server product for these queries to be available to Internet-based users.

An alternative strategy we refer to as Internal Map Server Technology (IMST), has been adopted by MCEER researchers that uses a low-cost desktop GIS software product, Manifold GIS, with an embedded map server. Manifold is a fully functional GIS (Lembo, 2004), and implements the emerging IMS technology illustrated in Figure 2. Using IMST, much of the functionality within the desktop GIS is immediately available for use on the Internet. Also, al-



■ Figure 2. Emerging Internal Map Server Technology (IMST) showing the integration of the map server component within the desktop GIS software. This approach enables the same toolset within the desktop GIS to be available for the Internet developer.

lowing the desktop GIS to be the actual map server exposes all data, queries, and cartographic display parameters to Internet users.

Table 1 lists the benefits of IMST. The attributes of the IMST approach are consistent with the ideal characteristics of a geographical central repository in its ability to store large data sets, support multiple graphics, allow for easy access and manipulation of data, and work with minimal additional software.

MCEER Web-based GIS Technology

This project began with the collection and conversion of hardcopy geotechnical data for acute care facilities into digital format. The digital data was then structured in a GIS format. Other, ancillary databases were integrated within the project to augment the geotechnical data. Some of the data sources integrated within the spatial database included political boundaries, major and minor roads, and water features from the California Spatial Information Library (*http://gis.ca.gov/*). Liquefaction and landslide hazard data were obtained from the California Geological Survey (*http://gmw.consrv.ca.gov/shmp/*). Over 190 GB of digital orthophoto imagery from the USGS is linked to the site through a remote server that stores the imagery in an Image Web Server. Also, borehole data from researchers at USC is currently under review to determine its possible use within the system.

Table 1. Benefits of IMST for Web-based GIS

Benefit	Description
Ease of Use	Microsoft Windows-based system, with an easy to use graphical user interface.
Cost	Comparatively low cost that includes both GIS and map server technology.
Ease of Administration	No separate middleware product; no additional software needed to publish the GIS application on the Internet, with the exception of an Internet web server.
Expanded Spatial SQL Operators	Software utilizes structured query language (SQL) in addition to spatial operators built within SQL to perform sophisticated GIS tasks. When Spatial queries with SQL are written in the desktop system, they are immediately available on the Internet.
Web Server Built into GIS Software	IMS is built directly within the desktop GIS software. All data, cartographic rendering, and queries are immediately available for Internet use, without the need for separate map server software, or reprogramming queries, data, or cartographic rendering within a separate product.
Pack and Ship Philosophy	Each GIS project file is a self-contained unit, allowing the entire desktop application to be copied and placed on another machine. This is especially important for users who want access to the desktop GIS software to enable more flexible and faster use of the data.

Collaborative Partners

California Geological Survey

California Office of Statewide Health Planning and Development (OSHPD)

Caltrans

Cornell University

ESRI

ImageCat, Inc.

Los Angeles Department of Water and Power

Manifold Systems

MACTEC Engineering and Consulting, Inc.

Rensselaer Polytechnic Institute

University of Southern California

The site provides basic navigation functions such as zoom and pan, and includes facilities for obtaining database information by clicking on an object (Figure 3). Once a facility is selected, users can display a scanned drawing of the facility (Figure 4).

Other capabilities include querying geographic objects based on user defined criteria for facility characteristics such as liquefac-

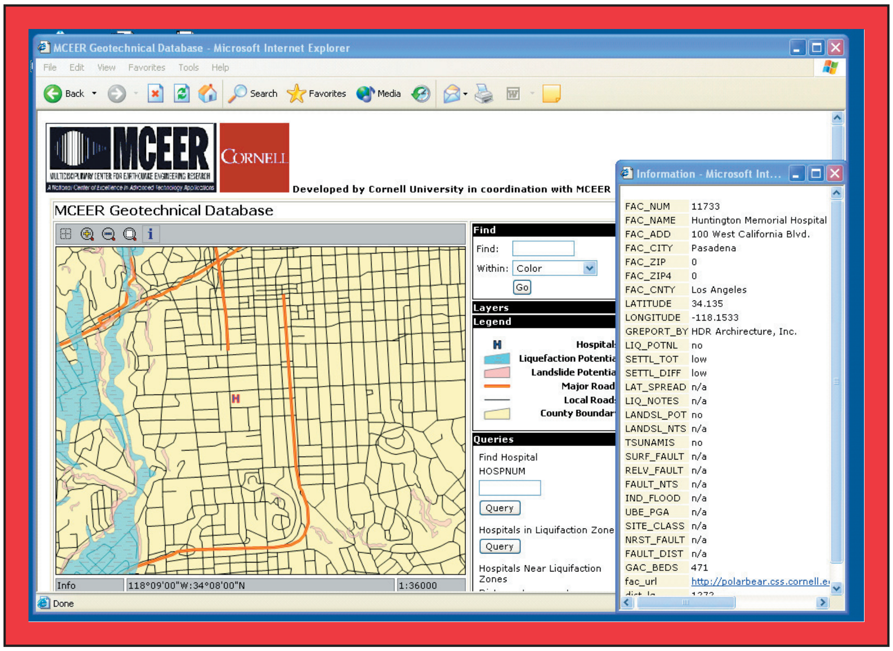


Figure 3. Using the Identify button, a user can select a facility location and obtain information on the particular facility.

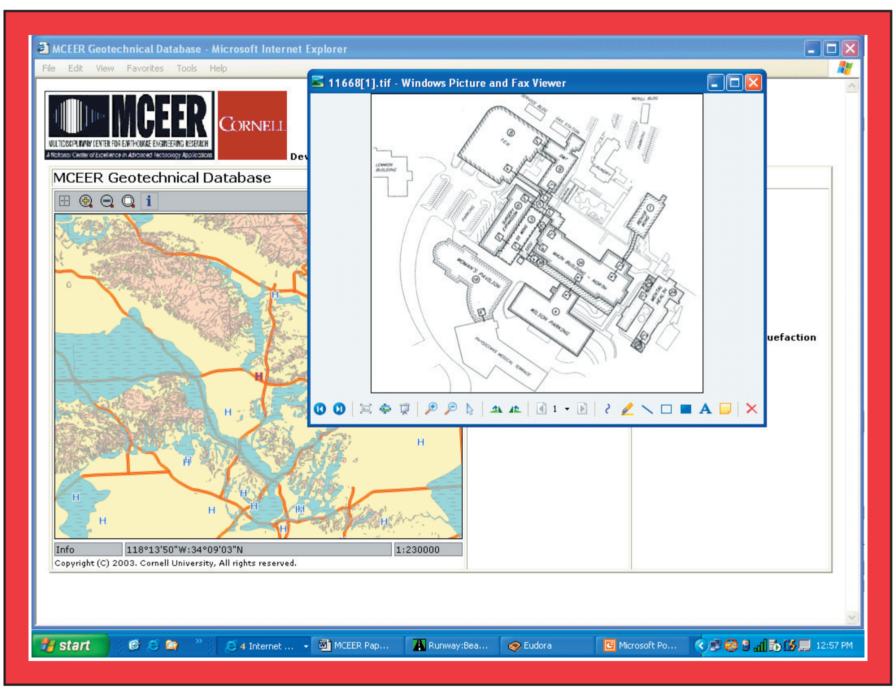
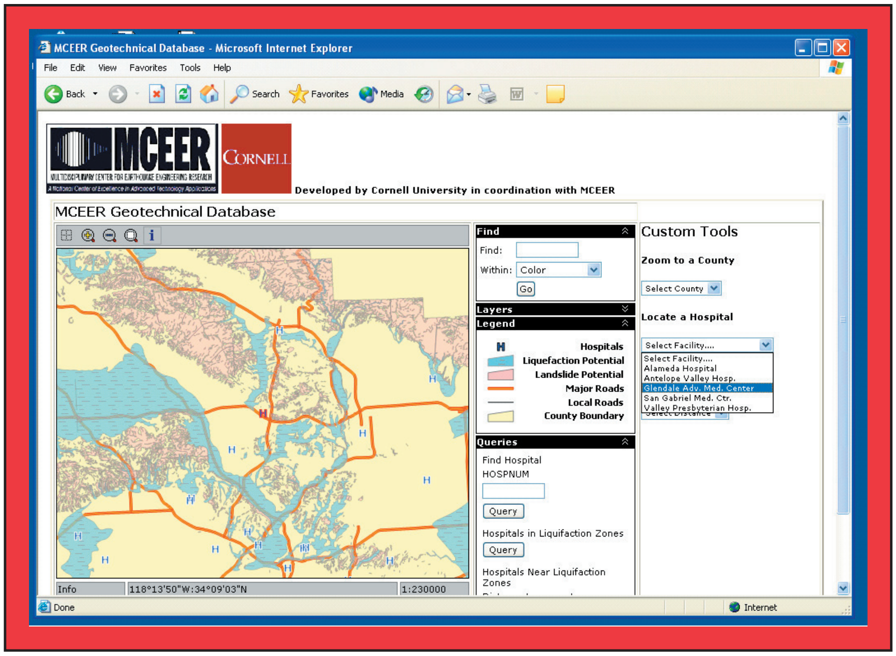


Figure 4. Selecting a facility site brings up a scanned drawing of the facility.



■ Figure 5. Users can select individual facility names and zoom to the facility.

tion, landslide, or tsunami potential, lateral spread, or settling totals, distance and direction to the nearest fault, the nearest fault name for a facility, and the number of beds within the facility.

Customized pull-down tools allow a user to select and zoom to a specific county, hospital facility (Figure 5), or select facilities within a certain distance from a liquefaction zone. Once data is selected in a table, it may be easily copied into a spreadsheet for further analysis.

Post Earthquake Reconnaissance and Emergency Response

GIS and IMS technology may assist post-disaster damage detection and restoration because it makes geographic data immediately understandable and accessible through the Internet. These technologies were used in the aftermath of the 2003 Bam, Iran earthquake (Adams et al., 2004). An interesting feature of the Bam activity was the use of portable notebooks, satellite imagery, and GPS technology directing responders to the hardest hit areas, using a preliminary regional damage assessment (Adams et al., 2003). More detailed damage information, including the locations of collapsed buildings, were identified using high-resolution satellite coverage.

The researchers indicated that back in the office, the datasets from the field were transferred to a GIS environment for further analysis. However, with the emerging technologies discussed in this work, much of the GIS and IMS activities can be provided directly on site as shown in Figure 6.

The approach shown in Figure 6 illustrates the integrated implementation of a low-cost pack and ship philosophy, combined GIS and web server technology, and

Related Web Sites

Example Site:
http://polarbear.css.cornell.edu/mceerhosp

Manifold GIS System:
www.manifold.net

ESRI GIS and Mapping Software:
www.esri.com

California Geological Survey - Seismic Hazards Mapping Project:
http://gmw.consrv.ca.gov/shmp/

"This kind of rapid development demonstrates a unique opportunity to assemble data for use by first responders within a very short period of time, using relatively inexpensive computer architecture."

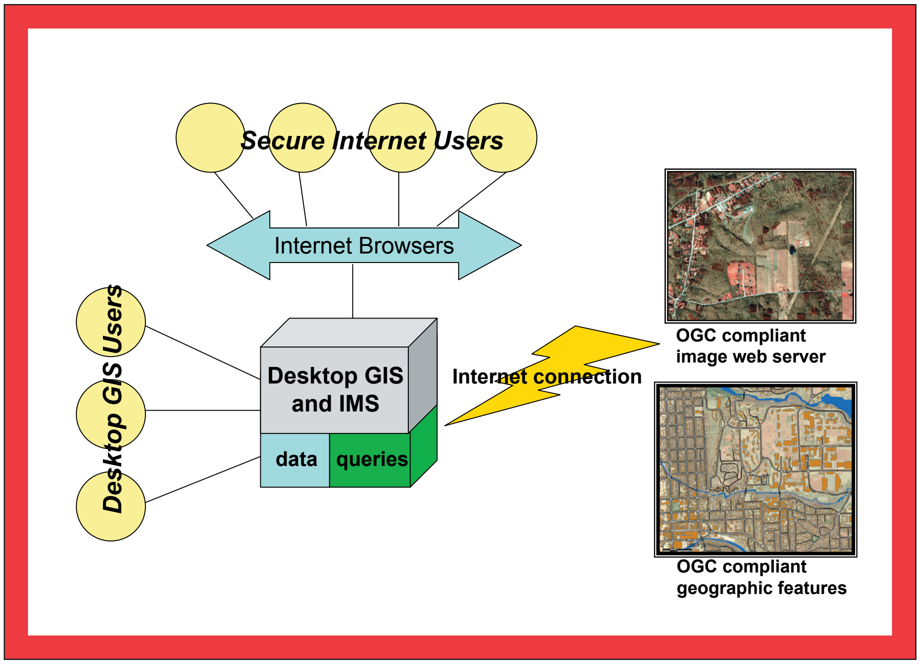


Figure 6. GIS/IMS architecture to deploy geospatial data on-site for emergency response through Internet technology, and classical desktop GIS access.

portable architecture. Because the GIS itself acts as its own IMS, all the data and queries related to the specific site are available to 1) users via the Internet through browser technology, 2) desk or laptop GIS software users through Internet connections or 3) direct copy of the primary map database to a desktop GIS user. Additionally, Open GIS Consortium (OGC) compliant databases storing very large spatial databases (gigabytes) of imagery, GIS basemaps, and geocoding databases can be accessed through a wide area network.

In this scenario, the base geospatial data layers such as critical infrastructure, political boundaries, acute care facilities, and environmental datasets are stored within a single map database. Internet users have access to the data and queries using Internet browsers via the IMS. The IMS application described in this paper contains approximately 200 mb of geographic data, compressed down to 56 mb. Therefore, the database and queries are easily shared among desktop researchers using CD-ROMs, USB portable drives, or even email attachments. However, the application also links to USGS digital orthophotographs for the entire state of California.

The database of digital orthophotographs contains 198 GB of imagery, stored on a remote server using a fast image processing technology. Therefore, MCEER is not burdened with the task of maintaining or storing the enormous amounts of digital imagery, but rather utilizes a virtual link to the database stored elsewhere. Figure 7 illustrates the integration of the digital orthophotographs with the acute care facilities and other geographic databases.

Using the emerging technologies also provides for rapid implementation. For example, the

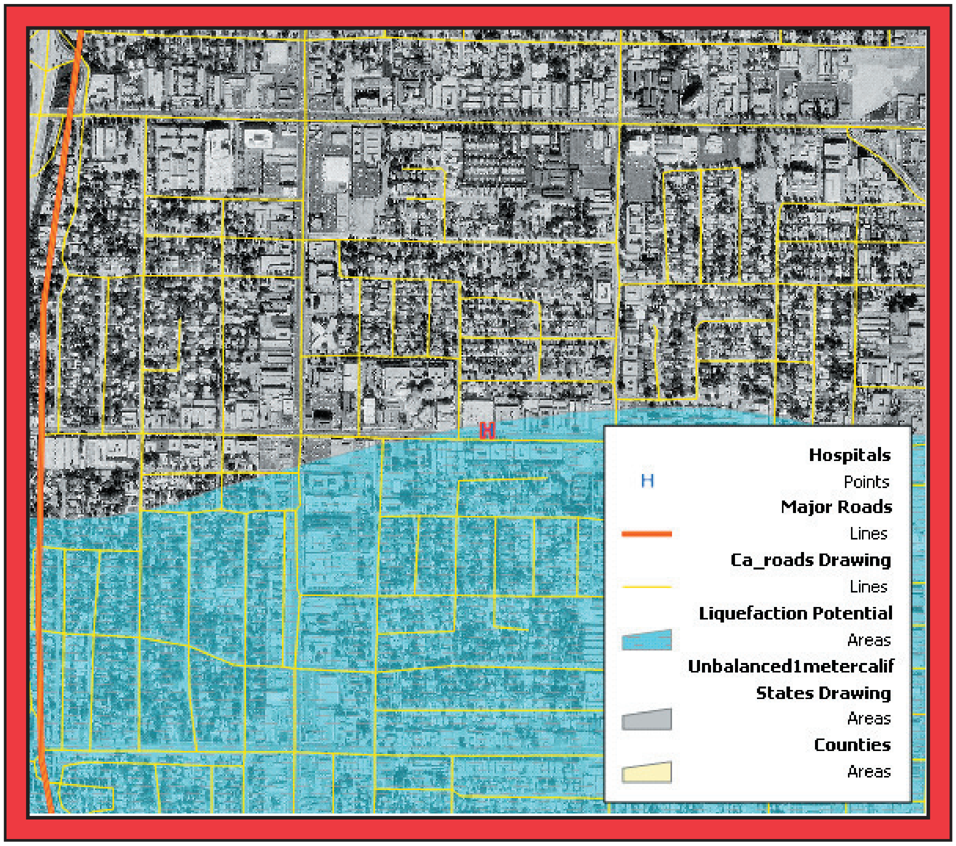


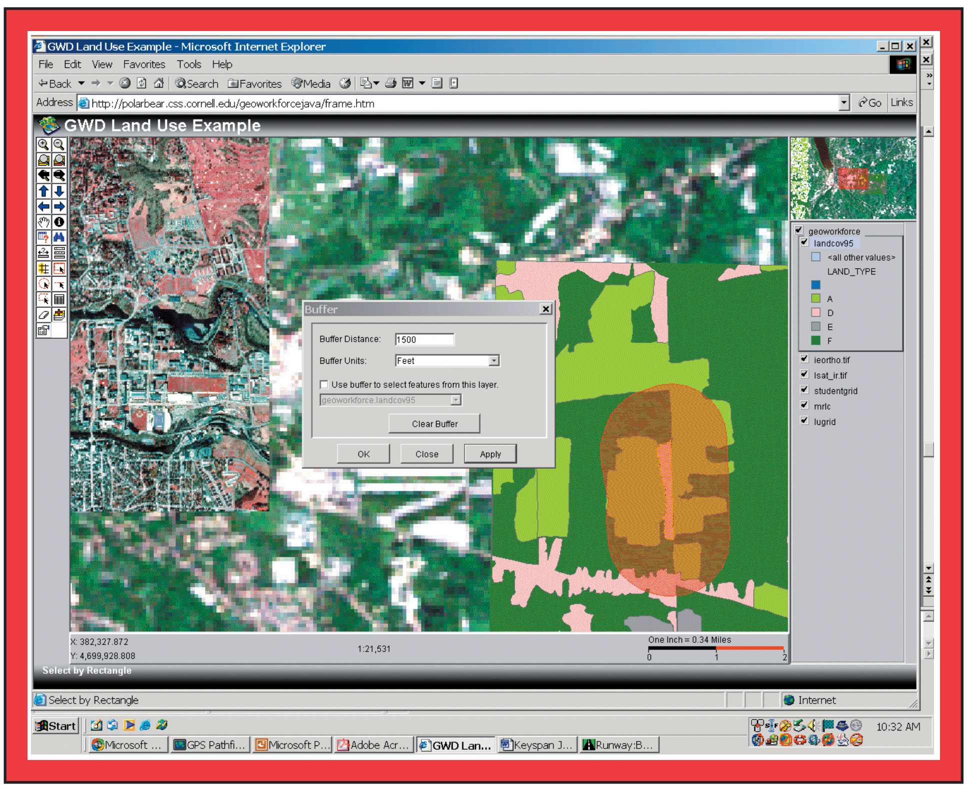
Figure 7. Integration of geospatial data collected for MCEER research, dynamically linked to a large image web server, hosting over 198 GB of digital orthoimagery.

architecture described in Figure 6 was implemented using a laptop computer as the primary server. The loading of data, development of the IMS site, creation of example queries, and connection to third party OGC compliant databases was completed in less than one hour using a laptop computer as both the desktop and Internet map server. This kind of rapid development demonstrates a unique opportunity to assemble data for use by first responders within a very short period of time, using relatively inexpensive computer architecture. Thus, emergency responders would have the ability to access building plans and outside visuals of damaged buildings via laptop on their way to the site of a disaster. Rapid access to this type of information can help rescue efforts and promote safety of personnel.

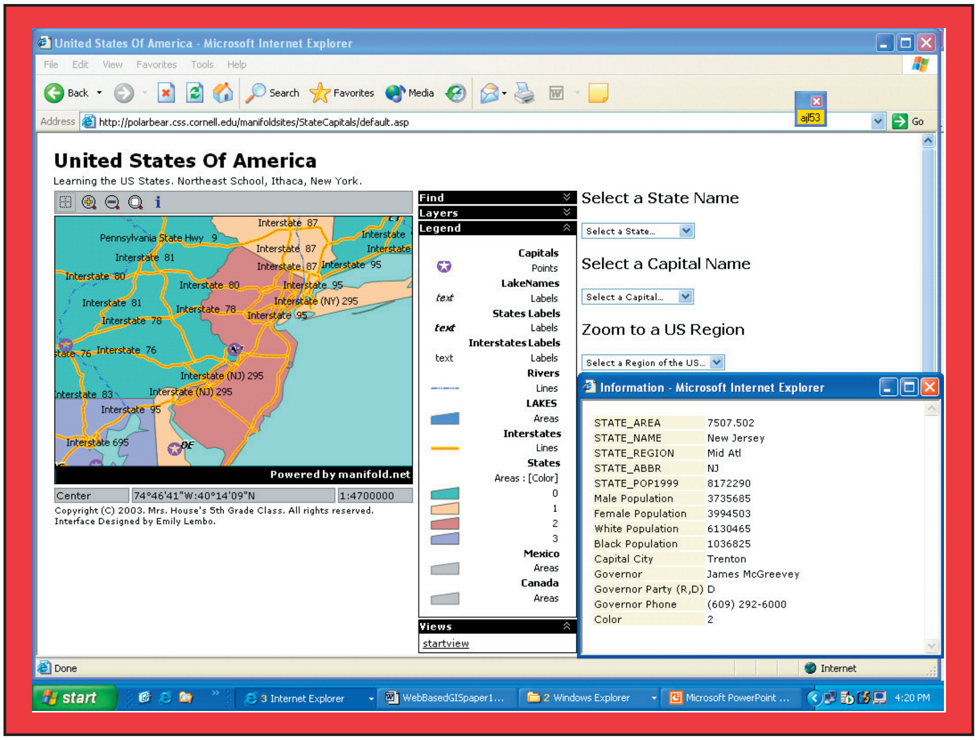
Educational Uses

MCEER researchers at Cornell University have received a Faculty Innovation in Teaching Award (FIT) to develop an IMS based spatial display and exploration system (SPADES) to supplement course material (*http://www.innovation.cornell.edu/*), and a grant from the National Aeronautical and Space Administration (NASA) to develop courseware in geospatial information technology for Internet delivery (*http://geoworkforce.olemiss.edu*). The SPADES system provides a repository of GIS data for students to work with, and facilitates geo-processing of data right in the students' dormitory or the campus library. GIS data files for laboratory exercises are stored on a university server, and ESRI-based IMS applications were developed to allow students access to the data and applications. Not only do the IMS exercises allow students to perform geo-processing over the Internet, but other students, with less experience using GIS, could become familiar with the technology from the comfort of their own dorm room. Additionally, data for demonstrations in lectures are available on the IMS site for use by the students to reinforce the concepts presented in the lecture. Future activities will focus on expanding the IMS application to include geotechnical information and analysis.

The IMS technology is also used to support classroom exercises at an elementary school in Ithaca, New York. The technology makes use of Manifold's IMST, allowing fifth-grade students to access geographic data related to state capitals from their classroom or homes.



■ Figure 8. Example of student IMS exercise that enables students with an Internet connection to perform laboratory-based exercises from their dormitory. This example shows the integration of digital orthophotography, a Landsat satellite image, and a vector land cover map into a single IMS application. In this example, a student has selected a specific land cover polygon, created a buffer around the area, and selected all features falling within the buffer.



■ Figure 9. Example of IMS technology for use by elementary school age children as an exploratory system of state demographic and political data.

Future Directions

Satellite imaging, remote sensing, and high-resolution aerial photography provide new capabilities to capture and update inventory information on the natural and built environment prior to an earthquake, and to provide near real-time damage assessments after an event (O'Rourke, 2003). Internet based mapping solutions provide an excellent repository for storing and accessing these data during and after an extreme event. The integration of very large spatial databases and image web servers illustrates the possibilities of leveraging emerging technologies. The emerging technologies used in this research allowed for the rapid creation of an advanced Internet-based GIS discovery and database management tool for acute care facilities, and provided a great deal of flexibility within the IMST architecture, creating the possibility to expand on this work by leveraging other emerging technologies such as broadband wireless communications, or personal digital assistants (PDA) for location-based services.

These emerging technologies provide an opportunity to expand this research to include other lifeline systems, integration of statewide geocoding engines to locate any address within the State rather than just hospital locations, enable connectivity with other large Internet based storehouses of geographic information, and provide a live link with other databases accessible on the Internet, thus providing a more dynamic visualization of the geographic data. Additionally, MCEER related research is helping to develop many of the emerging technologies within commercial GIS software. MCEER researchers at Cornell University are currently beta-testing new features associated with the IMST approach in collaboration with Manifold Systems. The results of the beta testing have introduced new software functionality to support MCEER research.

These activities will provide an interesting test-bed to determine the appropriateness of a rapidly established IMS site for use in emergency response activities.

Concluding Remarks

MCEER has assembled a unique database for California hospital sites that includes political boundaries, major and minor roads, water features, liquefaction and landslide hazard data, and digital orthophoto imagery. The opportunities for data mining with this database are being exploited through the creation of an Internet-based center for subsurface data and borehole information in GIS format. MCEER has focused on an IMST approach that integrates map server capabilities with desk or laptop GIS for direct access, queries, and database management through the Internet. This approach embodies substantial benefits over relative conventional IMS applications in the form of ease of use, lower cost, more effective administration, access to expanded spatial SQL operators, a web server built into the GIS software and adherence to a pack and ship philosophy. In the MCEER approach, web servers at various user/developer sites contain data, metadata, and/or indices that permit access through various linked databases from many contributors. The technology under development at MCEER currently integrates databases from the USGS, the California Spatial Information Library and the California Geological Survey in GIS format. The applications of the technology include characterization and decision support systems for lifeline networks, regional complexes of hospitals, emergency response and recovery, and educational tools at the graduate, undergraduate, K-12, and local community levels.

Acknowledgements

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Defining and Measuring Economic Resilience to Earthquakes

by Adam Rose

Research Objectives

This research provides an in-depth analysis of economic resilience to earthquakes. It fine-tunes the definition to distinguish inherent and adaptive considerations, and it distinguishes the various levels at which resilience is operative. It explicitly links resilience to the behavior of individuals, markets, and the regional macroeconomy, including disequilibrium aspects of each. Finally, it examines the complementarities and tradeoffs between resilience and mitigation. The research is intended to reduce losses from earthquakes by helping to capitalize on and enhance the resilience of business and market operations.

The past decade has witnessed a number of devastating earthquakes in the U.S. and throughout the world. As large as the economic losses from them have been, the outcomes could have been worse had steps not been taken before, during, and after the events. Increasingly the emphasis has shifted to mitigation, or preventative actions taken before an earthquake to reduce loss (see, e.g., Mileti, 1999). Mitigation can reduce the probability and magnitude of the stimulus. It can also reduce our vulnerability. However, even in the absence of mitigation, we have the ability to cushion or reduce loss through *resilience*.

Economic resilience, as defined in this paper, refers to the inherent and adaptive responses to hazards that enable individuals and communities to avoid some potential losses. It can take place at the level of the firm, household, market, or macroeconomy. In contrast to the pre-event character of mitigation, economic resilience emphasizes ingenuity and resourcefulness applied during and after the event. Also, while mitigation often emphasizes new technology (e.g., seismic warning) or institutions (e.g., insurance markets), resilience has greater behavioral emphasis.[1] It focuses on the fact that individuals and organizations do not simply react passively or in a "business as usual manner" in the face of a disaster.

Three difficulties confront researchers in the resilience arena. At the conceptual level, there is the need to identify resilient actions, including those that may seem to violate established norms, such as rational behavior. At the operational level, it may be difficult to model individual, group, and community behavior in a single framework. At the empirical level, it

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Previous Summaries

2001-2003:
Rose and Liao,
http://mceer.buffalo.edu/publications/resaccom/0103/11rose.pdf

1999-2000:
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1997-1999:
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http://mceer.buffalo.edu/publications/resaccom/9799/Ch2tiern.pdf

is especially difficult to gather data on resilience to specify models.

The purpose of this paper is to summarize progress on all three planes. First, we define several important dimensions of economic resilience. Second, we show how computable general equilibrium (CGE) modeling represents a useful framework for analyzing the behavior of individuals, businesses, and markets. Third, we summarize recent progress in the conceptual and empirical modeling of resilience, including the incorporation of disequilibria and the recalibration of key behavioral parameters on the basis of empirical data. Fourth, we use the results of a case study to illustrate some important issues relating to the subject.

Defining Resilience and its Scope

Basic Definition

We begin by defining static *economic resilience* as the ability or capacity of a system to absorb or cushion against damage or loss (see, e.g., Holling, 1973; Perrings, 2001). A more general definition that incorporates dynamic considerations, including stability, is the ability of a system to recover from a severe shock.

We distinguish two types of resilience:

- *Inherent* – ability under normal circumstances (e.g., the ability to substitute other inputs for those curtailed by an external shock, or the ability of markets to reallocate resources in response to price signals).
- *Adaptive* – ability in crisis situations due to ingenuity or extra effort (e.g., increasing input substitution possibilities in individual business operations, or strengthening the market by providing information to match suppliers without customers to customers without suppliers).

Resilience emanates both from internal motivation and the stimulus of private or public policy decisions (Mileti, 1999). Also, resilience, as defined in this paper, refers to post-disaster conditions and response, which are distinguished from pre-disaster activities to reduce potential losses through mitigation. The consequences of these two approaches are not mutually exclusive, and below we shed some light on the influence of mitigation on resilience and visa versa.

The concept of resilience emanates from several sources. For

The operational definitions and models produced by this research should be of broad usefulness. Business managers will be better able to assess the inherent role and potential to improve economic resilience to earthquakes. Utility managers will be better able to estimate losses from service disruptions. Emergency planners will be better able to exploit the costless ability of market forces to reallocate scarce resources so as to minimize economic losses from earthquakes.

example, Holling (1973) and other ecologists, as well as Perrings (2001) and other ecological economists, have defined it in terms of the broader concept of sustainability as the capacity to absorb stress and shocks. Tinch (1998) has enumerated several similar measures including: stability, persistence, resistance, non-vulnerability, stochastic return time and resilience. However, Perrings (2001; p. 323) notes: "The property that most closely connects with the idea of sustainability as conservation of opportunity is resilience."

In disaster research, resilience has been emphasized most by Tierney (1997) in terms of business coping behavior and community response, by Comfort (1999) in terms of nonlinear adaptive response of organizations (broadly defined to include both the public and private sectors), and by Petak (2002) in terms of system performance. Recently, Bruneau et al. (2003; p. 3) have defined *community earthquake resilience* as "the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effectors of further earthquakes." Further, they divide resilience into three aspects, which correspond to the concepts defined above in an economic context. First is reduced failure probability, which we view as equivalent to mitigation in this paper. Second is reduced consequences from failure, which corresponds to our basic static definition of resilience. Third is reduced time to recovery, which adds a temporal dimension to our basic definition.[2] Note that in the infancy of conceptual and especially empirical analysis of economic resilience, we believe it is prudent to pin down fundamental considerations first. Dynamic aspects of resilience, including intertemporal tradeoffs, system "flipping," irreversibilities, and extreme nonlinearities, are beyond the scope of this paper. In sum, Bruneau et al. (2003) have offered a very broad definition of resilience to cover all actions that reduce losses from hazards, including mitigation and more rapid recovery. These refer to how a community reduces the probability of structural or system failure, in the case of the former, and how quickly it returns to normal in the case of the latter. We have focused on the essence of resilience—the innate aspects of the economic system at all levels to cushion itself against losses in a given period.

Scope

There are several categories of loss from disasters (see, e.g., Rose, 2004). Although property damage has traditionally received the most attention, direct and indirect business interruption losses can be just as prominent (see Tierney, 1997; Webb et al., 2000; Rose and Liao, 2004). Unlike property damage, which refers to structures (buildings, bridges, highways), business interruption refers to human operation of businesses, organizations and institutions. Moreover, unlike the stock measure of property, which incurs its damage during the relatively short period of the disaster stimulus, the flow measure of business interruption takes place for the relatively long

Links to Current Research

This research is part of MCEER's mission of enhancing community resilience to earthquakes. It focuses on how private and public sector decisions influence important dimensions of this issue. It will be tested in an application to the Los Angeles Demonstration Project.

period of recovery. Our analysis will focus on these flow measures, which will also be more useful for dynamic extensions.

Resilience can take place at three levels:

- *Microeconomic* – individual behavior of firms, households, or organizations.
- *Mesoeconomic* – economic sector, individual market, or cooperative group.
- *Macroeconomic* – all individual units and markets combined, though the whole is not simply the sum of its parts, due to interactive effects of an economy.

Examples of individual resilience are well documented in the literature, as are examples of the operation of businesses and organizations (Tierney, 1997; Comfort, 1999). What is often less appreciated by disaster researchers outside economics and closely related disciplines is the inherent resilience of markets. Prices act as the "invisible hand" that can guide resources to their best allocation even in the aftermath of a disaster. Some pricing mechanisms have been established expressly to deal with such a situation, as in the case of non-interruptible service premia that enable customers to estimate the value of a continuous supply of electricity and to pay in advance for receiving priority service during an outage (Rose and Benavides, 1999).

The price mechanism is a relatively costless way of redirecting goods and services. Price increases, though often viewed as "gouging," serve a useful purpose of reflecting highest value use, even in the broader social setting. Moreover, if the allocation does violate principles of equity (fairness), the market allocations can be adjusted by income or material transfers to the needy.

Of course, markets are likely to be shocked by disasters, in an analogous manner to buildings and humans. In this case, we have two alternatives for some or all of the economy:

- substitute centralized decree or planning, though at a significantly higher cost of administration;
- bolster the market, such as in improving information flows (e.g., the creation of an information clearing house to match customers without suppliers to suppliers without customers).

The role of economic resilience in the extent of economic losses from disasters is summarized in Figure 1, in relation to other major loss reduction strategies—mitigation and recovery management. Both of these strategies can enhance innate economic resilience as defined in this paper, though to date this has not been a major emphasis of either. Mitigation is typically oriented toward reducing the probability of failure and also reducing vulnerability through improved resistance (resistance is defined here as a fixed measure, in contrast to the "bounce-back," or flexible, nature of resilience). Recovery management is usually oriented toward providing outside assistance to businesses and households affected by disaster, and to reducing recovery time. The former aspect of recovery is not consistent with resilience because resilience emphasizes the self-reliance of communities in terms of the broader concept of sustainability (Mileti, 1999). The latter, however, will be a key

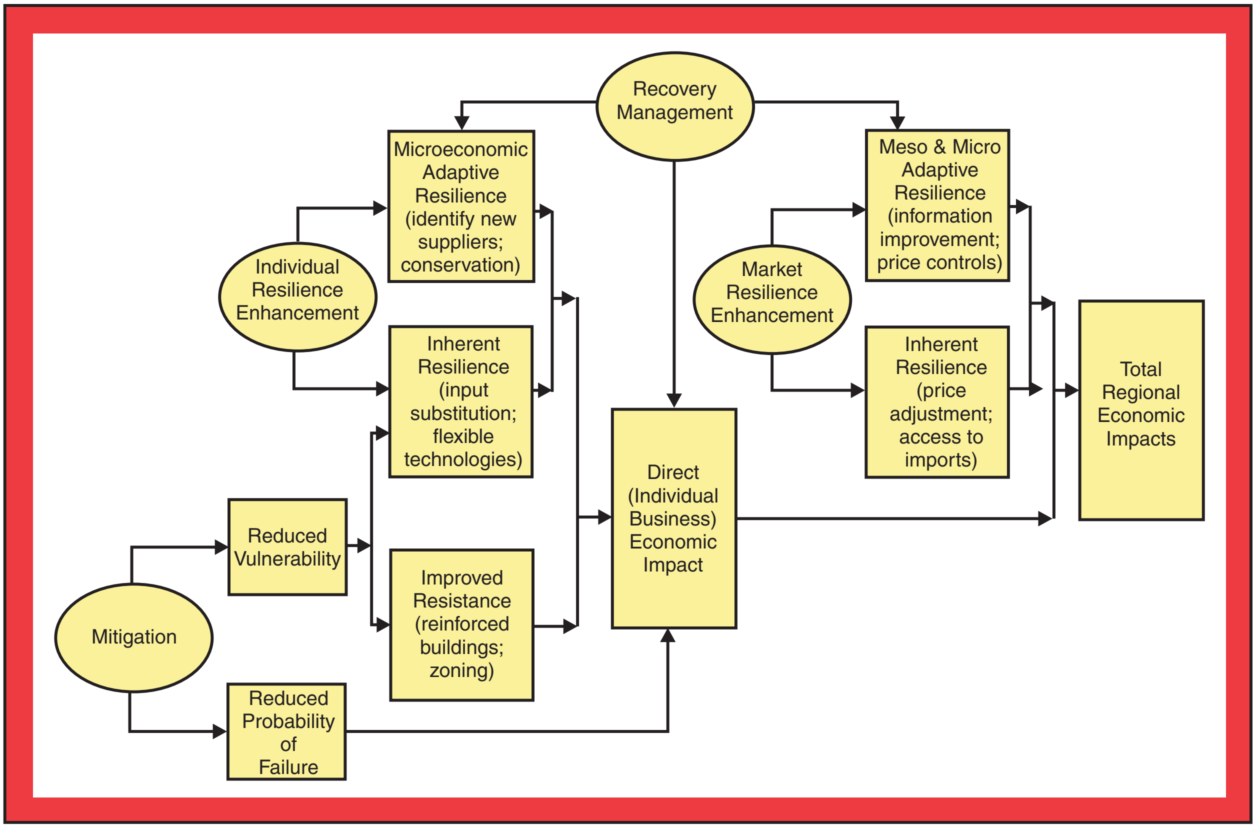

Figure 1. Role of Economic Resilience in Economic Losses from Disasters

to extending the concept of economic resilience presented in this paper to include more dynamic elements.[3]

Computable General Equilibrium Modeling Refinements

Computable General Equilibrium (CGE) analysis is the state-of-the-art in regional economic modeling, especially for impact and policy analysis. It is defined as a multimarket simulation model 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 (Rose, 1995).

The basic CGE model represents an excellent framework for analyzing natural hazard impacts and policy responses (Brookshire and McKee, 1992; Rose and Guha, 2004). CGE modeling encompasses all the elements in the scope of analysis presented in the previous section. In fact, it is the only economic modeling approach to incorporate micro, meso, and macro levels (see Rose, 2004, for a discussion in the context of disaster impact analysis).

“In the aftermath of a disaster, people behave in a more urgent manner and are more likely to call forth ingenuity.”

Business Responses to Hazards in a CGE Context

The production side of the CGE model developed by the author and his research team is composed of a standard, multi-layered, or multi-tiered, constant elasticity of substitution (CES) production function for each sector. The production function is normally applied to aggregate categories of major inputs of capital, labor, energy, and materials, with sub-aggregates possible for each (e.g., the energy aggregate is often decomposed by fuel type—electricity, oil, gas, and coal). In most prior CGE models, water has been omitted or incorporated as one of the materials (intermediate goods producing) sectors. In our illustration, we explicitly separate water as a major aggregate in the top tier of the production function so that we can analyze the impacts of a water service disruption.

This production function represents a type of hierarchical, or sequential, decision-making process. For a given level of output, the firm’s manager first chooses the optimal combination of capital and energy. He/she next juxtaposes that combination to labor to determine the optimal choice of inputs in the third tier, etc. In the top tier, input decisions are made regarding water in terms of the various ways it can be provided (the reader is referred to last year’s *Research Accomplishments* report for the mathematical specification of the production function).

Inherent resiliency is embodied in the basic production function for individual businesses and in the combination of producers, consumers, and markets (including interaction effects) for the economy as a whole. Adaptive resilience is captured by changes in the parameters. For example, an increase in the productivity term for water would reflect conservation, while an increase in the substitution elasticity would reflect increased substitution possibilities between utility water service and other inputs (such as bottled water). In the aftermath of a disaster, people behave in a more urgent manner and are more likely to call forth ingenuity. For example, for short periods, maintenance can be skipped, water fountains can be turned off, water can be reused, etc. Also, in general, inefficient practices can come to light and new opportunities can be initiated. There is an extensive literature suggesting that managers can become more clever in emergency situations. There is additional literature, now very prominent in the energy and environmental fields, indicating a much greater range of conservation opportunities when one looks at the production process from a holistic standpoint (see, e.g., Porter and van der Linde, 1995).

Economy-Wide Responses and Disequilibria

As noted above, the market system is inherently resilient to shocks and can be bolstered by various policies. All of this can best be modeled in a CGE framework. However, an inherent shortcoming of CGE is its equilibrium emphasis. Following a major disaster, a sustained period of disequilibrium is likely to ensue. Fortunately, several refinements of CGE modeling by the author and others have moved to overcome this limitation. These disequilibria are typically related to closure rules, or account balance conditions.

It is now possible to operate a CGE model in situations where demand need not always equal supply in the following cases:

1. The labor market, which allows for unemployment
2. The government budget, which allows for deficit spending
3. Trade, which allows for import/export imbalances
4. Goods and services, which allows for explicit shortages

The last of these advances bears some elaboration. Ordinarily, any gap between supply and demand is resolved by a change in price. However, it is possible in CGE modeling to fix the price of a commodity and have the supply constrained, so that potential demand exceeds actual demand. This refinement is facilitated by the development of new software that uses a complementarity programming approach, thereby allowing for some "slack" in the system, and hence disequilibrium. For example, in the study to be discussed below, we were able to limit the supply of water to each sector. Ordinarily this would increase the price of water, but this is unrealistic given the fact that water is not priced in an ordinary market but rather under the administrative authority of a public service agency. We therefore fixed the price of water as well, essentially modeling it as a disequilibrium market. The slack is taken up by a reduction in the profit margin in the water sector.

Closely related are the many ad hoc adjustments and temporary equilibria that ensue after a disaster, many of which can be incorporated through further refinement of the CGE model. Examples identified by West and Lenze (1994) include additions to the labor market in the form of outside government and NGO volunteers, by Cochrane (1997) include households dipping deep into savings or increasing their borrowing to fund repairs, and by Rose and Lim (2002) include businesses recapturing lost production through overtime work at a later date.

Empirical Specification

CGE models used for hazard analysis are likely to yield estimates of business disruptions for some if not all sectors of an economy that differ significantly from the direct loss estimates provided by empirical studies. This is because production function parameters are not typically based on solid data, or, even where they are, the data stem from ordinary operating experience (inherent resilience only) rather than from emergency situations. Hence, it is necessary to explicitly incorporate adaptive resilience responses into the analysis.

Rose and Liao (2004) have recently developed a methodology for altering the behavioral parameters in the sectoral production functions of the CGE model based on an optimizing routine and solutions utilizing both analytical and numerical methods. Empirical or simulation model estimates of direct output changes, emanating from an input supply disruption, are used to recalibrate productivity and substitution elasticity parameters of the CES production function. When the initial parameters are accurate for business as usual contexts, we say they embody "inherent" resilience. The difference between these original and the recalibrated parameters would then reflect "adaptive" resilience. Unfortunately, accurate initial parameters are rarely available, so that in such cases, while the recalibration encompasses both types of resilience, the overall effect cannot yet be accurately decomposed into its two components. Still, the method is sufficiently general to be able to do so when better parameter data become available.

Illustration

Portland Water System and Economy

The Portland (Oregon) Bureau of Water Works (PBWW) is a rate-financed, City-owned utility that serves 840,000 people in portions of the Portland Metro Area (including businesses responsible for 98% and 72% of sales in Multnomah County and Washington County, respectively). In 1999, PBWW water sales amounted to 39 billion gallons. The largest customers are major manufacturing companies, the Portland City Bureau of Parks and Recreation, and several hospitals.

The PBWW transmission and distribution is comprised of nearly 2000 kilometers of pipelines, 29 pump stations, and 69 major storage tanks. About 70% of the system still consists of cast iron pipes, even though the agency began installing ductile iron in the 1960s. Additional information on the PBWW, and its earthquake vulnerability and mitigation costs, can be found in Chang et al. (2002).

We constructed a CGE model of the portion of Portland Metropolitan Area economy that overlaps with the Portland Bureau of Water Works (PBWW) Service Area (Rose and Liao, 2004). The main data upon which the empirical model is based are the 1998 IMPLAN Social Accounting Matrix (SAM) and Input-Output Table for Multnomah County and Washington County (MIG, 2000). It is divided into several partitions that reveal the structure of the regional economy, including the industry, commodity, factor income, household, government, capital, and trade accounts.[4]

Water Disruption Simulations

Chang et al. (2002) performed simulations for alternative combinations of earthquake types, calendar years, and mitigation options, using several sophisticated geological and engineering models. Each case was subject to 100 Monte Carlo simulations. These simulations were used to estimate direct losses in sectoral output, factoring in resilience but without any specification of the type of resilience response. We adapted the results of a questionnaire survey by Tierney (1997) for the Northridge earthquake to assume that water conservation and substitutability were likely to be the primary ways that customers implemented adaptive resilience (see Rose and Liao, 2004).

Our simulations are based on an engineering fragility analysis of the Portland water utility system and the direct loss estimation simulations of Chang et al. (2002) described above. Although Chang's engineering vulnerability and direct loss simulations involve many scenarios relating to alternative earthquake magnitudes, outage durations, and resilience responses, this paper focuses on a subset of scenarios characterized by:

- One earthquake type (Bolton crustal fault) of magnitude 6.1
- Impacts in the Year 2000
- Scenarios for Business as Usual (No Mitigation) and Pipe Replacement (Mitigation)
- Outages of varying lengths from 3 to 9 weeks

We focused on the first characteristic because it represented the "most likely" case, and on the latter three to keep the number of simulations manageable.

Resilience in the Absence of Mitigation

The results of our simulations for the Business as Usual Scenario (no mitigation) are presented in the first column of Table 1. Note that the duration of this outage is projected to be four weeks, but the table summarizes the situation for the maximum disruption, which takes place during the first week.

Unmitigated sectoral water disruptions are estimated by Chang to average 50.5 percent of pre-earthquake levels. However, direct output losses are estimated to be only 33.7 percent, because they incorporate direct sectoral resilience to water service outages. Our measure of *direct regional economic resilience (DRER)* is the extent to which the estimated direct output reduction deviated from the likely (fixed-coefficient) maximum, which is equivalent to

Table 1. Economic Resilience to a Water Service Disruption in the Portland Metro Area (percentage)

	Pre-Mitigation	Post-Mitigation
Direct Water Outage	50.5	31.0
Direct Output Reduction	33.7	21.3
Indirect Output Reduction	7.3	9.2
Total Output Reduction	41.0	30.5
Direct Economic Resilience	33.0	31.3
Total Economic Resilience	60.4	48.2

the percentage water input disruption in our linear approach to baseline estimation:

$$DRER = \frac{\%\Delta DQ^m - \%\Delta DQ}{\%\Delta DQ^m} \qquad (1)$$

where $\%\Delta DQ^m$ is the maximum percent change in direct output and $\%\Delta DQ$ is the estimated percent change in direct output.

The measure of *DRER* is 33.3 percent in this scenario [(50.5-33.7) ÷ 50.5].[5]

Our estimates of the indirect (net general equilibrium) and total regional (gross general equilibrium) economic impacts of the water lifeline disruption are presented in Rows 3 and 4 of Table 1. Overall, they yield only a 7.3 percent indirect reduction in regional gross output and a 41.0 percent total reduction in regional gross output for the first week. The former represents $99.9 million and the latter $561 million of lost sales.

Some interesting aspects of indirect output losses bear further discussion. First, they are only about 22 percent the size of direct output losses. In the context of an input-output (I-O) model, this would be a multiplier of only about 1.22. The Portland Metro economy-wide I-O multiplier is significantly larger

> ***"This paper has presented major conceptual, operational, and policy analysis advances in evaluating individual and regional economic resilience to earthquakes."***

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, the CGE model is able to capture price changes for intermediate goods from cost and demand pressures, various substitutions aside from those relating to water, and various income, substitution and spending considerations on the consumer side.

Our measure of *total regional economic resilience (TRER)* to earthquake disruptions of water services is the difference between the total fixed coefficient I-O multiplier and the CGE impacts:

$$TRER = \frac{\%\Delta TQ^m - \%\Delta TQ}{\%\Delta TQ^m} = \frac{M \bullet \%\Delta DQ^m - \%\Delta TQ}{M \bullet \%\Delta DQ^m} \qquad (2)$$

where M is the economy-wide average Type II input-output multiplier; $\%\Delta TQ^m$ is the maximum percent change in total output; and $\%\Delta TQ$ is the estimated percent change in total output.

The weighted average Type II output multiplier for the Portland Economy is 1.9, or a 90 percent increase over direct effects. Thus, *TRER* in this case is 60.4 percent {[(1.9)(50.5) – 41] ÷ [(1.9)(50.5)]}.

Resilience in the Aftermath of Mitigation

The results of the scenario of an M6.1 crustal fault earthquake but with cast-iron pipe replacement are also presented in the second column of Table 1. In this second scenario, the direct water outage is reduced from 50.5 percent to 31.0 percent. Chang estimates direct output losses to be 21.3 percent. The *DRER* index is 31.3 percent in this case [(31-21.3) ÷ 31]. Direct resilience thus decreases a bit from the 33.3 percent of Scenario 1, and this is likely due to the fact that resilience opportunities decrease as the size of the direct disruption decreases. Note also that *direct mitigation effectiveness*, with respect to the difference in direct water losses between the two scenarios, could be measured by a similar index and would equal 38.6 percent [(50.5-31.0) ÷ 50.5].

The parameter recalibrations needed for the model to replicate the Chang direct loss estimates are lower than the corresponding parameter values in our initial simulation, because the direct output losses are projected to be lower in each sector following mitigation. Note that this seemingly counterintuitive result has a valid explanation – because water disruptions are smaller after mitigation, there is less need and less room to maneuver (fewer opportunities for adaptive resilience). Mitigation lowers direct losses, but there is a partially offsetting effect from lowering adaptive capability.[6]

Interestingly, our estimate of "indirect" losses in Scenario 2 is 9.2 percent, which is 43.2 percent the size of direct losses. Thus, the percentage increase over direct losses is higher in Scenario 2 than in Scenario 1, as is the absolute level (not shown). This appears surprising at first glance. It would be an impossibility, for example, in the context of an I-O model (where multiplier values are the same at all scales). However, our CGE model is nonlinear. Secondly, we have changed parameters (with respect to water substitution), so, even in an I-O context, multipliers would differ (though likely only slightly given the small size of our parameter changes, which would correspond to coefficient changes in an I-O model). One explanation for the relatively higher percentage of general equilibrium effects in Scenario 2 is the fact that water substitution and productivity term parameters are lower than in Scenario 1, meaning that not only is the direct response less flexible, but so is the indirect response relating to water. Another explanation is the difference in the sectoral mix of direct water disruptions in relation to Scenario 1. This changes relative prices, and the model responds accordingly.

The discussion above can be summarized and quantified in the *TRER* for the post-mitigation case, which is 48.2 percent {[(1.9)(31) – 30.5] ÷ [(1.9)(31)]}. The difference between *TRER* and *DRER* is a measure of *indirect regional economic resilience* (*IRER*), which is relatively lower in the post-mitigation case.[7]

Overall, the *DRER* is higher than *IRER* in both scenarios. This suggests that the overall resilience of individual businesses is greater than the overall resilience of markets in the Portland economy.

Conclusion

This paper has presented major conceptual, operational, and policy analysis advances in evaluating individual and regional economic resilience to earthquakes. We provided an operational, though relatively narrow, definition of resilience and couched it in terms of economic theory. We then summarized a methodology for incorporating disequilibria and recalibrating CGE model parameters in light of empirical estimates of production losses due to a lifeline supply disruption. Our application to a disruption of water services in the Portland Metro economy showed how indirect (pure general equilibrium) economic losses vary according to the overall level and sectoral mix of water shortages, the extent of pre-event mitigation, and post-event inherent and adaptive resilience. It also identified some major complementarities and tradeoffs between mitigation and resilience. Our methodology can be adapted to other applications of CGE models for response to other types of disasters, including terrorist attacks on economic targets.

The measurement of resilience is important because it enables us to evaluate an important strategy for reducing economic losses from earthquakes. Failure to incorporate resilience in loss estimation will result in inflated assessments of business interruption from earthquakes. Failure to include resilience in policy-making will result in missed opportunities to further reduce losses.

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Endnotes

[1] There is growing awareness of the behavioral aspects of the implementation of mitigation. For example, even promising new technology and policies may incur obstacles to its implementation and use (see, e.g., Alesch and Petak, 2001).

[2] Recently, Chang and Shinozuka (2004) have operationalized a portion of this framework to examine the effects of mitigation, based on engineering performance standards for a water system, on basic measures of technological, organizational, and economic resilience. Their work differs from the presentation in this paper in terms of the definition of economic resilience overall, more in-depth analysis of the concept here, and our inclusion of region-wide economic losses.

[3] We briefly note the relationship between resilience and two other concepts. *Preparedness* refers to steps taken before a disaster to subsequently reduce losses. Some of these actions, such as the building up of inventories, improve the capacity of inherent resilience, while others, such as the establishment of an improved communication network, increase adaptive resilience capacity. Preparedness typically focuses on ways of enhancing resilience before the event, while resilience emphasizes the reduction of economic losses due to an earthquake during and after the ground shaking (i.e., the benefits of reduced losses). Moreover, not all preparedness affects innate resilience (e.g., that which is pure mitigation), and not all resilience stems from preparedness (e.g., innate human ingenuity and the natural self-adjusting feature of markets). Note also that resilience differs from the concept of adaptation. *Adaptation* consists of two components: an active effect to reduce losses after an event has taken place (e.g., migration) and a passive absorption ("suffering") of the loss. Our concept of adaptive resilience overlaps with the first component.

[4] The computational procedure we have developed to improve model accuracy also generates an additional dividend of enabling us to decompose loss estimates into direct (partial equilibrium) and indirect (total general minus partial equilibrium) effects. While the I-O model automatically makes this distinction, our methodology to decompose the two categories of effects is a necessary advance in CGE modeling to do so.

[5] The fixed coefficient production function of an I-O model yields an upper-bound estimate of direct output losses from water input disruption, where the percentage loss of the former would be equal to the percentage loss for the latter. All other types of production functions would yield percentage output losses lower than the percentage decrease in water availability because of substitution possibilities. We measure *direct individual business* (*or sectoral*) *resilience (DIBR)* as the difference between the fixed coefficient (proportional) result and the flexible input (disproportional) result, which is attributable both to the various response mechanisms related to water services (1st Tier) and inherent in the overall production function with respect to other inputs (Tiers 2-4). *DRER* is simply the weighted average of *DIBR* for all businesses in the region.

Note that our choice of a linear reference base for resiliency estimation is reasonable but still somewhat arbitrary pending more empirical work. There are instances in which the maximum potential loss is greater than a proportional impact (i.e., a situation in which an X% loss of water results in greater than an X% loss of output). However, our general loss estimation and resilience modeling methodologies are sufficiently general to accommodate these definitional changes.

[6] This reduction in resilience is more than offset by the beneficial effect of mitigation in reducing recovery time (Chang et al., 2002), but it is a negative side effect of mitigation just the same and may dominate the recovery time benefit in other cases.

[7] Note that we have not been able to distinguish between inherent and adaptive resilience in the sectoral (summed to direct regional) case because of limitations of accuracy of our initial elasticity estimate. It would appear that *TRER* includes only inherent resiliency, since we have not included any explicit adaptive considerations. However, our assumption of return to equilibrium (in all markets except water, labor, and the government budget) in a period of only 3-4 weeks invokes some implicit adaptive responses (such as improved information flows). In fact, the 3-4 week adjustment is greatly optimistic, such that our *TRER* estimates contain a significant upward bias.

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Restoration Modeling of Lifeline Systems

by Rachel A. Davidson and Zehra Çagnan

Research Objectives

The main objective of this research is to develop improved models of the post-earthquake restoration processes for electric power and water supply systems. The restoration models will use estimates of physical damage to the systems and an understanding of the repair and recovery operations to estimate geographically-disaggregated restoration curves for each system (percentage system functional versus time), including uncertainty bounds on those curves and explicit representation of the key decision variables guiding the process.

Earthquakes have caused significant damage to electric power and water supply systems around the world. In the 1994 Northridge earthquake, for example, all of the Los Angeles Department of Water and Power's (LADWP's) 1.5 million power customers lost service, and about 50,000 LADWP water customers lost service, many for a week or more (Schiff 1995). Earthquake-related damage to electric power systems can cause considerable direct repair and restoration costs, business interruption, inconvenience, and permanent loss of data, food, and perishable goods. Even brief power interruptions may compromise security systems or the reliability of financial transactions. Similarly, earthquake damage to water supply systems can have serious economic and health consequences. Because of the many interdependencies that exist among infrastructure systems, communication, traffic signaling, wastewater treatment, and other lifelines may be affected as well. Thus, the general public may be inconvenienced along with the power and water utilities and their customers. The longer these service interruptions last, the more severe the negative effects are.

This research aims to develop improved models of the post-earthquake electric power and water supply system restoration processes. The discrete event simulation models will use estimates of initial physical damage to the systems and an understanding of the repair and restoration operations to estimate geographically-disaggregated, quantitative restoration curves, including uncertainty bounds on those curves and explicit representations of the company's decision variables (e.g., number of repair crews to have).

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The models are being developed in collaboration with the Los Angeles Department of Water and Power, using their systems as case study applications.

These new post-earthquake restoration models can provide two main benefits. First, they can improve the quantitative estimates of restoration times that are required to estimate economic losses due to business interruption, part of MCEER's larger effort to assess regional earthquake impacts. They can help assess the rapidity dimension of electric power and water supply system resilience, which in turn, are critical determinants of a community's economic resilience. Second, by explicitly representing the actual processes that the utility company goes through to restore services, the models can be used to help identify ways to improve the processes in future earthquakes. Since the company's decision variables are explicit, sensitivity analyses can be conducted to explore their relative effects on the restoration curves. The restoration process is complicated by the many decisions that must be made simultaneously, in a short time frame, with limited information, and under adverse conditions (in the aftermath of a major earthquake). Each utility company has relatively infrequent experiences with major earthquakes and each event is different, so it will be very valuable to be able to experiment with different strategies in a risk-free, virtual environment, and to examine the effects of different decisions on the overall restoration process.

Simulation-Based Restoration Modeling Approach

In discrete event simulation, the modeling method used in this study, an artificial history of the system being modeled is generated and observations are collected to estimate system performance measures. The technique "bases simulations on the events that take place in the simulated system and then recognizes the effects that these events have on the state of the system" (Law and Kelton 1991). Discrete event simulation is a dynamic simulation approach that can be either deterministic or stochastic.

The key elements in a discrete event simulation are entities, variables, and events. Objects of

> LADWP and other electric power and water supply utility companies can use this work to help improve their post-earthquake restoration processes. By running the simulation models for various hypothetical earthquakes, companies can explore in a risk-free, virtual environment, the effects of various changes in their decision variables (e.g., how many repair teams to have). In this way, they can identify improvements that can shorten average restoration times and/or reduce expenses. Emergency response agencies and other risk managers can use this research to better estimate economic losses due to business interruption caused by power and water service outages.

interest in the real system exist as *entities* in the simulation model (e.g., substations, pumping stations). *Resources* are a special type of entity that provide service to other objects of the system (e.g., damage assessment teams). *Variables* (e.g., damage state of a system component) describe the system state. Variables can be of two kinds—*Global variables* apply to the whole system, and *attributes* are attached to specific entities. Simulations are based on keeping track of changes in certain variables as time proceeds (Ross 2002). Whenever an *event* (e.g., inspection or repair of a component) occurs, the values of variables are updated. The one-to-one mapping between objects in the real-life system being modeled and their abstractions in the simulation model enables modeling the system under consideration quite accurately without the need to make significant simplifications. Simulation models are usually built by specifying the entities in a system and the processes they follow as they go through the system (Banks et al., 1996). This implementation strategy, known as a process-interaction world view, allows interactions between objects of the system to be included in the model easily.

The discrete event simulation approach aims to build on previous research and overcome some of the limitations of that work. Çagnan and Davidson (2004) summarize the literature through descriptions of four past approaches: (1) statistical curve fitting, (2) deterministic resource constraints, (3) Markov processes, and (4) network models, and the advantages and disadvantages of each.

There are several key desirable characteristics of the discrete event simulation approach chosen for this work. First, it includes the utility company's decision variables explicitly, allowing investigation of their effects on the speed of the restoration and enabling future integration with optimization modeling (see Future Work). Possible decision variables include number of response personnel of different types, amount of repair materials of different types, and repair prioritization rules. The simulation approach can produce different restoration curves for each region within the service area rather than just one curve for the whole system. This facilitates modeling the economic impact of service interruptions. Models based on this approach can represent the uncertainty in the restoration curve. They model the real-life restoration process explicitly, potentially offering insights into the restoration process that are generalizable to other situations. The simulation approach requires only available data, and is flexible so that it can be applied to other lifelines and hazards, and so that it can be adapted to changes in the restoration process or data, and ultimately can accommodate multi-lifeline interactions.

Electric Power Restoration Model

In this section, the discrete event simulation approach is applied to the LADWP electric power system. Efforts are underway to apply the same approach to the LADWP water supply system, and it could be applied to other lifelines as well.

Links to Current Research

This research forms a critical link between MCEER projects that involve estimating damage to electric power systems (Shinozuka) and water supply systems (O'Rourke), and those that involve measuring the economic and societal aspects of community resilience (Chang).

The details will differ in each application, but the model structure and types of elements will be the same. Since the restoration model is based on an initial damage state provided by the MCEER-LADWP electric power system damage estimation model (Shinozuka et al., 1998, Dong 2002), it is subject to the same assumptions as that damage model. Currently, the damage model considers only damage to high voltage substations, not, for example, transmission lines or generation stations (Shinozuka et al., 1998). It has been observed that high voltage substations are the most vulnerable components of an electric power system, however, so this is considered a reasonable assumption (Shinozuka et al., 1998).

The electric power system restoration model was constructed using Promodel simulation software (Promodel 2003). It is based on an extensive collection of qualitative and quantitative data gathered from the LADWP emergency response plan (LADWP 2003), the post-Northridge restoration report (LADWP 1994), interviews with LADWP personnel in charge of post-disaster power restoration, and tours of the facilities. Table 1 lists examples of the entities, attributes, global variables, resources, and events in the model. The events are the services that the resources provide to the substations and generation stations.

Table 1. Examples of Electric Power System Model Components

Model Component Type	Examples
Entities	Substations Power generation stations
Attributes of generation stations	Type of station (e.g., hydro, steam) Critical restart time limits Status before the earthquake (on or off) Distance to earthquake epicenter
Attributes of substations	Number of circuit breakers, transformers, disconnect switches in the substation that are damaged* Distance to earthquake epicenter
Global variables	Status of each substation, generation station after the earthquake (on or off) Duration during which each load bank is without power
Resources	On-duty substation operators On-duty generation station operators Off-duty substation operators Damage assessment teams (DATs) Repair teams Repair material of different types
Events	Inspection Damage assessment Repair Reenergizing

* These are the three substation components included in the damage model (Shinozuka *et al.* 2003).

The restoration of electric power systems can be divided into four main phases:

1. Initial inspection
2. Damage assessment
3. Repair
4. Reenergizing

These correspond to the events that take place in the simulation. First, on-duty operators inspect generation stations and substations. The duration of this service is defined as a random variable. At the end of this phase, the attribute indicating whether the entity is inspected or not is updated. Meanwhile, off-duty operators and damage assessment teams (DATs) become available at district yards and LADWP headquarters, respectively. District yards are service centers where repair materials are stored. These resources become available a specified time after the beginning of simulation because in previous earthquakes, it has been observed that restoration personnel report back to work 0.5 to 1 hour after an earthquake. All off-duty resources can not be available immediately after the earthquake; rather, their number increases as time goes on. This is taken into account by progressively increasing the number of available resources in the model up to a set maximum. Off-duty operators are dispatched immediately to substations at which no on-duty operators are available. Priority is given to substations that are near the epicenter of the earthquake, and hence are more likely to be damaged. Again at the end of inspection, the duration of which is defined as a random variable, the attribute indicating whether or not the entity has been inspected is updated. Off-duty substation operators have two 12-hour shifts per day.

In the second phase, DATs are dispatched to substations. Those inspected and reported to be damaged have priority, as do substations in the heavily shaken area. The duration of the damage assessment phase is defined as a random variable and is dependent on the size of the substation under consideration. At the end of this phase, the attribute indicating whether or not the entity has been inspected by the DATs is updated. DATs have two 7-hour shifts per day, and they only work during daylight hours.

For the resources that are dispatched from district yards and LADWP headquarters, travel times are taken into account by defining them in the model as movable resources, which have the capability to travel along defined paths. Different travel speeds can be assigned to these resources along different portions of the travel path. This enables the inclusion of additional delays due to damaged roads and bridges. In the current model, travel delays are simplified by dividing the path networks into just three main zones depending on the travel distance (0 km to 20 km, 20 km to 40 km, and 40 km to 60 km), and assigning a different travel time distribution for each zone.

Like off-duty substation operators, repair teams become available at district yards a specified time after the beginning of the simulation. In the third phase, the district yard closest to the heavily shaken area becomes the field command center. Repair material and repair personnel are moved from other district yards to the field command center once it is activated. Repair teams and repair material are dispatched from the field command center to the damaged substations that have been inspected by DATs. Repair teams have three 8-hour shifts per day. Priority is given to substations that are not heavily damaged. The duration of repair for each substation component included in the damage model is modeled as a random variable. The overall substation repair times are obtained by adding all the random component repair times after multiplying each by the corresponding number of damaged components. When repair is complete, the attribute indicating the damage level of the entity is updated.

The reenergizing phase starts once the initial inspection of generation stations is complete. On-duty operators at generation stations are in charge of reenergizing. Generators away from the epicenter of the earthquake are given priority, since it is likely that substations connected to these stations are not damaged. The time required for each generation station to pick up load depends on the type of the station, status before the earthquake, and its black start capability. Its black start capability describes how easily a generating unit can start up on its own without any power supply from the network. Once the station is ready to pick up load, the global variable indicating its status is updated, as are the global variables indicating the status of each undamaged substation that is connected to the reenergized station.

Sample Results

The electric power restoration model was run assuming the initial damage state from the Northridge earthquake, as reported in LADWP (1994) and Schiff (1995). The probability distributions on inspection, repair, and other event durations were estimated based on data from the 1994 Northridge earthquake and assessments by LADWP emergency response personnel. LADWP system details were obtained from Dong (2002). While calibration of the electric power restoration model is still being finalized, the following preliminary results can illustrate the many types of useful output it will be able to provide.

Figure 1 shows the mean restoration curve with 95% confidence intervals from 100 iterations of the simulation for the entire LADWP electric power system. The figure suggests, for example, that after 6 hours, about 50% of households will have service restored, and after 24 hours, about 70% of households will have service restored. The exponential shape of the curve is similar to those observed following many recent earthquakes. The slope of the curve is steep early in the process when the restoration is focused on restoring power to undamaged generation stations and substations by rerouting power. The curve then flattens out and becomes increasingly uncertain when restoration of power to the remaining substations requires repairing damage, which is more time-consuming.

In these preliminary results, although the order in which substations were restored matches the observed order very well, the restoration curve flattens out more quickly than it actually did in the Northridge earthquake. This is probably because the simulation model currently assumes that each load bank within a substation serves the same number of customers.

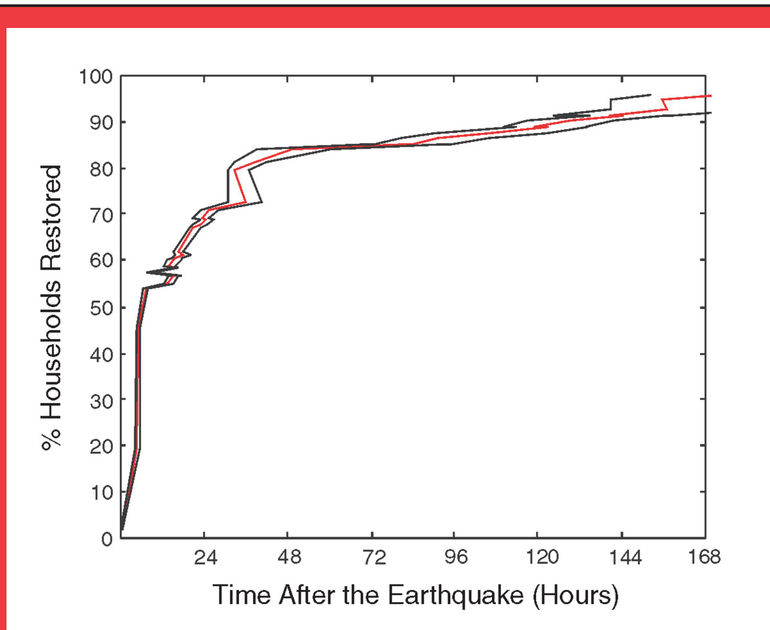
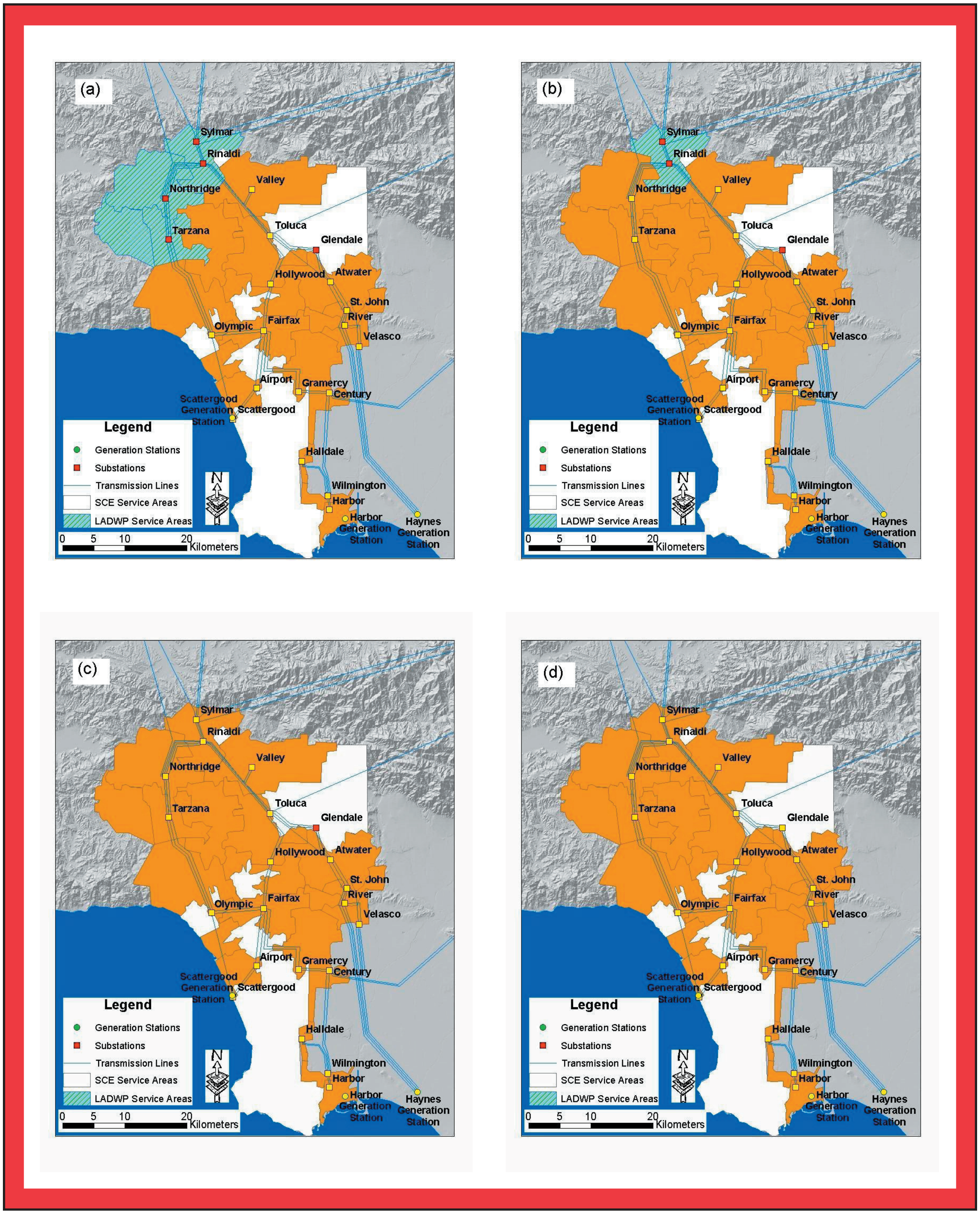


Figure 1. Mean restoration curve with 95% confidence intervals, estimated by 100 iterations of the simulation model

When data become available to indicate how many customers each load bank serves, that can be improved. Note also that the model is actually capable of creating similar restoration curves for each area served by a particular substation (rather than just one for the entire LADWP service area). However, to do so would require certain input data that are currently unavailable. At this time, therefore, the output includes just one restoration curve with uncertainty bounds for the whole service area.

Figures 2a - d provide a geographic representation of the evolution of the restoration process. Since the restoration is updated in the model every minute, similar maps could be produced for any point in time following the earthquake. Each map indicates which substations and generation stations have power (yellow points) and which do not (red points), and which areas have power (brown) and which do not (blue hatched) at the specified moment in time. In the Northridge earthquake, ten of the substations experienced some damage (Fairfax, Glendale, Northridge, Olympic, Rinaldi, St. John, Sylmar, Tarzana, Toluca, and Velasco). Immediately following the earthquake, none of the LADWP generation stations or substations had power, because even those that were undamaged lost power due to the activation of protective devices or loss of network connectivity. The priority in Northridge (replicated in the simulation) was to first extend power to the substations away from the epicenter that were less likely to be damaged, and to reenergize the generation stations by extending power to them as quickly as possible. For example, the Harbor generation station was reenergized by extending power from the Century substation, the first substation to be brought back on line. According to the simulation, within the first 12 hours, 13 substations (Century, Velasco, Willmington, Halldale, Harbor, St. John, Atwater, Hollywood, Fairfax, Olympic, Toluca, Valley, and Scattergood) and three generation stations (Harbor, Haynes, Scattergood) were reenergized (Figure 2a). The Northridge, Rinaldi, Sylmar, and Tarzana substations sustained considerable damage, and hence took longer to be reenergized. Between 12 and 18 hours after the earthquake, Northridge and Tarzana substations were reenergized as well (Figure 2b). By the end of the first day, the Rinaldi and Sylmar substations were reenergized, leaving Glendale as the only substation in the system still without power (Figure 2c). The simulation results indicate that the Glendale substation was reenergized 40 hours after the earthquake (Figure 2d). The time required to reenergize each substation in the simulation agrees quite well with what took place in reality.

In addition to producing restoration curves and maps, like those in Figures 1 and 2, because the simulation models the actual restoration process explicitly, many other observations can be made about how the actual process is expected to unfold. For example, for any simulation run, the user can look at how much time different types of crews spent actually working (doing inspection, damage assessment, or repair) versus traveling or sitting idle, or which type of crew was working the larg-



■ Figure 2. Maps showing LADWP service area regions without service at 12, 18, 24 and 48 hours, respectively, following the Northridge earthquake. Yellow substations and generation stations have power; red ones do not. Brown areas have power; blue areas do not.

est percentage of the time. One could also see, for example, for a set of many different earthquakes, how much each district yard is being used. This type of output may provide insights that strictly empirical methods cannot provide.

Having the ability to estimate these types of output for any possible earthquake can be useful both to risk analysts and utility companies. By knowing what industries are located in each part of the service area, risk analysts can use the estimates of when power will be restored to each of those areas to better determine the economic losses associated with business interruption. A utility company can use the model outputs to help identify bottlenecks in the restoration process and suggest ways it might be changed to shorten average restoration times and/or reduce expenses. By running the simulation for various hypothetical earthquakes, it can explore in a risk-free, virtual environment, the effects of various changes in the decision variables (e.g., how many repair teams to have, how many district yards to have and where). Simulating the restoration process for a suite of earthquakes can help demonstrate how the effectiveness of the restoration process will vary depending on the particular earthquake that occurs. This may help the company avoid basing its emergency response too much on one particular past experience, when future earthquakes may be quite different, requiring a different restoration plan.

Conclusions and Future Research

This paper describes a discrete event simulation approach to modeling the post-earthquake restoration process for electric power and water supply systems. A model was developed specifically for the LADWP electric power system. Key advantages of this approach are its explicit representation of the company's decision variables, ability to produce spatially disaggregated restoration curves, representation of uncertainty in the restoration curves, explicit, realistic modeling of the real-life restoration process, and flexibility to accommodate changes in the model.

After the electric power restoration model is finalized, three avenues of future work are planned. First, the investigators will apply the electric power restoration model for the suite of earthquakes selected by other MCEER researchers to represent the seismicity of the LADWP service area. The results of those analyses will be used in other MCEER projects to estimate the associated economic losses. A sensitivity analysis will be conducted to systematically explore the effects of various decision variables on the restoration curves. Second, the investigators will develop a similar type of post-earthquake restoration model for LADWP's water supply system and will apply it for the same suite of earthquakes. Finally, future efforts will involve developing optimization models that will help determine the *best* way to conduct the restoration process (e.g., how many of each type of repair crew and material to keep). Whereas the simulation models describe how the restoration works currently, the optimization will suggest the optimal way to conduct it so as to minimize the average restoration time or meet some other objective.

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Resilience of Integrated Power and Water Systems

by Masanubu Shinozuka, Stepahanie E. Chang, Tsen-Chung Cheng, Maria Feng, Thomas D. O'Rourke, M. Ala Saadeghvaziri, Xuejiang Dong, Xianhe Jin, Yu Wang, and Peixin Shi

Research Objectives

The primary objective of this study is to develop an analysis procedure and a database to evaluate the performance of electric power and water supply systems before and after a major catastrophic event, such as an earthquake, an accidental or manmade disablement of system components. Furthermore, the procedure and database can be incorporated as an integral part of the overarching framework of MCEER's methodology that can be used to enhance the seismic resilience of communities. Based on our experience in the analysis of the seismic performance of the Los Angeles Department of Water and Power (LADWP) system after the Northridge earthquake, we believe that we have derived a useful set of data and gained significant knowledge on the system's robustness during and after a catastrophic event. In this context, the present study adds new foci on modeling the restoration process after earthquakes and integrates the performance of water and power systems using LADWP's systems as a testbed. This study is believed to advance the state-of-the-art on evaluating the seismic resilience of communities.

In this study, the performance analysis of LADWP's power system is presented first, emphasizing newly developed system resilience analysis. Next, an integrative analysis between power and water systems is presented, focusing on their interaction through the process of restoration.

Electric power is essential for virtually every urban and economic function. Failures of electric power networks and grids – whether from natural disaster, technological accident, or man-made disaster such as terrorist attack – can cause severe and widespread societal and economic disruption. In the 1994 Northridge earthquake that struck Los Angeles, some 2.5 million customers lost electric power. For the first time in its history, the entire city of Los Angeles was blacked out. Power outages were experienced in many areas of the western U.S. outside the earthquake region and as far away as Canada (Hall, 1995). On August 14, 2003, a blackout of unprecedented proportions rippled out from Akron, Ohio, across the northeastern U.S. and parts of Canada, affecting an area with a population of some 50 million (U.S.-Canada Power System Outage Task Force, 2003). In September of

Sponsors

National Science Foundation, Earthquake Engineering Research Centers Program

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Previous Summaries

2001-2003:
Shinozuka et al.,
http://mceer.buffalo.edu/publications/resaccom/0103/01shinozuka.pdf

2000-2001:
Saadeghvaziri et al.,
http://mceer.buffalo.edu/publications/resaccom/0001/rpa_pdfs/04Saad2.pdf

1997-1999:
Shinozuka et al.,
http://mceer.buffalo.edu/publications/resaccom/9799/Ch7shino.pdf

2003, a power outage that began in Switzerland cascaded over a large region of Italy. Examples such as these indicate the importance of being able to anticipate potential power system failures and identify effective mitigation strategies.

Modeling the impacts of electric power disruption is, however, a highly complex problem. Many of the inherent challenges relate to the need to integrate across disciplines – not only civil, mechanical, and electrical engineering, but also economics and other social science disciplines. For example, one must assess how damage to individual pieces of electric power equipment affects power flow across the network. One must model how a damaged network would be repaired and how electric power would be restored over space and time. Additionally, one must capture how the loss of electric power would affect households, businesses, and other units of society, not only directly but also indirectly through the cascading failure of other utilities, typically water systems.

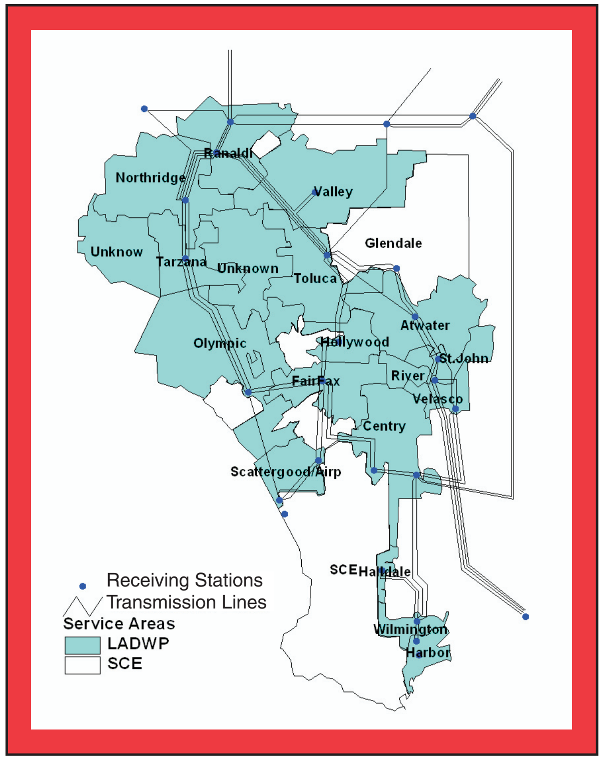
The LADWP's power system was used as a test-bed in this research. Figures 1 and 2 show LADWP's electric power service areas and the power supply at a typical time of peak demand. The areas not colored are serviced by Southern California Edison (SCE). Figures 3a-d show the distribution of residential population, daytime population, households and hospitals over LADWP's service areas, which is the data that will be used in the ensuing analysis. To study the seismic resilience of power systems, the fragility curves for electrical power equipment, such as transformers, circuit breakers, disconnect switches and buses in the transmission network, play a significant role and were developed on the basis of damage information from the 1994 Northridge earthquake. The present analysis also uses fragility information obtained from an inventory survey and analytical/laboratory studies performed by MCEER researchers. The seismic performance analysis of LADWP's power system was then carried out under actual and simulated earthquakes, using a net-

Perceived and actual users of the results from this research include utility engineers and managers, regulatory agencies, local, state, and regional emergency response agencies, civil, electrical, mechanical and systems engineers, and power equipment manufacturers. Typically, users include LADWP (Los Angeles Department of Water and Power) and SCE (Southern California Edison), California State Office of Emergency Services and Los Angeles City Office of Emergency Response.

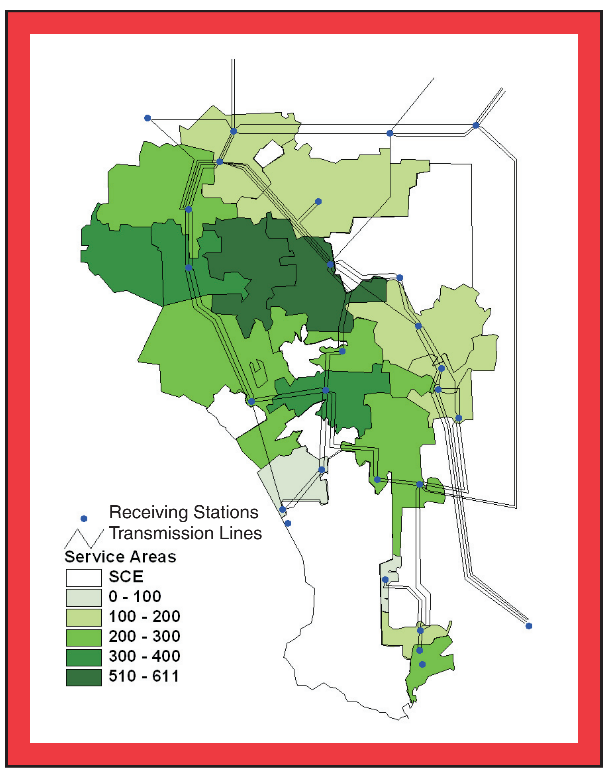
work inventory database, available fragility information, and Monte Carlo simulation techniques. This is a unique research work in which the Western Electricity Coordinating Council's (WECC's) database is used for the systems analysis, in conjunction with the computer code IPFLOW (version 5.2b), licensed by the Electric Power Research Institute (EPRI).

To gain more complete understanding of the performance of LADWP's power system under the possible seismic scenarios in the study area, 47 scenario earthquake events (*http://shino8.eng.uci.edu/Secnario_Earthquakes/47Scenario.pdf*) were selected and corresponding peak ground acceleration (PGA) maps were generated. By including each scenario's associated annual "equivalent probabilities" of occurrence, they represent the full range of regional seismic hazard curves (Chang et al., 2000). Based on the power analysis results from these 47 events, the risk curves for system performance degradation, for example, reduction of power supply, households without power and reduction in GRP (Gross Regional Product) immediately after an earthquake in LADWP's service areas were developed.

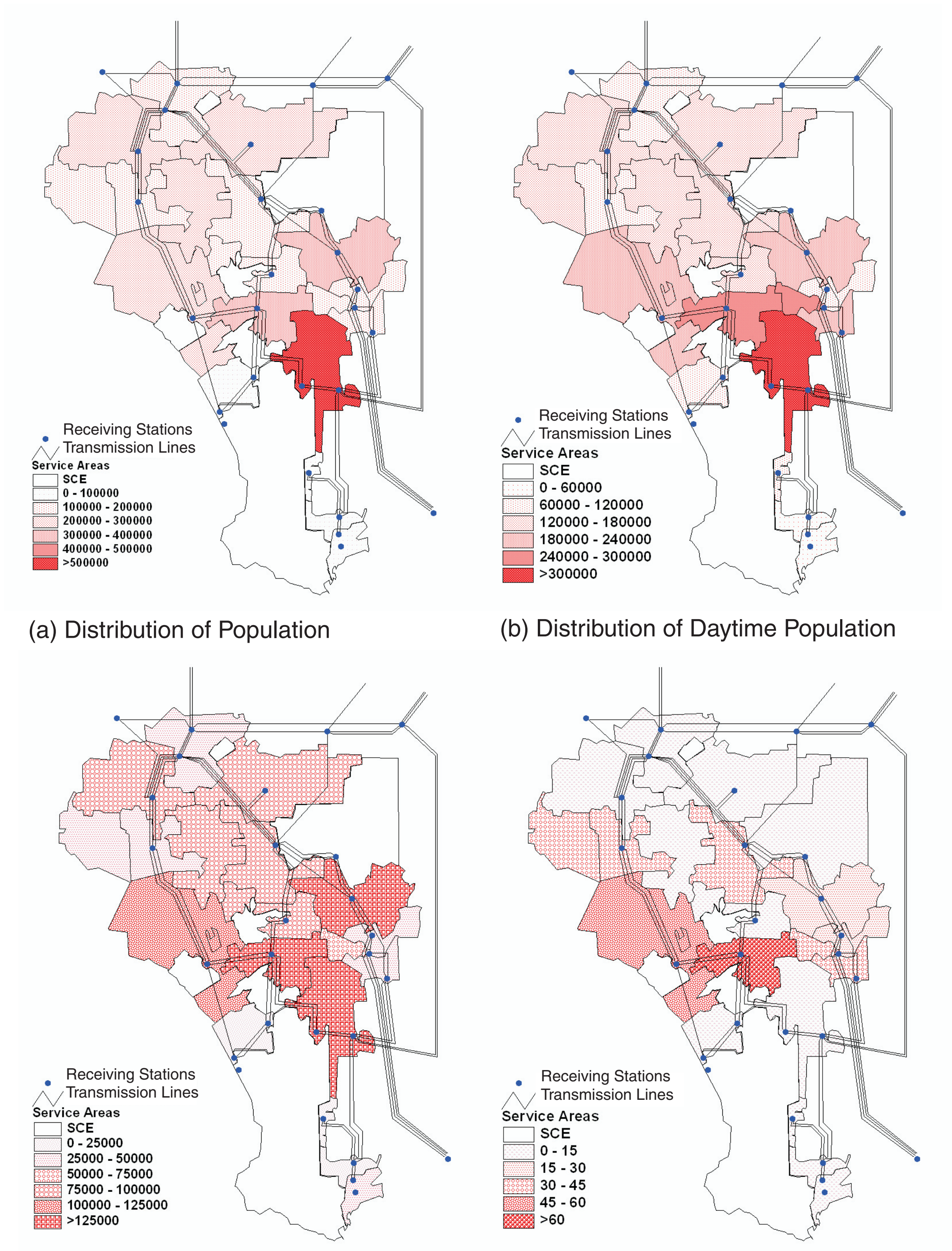
A repair and restoration model was also developed, calibrating with the Northridge restoration data, to evaluate the restoration process of the power systems. The system restoration process was then simulated accounting for restoration of disabled transmission equipment, and restoration curves were developed.



■ Figure 1. Transmission Network and Service Areas of LADWP's Power System



■ Figure 2. Electric Power Output for LADWP's Service Areas Under Intact Condition



(a) Distribution of Population

(b) Distribution of Daytime Population

(c) Distribution of Households

(d) Distribution of Hospitals

■ Figure 3. Key Customers Distribution Data

Seismic Performance of LADWP's Power System

Collaborative Partners

Jon Mochizuki *and* ***Ron Tognazzini****, Los Angeles Department of Water and Power*

Nobuo Murota*, Bridgestone, Japan*

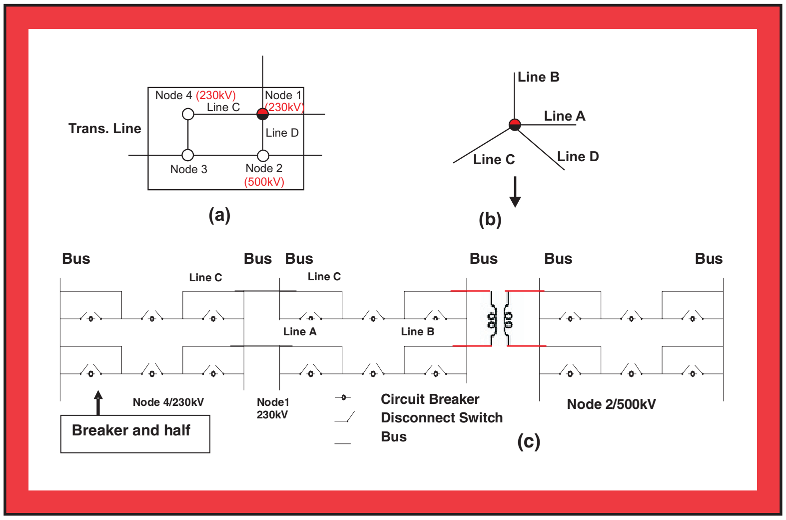
Scenario Earthquakes

For electric power and other urban infrastructure systems, evaluating potential impacts of damage is complicated by the fact that the networks are spatially distributed across a wide area. Risk analysis must account for how the system performs given that the hazard (e.g., earthquake ground motion) is not only spatially variant across a wide area but also, for any given disaster, spatially correlated. Hence, traditional probabilistic methods that can readily be applied for site-specific facilities such as individual buildings cannot be used for these spatially distributed networks.

The current study therefore analyzes system functionality and impacts in the context of scenarios of individual earthquake events, then combines the scenario results probabilistically to gain a complete understanding of the seismic performance of LADWP's power system. In total, 47 scenario earthquakes for the Los Angeles region were selected and simulated, as discussed later in detail. These scenarios were developed by Chang et al., 2000, applying a loss estimation software tool, EPEDAT, based on K. Campbell's attenuation law (Campbell and Bozorgnia, 1994), which was used to generate regional ground motion patterns for a given earthquake epicenter, magnitude, and depth (USC-EPEDAT, 1999). The 47 events include 13 maximum credible earthquakes (MCEs) on various faults in the Los Angeles region and 34 other events of magnitude 6.0 or higher. These scenario earthquakes are associated with annual "equivalent probabilities" of occurrence so that collectively, they represent the full range of the regional seismic hazard (Chang et al., 2000).

Transmission Systems

A utility power system consists of generating stations, transmission systems and distribution network. The present study focuses on transmission systems including receiving stations. Throughout the analysis, it is assumed that the transmission lines will not fail under seismic conditions. This assumption is generally acceptable for LADWP's system and allows one to concentrate on the receiving stations. There are many electric/mechanical components in receiving stations, such as transformers, circuit breakers, disconnect switches, lightening arresters, current transformers, coupling voltage transformers, potential transformer, wave trap and circuit switches. These components are integrated to transmission lines through buses at nodes. Transmission lines then serve as links between generating stations and distribution systems and lead to other power systems. In general, if the voltage between two buses is different, then there must be at least one transformer between them. Figure 4 models receiving stations and nodes. Fig. 4a is a model of a receiving station with four nodes, while Figure 4b depicts a node at which four

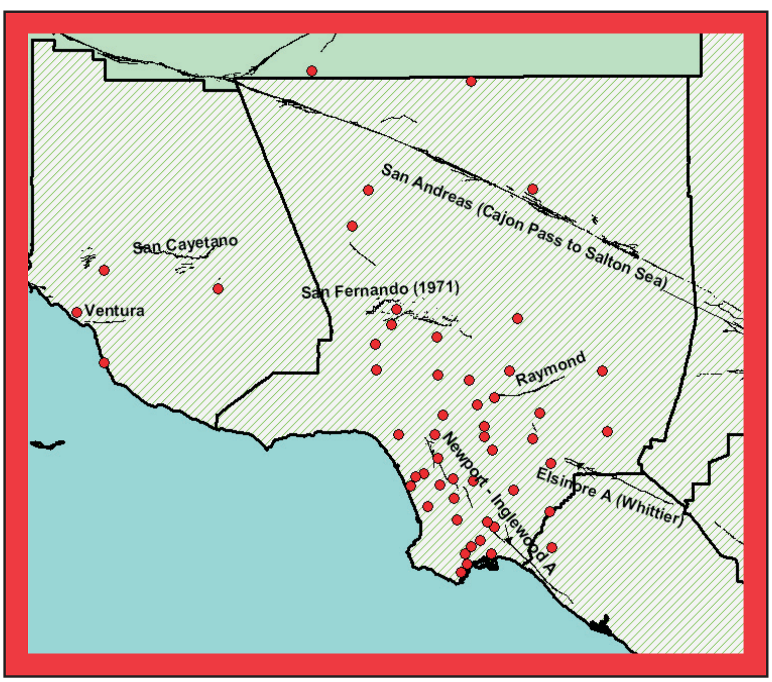


■ Figure 4. Models for Receiving Station and Node

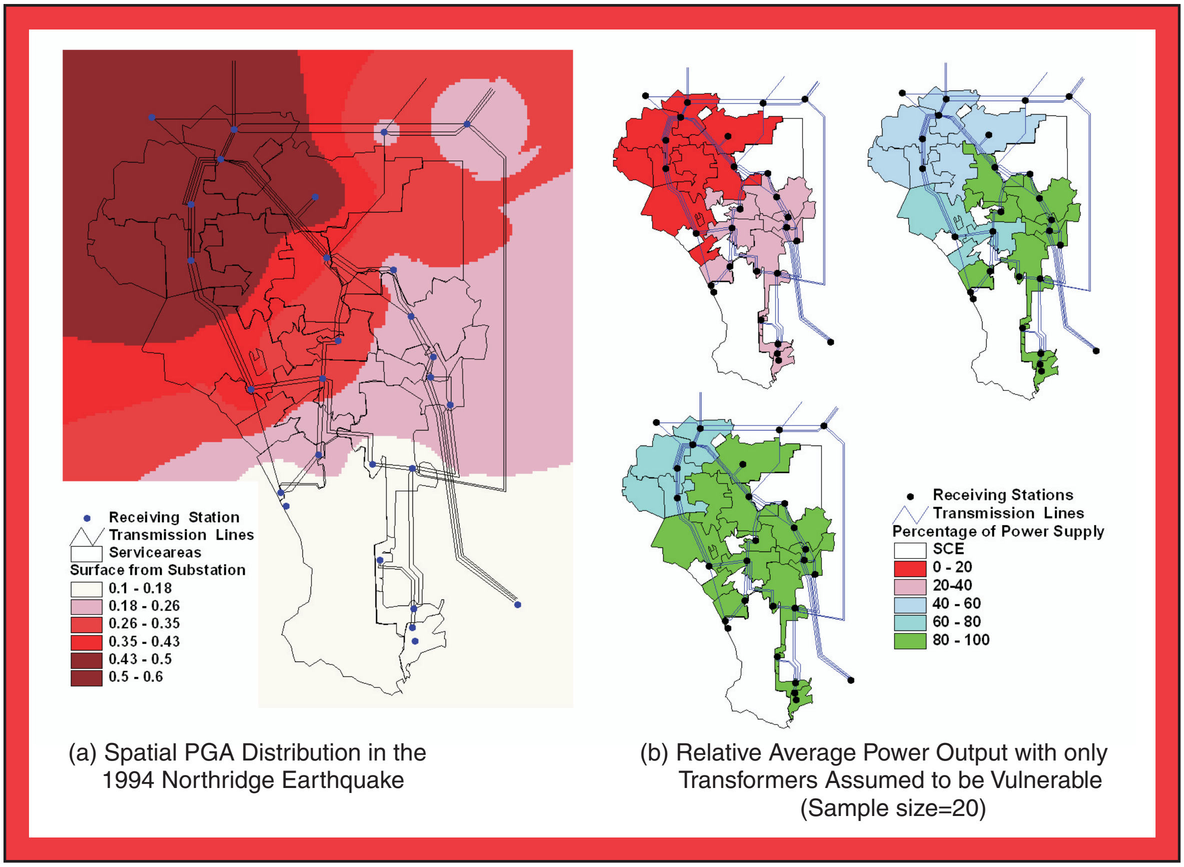
transmission lines are connected. A node facilitates movement of electric power protected by buses, circuit breakers and disconnect switches. A node's configuration is complex and designed to be redundant to minimize the chance that the transmission lines become disconnected from the power network. A popular node configuration is shown in Figure 4c, which is known as a "breaker and half" model. This model is used in the present analysis.

Seismic Performance of Power System

LADWP's network is part of the large WECC power grid, covering 14 western states in the U.S., two Canadian provinces and northern Baja California in Mexico. The present analysis considers 52 receiving stations (some in LADWP and others in SCE power systems) within the WECC network (see *http://www.wecc.biz/main.html*). They are subjected to significant ground motion intensity under some of the 47 scenario earthquakes and consequential to LADPW's system damage. Using an ArcGIS platform, the map of 52 receiving stations in Figure 5 is overlaid on the map of peak ground acceleration (PGA) from the 1994 Northridge earthquake as shown in Figure 6(a) to identify the PGA value at the location of each receiving station. The fragility curves provided in Figure 7 were then used to simulate the damage state for transformers at each of the 52 receiving stations. Note that three fragility curves (labeled Case 1, 2 and 3) are given in Figure 7, where the Case 1 curve is obtained empirically from the Northridge earthquake damage data, Case 2 curve represents improvement of the Case 1 curve by 50% (in terms of median value) and Case 3 curve by 100%. These improvements are deemed possible on the basis of analytical and experimental studies by Feng and Saadeghvaziri (2001) and Dong



■ Figure 5. Locations of Earthquake Faults and 52 Receiving Stations

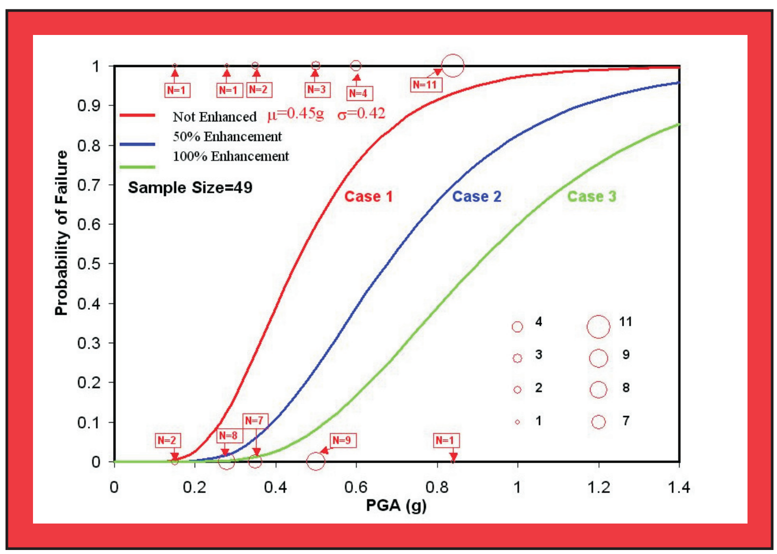


■ Figure 6. (a) Spatial PGA Distribution in the 1994 Northridge Earthquake and (b) Relative Average Power Output with only Transformers Assumed to be Vulnerable (Sample size=20)

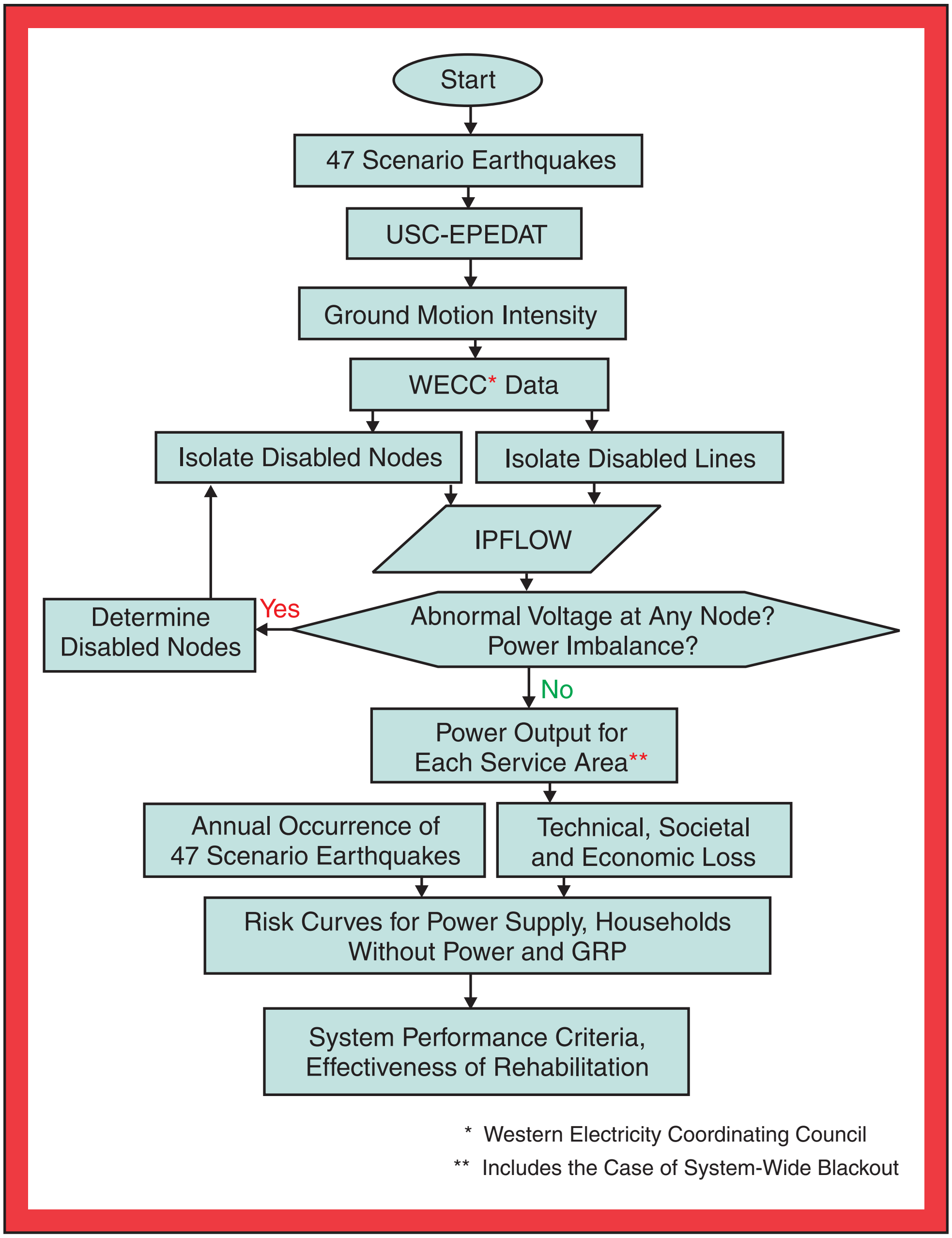
(2002). For each system analysis, connectivity and power flow were examined with the aid of IPFLOW, where LADWP's power system was treated as part of the overall WECC system.

The analysis procedure for the seismic performance of the electric power network is described in the following steps and is also depicted in the flowchart in Figure 8. The entire process is tightly integrated with a GIS database involved in the analysis.

- For each of the 47 scenario earthquakes described earlier, spatial distribution of PGA is generated using the appropriate attenuation law.
- For each scenario earthquake, by Monte Carlo techniques,



■ Figure 7. Fragility Curves for Transformers With and Without Enhancement



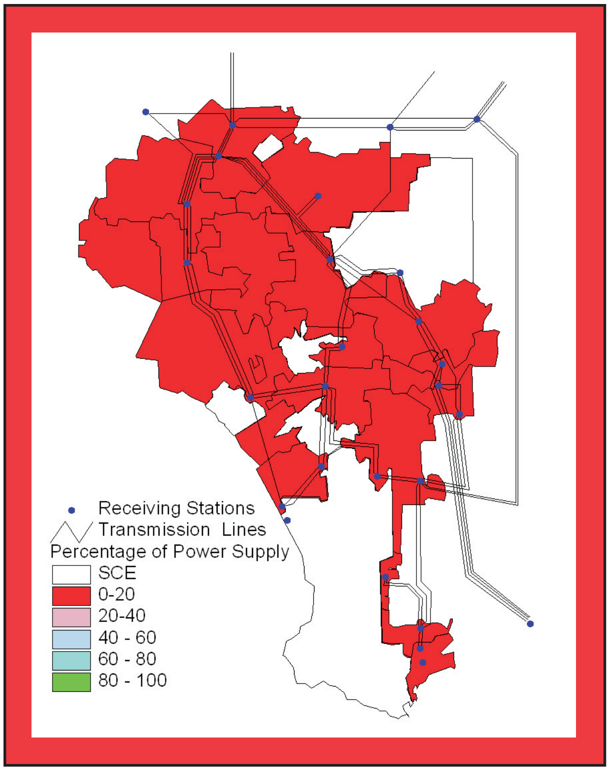
■ Figure 8. Flowchart for GIS-based Power Performance Analysis

the state of equipment damage is simulated using fragility curves for transformers with and without rehabilitation.

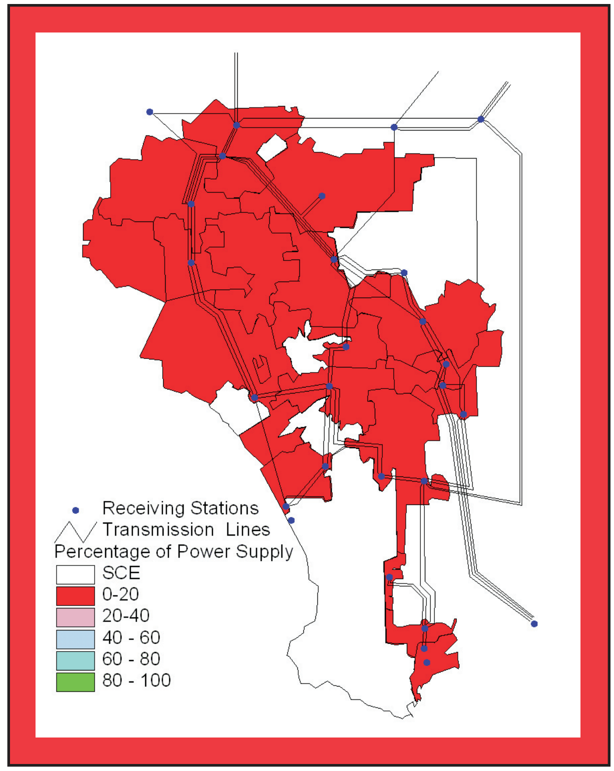
- The state of damage to the transmission network is simulated under each scenario earthquake.
- The power flow is calculated using the IPFLOW code, taking into consideration the following network failure criteria:

1. Imbalance of power: supply/demand ratio outside the range

$$1.05 \leq \frac{total\ supply}{total\ demand} \leq 1.1 \quad (1)$$



■ Figure 9. Relative Average Power Output with Transformers and Circuit Breakers Vulnerable



■ Figure 10. Relative Average Power Output with Transformers and Disconnect Switches Vulnerable

2. Abnormal voltage

$$\left| \frac{V_{intact} - V_{damaged}}{V_{intact}} \right| > 0.1 \quad (2)$$

3. Frequency change (IPFLOW does not check this criteria)
4. Loss of connectivity

- The seismic performance of the power network is computed, e.g., in terms of percentage of power supply and households with power after the earthquake. This is done for the entire area of service as well as for each service area under each scenario earthquake. The percentage is relative to the performance under the intact system condition.
- A seismic risk curve is developed (which plots the annual probability that system performance will be reduced more than a specified level due to earthquake as a function of that level).
- System performance is examined relative to performance criteria, with and without rehabilitation (of transformers in this study).
- Effectiveness of rehabilitation is determined.
- In combination with regional economical analysis, risk curves are developed for the loss of Gross Regional Product (GRP).

Using Monte Carlo simulation techniques involving the fragility curves, the power flow analysis is performed 20 times under each scenario earthquake. Each simulation result represents a unique state of network damage. Figure

Links to Current Research

This study develops an analysis procedure that can be used to evaluate seismic resilience of critical systems taking their interaction and combined impact on communities in technical, organizational, economical and social dimensions.

6(b) shows the ratio of the average power supply of the damaged network to that associated with the intact network for each service area, when only transformers are considered to be vulnerable. The average is taken over all 20 simulations. The extent to which the rehabilitation of transformers contributes to improvement of system performance is evident if we compare the power supply ratio under Case 1 (not enhanced), Case 2 (50% enhanced) and Case 3 (100% enhanced).

In addition to transformers, functionality of circuit breakers, disconnect switches and buses are critical for basic operation of receiving stations. Figures 9 and 10 present the results of the seismic performance analysis when these components are also assumed to be vulnerable, using the same fragility characteristics as transformers. These results indicate that if the additional equipment are considered vulnerable, the LADWP suffers from the total blackout under the Northridge earthquake as we observed in January 17, 1994. More comprehensive results of the analysis involving these types of equipment will be presented later.

Economic Impact

The preceding analysis of systems performance can be readily extended from impacts on households to impacts on the regional economy. Here, direct economic losses are evaluated using a methodology that relates the spatial pattern of electric power outage to the regional distribution of economic activity (see Chang and Seligson, 2003; Chang, 1998).

Direct economic loss, L (dollars), is evaluated for each earthquake simulation and each mitigation condition as follows:

$$L = \sum_s \sum_j l_j \cdot d_s \cdot e_{sj} \tag{3}$$

where l_j is a loss factor for industry j ($0 \leq 1 \leq 1$), d_s is a disruption indicator for service area s ($d = 1$ in case of power outage, $d = 0$ in case of no outage), and $e_{s,j}$ is daily industry j economic activity in area s (dollars). The disruption indicators d_s for each electric power service area derive directly from the power supply simulation results described previously.

The loss factors l_j reflect the dependency of each industry on electric power. They were developed empirically on the basis of survey data collected following the 1994 Northridge earthquake that struck the Los Angeles region. Specifically, a large survey of over 1,100 businesses was conducted by K. Tierney and colleagues at the Disaster Research Center of the University of Delaware (Webb et al., 2000). Data from this survey that were used in the current study included information on whether a business lost electric power, for how long, the level of disruptiveness associated with this outage, and whether or not the business closed temporarily in the disaster. Data on other sources of disruption (e.g., building damage, loss of water, etc.) were also used to estimate the net effect of electric power outage. For details on the methodology, see Chang and Seligson (2003). The loss factors range from a low of 0.39 for mining and construction to a high of 0.60 for manufacturing. These factors pertain to a one-day power outage.

Estimates of industry economic activity by service area, e_{sj}, were based on industry employment data. Employment by industry and zip code were obtained from the Southern California Association of Governments (SCAG) and aggregated, using GIS overlays, to the LADWP service areas. Employment was converted into output using estimates of output per employee in each industry. These productivity estimates were based on California gross state product (GSP) and employment data available from the Bureau of Economic Analysis (BEA).

Loss results are expressed as the percent of gross regional product (GRP) in the LADWP service area that would be lost given electric power outage in each earthquake simulation. At this stage, results are assessed in terms of daily GRP loss. This can be interpreted as the loss that would be sustained if the outage pattern lasted for one day.

Risk Evaluation of Power Systems

Analysis using these probabilistic earthquake scenarios allows the estimation of "risk curves" that graphically summarize system risk in terms of the likelihood of experiencing different levels of performance degradation in disasters. Risk curves can be developed for performance parameters associated with different dimensions of resilience, including the technical (e.g., power supply in each service area), societal (e.g., rate of households without power supply), organizational (e.g., rapidity in repair and restoration efficiency), and economic (e.g., regional output or employment loss).

Risk Curves for LADWP's Power System

Reduction in power supply, households without power and reduction in GRP immediately after an earthquake are risk measures of technical, societal and economic concern, and the associated risk curves are plotted in Figures 11-13. These risk curves indicate the percentages of reduction in power supply, households without power and reduction in GRP immediately after earthquake, and are computed utilizing the results of power flow analysis and census data (Figure 3) on the spatial distribution of households across LADWP's service areas as shown below. As for the details of evaluation in GRP, readers are referred to Shinozuka and Chang (2004).

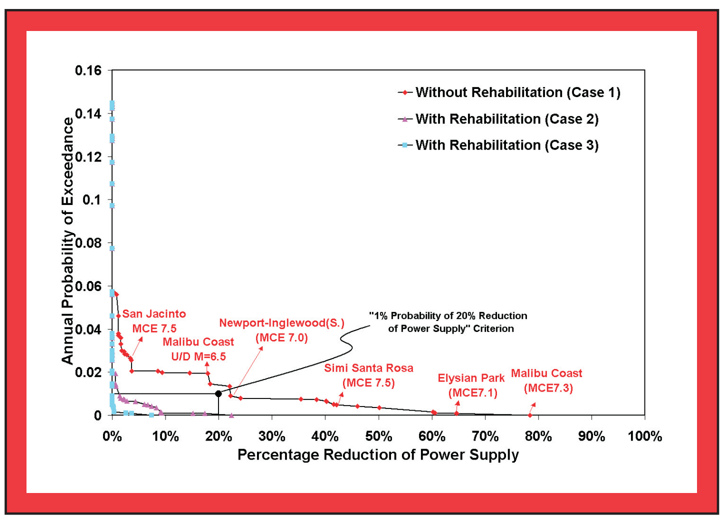


Figure 11. Risk Curves for Power Supply Reduction

Related Web Sites

Professor Shinozuka:
http://shino8.eng.uci.edu

Shake Map Home Page:
http://quake.wr.usgs.gov/research/strongmotion/effects/shake

Western Electricity Coordinating Council:
http://www.wecc.biz/main.html

Scenario Earthquakes:
http://shino8.eng.uci.edu/Secnario_Earthquakes/47Scenario.pdf

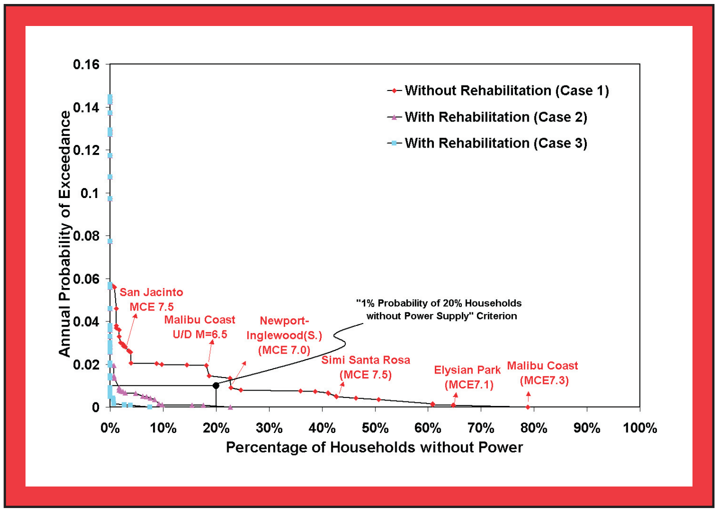


Figure 12. Risk Curves for Household Power Outage

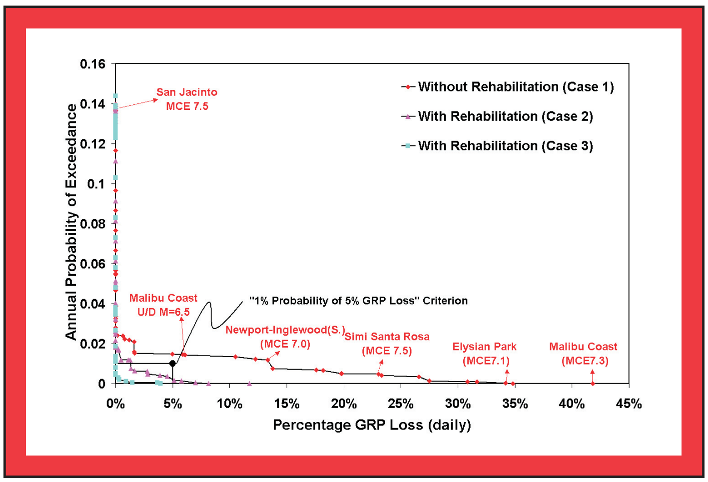


Figure 13. Risk Curves for Economic Loss

Percentage P_w of power supply

$$P_w = \frac{\sum_{m=1}^{M} \frac{1}{N} \sum_{n=1}^{N} Pd(m,n)}{\sum_{m=1}^{M} P(m)} x100\% \quad (4)$$

Percentage P_{wo} of reduction in power supply

$$P_{wo} = 100\% - P_w \quad (5)$$

Percentage H_w of households with power

$$H_w = \frac{\sum_{m=1}^{M} \frac{1}{N} \sum_{n=1}^{N} Rd(m,n) \times Hshld(m)}{\sum_{m=1}^{M} Hshld(m)} \times 100 \quad (6)$$

Percentage H_{wo} of households without power

$$H_{wo} = 100\% - H_w \quad (7)$$

where m is the service area number (1,2,…,M), M=21 in this example; n is the simulation number (1,2,…,N); N equals 20 in this example; $Pd(m,n)$ is the power output in service area m under n-th simulation; $P(m)$ is the power output in service area m under normal conditions; $Rd(m,n)$ is the power output ratio in service area m under n-th simulation; and $Hshld(m)$ is the number of households in service area m.

The risk curves in this study plot the expected annual probability as a function of loss of system power supply in Figure 11, the percentage of households without power in Figure 12 and the reduction of GRP in Figure 13 after an earthquake. Each point in the figures represent one of the scenario events with their occurrence probabilities cumulatively added backward beginning from the scenario earthquake producing the largest percentage so that the risk curve represents a complimentary cumulative distribution function of the performance variable (such as percentage of power supply reduction). The risk curve approach is also useful for economic impact analysis, as well as cost-benefit analysis to determine the effectiveness of enhancement technologies (see the curves with solid triangles and squares) (Dong, 2002). Of equal importance is the use of the risk curve in relation to the verification of performance criteria.

System Performance Criteria

The performance criteria for power systems listed in Tables 1 and 2, demonstrate a possible format in which the criteria can be given. Table 1 lists criteria to be satisfied in pre-event assessment (e.g., through seismic retrofit), and Table 2, those in post-event emergency response (e.g., through disaster response planning). These tables also include performance criteria for water and acute care hospital systems. This general format for performance criteria for structures and lifelines has been provided by Shinozuka and Dong (2002) and Bruneau *et al.* (2003). In combination, they conceptually establish the degree of community resilience in terms of robustness, rapidity and reliability. Specific values (in percentages for robustness, rapidity in restoration, and reliability) are examples so that the concept can be better understood.

Data collection and modeling for rapidity in restoration are much more difficult to pursue (Shinozuka and Dong, 2002). Further research is needed to develop analytical models based on past experience so that performance criteria, such as those shown in Table 2, become meaningful in practice. However, a simulation was performed in this study and compared with the Northridge repair/restoration data. The results from this study provide a potentially successful method of pursuit in this area as demonstrated below in "System Restoration."

Similar tables for GRP associated with the same systems are currently being constructed. For the sake of discussion, robustness of the power system in terms of GRP has a criterion of 5% loss with an annual probability of 1%.

The solid circles in Figures 11-13 indicate example performance criteria for the electric power system in technical, societal and economic terms. In these cases, the criteria specify that percentage of reduction in power supply, of households without power and of

■ Table 1. System Performance Criterion I for Pre-event Assessment and Rehabilitation

	Robustness	Reliability
Power	A majority (at least 80%) of households will have continued power supply after earthquake	With a high level of reliability (at least 99% per year)
Water	A majority (at least 80%) of households will have continued water supply after earthquake	With a high level of reliability (at least 99% per year)
Hospital	A majority (at least 95%) of injured or otherwise traumatized individuals will be accommodated in acute care hospitals for medical care	With a high level of reliability (at least 99% per year)

■ Table 2. System Performance Criterion II for Post-Event Response and Recovery

	Rapidity in Restoration	Reliability
Power	A majority (at least 95%) of households will have power supply as rapidly as possible within a short period of time (3 days)	With a high level of reliability (at least 90% of earthquake events)
Water	A majority (at least 95%) of households will have water supply as rapidly as possible within a short period of time (3 days)	With a high level of reliability (at least 90% of earthquake events)
Hospital	All the injured and traumatized individuals will be accommodated in acute care hospitals as rapidly as possible within a short period of time (1 day)	With a high level of reliability (at least 90% of earthquake events)

GRP loss immediately after earthquake should not exceed, respectively, 20 %, 20 % and 5 %, all with 1 % annual probability. In these instances, Figures 11-13 show that the unmitigated system (Case 1) will not meet the stated performance criteria, but rehabilitated systems (both Cases 2 and 3) will satisfy the performance criteria.

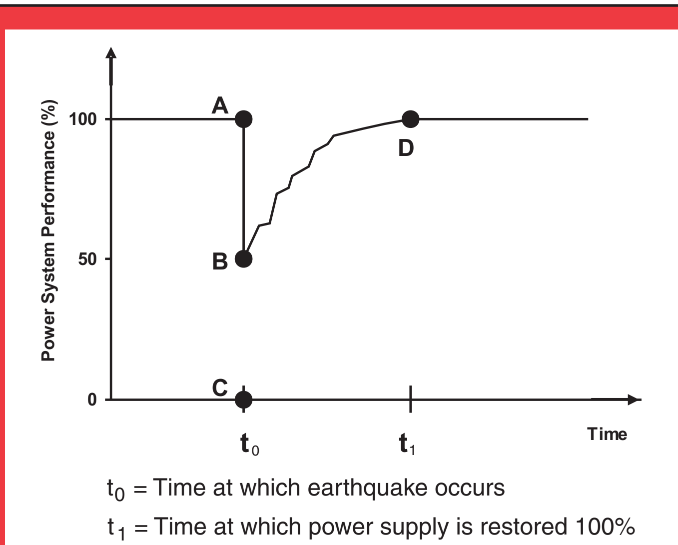


Figure 14. Power Supply as a Function of Time

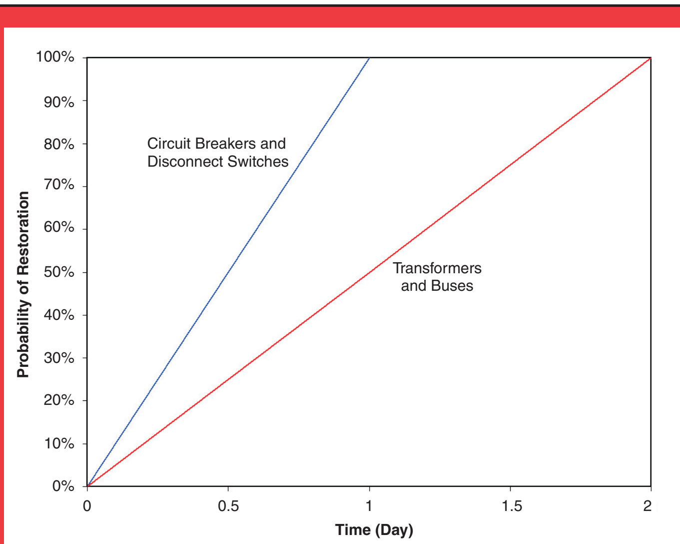


Figure 15. Restoration Curve for Transformers, Circuit Breakers and Disconnect Switches

Resilience Framework and System Restoration

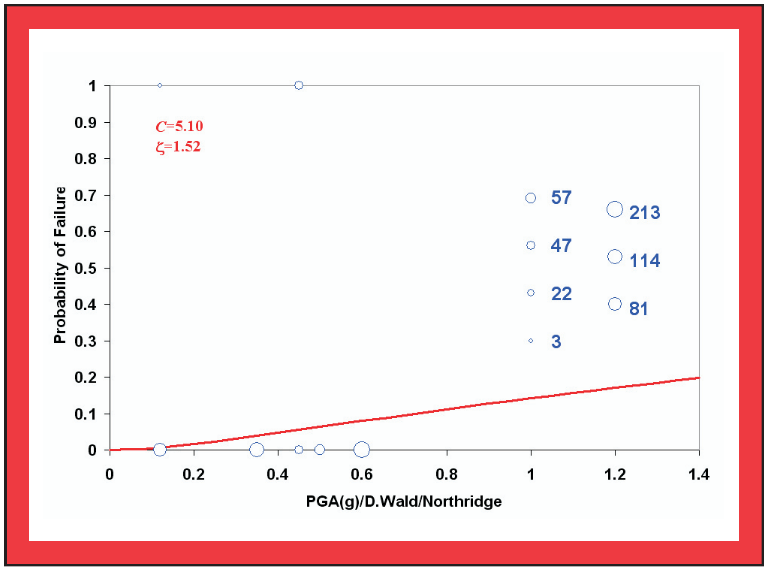
Resilience is an important concept for the disaster management of infrastructure systems. Two key dimensions of resilience can be referred to as robustness and rapidity in restoration as described in the preceding sections. These can be expressed utilizing a restoration curve typically having characteristics as shown in Figure 14.

The curve plots system performance as a function of time. The reduction in performance from 100% at point A (time t_0) to 50% (in this example) at point B results from the damaging seismic impact to the system. The restoration curve starting from the initial distress point B, to the complete recovery point D (back to 100% at time t_1), demonstrates the process of restoration. Hence, the performance percentage corresponding to B (or B-C, with C associated with zero performance) represents robustness (Equation 8), and the elapsed time for the total restoration (t_1-t_0) can be used to quantify rapidity (Equation 9), although Equation 9 may admittedly be too simplistic.

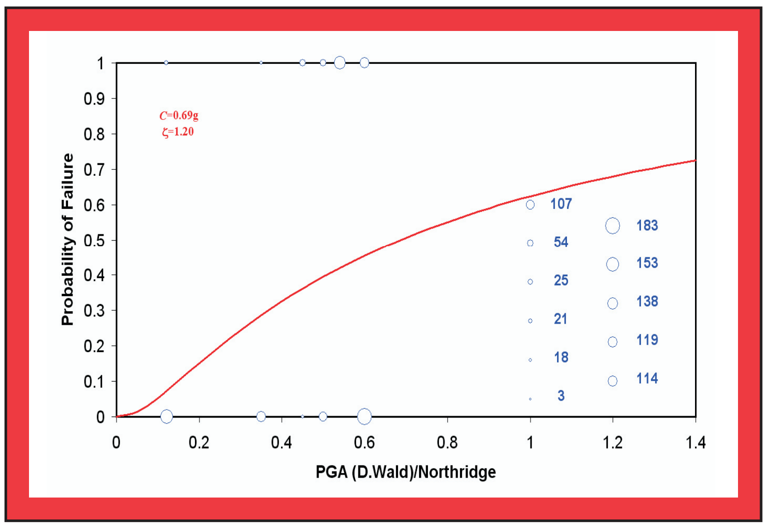
$$\text{Robustness} = B - C \quad (\text{in percentage}) \qquad (8)$$

$$\text{Rapidity} = \frac{A - B}{t_1 - t_0} \quad \text{(average recovery rate in percentage /time)} \qquad (9)$$

It has been demonstrated that the restoration for power systems tends to be rapid compared with that for water, gas and transportation systems. Figure 15 shows the assumed repair or replacement

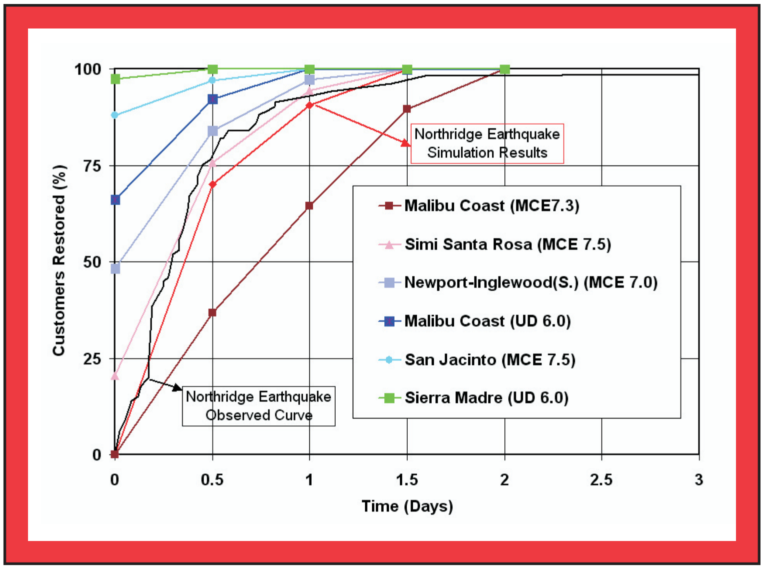


■ Figure 16. Fragility Curve for Circuit Breakers

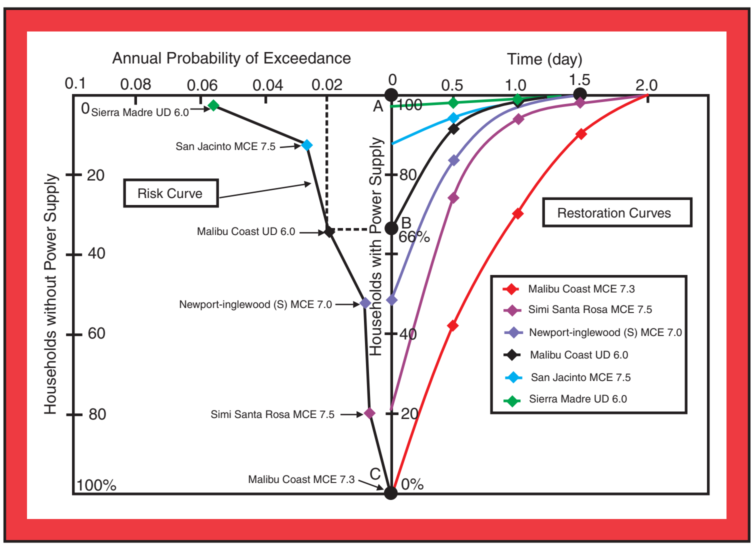


■ Figure 17. Fragility Curve for Disconnect Switches and Buses

curves for the LADWP system after the Northridge earthquake. The curve plots the probability of damaged equipment being restored (repaired or replaced) as a function of time (in days). This model may indeed represent organizational effectiveness in the sense that it asserts that LADWP has the capacity to repair/replace all the damaged components within 2 days, with each damaged component given equal chance to be repaired/replaced in the interval of 2 days. It is postulated that circuit breakers and disconnect switches are more rapidly restored with uniformly distributed probability density over the first one day period, and transformers and buses over the first two days. This not only reflects the relative ease with which each component is repaired /replaced, but also the cost of its replacement. The resulting curve indicates, for example, that a damaged transformer can be replaced or repaired within a half day with a probability of 25%. This is merely an assumption on which we initiate and gain numerical insight for the restoration simulation. In reality, a transformer probably cannot be replaced or repaired with such rapidity unless the degree of damage is slight, i.e., less than moderate. As for the fragility information, we use Figure 7 (Case 1) for transformers, Figure 16 for circuit breakers and Figure 17 for disconnect switches and buses. The fragility curves for circuit breakers and disconnect switches are also developed from the Northridge damage data. Then, a power flow analysis is performed as outlined in earlier sections, adding an extra layer of Monte Carlo simulation where damaged components are restored in accordance with the restoration curves assumed in Figure 15. The resulting simulation of restoration (in % of households) is represented by four points in Figure 18, which underestimates the speed of restoration (in % of customers) actually observed in the aftermath of the Northridge earthquake. The difference between household- and customer-based percentage restoration is assumed to be negligible here. Figure 18 also includes simulated restoration



■ Figure 18. LADWP Power System Customers Restoration



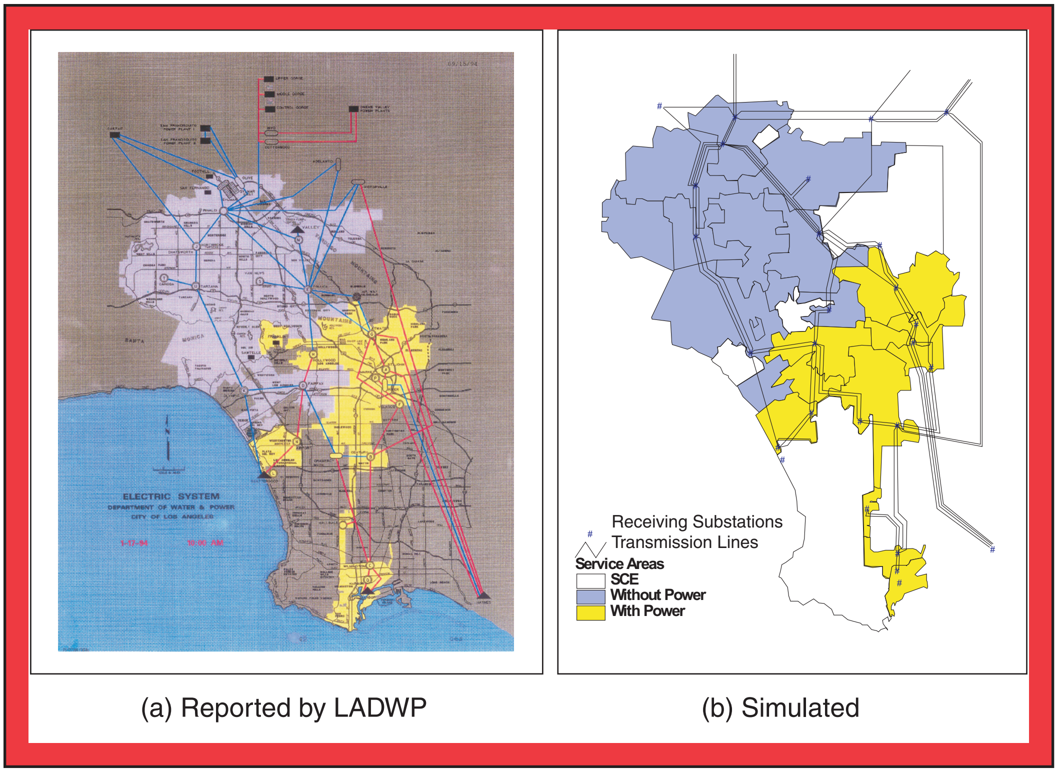
■ Figure 19. Risk Curve and Restoration Curves for LADWP''s System

curves for two other less damaging scenario earthquakes. Note their shapes are, in essence, the same as the curve BD in Figure 11. We note that power system restoration procedures may repair or replace damaged components in an order reflecting the priority established by the utility for the purpose of accelerating the entire network restoration. If such a procedure were taken into consideration, the simulation performed here might have more closely agreed with the empirical curve. The simulated states of restoration as time proceeds can be depicted in GIS format. Figure 20 (a) shows a snapshot at 6 hours after the earthquake of this spatio-temporal progression of restoration process as reported by LADWP, whereas Figure 21(b) shows the simulated version of the state of restoration at the same time.

Water and Power Systems Integration

Figure 21a shows the LADWP electric transmission network superimposed on the major highway system and topography of Los Angeles. Figures 21b and 21c show the pump stations for water distribution and groundwater wells, respectively.

The water distribution system contains 73 pump stations, many of which use several pumps in parallel, resulting in 284 pumps throughout the system. As indicated in Figure 21c, the water distribution system contains an additional 151 pumps for groundwater wells. Of significance is the Van Norman Complex in northern San Fernando Valley, which operates with two pump stations.

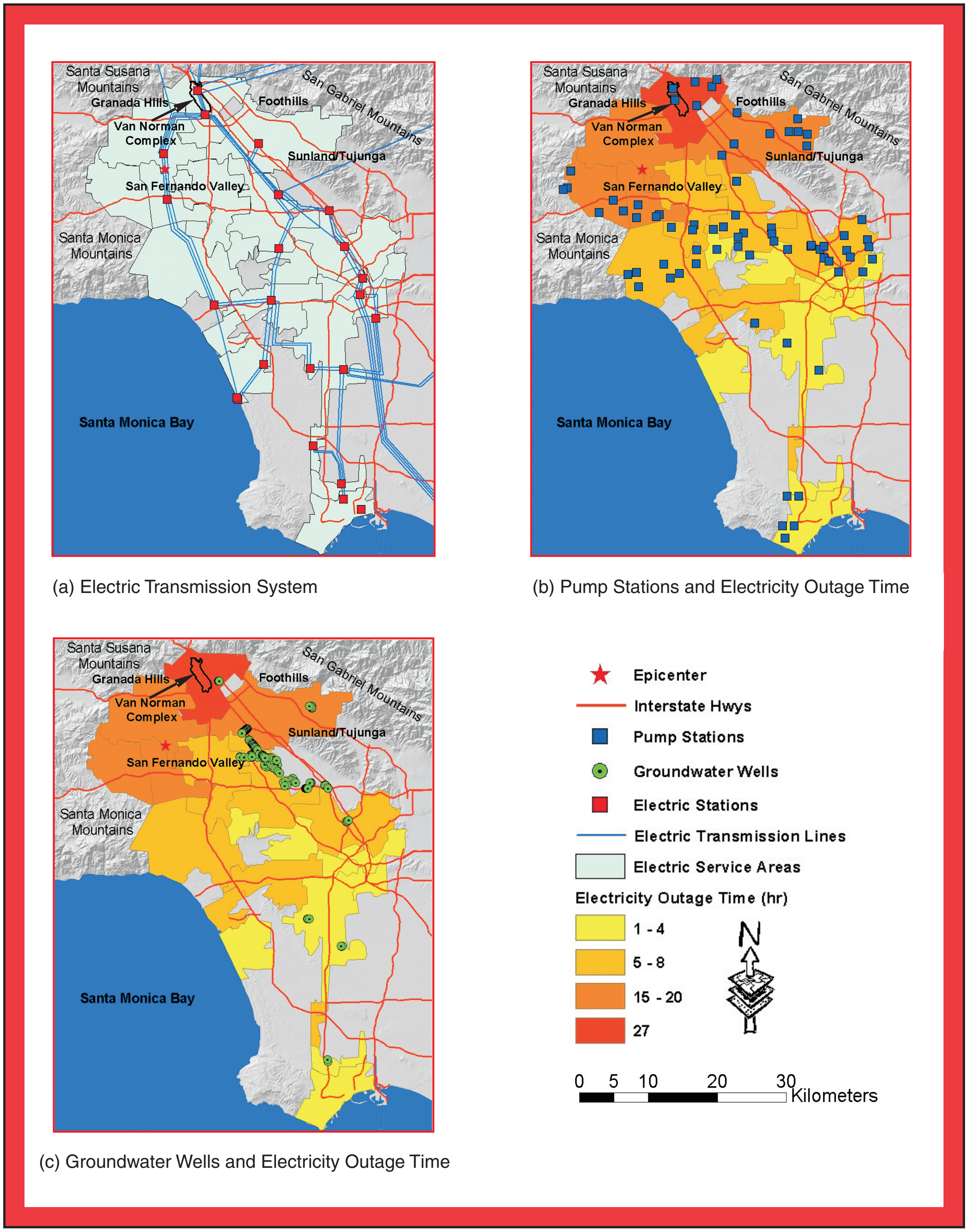


■ Figure 20. State of LADWP Power Supply Restoration at 6 hours after the Northridge Earthquake

Pump stations and groundwater wells generally performed well during the 1994 Northridge earthquake. The damage to these facilities was minimal, except for the loss of pumping capacity due to interruption of electric power (Lund and Cooper, 1995). Most pump stations have emergency backup internal combustion generators or pump units to provide at least the capacity of one electric pump unit. The emergency capacity, however, is less than the pumping capacity with normal electric service at most of the stations. The post-earthquake capability of pump stations to operate at a normal level of service was therefore related to the restoration of electric power.

LADWP (1994) provided information about the electric power system restoration after the Northridge earthquake, which was incorporated into a combined GIS for water and electric power, and evaluated in light of other data sources (Schiff et al.,1995; LADWP, 1994; EERI, 1995). Figure 21 shows the LADWP electric transmission system, as well as the time for power restoration, superimposed on pump stations and groundwater wells. Power was restored first in the southern portion of the service area, and then was expanded gradually to the north. The outage time in the Central City areas was less than several hours. In contrast, the outage for much of San Fernando Valley lasted 15 to 27 hours.

The restoration of electricity was accomplished by reinstatement of power in the least damaged, southern portion of the network at the same time that inspections and repairs were initiated in the most heavily damaged northern part



(a) Electric Transmission System

(b) Pump Stations and Electricity Outage Time

(c) Groundwater Wells and Electricity Outage Time

■ Figure 21. Water Distribution and Electricity Power System Interaction After the 1994 Northridge Earthquake

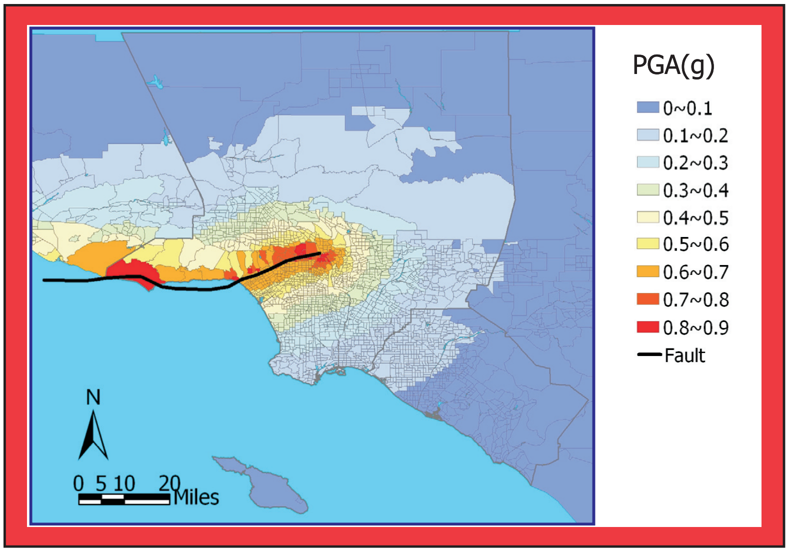


Figure 22. PGA Distribution (Malibu Coast M7.3)

of the network. In general, restoration proceeds from locations outside the most heavily damaged areas where the opportunity for power resumption is highest. This progression from areas of lesser to greater damage also supports a general resumption of services that helps in the repair of components with highest damage.

Electric service to most pump stations and groundwater water wells was reinstated by noon following the main shock. Electricity outage at the Van Norman Complex lasted as long as 27 hours. Emergency power to run the smallest of the two pump stations at the Complex at full capacity was provided during that time by internal combustion units. Even after electric power was restored to both pump stations at the Complex, the ability to convey water was impeded by earthquake-induced damage to major trunk lines.

MCEER investigations of earthquake effects on the combined water and power systems, as illustrated in this case history assessment, show the spatial interaction of both networks. GIS-assisted modeling illustrates both the temporal and spatial aspects of combined system performance, and helps to formulate future strategies for coordinated service reinstatement.

Figures 21a and 21b can also be demonstrated by utilizing the spatio-temporal restoration map of the power supply reported by LADWP for the Northridge earthquake as in Figure 20a. The method of simulation for the restoration process which was developed in Figure 20b can be used for one of the Maximum Credible Earthquakes, Malibu Coast M7.3, with a PGA distribution as depicted in Figure 22. The progression of the restoration process is then shown in Figure 23, in which the state of the restoration is demonstrated in GIS format immediately after and at 12 hours, 24 hours and 48 hours after the earthquake. This restoration simulation as exemplified in Figure 23 is pivotal in the pre-event assessment of restoration and related recovery processes.

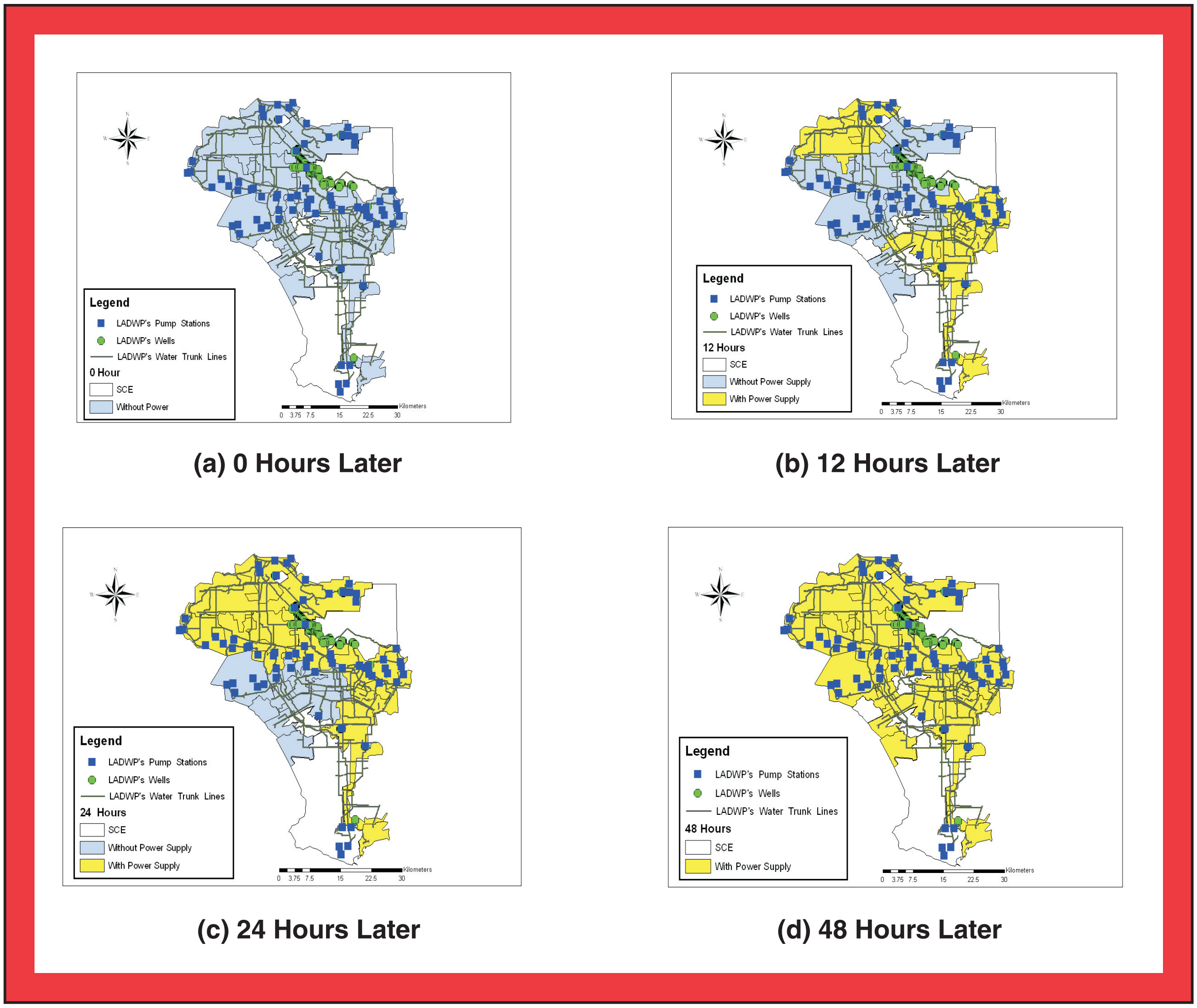


Figure 23. Pump Stations with Power Supply after Earthquake (Malibu Coast MCE 7.3)

Conclusion and Future Research

This research integrated the data and methods developed by the authors over many years, including the GIS inventory data of the LADWP electric power transmission system, multiple scenario earthquakes representing the Los Angeles area seismic hazard, fragility characteristics of system components with and without seismic retrofit, and systems analysis techniques using WECC's database and EPRI's IPFLOW computer code. This integration leads to the capability to evaluate the performance of power systems and the consequences of system interruptions caused by earthquakes. In addition, the research developed and proposed a form of performance criteria that can be quantitatively mapped into the response space, in terms of the technological, economic, organizational, and social dimensions of disaster resilience. A model of the system restoration process was recently added for the purpose of pre-event simulation in order to assess the economic loss resulting from system disruption. Research on integrative water and power performance has been initiated concentrating on the pump stations vulnerable to the interruption of power supply. Joint performance of power systems with other critical systems, such as emergency response organizations, medical care systems (e.g., acute care hospitals) and highway transportation systems is a critical issue to be addressed more comprehensively from the viewpoint of community resilience, and is currently being studied.

Acknowledgements

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Assessing the Role of Lifeline Systems in Community Disaster Resilience

by Stephanie E. Chang and Christopher Chamberlin

Research Objectives

The objective of this research is to advance the state-of-the-art of disaster loss modeling, with particular emphasis on understanding how mitigating lifeline infrastructure systems can improve the disaster resilience of a community. A model will be developed that focuses on direct social and economic losses. It will be applied to the Los Angeles Department of Water and Power (LADWP). Key advances in this model will include evaluating lifeline-related losses within the broader context of the disaster, and developing a socio-economic loss model that is agent-based.

Urban infrastructure systems such as water and electric power networks provide critical services to all sectors of a community. Evaluation of alternative seismic upgrading strategies for these systems should therefore take into account not just the utility provider's own costs and benefits, but the potential impacts on the community as a whole. In this context, MCEER researchers have proposed the concept of "community disaster resilience" as a framework for evaluating and comparing loss reduction strategies (Bruneau et al., 2003). This paper addresses a central question in the resilience framework: how to evaluate the benefits of lifeline mitigations for disaster resilience of the entire community.

This effort builds on research in previous years that focused on the water and electric powers systems serving Memphis, Tennessee. Prior research developed integrated engineering-economic loss estimation models (Chang et al., 2002; Shinozuka et al., 1998), explored the relationship between loss estimation and resilience modeling, and applied the resilience approach to an analysis of alternative seismic upgrading strategies for the Memphis Light, Gas and Water Division (Chang and Shinozuka, 2004).

Currently, the Memphis model is being transferred with major enhancements to a case study of the Los Angeles Department of Water and Power's (LADWP's) systems. As described in the current paper, a key enhancement is the setting of lifeline outage impacts in the context of other earthquake damage (e.g., to buildings), which provides a more realistic and accurate assessment than modeling lifeline outages in isolation. Another important modification consists of the shift from an area-based to an agent-based model

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Previous Summaries

1999-2000:
Chang et al., http://mceer.buffalo.edu/publications/resaccom/9900/Chapter1.pdf

structure. Economic impacts are now evaluated at the level of the business, rather than the census tract. This approach affords modeling advantages in terms of scalability, ease of simulation, validation capability, and consistency with underlying empirical data. This paper describes progress to date on the Los Angeles resilience model. The principal areas of progress are development of a multi-source economic loss model, derivation of a business sample for simulation, and software implementation.

Multi-Source Economic Loss Model

Figure 1 provides a schematic diagram of the community resilience model (blue box) and its relationship to the overall MCEER study of LADWP systems. For a given scenario earthquake, the community resilience model evaluates economic impacts, social impacts, and resilience outcomes. Key inputs from MCEER engineering investigators include the availability of water and electric power for spatial units (e.g., census tracts, electric power service areas) at various points in time following the earthquake. The status of buildings is assessed using the Federal Emergency Management Agency's (FEMA's) HAZUS loss estimation software.

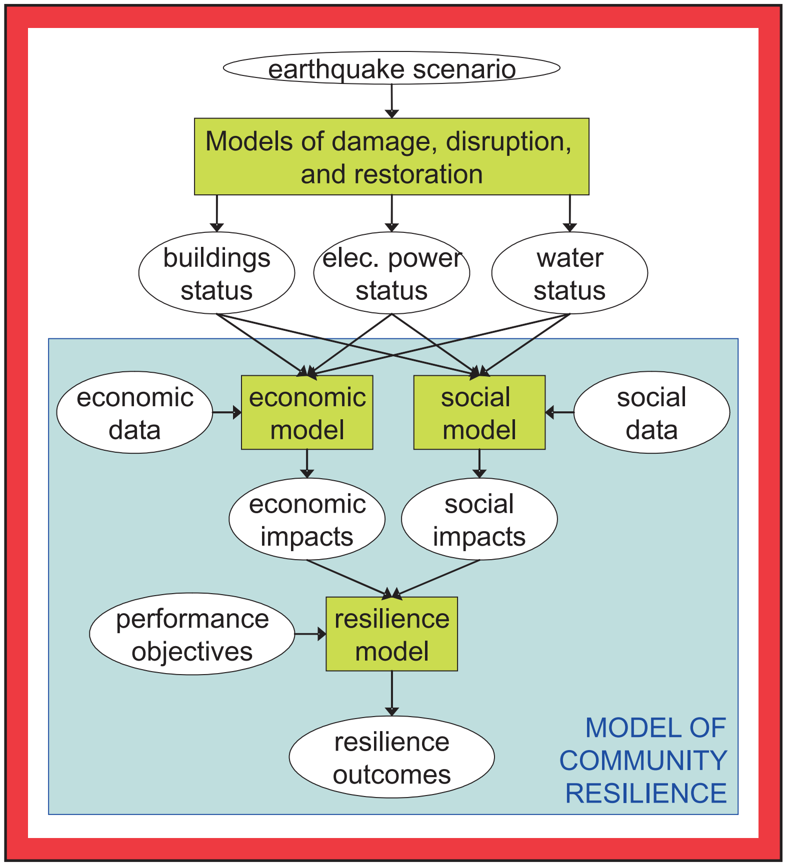
The simultaneous evaluation of economic disruption from loss of building, water, and electric power is an important advance. It avoids the potential inflation of losses attributable to any of these sources individually. For example, a business may be unable to operate if it loses either water or electric power. Suppose it loses both in an earthquake. Evaluating water and electric power impacts simultaneously, rather than separately (as is the case with most current models), ensures that this business's losses will not be counted twice. This enables a more accurate assessment of potential losses, as well as potential benefits of lifeline mitigations.

Data to develop and calibrate the multi-source economic loss model were obtained from two large business surveys conducted by K. Tierney and colleagues at the Disaster Research Center of the University of Delaware following the 1989 Loma Prieta and 1994 Northridge earthquakes. Together, these surveys include over 2,000 businesses in the Santa Cruz and Los Angeles areas. Here, we used data from survey questions on sources of disruption (e.g., whether the business lost electric power), the associated levels of disruptiveness

The primary users of this research are intended to be utilities, as well as local emergency managers and planners. This research addresses the questions of how utility losses in earthquakes will affect the community as a whole, and how seismic mitigation of utility infrastructure would improve the community's resilience to future disasters.

(e.g., "very disruptive"), whether the business closed temporarily, for how long, and the major reasons for this closure.

Based on these data, a three-step model was developed in which losses are evaluated for each business in the simulation. The first step involves determining the degree of building damage, water loss, and electric power outage suffered, primarily on the basis of the business's location in the study area. The second step translates these physical losses into disruptiveness to the business's activities. Disruptiveness is measured according to the qualitative scale used in the Loma Prieta and Northridge surveys. Table 1 shows the probabilistic model that relates water outage to business disruption. As shown in the table, outage is more likely to be disruptive for businesses in some industries, such as health services, than for others. For a particular business, a deterministic disruptiveness state is assigned using Table 1 and a random number generator. Similar tables (not shown) were also developed for building and electric power loss.



■ Figure 1. Schematic of Community Resilience Model

■ Table 1. Probability of Disruptiveness Level due to Water Outage

Industry	Disruptiveness Level			
	"Not at all disruptive"	"Not very disruptive"	"Disruptive"	"Very disruptive"
Agriculture	8 %	15 %	42 %	35 %
Mining, construction, transportation, communications, utilities	8 %	31 %	37 %	24 %
Manufacturing	0 %	35 %	26 %	39 %
Wholesale and retail trade	10 %	23 %	26 %	41 %
Finance, insurance, real estate	5 %	24 %	29 %	43 %
Health services	2 %	6 %	22 %	70 %
All other services	7 %	29 %	24 %	41 %
ALL INDUSTRIES	7 %	25 %	27 %	42 %

Note: Row sums may not add to 100% due to rounding error.

■ Table 2. Probability of Business Closure

Case	Number of sources in each disruptiveness category				Probability of closure
	"Not at all disruptive"	"Not very disruptive"	"Disruptive"	"Very disruptive"	
A				2+	90%
B			1+	1	80%
C			0	1	63%
D			1+	0	54%
E		1+	0	0	30%
F	3	0	0	0	0%

The third step translates business disruption into economic loss. For each business, the disruptiveness levels from buildings, water, and power are tallied and related to a probability of temporary business closure, as shown in Table 2. For example, a business that experienced "very disruptive" electric power and water outage, as well as "not very disruptive" building damage, would be considered Case A in the table and assigned a 90% probability of closure. The closure probabilities are translated into deterministic closure states using a random number generator. Note that this economic disruption model is evaluated at multiple timesteps (e.g., at weekly intervals) until the business reopens.

Initial results of the economic impact model include the duration of closure (if any) for each business in the simulation. These results are then scaled up to the industry level for the entire study area and translated into dollar losses. For this purpose, it is assumed that a business produces no output while it is temporarily closed, and normal output when it is open. Note that this evaluation is currently limited to only direct business disruption loss.

Business Sample

As noted above, economic impacts are simulated at the business level and aggregated to the entire study area. Data from Dun & Bradstreet (D&B) indicate that there are some 372,000 businesses in Los Angeles County, accounting for about 3.4 million jobs. Table 3 shows the distribution by the industry classification used in the model. Note that the vast majority of businesses in all industries are small (i.e., with less than 20 employees). Information on individual businesses is available from Dun & Bradstreet; however, this database is prohibitively expensive. Instead, we obtained an aggregated database with information for each census tract in the county. Data include the number

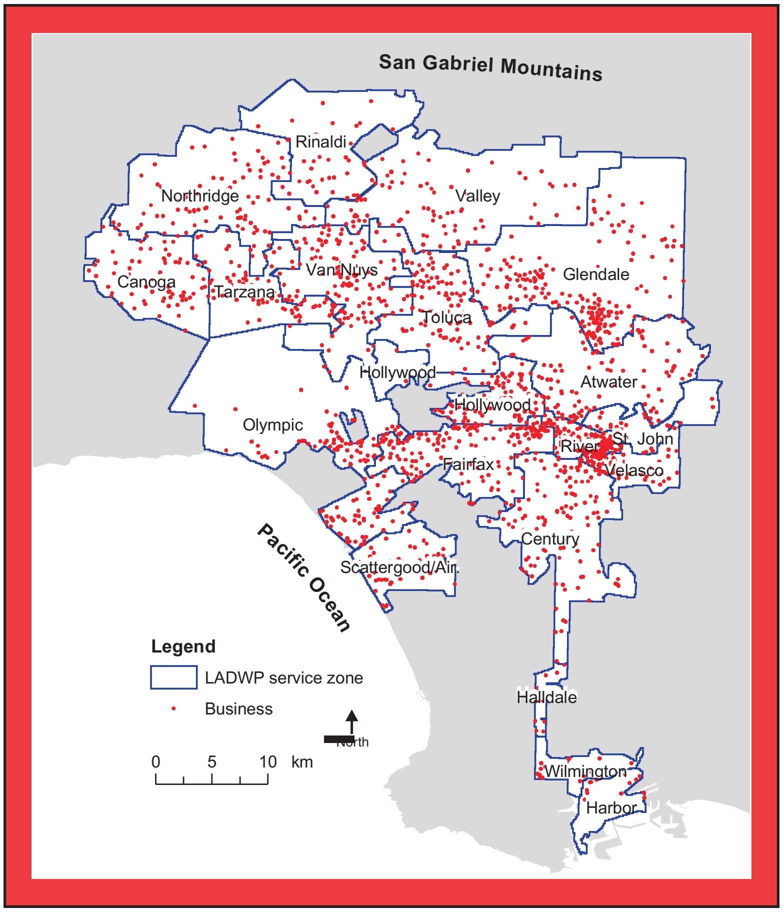
■ Table 3. Businesses and Employment in Los Angeles County

Industry Group	Number of Employees	Number of Businesses	Percent Small Businesses(1)
Agriculture	20,263	3,564	94%
Mining, construction, transportation, communications, utilities	341,594	33,358	91%
Manufacturing	500,045	23,860	79%
Wholesale and retail trade	821,125	105,046	92%
Finance, insurance, real estate	237,697	32,280	93%
Health services	259,578	24,608	94%
All other services	1,222,791	149,675	93%
TOTAL	3,403,093	372,391	92%
Note: (1) less than 20 employees			

Dun & Bradstreet database (December 2003) of jobs and businesses by industry and size class.

From this database, we created a "pseudo-sample" of 3,724 businesses, or 1% of the total population of businesses in Los Angeles County. The Dun and Bradstreet (D&B) database was aggregated from 4-digit Standard Industrial Classification (SIC) codes to the 7-industry grouping shown in Table 2. Each of the 3,724 "business objects" corresponds to a hypothetical business. Each was assigned to an industry such that the sample would have the same industry distribution as the population as a whole. Assigning numbers of employees to the businesses was more complicated since the D&B database only contained aggregate data by business size class. A lognormal curve of business size distribution was therefore generated for each industry, such that it matched the benchmark size class subtotals in the D&B database. Each business object was then assigned a number of employees using the appropriate lognormal curve and a random number generator. Further, for each business subtype, the spatial distribution across census tracts was calculated. Each business object was then assigned a census tract location using the appropriate spatial distribution and a random number generator.

Based on this procedure, a stratified 1% business sample was developed that reflects the total business population in terms of industry, size, and spatial distributions. Figure 2 shows the approximate locations of businesses in the 1% sample, in relation to LADWP's electric power service areas. As noted earlier, the model evaluates



■ Figure 2. Business Sample and LADWP Service Zones

earthquake losses for each business, then scales up to the entire study area. Currently, the study area is LADWP's service territory, which constitutes the majority of Los Angeles County.

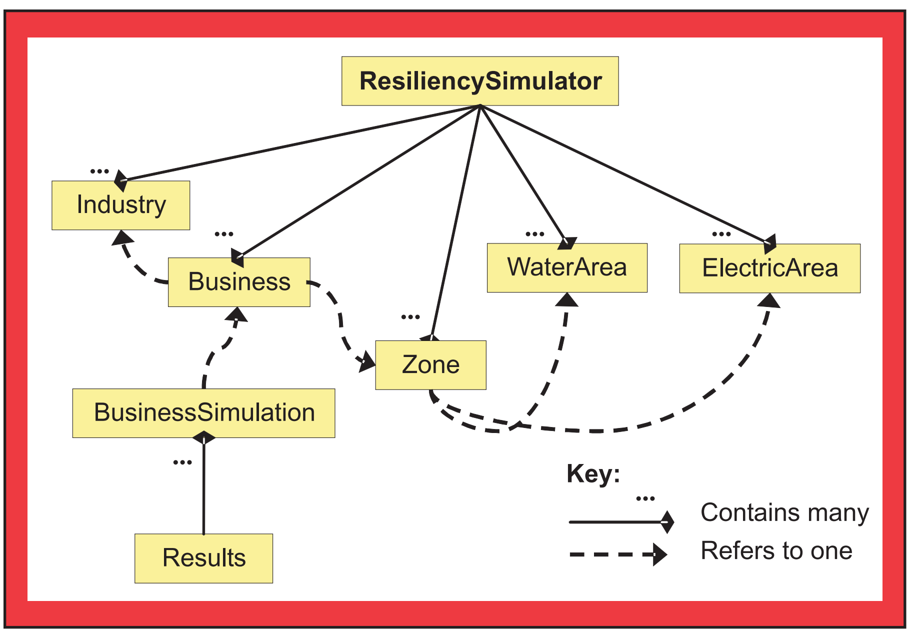
Software Implementation

The simulator for the model is implemented in the object-oriented programming language C++. (The earlier loss model of the Memphis water system had been implemented in Fortran.) Each key component of the model has a corresponding object (C++ class) in the simulation software. An object-oriented environment is useful for

Los Angeles Department of Water and Power

this type of model implementation because it enables clearly defined relationships between the various components, and protects data that should be static from modification.

Further, the C++ inheritance mechanism makes it straightforward to add modified or improved components of the model without affecting the rest of the code. For example, the current model for outage and recovery of water and electric lifelines is very simple. Better empirical data or a more sophisticated model, when available, can be implemented in a class derived from the existing one, which defines the interface to the object used by the rest of the system. Further, it would be possible to mix several implementations of a given component, with different functionality, together in one simulation. The object interfaces make these implementation details invisible to the rest of the simulation.



■ Figure 3. Object Model Overview for Economic Resilience Simulation

The overview in Figure 3 shows the major components of the system. Some minor utility classes and the derived implementations described above are not shown. The major components are as follows:

ResiliencySimulator – This is a unique object that contains the rest of the objects for the simulation. The top-level loops for the simulation are here. Because the *ResiliencySimulator* is unable to change the scenario data, these are protected from accidental modification.

Business – This is a basic class that holds data about one business. It holds the business employment size and pointers to the industry and zone the business is in. Results from simulation are stored in *BusinessSimulation*, not here.

Zone – This corresponds to a section of the study area, usually a census tract. It has an ID value and pointers to the lifeline service areas that this zone is contained within. It also contains building damage rates.

WaterArea/ElectricArea – Currently, these objects are identical, but derived classes could implement different models. These objects are capable of returning the lifeline status (available or unavailable) at any given time step.

Industry – This contains data about a given industry group, including the susceptibility to closure due to building or lifeline damage.

BusinessSimulation – This contains the results of simulation for one *Business* object, particularly the closure status at given time steps.

Results – This is the top level results object. It contains all of the *BusinessSimulation* objects. After they are computed, code in this object aggregates them and saves the results to disk.

The *Results* objects can be deleted after a run's results are saved without affecting the rest of the data structures, so the simulation is very efficient to reset for another run because the bulk of the data does not need to be recreated. Thus, the multiple runs which are required of this nondeterministic simulator can be executed relatively quickly.

The model uses two types of input data. *Model calibration data* is integral to the calibration of the entire model. Changes here would represent actual changes to the model itself. For example, the *Industry* objects are calibrated for the probability of closure due to building damage, based on empirical surveys. Second, *scenario data* will vary depending on the earthquake scenario being used, such as building and lifeline damage. However, scenario data are static once the simulator starts, because they are part of the unchanging input data for each simulation run. In the simulator, these data are found in classes such as *Business*, *Zone*, and the lifeline areas.

To date, the simulation model has been partially tested for one scenario earthquake, a M7.0 Malibu Coast fault event. This scenario is one (#43) of 47 Los Angeles area events that together have been proposed for probabilistic scenario-based analysis (Chang et al., 2000). Full testing of the model will be conducted when results are available from engineering collaborators on lifeline outages and restoration.

Conclusions and Future Research

Substantial progress has been made in the development of a community resilience model and simulation software. In contrast to an earlier lifeline loss estimation model on which it is based, the resilience model accounts for multiple sources of loss, simulates impacts at the business level, and is implemented in an object-oriented programming language. Efforts to date have focused on assessing economic resilience.

Future research will aim to complete development of the community resilience model. Linkages will be made to other MCEER research on the LADWP case, including indirect economic losses, water and electric power outage, and lifeline restoration. The resilience model will be expanded to address social impacts such as displaced households and disruption to hospitals. Major efforts will also be made to refine the specification of performance objectives – which play a central role in resilience analysis – through stakeholder participation.

Links to Current Research

This effort focuses on the modeling and assessment of earthquake resilience at the community level, with emphasis on economic and social dimensions of resilience. The community resilience model is developed in coordination with other MCEER research on lifeline damage, outage, and restoration (by Shinozuka, O'Rourke, Grigoriu, and Davidson).

Acknowledgements

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Seismic Response Modification of Structural and Nonstructural Systems and Components in Acute Care Facilities

by Amjad Aref, Michel Bruneau, Michael Constantinou, Andre Filiatrault (Coordinating Author), George C. Lee, Andrei M. Reinhorn and Andrew S. Whittaker

Research Objectives

The main objective of this research is to develop a better understanding of the applications of various seismic response modification technologies to protect structural and nonstructural systems and components in acute care facilities from the effects of earthquakes. A secondary objective of the research is to establish a relationship between the performance of nonstructural components and structural demands in order to optimize and harmonize performance objectives between structural and nonstructural systems and components in acute care facilities. A broad range of seismic response modification technologies are under investigation, from those close to implementation to others that require long-term investigation. Results from the analytical and experimental investigations are being used in fragility studies to probabilistically quantify the relative merits and potential benefits to structural and nonstructural components of implementing these technologies. Eventually, the results will be quantified and included in decision support methodologies that integrate both engineering and social science aspects.

Achieving a given target seismic resiliency for acute care facilities requires harmonizing the performance levels between structural and nonstructural components. Even if the structural components of a hospital building achieve an immediate occupancy performance level after an earthquake, failure of architectural, mechanical, or electrical components can lower the performance level of the entire building system. This reduction in performance caused by the vulnerability of nonstructural components has been observed in several buildings during the recent 2001 Nisqually earthquake in the Seattle-Tacoma area (Filiatrault et al., 2001) and during several other earthquakes that have occurred in the last 40 years (Ayres et al., 1973, Ayres and Sun, 1973, Ding and Arnold, 1990, Reitherman 1994, Reitherman and Sabol, 1995, Gates and McGavin, 1998). Figure 1 illustrates typical investments in structural framing, nonstructural components and building contents in office, hotel and hospital construction (Miranda 2003). Clearly, the investment in nonstructural components and building contents is far greater than that of structural components and framing. Therefore, it

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Previous Summaries

2001-2003:
Bruneau et al.,
http://mceer.buffalo.edu/publications/resaccom/0103/06bruneau.pdf

2000-2001:
Vian et al.,
http://mceer.buffalo.edu/publications/resaccom/0001/rpa_pdfs/08bruneau4.pdf

Constantinou et al.,
http://mceer.buffalo.edu/publications/resaccom/0001/rpa_pdfs/10Lee-ketter-2.pdf

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Lee et al.,
http://mceer.buffalo.edu/publications/resaccom/9799/Ch4lee.pdf

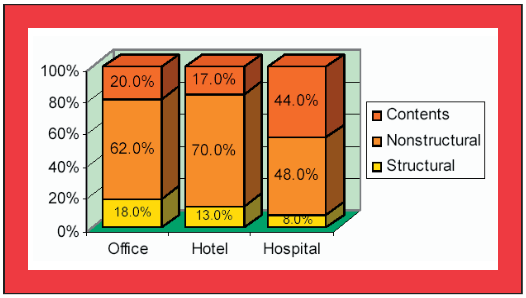
is not surprising that in many past earthquakes, losses from damage to nonstructural building components exceeded losses from structural damage. This was clearly the case in the recent 2001 Nisqually earthquake (Filiatrault et al., 2001). Furthermore, failure of nonstructural building components could become safety hazards or could affect the safe movement of occupants evacuating or rescue workers entering buildings.

In comparison to structural components and systems, there is still relatively limited information on the seismic performance of nonstructural components. Basic research work in this area has been sparse, and the available codes and guidelines (FEMA 1994, ASCE 2000, Canadian Standard Association 2002) are usually, for the most part, based on past experiences, engineering judgment, and intuition, rather than on experimental and analytical results. Often, design engineers are forced to start almost from square one after each earthquake event: observe what went wrong and try to prevent repetitions. This is a consequence of the empirical nature of current seismic regulations and guidelines for nonstructural components.

Retrofitting hospitals using seismic response modification technologies can make it possible to harmonize the performance of structural and nonstructural components in order for the entire facility to meet or exceed a specified resiliency level during and after an earthquake. The initial expense of these technologies may be considered high at first glance, but increased implementation based on sustained research efforts is expected to reduce costs in the future to the point where they will be the same or less than conventional retrofitting techniques. Furthermore, the use of response modification technologies that reduce the seismic demands on nonstructural components can significantly lower the cost of retrofitting these items, which often represents the bulk of the facility investment.

Figure 2 presents, as an example, sample fragility curves for suspended ceiling systems (SCS) (Badillo et al., 2002). Failure of SCS has been one of the most widely reported types of nonstructural damage in past earthquakes. Ensembles of fragility curves were developed by MCEER researchers based on twenty-seven sets of earthquake-simu-

Design engineers and researchers can use the technologies investigated and developed in this research to improve the seismic resilience of critical facilities. Results will be integrated into a decision support methodology to aid hospital administrators in selecting the most appropriate strengthening techniques for their specific situation, to assess loss of performance/capabilities and time to recovery, and to determine the cost/benefit of using these technologies. The demonstration hospitals can be used as a baseline analytical tool in undergraduate and graduate courses in earthquake engineering.



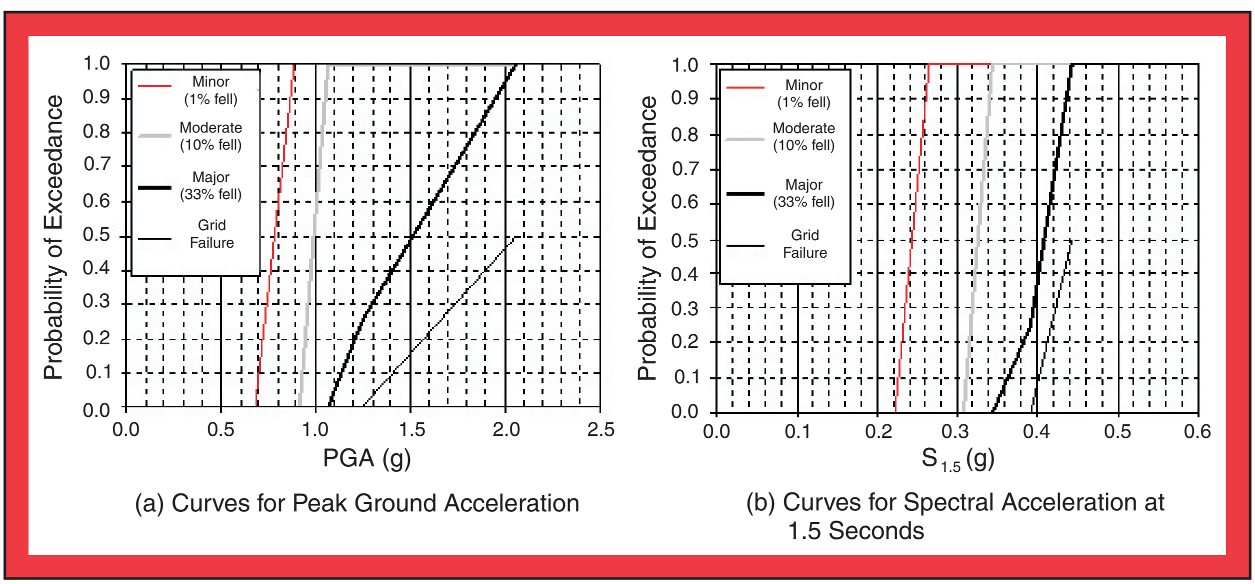
Miranda 2003

■ Figure 1. Investments in Building Construction

lator tests on six tile-suspension systems. The specific objectives of the research program were: (1) to study the performance of a SCS that is commonly installed in the United States; (2) to evaluate improvements in response offered by the use of retainer clips that secure the ceiling panels (tiles) to a suspension system; (3) to investigate the effectiveness of including a vertical strut (or compression post) as seismic reinforcement in ceiling systems; and (4) to evaluate the effect of different boundary conditions on the response of a SCS.

It was found that the use of retainer clips substantially improved the behavior of the SCS in terms of loss of tiles but also increased damage to the suspension system. This example illustrates the fact that if the use of structural technologies can sufficiently reduce the seismic demands on SCS, these components may not need any retainer clips, or other retrofit methodologies, to perform adequately, thereby contributing to the overall seismic resiliency of the facility.

This paper briefly describes the research currently underway at MCEER on the development of response modification technologies for the seismic protection of structural and nonstructural systems and components in acute care facilities. This work is innovative and important since the application of these response modification technologies in building structures to date has been based solely on structural performance. It is only when the variations in seismic fragility of coupled structural and nonstructural components



■ Figure 2. Sample Experimental Fragility Curves for Suspended Ceiling Systems (SCS)

Links to Current Research

The seismic retrofit technologies and response modification methods investigated in this effort will be incorporated into integrated decision support systems under development by Alesch, Dargush, Grigoriu, Petak and von Winterfeldt.

as a function of the structural systems (including seismic response modification technologies) and/or equipment retrofit is available that robust decision-making tools can be implemented.

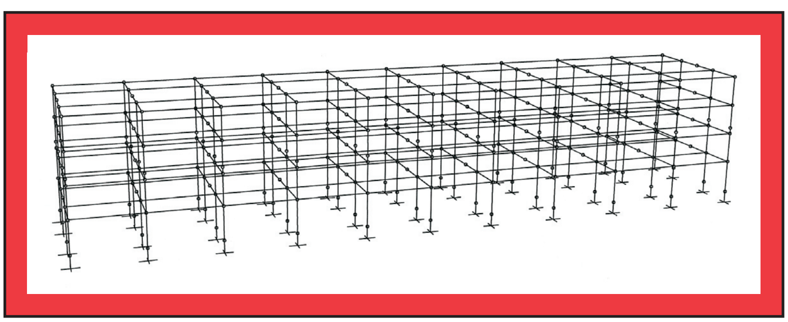
Seismic Response Modification Using Technologies Developed at MCEER

This section presents the various studies aimed at controlling the seismic response of structural and nonstructural systems and components in acute care facilities. These studies are conducted using various advanced technologies developed by MCEER researchers.

Studies on MCEER West Coast Demonstration Hospital

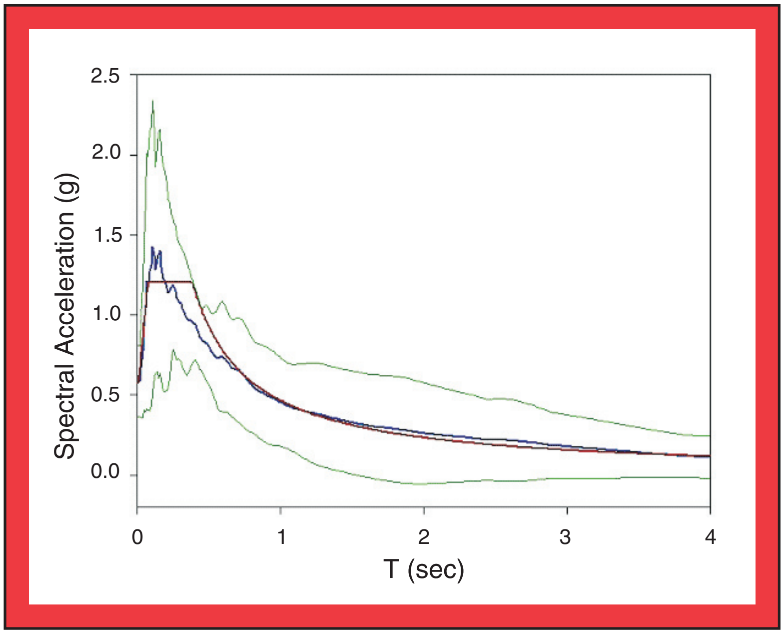
MCEER researchers are investigating the seismic demands on structural and nonstructural systems and components in acute care facilities through two- and three-dimensional numerical modeling of a demonstration hospital in a variety of computer platforms. The facility chosen as the MCEER west coast demonstration hospital is an existing structure in the San Fernando Valley in Southern California (Bruneau et al., 2003). The hospital facility was constructed in the early 1970's to meet the seismic requirements of the 1970 Uniform Building Code. One particular building of the facility's campus, a rectangular four-story steel moment-resisting frame, referred to herein as WC70, was selected for in-depth studies. Figure 3 shows an isometric view of the framing of this building. By using these numerical models, MCEER researchers are able to compute demands on nonstructural components and judge the utility and efficiency of different seismic modification technologies to reduce the vulnerability of nonstructural components. Model verification is on-going across the various computer platforms to ensure consistency of results.

The computer platform IDARC2D, developed by MCEER researchers, was used to judge the impact of plausible variations in structural-framing modeling assumptions on the demands on the nonstructural components, including modeling the non-seismic steel moment-frame connections as rigid (Model 1), semi-rigid (Model 2) and pinned (Model 3), and modeling the column base connections as rigid, semi-rigid and pinned. Nonlinear response-history analyses of the two-dimensional models were performed using 20 earthquake historical ground motion time histories whose average spectrum matched a 10% in 50 year NEHRP Site Class B design spectrum for Los Angeles. Figure 4 shows the target spectrum, the median spectrum of the 20 histories and the maximum and minimum spectral ordinates for



■ Figure 3. Three-Dimensional Numerical Model of MCEER West Coast Demonstration Hospital WC70 Building the 20 histories. The fundamental periods of the building model in the transverse (short) and longitudinal directions are 0.70 sec and 0.76 sec, respectively.

Figure 5 presents the scatter in the median maximum floor displacements from response-history analysis using the 20 earthquake histories, as well as the scatter in maximum floor displacement for Model 2 for the 20 earthquake histories of Figure 2. For this building and the chosen ground motions, the dispersion due to modeling assumptions is relatively small. However, the scatter due to variations in ground motion characteristics is much larger.

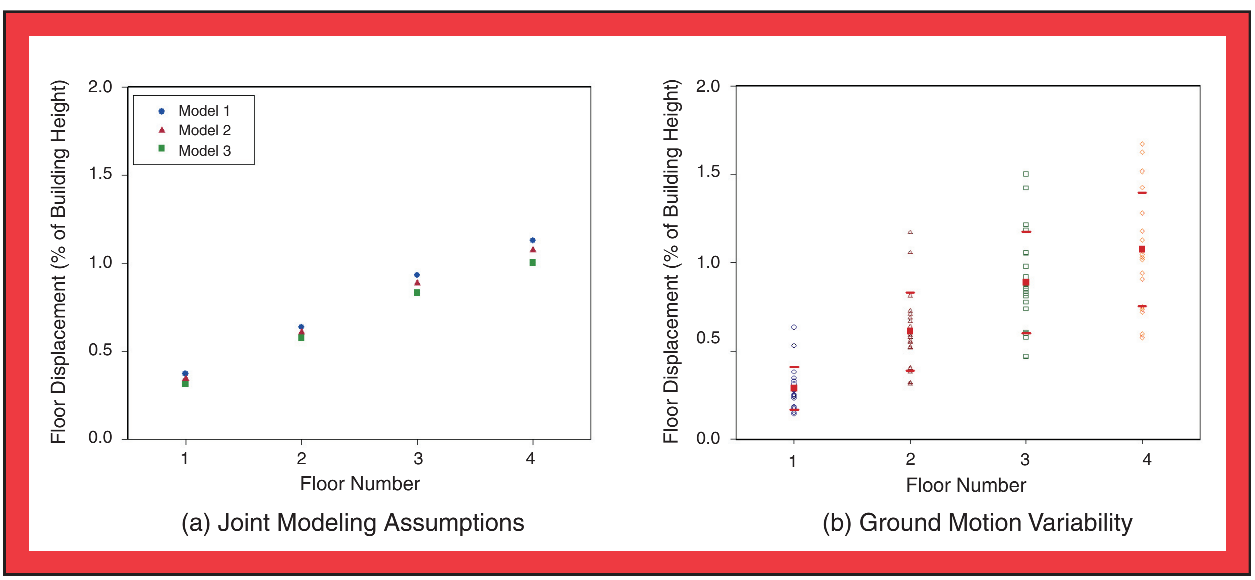


■ Figure 4. Target, Median, Maximum and Minimum 5% Damped Spectral Acceleration Ordinates for 20 Historical Ground Motion Time Histories

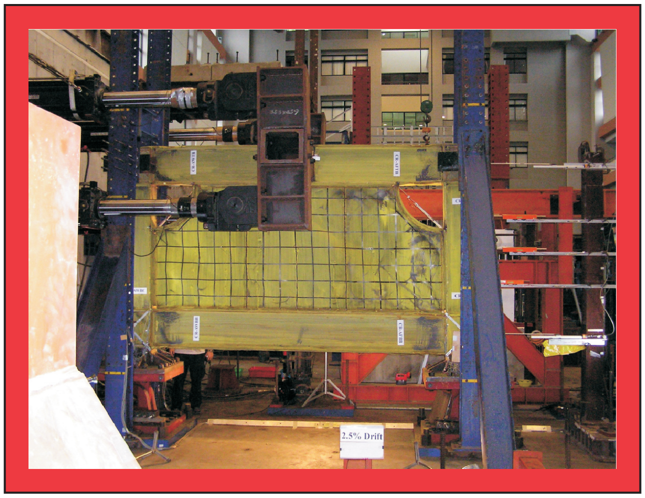
Studies on Metallic Energy Dissipation Systems

Steel Plate Walls with Low Yield Strength Steel Panels

A previous article (Bruneau et al., 2003) summarized work done to use light-gauge, cold-formed steel panels in a new application (Bruneau and Berman, 2003) of Steel Plate Walls (SPW). The SPWs made it possible to overcome the fact that panel thickness, using a typical material yield stress required by a given design situation, is often much thinner than the plate actually available from steel mills (recall that walls having metallic infills are

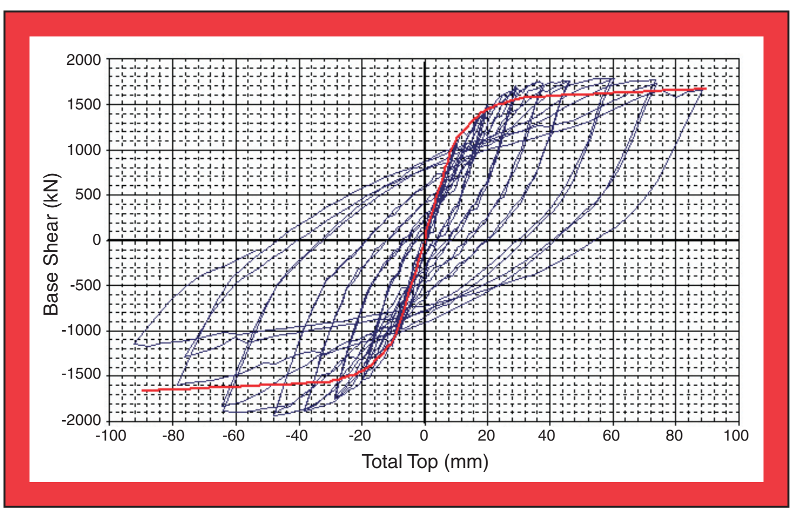


■ Figure 5. Dispersion in Floor Absolute Displacements for WC70 Building Excited by 20 Historical Ground Motion Time Histories



■ Figure 6. SPW Specimen with Cutout Corners to Accommodate Nonstructural Systems

allowed to develop shear buckling, with lateral load carried in the panel via the subsequently developed tension field). To improve the SPW design concept and use hot rolled steels, MCEER initiated a cooperative experimental program with National Taiwan University (NTU) and the National Center for Research on Earthquake Engineering (NCREE). The project investigated the seismic performance of SPW designed and fabricated using low yield strength (LYS) steel panels with reduced beam sections added to the beam ends in order to force all inelastic action in the beams to those locations. It was felt that this would promote increasingly efficient designs of the "anchor beams," defined as the top and bottom beams in a multistory frame, which "anchor" the tension field forces of the SPW infill panel.



■ Figure 7. Hysteresis Loops for Solid Panel Specimen S1

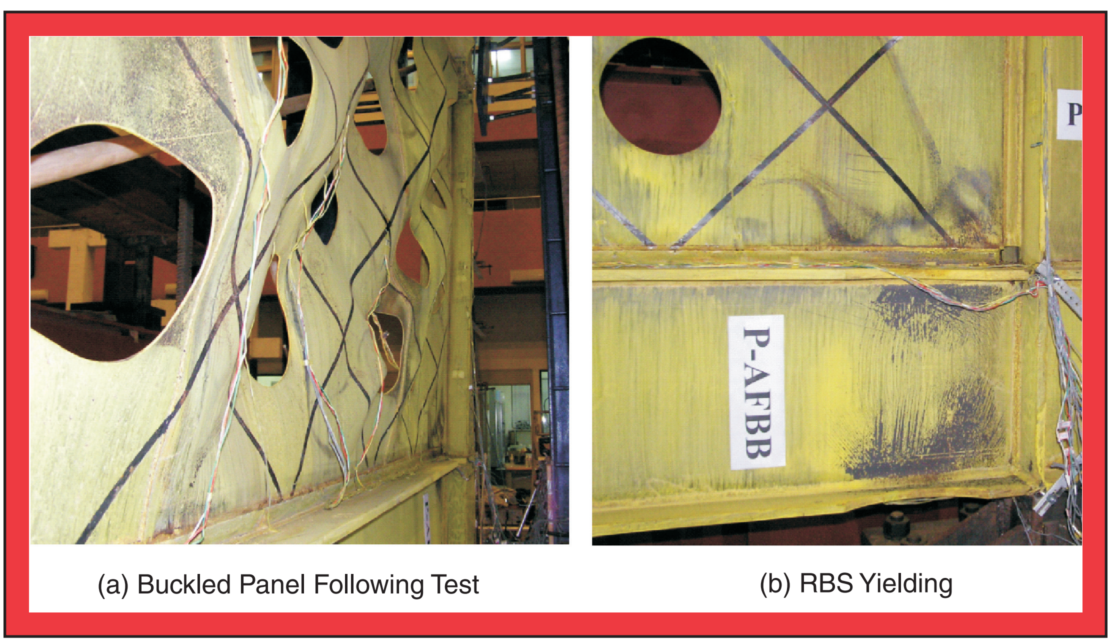
A total of four LYS SPW specimens were designed by MCEER researchers, fabricated in Taiwan, and tested collaboratively by MCEER and NCREE researchers at the NCREE laboratory in Taiwan. The frames, consisting of 345 MPa steel members, were 4000 mm wide and 2000 mm high, measured between member centerlines. The infill panels were 2.6 mm thick, LYS, with an initial yield of 165 MPa. Two specimens had solid panels while the remaining two provided utility access through the panels by means of cutouts. One specimen consisted of a panel with a total of twenty holes, or perforations, each with a diameter of 200 mm. The other specimen was a solid panel, with the top corners of the panel cut out and reinforced to transmit panel forces to the surrounding framing, as shown in Figure 6. The intention of the final two specimens is to accommodate penetration by utilities, which is necessary for building operation.

All specimens were tested using a cyclic, pseudo-static loading protocol similar to ATC-24. Loading history was displacement-controlled, and applied horizontally to the center of the top beam using four actuators. A typical resulting hysteretic curve is shown in Figure 7.

SPW buildings with low yield strength steel panels appear to be a viable option for use in resisting lateral loads imparted during seismic excitation. The lower yield strength and thickness of these plates result in a reduced stiffness and earlier onset of energy dissipation by the panel as compared to a conventional hot-rolled plate. The perforated panel specimen shows promise towards alleviating stiffness and over-strength concerns using conventional hot-rolled plates. This option also provides access for utilities to penetrate the system, important in a retrofit situation, in which building use is pre-determined prior to SPW implementation. The reduced beam section details in the beams performed as designed, as shown in Figure 8. Use of this detail may result in more economical designs for beams "anchoring" an SPW system at the top and bottom of a multi-story frame. On-going research is focusing on developing reliable models that can capture the experimentally observed behavior, and investigating the benefits of this system on enhancing the seismic performance of nonstructural components, using the MCEER west coast demonstration hospital (Bruneau et al., 2003) for that purpose.

Structural Fuses

As part of the work on metallic energy dissipation systems, the structural fuse concept was revisited to investigate whether a systematic framework for optimal design could be implemented in the current context of formulating and operationalizing the seismic resilience concept. Multiple types of special devices for the passive seismic control of building response have been developed and implemented, starting in New Zealand in the late 1960's and early 1970's, and the research literature on displacement-based energy dissipation concepts and devices is extensive (e.g., Kelly et al., 1972, Skinner et al., 1975, Tyler 1978, Pall and Marsh, 1982, Tsai et al., 1993, Xia and Hanson



■ Figure 8. Buckled Panel and RBS Yielding of SPW Specimen

Collaborative Partners

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1992, Hanson et al., 1993, Iwata et al., 2000, to name a few). Some studies have also referred to the term "structural fuse concept," although the term has not been consistently defined in the past. In some cases, "fuses" have been defined as elements with well-defined plastic yielding locations, but not truly replaceable as a fuse (e.g., Roeder and Popov 1977, Fintel and Ghosh, 1981, and many more); in other cases, they were defined and used more in the context of reducing inelastic deformations of the existing frame and thus controlling damage (e.g., Whittaker et al., 1989, Dargush and Soong 1995, Connor et al., 1997, Constantinou et al., 1998, etc). In a few cases, for high rise buildings with long structural periods (i.e., T > 4 s), fuses were used to achieve elastic response of frames that would otherwise develop limited inelastic deformations (e.g., Wada et al., 1992, etc). Design procedures were also developed for systems with friction dampers intended to act as structural fuses (e.g., Filiatrault and Cherry, 1989), but these required design validation by nonlinear time history analyses. Many of these past studies also considered seismic excitations less severe than those corresponding to the 2% probability of exceedence in 50 year level currently specified by design codes.

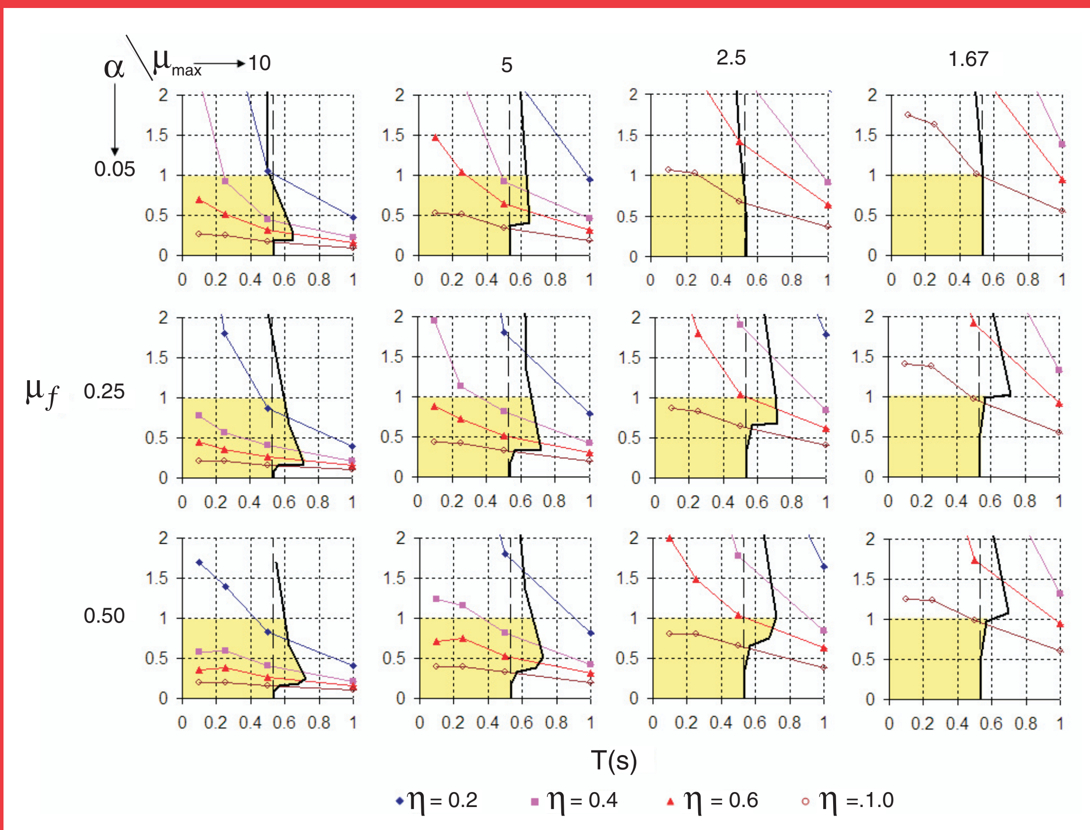
In that perspective, knowledge on how to achieve and implement a structural fuse concept that would limit damage to disposable structural elements for any general structure without the need for complex analyses is lacking. This would require identification of the key parameters that govern the behavior of systems having such structural fuses, and formulation of a general design approach that would make the concept broadly applicable, including for low rise buildings (e.g., single-degree-of-freedom systems). Furthermore, the existing research does not investigate the impact of introducing structural fuses on resulting floor accelerations and velocities, which can directly impact the seismic performance of nonstructural components and building contents (a key consideration in establishing the seismic resiliency of acute care facilities).

A general formulation was sought that would be applicable in any instance where passive energy dissipation devices have been implemented to enhance structural performance by reducing seismically-induced structural damage (and, indirectly to some extent, nonstructural damage). In this context, metallic dampers are defined to be structural fuses when they are designed such that all damage is concentrated on the passive energy dissipation devices, allowing the primary structure to remain elastic. Following a damaging earthquake, only the dampers would need to be replaced (hence the fuse analogy), making repair work easier and more expedient, without the need to shore the building in the process. Furthermore, structural fuses introduce self-centering capabilities to the structure in that, once the ductile fuse devices have been removed, the elastic structure would return to its original position.

A parametric study was conducted leading to the identification of the possible combinations of key parameters essential to ensure adequate seismic performance for structural fuse systems. Nonlinear time history dynamic analyses were conducted for several combinations of parameters, which were chosen to cover a range of feasible designs. Synthetic earthquakes generated to match selected target design spectrum were used. The effects of earthquake duration and strain-hardening on the seismic response of short and long period systems were also considered as part of this process.

Figure 9 presents the system response in terms of dimensionless global and local ductility charts, as a function of selected key design parameters. These charts show, as shaded areas, the regions of admissible solutions for the SF concept. Time history results and hysteresis loops are presented to verify the significance of earthquake duration and strain-hardening on the system behavior, as well as on the hysteretic energy dissipated. Viable combinations of parameters are identified and used to provide guidelines to design and retrofit systems using Unbonded Braces (UB), Triangular Added Damping and Stiffness (TADAS), and Shear Panels (SP) as metallic dampers working as structural fuses. The concept is also being used to investigate the effectiveness of Steel Plate Walls.

Further studies, as part of this research, are being conducted to investigate floor demands in terms



■ Figure 9. Dimensionless Metallic System Response in Terms of Global and Local Ductility Demand, as a Function of Selected Key Design Parameters

Related Web Sites

MCEER Research Summaries:
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of velocities and accelerations, to assess the applicability of the structural fuse concept to protect nonstructural components. Future work will also focus on multi-degree-of-freedom (MDOF) systems.

Studies on the Response of Nonstructural Systems in Structures with Seismic Isolation and Damping Systems

It is desirable, but not always achievable, to design hospitals to the performance level of either "Immediate Occupancy" or "Operational." Seismic isolation and energy dissipation or damping, particularly as described in the 2000 and 2003 *NEHRP Recommended Provisions for Seismic Regulations* (FEMA 2001, 2004), may be the only proven construction technologies that can achieve these performance objectives. Early studies at MCEER (then NCEER) showed promising performance for the application of such technologies (Juhn et al., 1992). Yet, methodologies for the design of nonstructural systems to achieve these performance levels are not available.

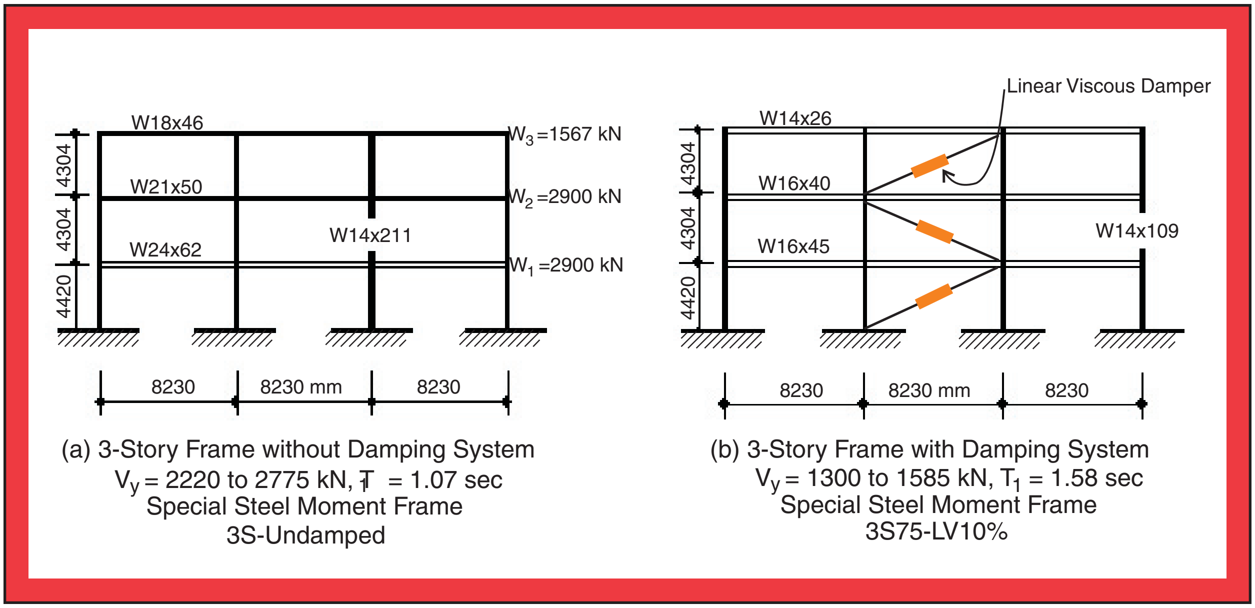
In order to develop methodologies for the design of hospitals for the "Immediate Occupancy" and "Operational" performance levels, it is necessary that (a) performance limits for nonstructural systems are established, and (b) the dynamic response of nonstructural systems is determined. Recently completed studies on the behavior of structures with seismic isolation and damping systems (Wolff and Constantinou, 2004) resulted in (a) a wealth of experimental results on systems of contemporary design, including data related to nonstructural (secondary) system response, and (b) comparisons of analytical and experimental responses that demonstrate the capability of nonlinear response history analysis methods to predict the response of nonstructural systems.

With the verification of accuracy of methods of analysis of nonstructural systems in structures with seismic isolation and damping systems, MCEER investigators performed studies of the response of these systems to provide:

- A comparison of performance of nonstructural systems in structures designed with contemporary seismic isolation and damping systems with a range of design parameters.
- Guidelines on selecting seismic isolation and damping hardware to achieve specific performance levels.

The approach followed was based on dynamic analysis of structures with the following attributes:

- Range of structural systems with different stiffness (period) characteristics.
- Range of seismic isolation and damping systems, including lead-core, elastomeric, friction pendulum, linear viscous, nonlinear viscous and yielding steel systems.
- Range of parameters for each system, including parameters for upper/lower bound analysis for each particular system.
- Range of seismic excitations, including far-field, near-field and soft-soil motions, all represented by suites of motions having a representative average spectrum.

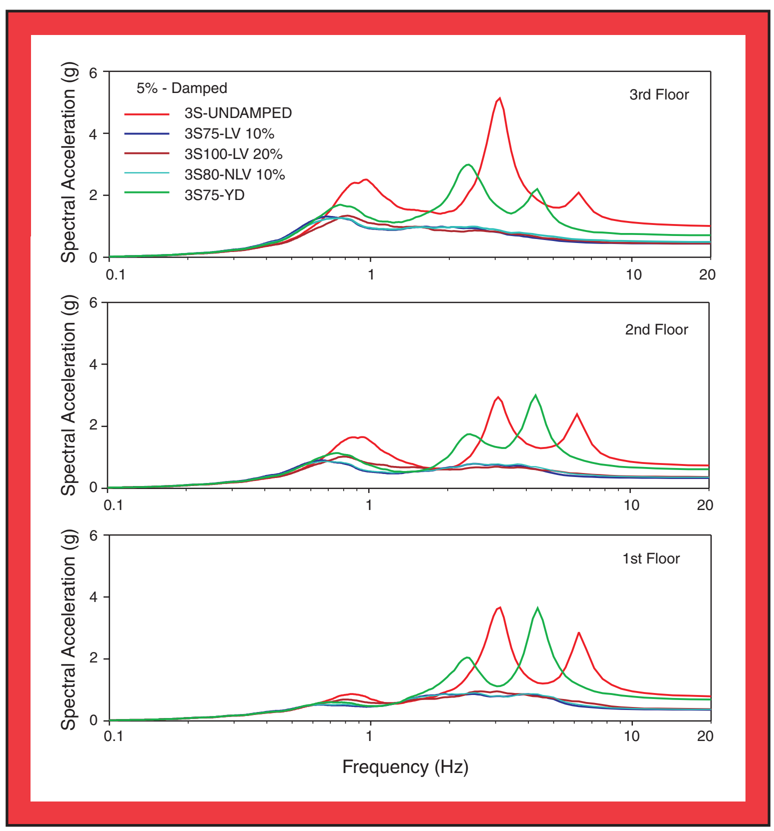


■ Figure 10. Example of Undamped (a) and Damped Frames (b)

Analyses have been completed for structures with damping systems and are on-going for seismically isolated structures. The assessment of performance is based on response quantities of points of attachment of non-structural systems (neglecting the interaction of the structure and the nonstructural systems), which include peak accelerations, peak velocities and spectral accelerations over a wide range of frequencies, as well as inter-story drifts.

Figure 10 illustrates two frames that represent part of the lateral force resisting system of two buildings. Both frames meet the criteria of the 2000 (also 2003) NEHRP recommended provisions for buildings without (frame on the left) and with damping systems (frame on the right, damped at 10% of critical). Note the substantial differences in the properties of the two frames (in terms of period T_1 and yield strength V_y).

Figure 11 presents calculated average (among 20 analyses) 5%-damped floor response spectra of the undamped building (red line), and of the building with the NEHRP-compliant damping system

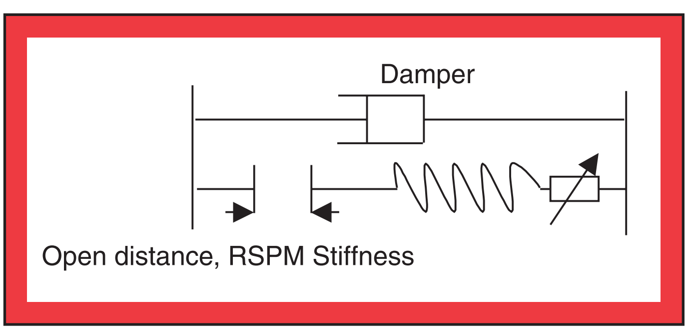


■ Figure 11. Floor Response Spectra in Damped and Undamped Structures

(3S-LV-10%, that is a linear viscous damping system providing a damping ratio of 10% in the first mode), as well other damping systems: two viscous systems designated LV-20% (a linear viscous system providing 20% damping ratio in the first mode), NLV-10% (a nonlinear viscous damping system providing an effective damping ratio of 10% in the first mode), and a yielding steel system, designated as YD. It should be noted that the undamped structure, the damped structure with the yielding steel system and the damped structures with the viscous systems at 10% effective damping just meet the NEHRP criteria for drift. The damped structure with the viscous system at 20% effective damping exceeds the NEHRP criteria for drift.

The results presented in Figure 11 are valid for an excitation with far field characteristics and stiff soil conditions. However, similar results were obtained with near-field motions and motions representative of soft soils. The results on floor acceleration response spectra and on floor velocities (not presented here) demonstrate clear advantages of certain, but not all, damping systems.

Results of this nature are currently produced by MCEER researchers for a range of structural systems, damping systems, isolation systems, and ground motion characteristics. The analysis also includes determination of the upper and lower bounds of the mechanical properties of the damping and isolation hardware, and use of these bounds in the analysis.



■ Figure 12. Combined RSPM and Passive Damping Hybrid Control System

Studies on Real-Time Structural Parameter Modification Systems

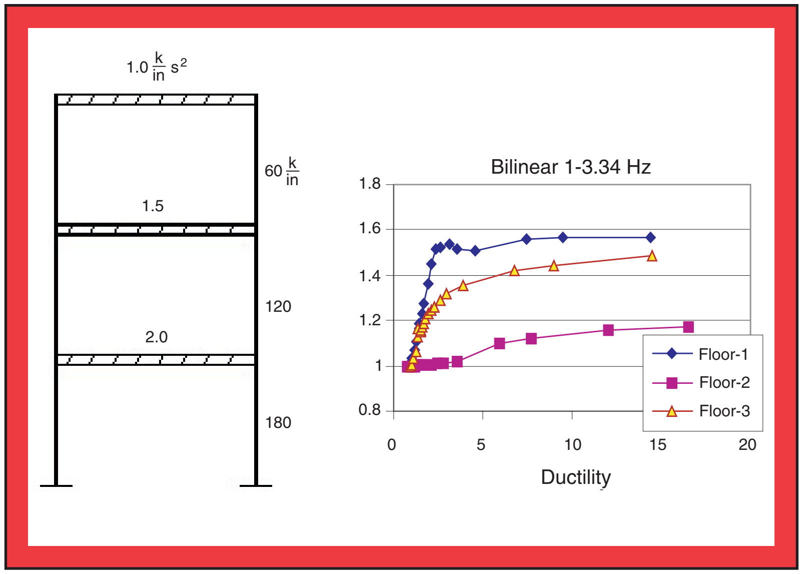
In an attempt to modify the response of the global structural system, a new method for modification of response was suggested to extend methodologies proposed in the last decade (Soong, 1990). The RSPM (Real-time Structural Parameter Modification) is a semi-active nonlinear control system for reducing seismic responses of structural and nonstructural systems and components. Figure 12 illustrates the operation of this innovative system developed by MCEER researchers. The system includes a passive damper and a controlled stiffness unit. The passive damper is always engaged to dissipate energy, but the stiffness unit is connected or disconnected based on a pre-set threshold. It is disconnected initially until a response threshold value—termed the open distance, is reached. If the relative displacement (positive or negative) becomes larger than the open distance, the stiffness unit is engaged to control the response. If, at any instant, the displacement becomes smaller than the threshold, the RSPM stiffness unit is disconnected. The semi-active control mechanism is activated only when the stiffness unit is connected. The devices are normally combined as a pair of tension and compression units working as a push-and-pull set.

The basic working principle of the semi-active system was described in Bruneau et al., 2003. MCEER research has been focused on the potential control benefit of the semi-active system over passive systems such as viscous dampers. The control effect of the semi-active system is targeted to seismic response reduction of nonlinear systems. To evaluate the seismic response behaviors in the linear and non-linear range, MCEER researchers have developed an index ratio of displacement incremental rate to the velocity incremental rate with respect to elastic responses. The mathematical definition of this ratio, η, is given below (see Chen et al., 2003, and 2004):

$$\eta = \frac{\max(d_{non}(t))/\max(d_{lin}(t))}{\max(v_{non}(t)/\max(v_{lin}(t))}$$

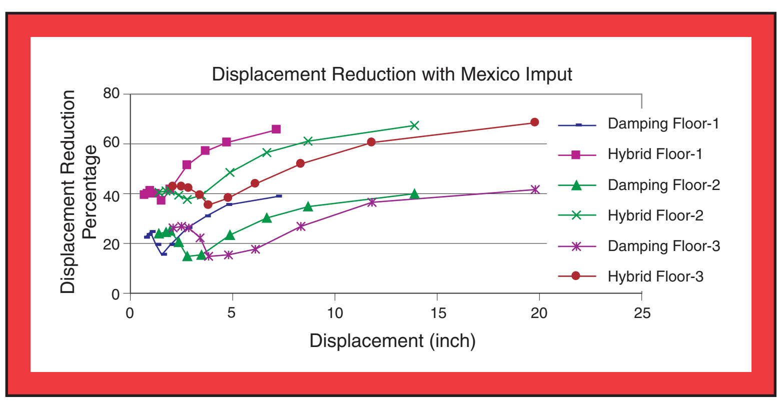
where d_{non} and d_{lin} are the inelastic and elastic displacement responses, respectively; v_{non} and v_{lin} are the inelastic and elastic velocity responses, respectively.

Using one- and three-story frame models, numerical studies under different ductility and natural frequency show that η is greater than unity, which means that the displacement responses increase much faster than the velocity responses. This behavior confirms that the displacement-based control is more effective than the velocity-based control in inelastic structural response reduction. Figure 13 shows the variation of η as a function of ductility for the bilinear inelastic responses of a three-story frame model. The study has also revealed that the change in η is strongly influenced by the yielding pattern (e.g., bilinear, tri-linear and continuous yielding), the natural period before and after yielding, and the ductility.



■ Figure 13. Variation of η with Ductility for a Three-Story Frame Model

Figure 14 compares a passive damper system with a hybrid system (passive damping plus semi-active) in the three-story frame model response control. The damping device has been chosen as a linear viscous damper, for which the damping ratio is 15%. In the hybrid control system, an equivalent 15% of the structural stiffness has been assigned to the RSPM control along with an equivalent damping



■ Figure 14. Seismic Response of Passive Damper and Hybrid Control System ratio of 15% contributed from the hybrid device. The selection of the hybrid control parameters is based on the actual configuration of the devices. Since RSPM is designed as an improvement to the passive damper, a semi-active component is generally added to enhance the performance of the passive damper. To show the effect of the semi-active component in the seismic response control, the comparison is carried out in a wide response range including: the elastic response, the yielding point and the large ductility range. Figure 14 shows that the displacement based semi-active control has a non-uniform control effect. In general, at each structural yielding point, the hybrid control effect outperforms the damping system; as ductility increases, the hybrid control effect also increases faster than the passive damping system.

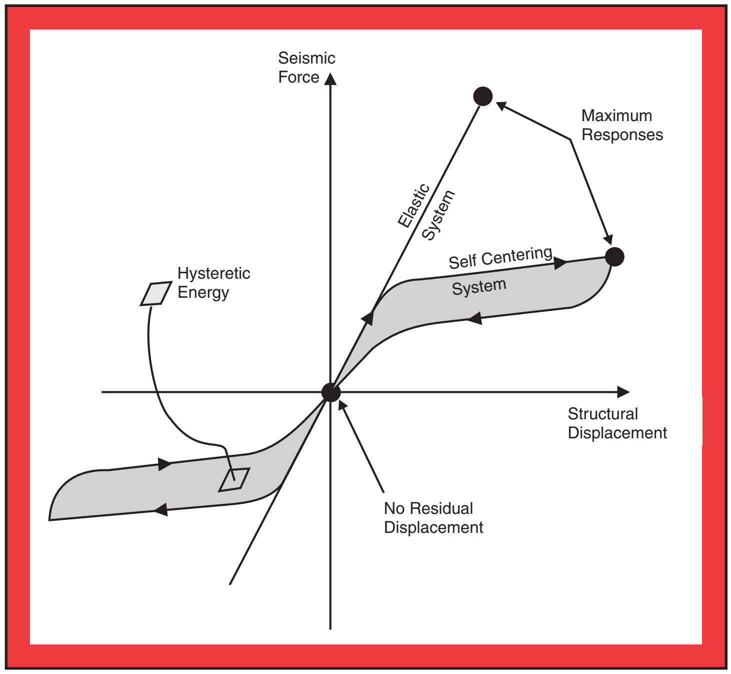
In summary, semi-active control strategies may be able to provide a larger control capability for seismically induced structural response reduction. In particular, they are better able to balance the difficult structural control requirements, such as limiting acceleration levels and controlling story responses, thus reducing structural response in both elastic and inelastic ranges. The progress described above will be further explored and considered for the MCEER Demonstration Hospital. It is hopeful that the semi-active control, together with other structural response technologies, will provide a much better floor response control for both linear and nonlinear response ranges. In turn, the reduced floor responses will result in less nonstructural component damage.

Studies on Self-Centering Systems

With current seismic design approaches, most structural systems, including those for hospital buildings, are designed to respond beyond the elastic limit and eventually to develop a mechanism involving ductile inelastic response in specific regions of the structural system. Although seismic design aimed at inelastic response is very appealing, particularly from the initial cost standpoint, regions in the principal lateral force resisting system will be damaged and may need repair in moderately strong earthquakes and may be damaged beyond repair in strong earthquakes. While the principle of mitigating loss of life in a strong earthquake still prevails, resilient communities require mission-control buildings, including hospital facilities, to survive a moderately strong earthquake with relatively little disturbance to business operation. The cost associated with the loss of business operation, damage to structural and nonstructural components following a moderately strong earthquake can be comparable, if not greater, to the cost of the structure itself. This implies that repairs requiring loss of business continuity should be avoided for protection against small and moderately strong events. In recent years, these issues have led to the development of structural systems that possess self-centering characteristics that are economically viable alternatives to current lateral force resisting systems.

Figure 15 shows the characteristic flag-shaped seismic response of such a self-centering system.

The amount of energy dissipation is reduced compared to that of a yielding system, but, more importantly, the system returns to the zero-force zero-displacement point at every cycle and at the end of the seismic loading.

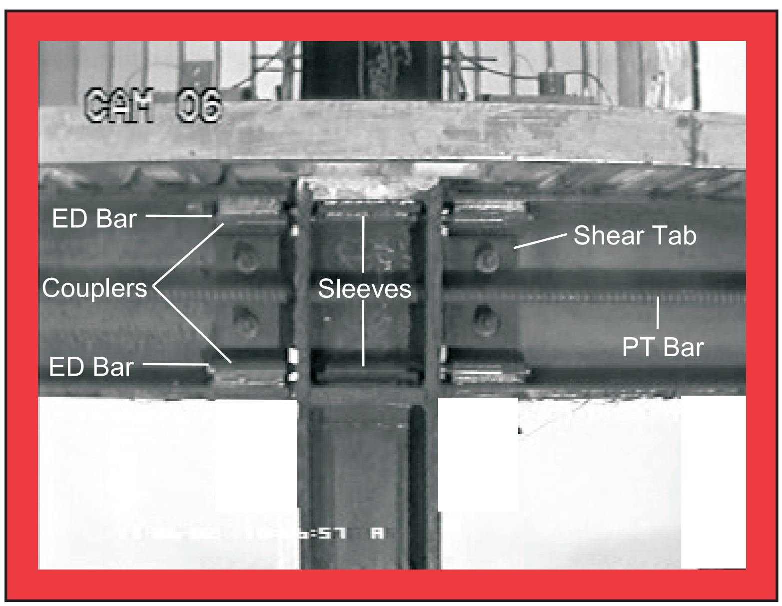


Christopoulos et al., 2002a

Figure 15. Idealized Seismic Response of Self-Centering Structures

Although several self-centering structural systems using shape memory alloys, or fluids constrained in specially-built containers or spring loaded friction systems have been proposed, the Post-Tensioned Energy Dissipating (PTED) steel frame shown in Figure 16 is particularly appealing for hospital buildings. In this system, unlike traditional moment-resisting frames, the beams and columns are not welded together. As shown in Figure 16, a post-tension (PT) self-centering force is provided at each floor by high strength bars or tendons located at mid-depth of the beam. Four symmetrically placed energy-dissipating (ED) bars are also included at each connection to provide energy dissipation under cyclic loading. These ED bars are threaded into couplers which are welded to the inside face of the beam flanges and to the continuity plates in the column for exterior connections, and to the inside face of adjacent beam flanges for interior connections. Holes are introduced in the column flanges to accommodate the PT and ED bars. To prevent the ED bars from buckling in compression under cyclic inelastic loading, they are inserted into confining steel sleeves that are welded to the beam flanges for exterior connections and to the column continuity plates for interior connections. The ED bars are initially stress-free since they are introduced into the connection after the application of the PT force.

MCEER researchers are investigating the seismic response of structural systems incorporating flag-shaped hysteretic structural behavior, with self-centering ca-

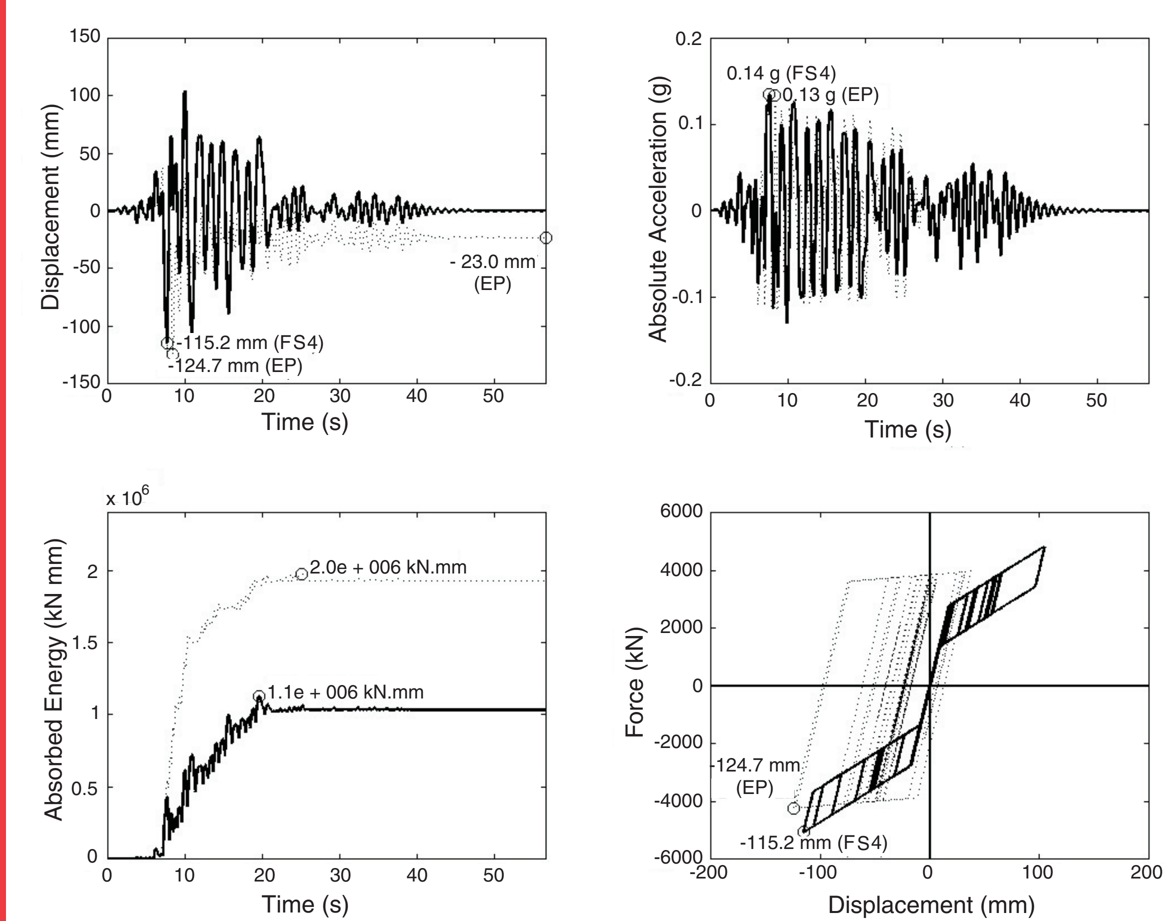


Christopoulos et al., 2002b

Figure 16. Concept of PTED Moment-resisting Steel Frames

pability. For a system with a given initial period and strength level, the flag-shaped hysteretic behavior will be fully defined by a post-yielding stiffness parameter and an energy dissipation parameter. Parametric studies are being conducted to determine the influence of these parameters on seismic response, in terms of displacement ductility and absolute acceleration, which are also demand parameters for nonstructural components. The responses of the flag-shaped hysteretic systems are being compared against the responses of similar bilinear elasto-plastic hysteretic systems, representative of traditional yielding structural systems.

Figure 17 presents the time-histories of displacement, acceleration, and absorbed energy for a one-story elasto-plastic (EP) system and for a flag-shaped (FS4) system that has the same initial natural period and 70% of the yield force of the EP system. The force-displacement responses of both systems are also compared in the figure. Note that



Christopoulos et al., 2002a

■ Figure 17. Comparative Seismic Response of Elasto-Plastic (EP) and Flagged-Shaped (FS4) Systems, 130% Loma Prieta (Hollister Differential Array) Record, a) Relative Displacement Time Histories, b) Absolute Acceleration Time Histories, c) Absorbed Energy Time Histories, and d) Force-Displacement Responses the elasto-plastic system deforms inelastically primarily in one direction, while the FS4 system has a similar amount of inelastic excursions in both directions. The FS4 system achieves a smaller maximum displacement than that of the EP system, while the maximum absolute accelerations are similar. The energy absorbed is considerably smaller for the FS4 system. Finally, unlike the EP system that sustains a residual displacement, the FS4 system returns to its initial zero position after the end of the earthquake.

Building structures with initial periods ranging from 0.1 to 2.0 s and various strength levels are being evaluated. Design envelopes for the post-yielding stiffness and energy-dissipation parameters will be determined in order to limit the demands that self-centering systems impose on nonstructural components to pre-determined levels.

Studies on Advanced Composite Infill Panels

One way to retrofit hospital buildings is by innovative design of infill walls. Even though infill construction has been popular since the late 19th century in seismic regions of the central and eastern United States, it is not until recently that polymer matrix composite (PMC) materials have received attention. Previously, structural frames infilled with unreinforced brick, concrete masonry, and structural clay tile dominated the industry. With the infrastructure of older buildings reaching a stage where there is significant deterioration and questionable functionality, many researchers have turned to more innovative strengthening schemes to improve on the disadvantages associated with traditional strengthening techniques. These modern rehabilitation techniques are needed to help simplify the construction process by reducing time, cost and inconvenience associated with seismic retrofitting.

Fiber reinforced polymer (FRP) materials have increasingly been evolving as a viable seismic retrofit strategy. The ability to use FRP material in the construction of infill walls is a great advantage. Prefabricated PMC infill systems have properties that can be tailored to achieve the desired response. Geometric configurations are able to remain unchanged, with the option to enhance structural performance by just changing fiber orientation and stacking sequence. In a structure seismically retrofitted with PMC infill walls, ductile behavior can be achieved through shear deformation of the walls instead of plastic hinge formation. This allows structures to remain functional following a seismic event, since the gravity load carrying system will not have irreparable damage.

This phase of the research builds upon the work of Jung (2003) and applies it to the MCEER demonstration hospitals. The main scope is to develop a simplified spring-dashpot model for the outer damping panel PMC infill system proposed so that dynamic analysis of the hospital structure can be performed with relative ease and reduced computation time. The proposed model should produce sufficient energy dissipation and ductility while keeping floor accelerations to a minimum. The outer damping panel system is made of FRP

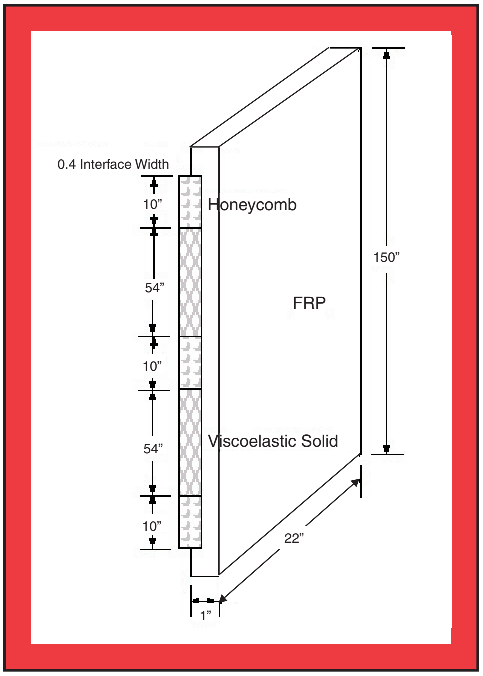


Figure 18. Details of Interface Layer of PMC Infill System

panels with an interface containing both flexible honeycomb and solid viscoelastic materials. Figure 18 shows a detail of the system. Combining viscoelastic materials with honeycomb at the interface between panels has proven to be an effective damping application and adds stiffness to the structure (Aref and Jung, 2003).

To evaluate the effectiveness of the PMC infill system, a moment-resisting frame from the MCEER west coast demonstration hospital described earlier is considered. A finite element model of the frame was created with the damping panels in the middle three bays, as shown in Figure 19. Cyclic analysis was then performed on the facility using the ABAQUS (1997) software package. The resulting global lateral force vs. displacement hysteresis loop of the structure is shown in Figure 20.

At this stage of the research, two fundamental issues are being considered: (1) the need for a robust viscoelastic model that works efficiently within the dynamic analysis in ABAQUS; and (2) the need for optimizing the size and distribution of the panels to obtain the proper modification to the floor accelerations and displacements in each demonstration structure.

Studies on Global Retrofit of Structures by Weakening and Damping

Another innovative approach developed by MCEER researchers to control the seismic response of structural and nonstructural systems and components consists of weakening existing structural components to reduce the maximum acceleration response, while adding energy dissipation systems (dampers) to control increased deformations (Viti et al., 2002). The method addresses simultaneous reduction of both the structure's accelerations and deformations. The effect of the weakening method can be viewed as similar to the effects of base isolation solutions, which decrease the global acceleration response of a structure while increasing its overall movement. However, the weaken-

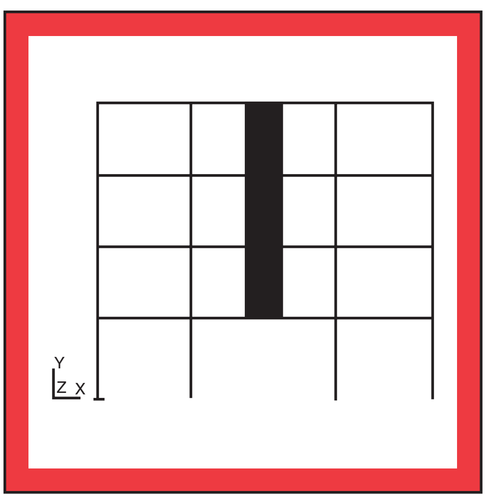


Figure 19. FE Model of Moment-Resisting Frame of MCEER West Coast Demonstration Hospital with PMC panels in Central Bay

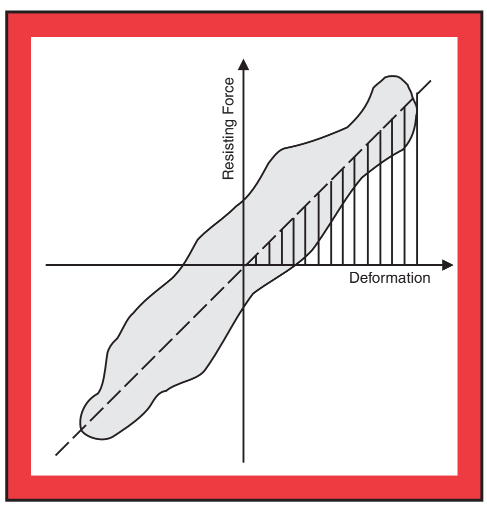


Figure 20. Global Hysteretic Response of Frame with PMC Panels

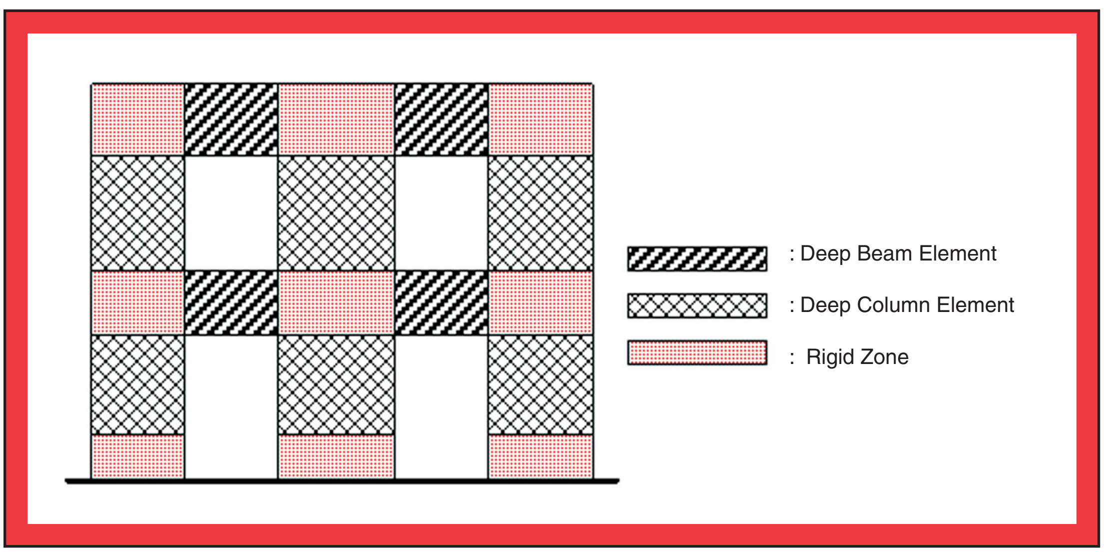
ing is not sufficient and requires control of deformations. The proposed solution requires modification of some of the structural components. Structures constructed with plain or perforated shear walls usually have high strength, and develop large accelerations during earthquakes, which leads to damage to equipment and nonstructural components.

Typical vulnerable hospital structures of this type are constructed mostly with walls that have openings for windows or access doors (identified herein as perforated walls). In an attempt to evaluate their behavior before and after applying the retrofit suggested above, a new modeling technique has been developed by MCEER researchers. According to the proposed technique, it is suggested to model such walls using a combination of frame models with deep beams and column elements with rigid connection panels as shown in Figure 21.

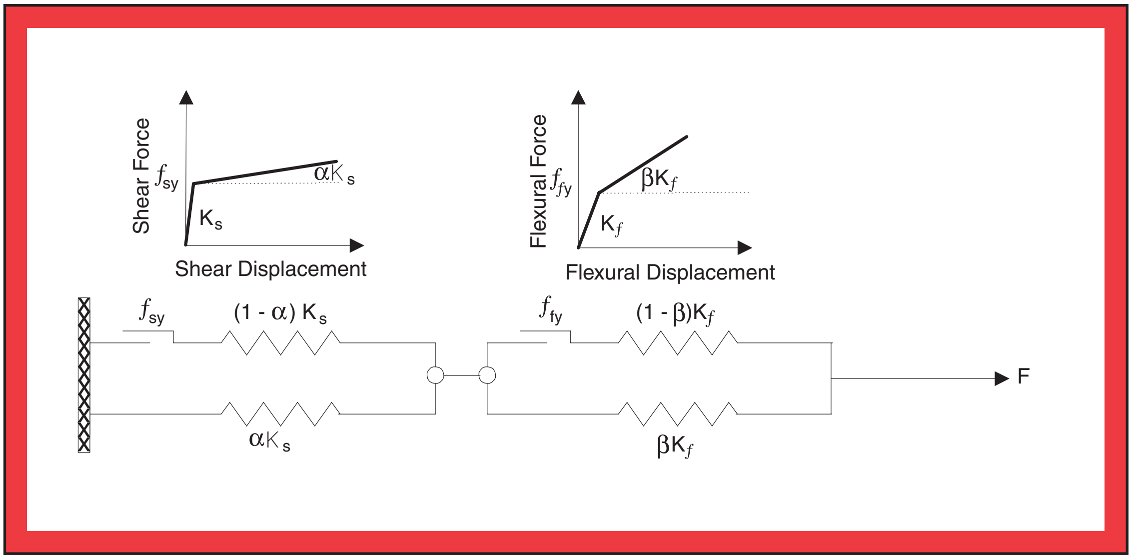
However, such models for "deep" beams and columns, which exhibit a strong interaction between their bending (flexure) and shear inelastic mechanisms, are not available in customary inelastic analysis computational platforms. MCEER researchers developed such models and implemented them in the inelastic structural analysis program IDARC2D leading to a new version (5.5), which is available to the MCEER Users Network and the specialized IDARC Users Group.

Deep beam and column elements can be expressed by a serial spring combination of shear and flexural stiffness, representing nonlinear behavior, as shown in Figure 22. Each bilinear nonlinear spring mechanism uses friction and linear spring elements to model the elastic stiffness and sudden transitions to post yielding stiffness.

There is only one difference between the deep beam and deep column elements: the "deep" column element can also resist axial loads. In the elastic range, the initial stiffness in shear ($(1-\alpha)K_s + \alpha K_s = K_s$) and flexure ($(1-\beta)K_f + \beta K_f = K_f$) are operating. Note that α is the ratio of yield to initial *shear* stiffness (K_{sy}/K_s); β is the ratio of



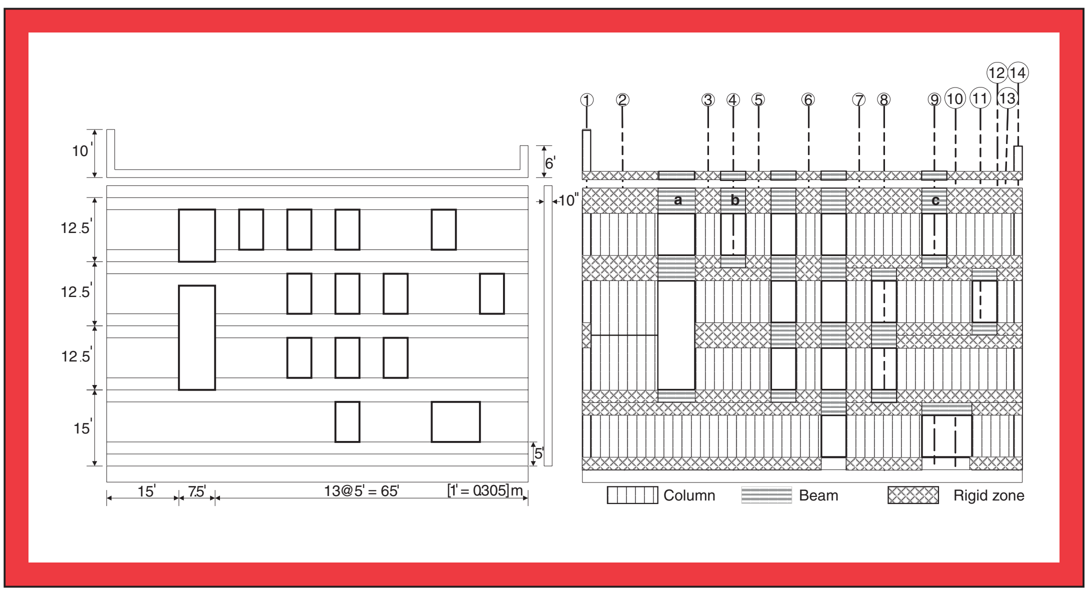
■ Figure 21. Model for Shear Wall with Regular Openings (Perforated Walls)



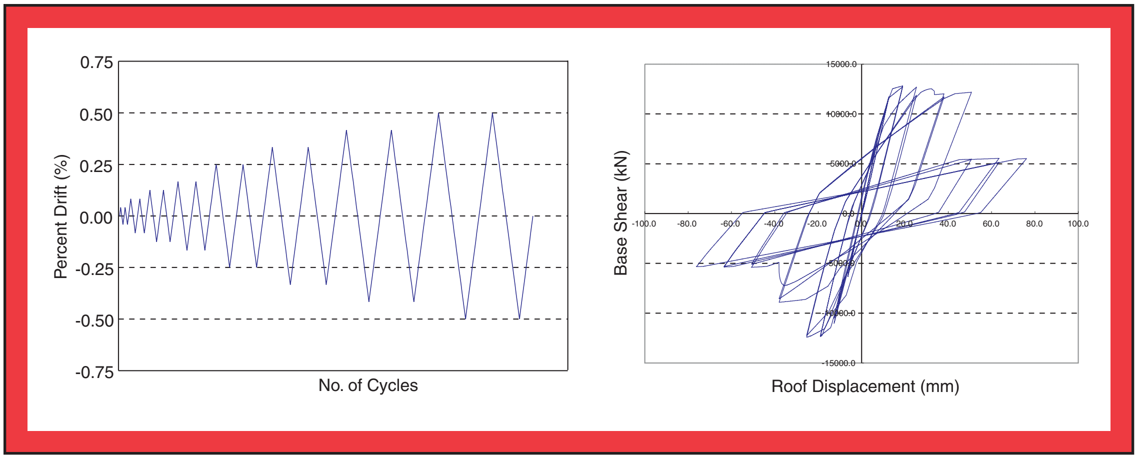
■ Figure 22. Macro-Model of Flexural-Shear Element

yield to initial *flexural* stiffness (K_{fy}/K_f). When yielding occurs in shear, flexure, or both, the friction elements are sliding, maintaining the yield force constant. The post yield (sliding) stiffness of each system is governed by the shear (αK_s) or flexural (βK_f) springs in parallel with the sliders. At this stage, the springs in series with the friction-sliders do not deform at all and do not contribute to any force increase.

An extensive verification of this approach was performed by MCEER researchers using a typical wall with openings (Figure 23) from a California hospital which required retrofitting. The model of the wall was analyzed with an increasing amplitude cyclic load and the performance was record-



■ Figure 23. Shear Wall with Openings Case Study, Geometry (Left) and Model (Right)



■ Figure 24. Shear Wall with Openings Case Study, Lateral Lading (Left), Hysteretic Response (Right)

ed in terms of force displacement evolution (Figure 24) and damage progression. The performance shows a sharp reduction in the force capacity of the wall due to local shear of peers between openings and some flexural yielding at the first floor. The damage indices calculated by IDARC2D (ver. 5.5) suggest that extensive damage is expected in the first floor although the strength of the wall is high.

The analytical tool developed by MCEER researchers enables evaluation of the wall structure and provides a way to determine the amount of strength reduction. IDARC2D can then be used to evaluate the influence of both weakening and the contribution of added energy dissipation systems.

MCEER Research Integration toward Enhancing Seismic Resilience of Nonstructural Systems and Components

With the objective to enhance knowledge of the seismic performance and fragility of nonstructural components, MCEER is planning to intensify its experimental studies on nonstructural components in acute care facilities. The general research methodology can be broken down into five distinct phases that will start with Year 8 research activities, as described below.

Phase 1. Generation of Ensembles of Strong Ground Motion Records

Ensembles of synthetic strong ground motions representative of the range of seismic hazard levels for a given region will be generated. The ground motions will be selected based on the de-aggregation of the seismic risk for a given region in terms of most-likely magnitude-epicentral distance scenarios. The analytical strong ground motion model for the eastern and western United States developed at MCEER by Papageorgiou 2001 et al., will be utilized to generate the strong ground motion records. This ground motion model is described in another paper in this Research Accomplishment volume. Two specific sites will be considered in this study corresponding to the two MCEER demonstration hospitals located in Southern California and New York State, respectively.

Phase 2. Generation of a Floor Acceleration Database

A floor acceleration database for the two demonstration hospitals will be generated based on time history dynamic analyses of various structural framing systems of these two structures using the ensembles of strong ground motion records generated in Phase 1. These analyses will be conducted as part of several integrated research projects within MCEER that are looking at enhancing the seismic performance of structural systems through seismic response control technologies, as described in this paper. This floor acceleration database represents demand functions for various seismic hazard levels, locations, floor levels, and structural framing systems incorporating various seismic response control technologies (e.g., passive damping, base isolation, etc.).

Phase 3. Taxonomy of Nonstructural Components in MCEER Demonstration Hospitals

Taxonomy of the most important nonstructural components in the two MCEER demonstration hospitals will be developed. Information will be collected from available MCEER data and from information available in the literature.

Phase 4. Experimental Assessment of Seismic Fragility of Nonstructural Components

Seismic (shake table) tests will be conducted on acceleration-sensitive nonstructural components typically contained in the MCEER hospital testbeds and other acute care facilities, as determined in Phase 3 of the research. The shake table floor motions used for the seismic testing will be obtained from Phase 2 of the research. Donations will be sought to obtain representative nonstructural components. A general purpose shake table testing platform will be constructed. The shake table testing will incorporate various phases, including different locations, seismic hazards, floor levels, and nonstructural components with and without seismic protection/restraint systems incorporated. The results of the shake table testing will provide guidance on the seismic design and retrofit of nonstructural components and will allow the construction of experimental seismic fragility curves for various limit states.

Phase 5. Formulation of Structural Design Objectives

Once the relationship between the seismic fragility of nonstructural components and the structural demands has been established, structural design objectives can be established for various target probabilities of failure of nonstructural components. These objectives can then be used to optimize the structural design of acute care facilities using particular seismic response control technologies, thereby providing a feedback loop to the research projects described in this paper. Furthermore, this fragility information represents a critical component to be implemented in the decision support methodologies for acute care facilities currently under development at MCEER (see Petak and Alesch in this volume).

Conclusions

This paper has briefly described the integrated research currently underway at MCEER to better understand the application of various seismic response control technologies to protect structural and nonstructural systems and components in acute care facilities from the effects of earthquakes. This innovative work is on schedule to deliver, by year 10, robust and applicable decision support methodologies for enhancing the seismic resilience of acute care facilities.

Acknowledgements

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Organizational Decision Making with Respect to Extreme Events: Healthcare Organizations Respond to California's SB 1953

by William J. Petak and Daniel J. Alesch

Research Objectives

Decisions about enhancing seismic safety in critical facilities require more than engineering choices about which technology is most appropriate. Such decisions are made in the context of organizational goals and strategy, financial capacity, choices about how safe is safe enough, and driving forces in the social, economic and political environment. This project is aimed at devising integrated decision-assisting models to help executives and engineers make informed choices about alternative approaches to improving seismic safety. The platforms integrate state of the art understanding of structural response, alternative means for mitigating the risk, normative decision-assisting models, and behavioral models of organizational choice and decision processes.

The Thrust Two research program of the Multidisciplinary Center for Earthquake Engineering Research aims at learning how to ensure the implementation, where appropriate, of technical means for reducing the effects of earthquakes on buildings and their contents. To achieve this end, three interrelated research projects are focused on two goals. The first goal is to learn how healthcare organizations make choices about whether and how to take precautions against extreme events, such as earthquakes, which vary in terms of size and where and when they occur. The writers have been working to understand that process. The second goal is to devise decision-assisting tools for healthcare organization leaders and for those who advise them so they might make appropriate choices.

Gary Dargush and Detlof von Winterfeldt are developing normative decision-assisting models to that end, each using a different approach, but both focused on generated and/or evaluating options for enhanced seismic safety at the level of the building and its components. Petak and Alesch (the writers) are developing a behavioral model of decision making at the level where organizational officers must make tradeoffs between mission, business objectives, and complying with regulations, often within the context of owning multiple facilities located in a variety of places.

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Previous Summaries

2001-2003:
Alesch et al.,
http://mceer.buffalo.edu/publications/resaccom/0103/07alesch.pdf

2000-2001:
Alesch and Petak,
http://mceer.buffalo.edu/publications/resaccom/0001/rpa_pdfs/02Alesch_final.pdf

The two research efforts are complementary. For those of us concerned with improving decision processes and choices, empirically-based behavioral models provide an appropriate starting point. Normative models must embrace the multi-variate rationality employed by real decision makers making real choices. The researchers worked to learn the extent to which their respective efforts can contribute to one another. They concluded that their approaches are more than complementary. It looks as though they can be linked to create a powerful set of decision-assisting tools for organizations faced with making choices about what, if anything, to do to protect themselves against low-probability/high-consequence events.

Linking the several models will not be a simple matter. Dargush and von Winterfeldt are building models that generate and evaluate alternative courses of action with respect to building, rebuilding, or retrofitting individual structures. We (Alesch and Petak) are working to understand how organizations frame the problem, visualize constraints, and devise alternatives within the organization's internal and external environments and, then, how they go about selecting from among alternative courses of action, given multiple objectives.

Together, we concluded that the Alesch and Petak model can provide important information about the range of alternatives healthcare organizations can realistically consider, given their circumstances at any given time, and the multiple goals they seek. That information would inform the von Winterfeldt models directly, but not by simply adding a line or two of equations to his models. Instead, the behavioral model will provide constraints and parameters.

Dargush is building two kinds of models. The first are based on simulating evolutionary processes. With those models, Dargush is able to test any number of engineering modifications to a set of equations representing a structure and subject that "structure" to a large array of seismic forces, representing many earthquakes of varying intensity located in many places in the structure's vicinity. These models nest within the Petak and Alesch model because of the way they generate and evaluate alter-

> The decision-assisting platforms are intended to help illuminate the consequences of choice for both engineering consultants and their clients. Since clients must consider a wider range of variables than their engineers when making choices about seismic safety, the models are intended to couple organizational and engineering concerns into one or more models to help create recommendations for seismic safety that meet the needs of all the critical stakeholders. Stakeholders may include companies interested in developing markets for new technologies, critical care facility owners required to meet legislated levels of seismic performance, local communities faced with prioritizing rehabilitation projects and/or federal agencies responsible for resource allocation.

native solutions. Coupling these modeling approaches is intended to provide an input to the strategic and capital planning process at the individual building/structure level to help select the optimal approach to the structural problem.

Dargush's second model links with both the Petak-Alesch model and the von Winterfeldt model. The model employs dynamic programming to simulate changes in stocks and flows of resources and other critical phenomena in a hospital. The Alesch-Petak work shows how hospitals are unable to pursue some desirable alternatives, for example, when resources are low or credit unavailable. Simulating changes in stocks and flows through time can enable decision makers to better understand the conditions under which various alternatives might be feasible.

It became clear while working with von Winterfeldt and Dargush that we (Alesch and Petak) would have to specify a descriptive model of healthcare organization decision making. This paper reports on our first attempt at such a model. At this point, the model consists of a process flowchart with accompanying text.

The three teams will attempt to operationalize their respective models and integrate those models in a West Coast Demonstration Hospital during MCEER's Year 7 (which corresponds, roughly, with 2004). In that effort, we continue to assess and elaborate our model and to generate values for its several variables. Those values will be the primary linkages with the von Winterfeldt and Dargush models.

Research Strategy

In our efforts to devise both a greater understanding of organizational decision making about extreme events, we focused on organizational response to a single phenomenon that applies to a large number of diverse California hospitals and healthcare organizations. In 1994, California enacted legislation requiring hospital facilities built before 1973 (at which time tougher standards were enacted for hospitals yet to be built) to be brought up to contemporary standards of earthquake resistance or to be withdrawn from service as an acute care facility. That law affected 1,023 individual buildings, about 38 percent of the hospital buildings in the State. Consequently, the statute has a broad impact across the State. The legislation, known as SB 1953, affords an excellent opportunity to identify and examine healthcare organization decision making on a specific set of seismic safety issues at essentially the same time and across a broad spectrum of healthcare organizations varying in size, financial viability, organizational structure, and location.

We have built on the research of others in public policy implementation and in organizational decision making.

Previously, we reviewed the policy development and implementation literature (Alesch and Petak, 2001). Much of that literature focuses on explaining why public program implementation was ineffective in one or another setting. This is valuable, but few of those who contributed to the policy implementation literature go beyond looking at governmental agency

Links to Current Research

The decision support systems under development in this effort will incorporate the seismic retrofit technologies and response modification methods developed in a parallel effort being carried out by Bruneau, Reinhorn and others in Thrust Area 2.

"...it is important to understand the decision making process in which organizations choose whether and how to implement risk reduction measures."

efforts to implement programs. In some instances, public agencies do actually take the steps necessary to result in the desired changes to the target system. In others, however, public agencies implement programs by attempting to induce or coerce private organizations to take the steps needed to effect the desired outcomes. Such is the case with SB 1953. Implementation for California's Office of Statewide Health Planning and Development (OSHPD) consists mainly of getting individual organizations to actually take the steps necessary to comply with the regulations. Those organizations may be investor-owned, not-for-profit, or governmental; what they have in common, for our purposes, is that they are called upon by state level public policy to take actions or to change their behavior so as to cause that public policy to have the desired community outcomes. Consequently, it is important to understand the decision making process in which organizations choose whether and how to implement risk reduction measures.

Those scholars who focus on program implementation rarely look at decision making by the multitude of organizations actually charged with taking the steps necessary to bring about the desired outcomes. At the same time, researchers concerned with organizational decision making seldom take cognizance of programs designed by others and intended to induce various behaviors in those organizations. To a somewhat greater extent, decision theorists have taken cognizance of the contextual environment within which organizational decision makers frame problems and make choices.

We think that understanding public policy implementation requires understanding the processes by which policy is enacted and the fundamental design of policy sanctions and incentives, as well as understanding the decision processes and criteria employed by organizations that are intended to actually produce the desired outcomes. Only then can one understand how to increase the probability that implementation will follow enactment. However, at the same time one identifies impediments to implementation, it is appropriate to focus on the other side of the equation; that is, under what conditions will organizations choose to implement earthquake hazard risk reduction measures?

Kingdon (1984) argues that it is necessary to improve the policy process. We recognize the need for better public policy that takes into consideration the larger picture and are conducting research on that as a parallel activity, but this part of our work focuses on organizational decision making in response to a mandate. For the larger question, several important questions have to be addressed. First, one must ask the extent to which "community outcomes" were considered in terms of delivery of health care needs to the people. Did the State consider this, or was it driven by a narrower objective of simply reducing seismic risk at the building level? Policy is silent on how many hospitals in which regions would be needed to provide the desired level of care following an earthquake. Further, the process does not appear to have taken into consideration all stakeholders' views, nor, apparently did lawmakers consider the impact on the overall health care system. The policy and legislative history seems to be silent on the need for protecting patients, staff, and capacity for other than acute care facilities, including psychiatric care, transition care, nursing home care, and elderly/senior citizen care facilities. They are all considered hospitals and under OSHPD oversight and licensing. Organizations could choose to remove an acute care facility from the inventory rather than fixing or replacing it, thus reducing the service available to the community.

For the current effort, it became clear that it would be necessary for us to devise a process model of how healthcare decision makers make choices about making investments to mitigate extreme events. The model must reflect actual behavior, as ascertained through field research, but it must also be grounded in theory drawn from both organizational decision making and public policy implementation. Our strategy became one of, first, documenting and generalizing processes and criteria employed by hospitals and, second, working to place the preliminary model into a more theoretical and more generalizable model. That way, the model would have application to a broader set of organizations faced with making choices about what to do when faced with extreme events – those events characterized by a low probability of occurrence and high consequences should they occur.

We conducted an extensive inquiry into SB 1953. We set out to learn how it came to be enacted as well as the regulatory requirements derived from the law. We then sought, with individual healthcare organizations, to learn what they decided to do in response to the legislation and program regulations and how they made that decision.

We employed soft systems methods (Checkland,1999) coupled with a grounded theory approach (Strauss and Corbin,1998) to develop and document our understanding of the processes and choices made by various healthcare organizations. We talked with more than 40 knowledgeable persons in northern and southern California, face to face, in open-ended discussions to learn about hospital responses to SB 1953. We talked with many of these people several times over a period of almost three years. These include hospital administrators, structural engineers, state-level policy implementors, staff from professional and organizational associations, and persons who were involved historically in the drafting and enacting SB 1953 process to try to get as complete an understanding from as many perspectives as we could. These people were able to provide specific information about the responses of a diverse set of healthcare organizations to SB 1953. Interviewing actors in the process who held different kinds of positions and different views about the same subject matter enabled the researchers to develop what they think is an accurate portrayal of how SB 1953 has been viewed and addressed.

Prerequisites to Action as a Fundamental Element of the Model

Prerequisites to Action: March and Olsen's Garbage Can

March and Olsen's Garbage Can Model of organizational decision making (March and Olsen, 1973) was useful when we attempted to understand why it took California municipalities so long to adopt retrofit ordinances for unreinforced masonry buildings (Alesch and Petak, 1986). The model posits that decisions are not made, nor is action taken, unless four independent streams come together simultaneously. The streams consist of a problem (about which there is a critical mass of agreement within the organization), a solution to the problem (which is credible for a critical mass of actors within the organization), space on the organizational agenda, and one or more persistent advocates pressing the issue. An important premise is that each of the four streams is independent of the others. That is, problems exist quite separately from whether solutions to them exist. Conversely, solutions abound quite independently from problems. Many people have a favorite solution that they try to impose on any number of problems, regardless of the quality of the match. It is important, too, to understand that even if a problem exists in the minds of organizational decision makers and a technical solution exists that most agree would address the problem effectively, nothing will happen unless the issue makes it to the top of the organization's agenda.

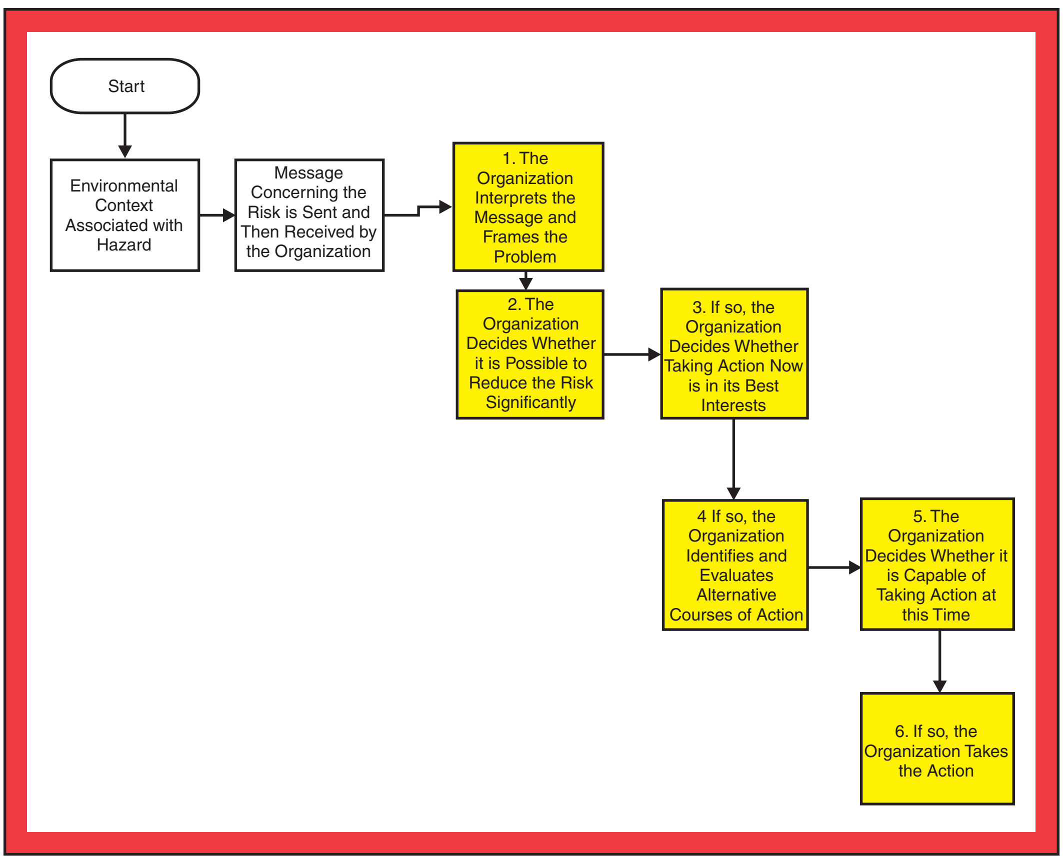
Although a policy may make its way onto an agenda and ultimately be adopted by a public policy making body, there is no certainty that implementation will occur. Those stakeholders required to implement the policy must also accept the definition of a problem and agree that the solution embodied in the policy is appropriate in their context. They must be in agreement with the policy as a solution to the problem as they understand it. Thus, in addition to the convergence of the four independent "streams," it is important to gain acceptance of the policy by the individuals and organizational decision makers critical to implementation. Addressing the issue associated with the need to gain acceptance by decision makers in multiple organizations, Lober (1997), building on the work by Kingdon (1984), suggested that the complexity created by the need to address multiple organizations or stakeholders requires an approach that allows for their collaboration in the agenda setting process. In the context of the "garbage can" model, this means adding and facilitating an "organizational stream" to facilitate collaboration necessary to increase organizations and stakeholders understanding of the problem, thereby helping to increase their willingness to accept the selected policy solution option and develop acceptable implementation approaches.

Moving Beyond March and Olsen: Five Prerequisites to Organizational Action

March and Olsen's prerequisites led us to consider whether there were other prerequisites to organizational action, particularly in the context of making choices about what to do about reducing potential losses from low-probability/high-consequence phenomena (Alesch and Petak, 2001).

Our analysis of decision making in response to SB 1953 suggested five fundamental organizational prerequisites for adoption and implementation of risk reduction measures (see Figure 1). These prerequisites are not inconsistent with those of March and Olsen, but we think they build on their construct. Our prerequisites are sequentially cumulative.

Awareness of the Issue. First, the organization must be aware of a threat, opportunity, or challenge from its relevant environment and believe it to be salient to the organization. This is similar to March and Olsen's problem prerequisite. We have expanded the notion to encompass both problems and opportunities. We also add the notion that an organization may become aware of the threat in any of several ways. It may detect a signal from its environment and interpret it as a threat. Or, it might have a sophisticated monitoring program that detects signals or patterns in the environment and translates those as either a problem or an opportunity. Alternatively,



■ Figure 1. Oversimplified Model of the Healthcare Organization Seismic Safety Investment Decision as in the case of SB 1953, a message might be sent directly to the organization by a regulator.

Internal Locus of Control and Belief in its Own Efficacy. Second, a critical mass of decision makers in the organization must believe that it is theoretically possible for the organization to take action to reduce adverse effects should the threat occur. The organization must feel that, at least in the abstract, it is possible to mitigate potential consequences of the threat. This requires that the organization have an internal locus of control and a sense of efficacy with respect to the threat; the "problem" cannot be perceived as either intractable or as existing outside the organization's locus of control. March and Olsen do not explicitly acknowledge the need for an internal locus of control and a sense of organizational efficacy with respect to the problem or opportunity. This is a crucial prerequisite and an addition to their model.

In the Organization's Best Interests to Act Now. Third, the organization must believe that it is in its best interests to act now rather than later or not at all. This is an agenda issue: how does this problem measure up to other concerns and priorities? Where should it be placed in the stack of things the organization has to deal with? We added a temporal dimension and proactive solution-seeking element to the March and Olsen model.

An Acceptable Solution Must Exist. Fourth, the organization must find or create a means for addressing the problem or opportunity that is congruent with the organization's values, mission and goals, fundamental strategy, and constraints. This is comparable to March and Olsen's solution.

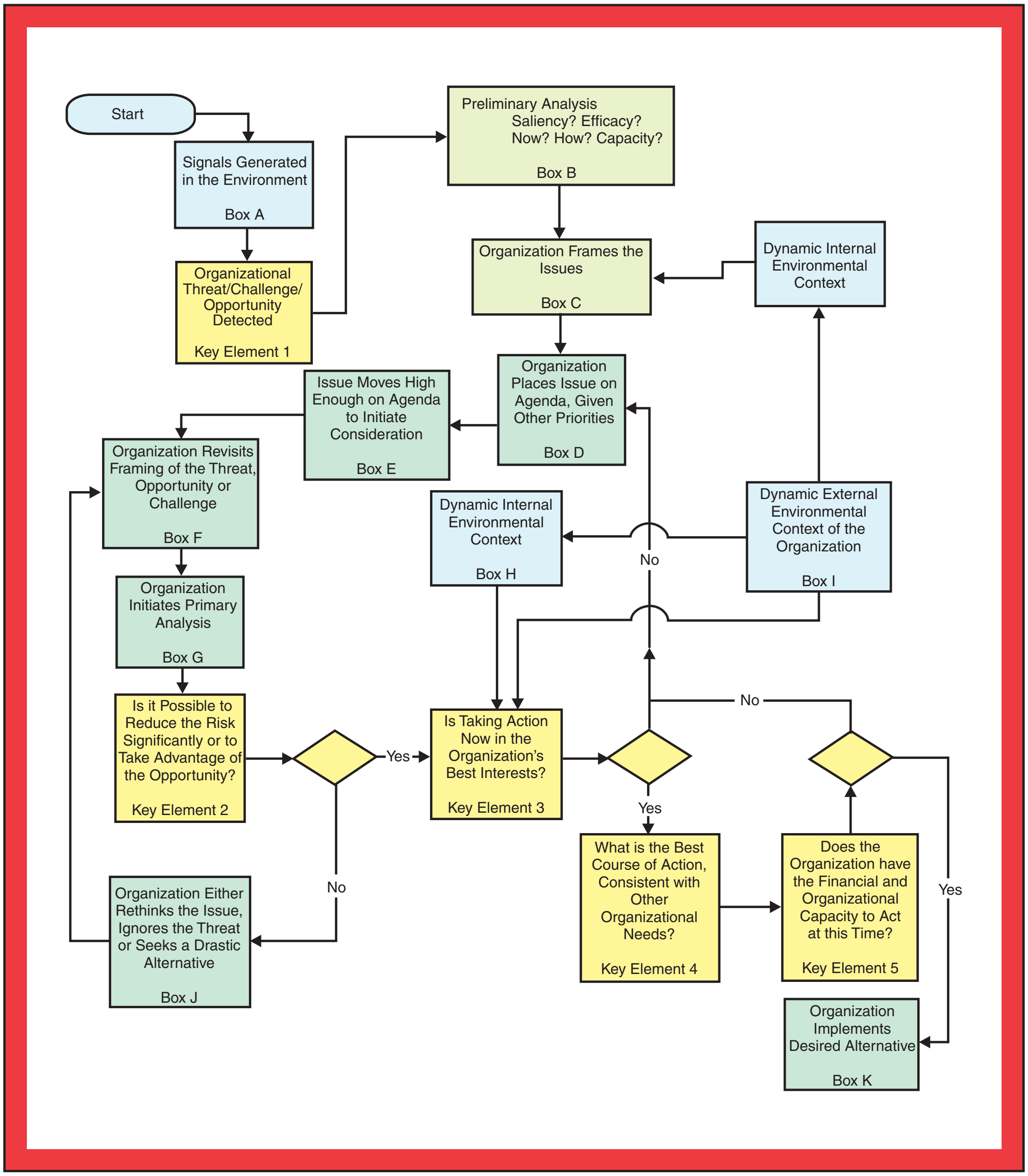
Must Have the Capacity to Act. Fifth, the organization must believe that it has the capacity to act at this time. Even with an agreed upon problem, an agreed upon solution, and a desire to act, an organization without requisite resources at a specific time and place will be unable to bring everything together to take the desired action. In that case, the organization must recycle its process to articulate, perhaps devise, a new set of options.

Elaborating and Applying the Model: Organizational Choice in Response to SB 1953

From our discussions with system actors, we created a flow diagram to represent the approach most healthcare organizations employed to decide how to respond to SB 1953. We framed it in terms of our list of prerequisites to organizational action to make it easier to generalize the model. We encountered some difficulty in developing the model, primarily because, while all the organizations we studied engaged in the same general process, individual processes varied in detail and emphasis. Moreover, virtually none of the organizations engaged in a strictly linear approach to solving the problem. Most organizations addressed it iteratively, circling back to earlier assumptions, building in new information and new perceptions, and rethinking options, discarding some, fleshing others out, and searching for new ones.

Another complicating factor is that most hospitals or healthcare campuses do not get to make the mitigation investment decision by themselves. When SB 1953 was enacted, there were many stand-alone facilities able to make those decisions. Today, most hospitals are part of larger corporations; individual facilities submit budget requests to the home office for final decisions. The model does not yet do a particularly effective job of integrating the multiple layers of corporate decision making. That will have to be added.

The process flowchart depicted in Figure 2 represents our concep-



■ Figure 2. Preliminary Model of the Healthcare Organization Seismic Safety Investment Decision tion of the behavioral decision process employed by healthcare organizations when making the mitigation investment decision. It is a preliminary model that the writers plan to test and elaborate, using an MCEER Demonstration Hospital as a test case.

Believing a Threat Exists: The Organization Picks up the Signal, Interprets it, and Frames the Problem

Our model requires that the organization receive a signal that there is a threat to its well-being or that an opportunity exists. For the sake of brevity, from now on we will refer to the signals only as threats. The signal is generated within the organization's relevant environment (Box A, Figure 2). The organization detects the signal, interprets it, confirms its authenticity, and conducts a preliminary analysis before it begins to frame the issues or problems implicit or explicit in the signal (Key Element 1 and Box B, Figure 2).

Message Transformation: Replacing the Initial, Ineffective Threat Message with a New One

We began with the assumption that the message sent to California healthcare organizations was that they were in danger of an earthquake that was likely to damage their facilities and reduce their capacity to carry out their missions. That message had been sent to Californians and to hospital administrators many times before by structural engineers, the California Seismic Safety Commission, reports of damage to hospitals in previous earthquakes, and from seemingly endless warnings from geologists and seismologists. A strong message was sent directly to hospitals in the form of the 1973 legislation requiring hospitals built after that date to meet high structural and nonstructural standards.

We found that hospital owners and administrators were aware of earthquakes, but that awareness failed to generate sufficient concern among most of them to alter their pre-1973 acute care facilities. Some hospital decision makers did not believe that their pre-1973 structures would collapse from earthquakes. Others had higher priorities, including how to provide service to the rapidly growing California population. It would have been extremely difficult to withdraw acute care facilities from the inventory and keep pace with providing high levels of demand for service.

Sometimes, when one message fails to have the desired effect, those sending the message replace it with a different one in hopes of stimulating action. With SB 1953, the State of California changed the message from "there is a potential for losses from earthquakes if you do not alter those old buildings" to "you will lose your hospital license if you do not repair or replace old buildings being used for acute care." The new message contained a far more plausible risk in the minds of administrators, making it much more salient and led to immediate responses, although not all the responses were those desired or expected by regulators.

The Contextual Setting of the New Message

SB 1953 was neither drafted nor enacted in a vacuum. Nor was it legislation hastily drafted and enacted in the immediate aftermath of an earthquake. It emerged from a context in which hospital regulators and structural engineers were genuinely concerned about the potential effects of seismic events on hospital patients, staff, and capacity.

Earthquake safety advocates were moved into action following the 1971 Sylmar earthquake in which hospitals failed, lives were lost, and post-event emergency health care capacity was diminished. This event led to enactment of legislation in California in 1973 requiring that all new hospitals be built to higher standards. Existing hospitals were excluded. Those who helped draft the 1973 Act expected that the stock of existing hospitals would be replaced over time. After all, many of them were quite old. The 1994 Northridge earthquake resulted in significant damage to several pre-1973 hospitals, thus stimulating earthquake safety advocates, mostly structural engineers, to be concerned that the stock of pre-1973 hospitals was not being taken out from service quickly enough and to believe that additional regulation was necessary to speed the process.

Healthcare organizations learned about SB 1953 as it was being developed and considered. For the most part, they appear to have supported the enactment of SB 1953, but they did so within a context in which other bills being considered were seen as Draconian. For many healthcare organizations, SB 1953 was the lesser of two evils.

First Iteration: A Preliminary Assessment

Once a message comes to the attention of an organization, we believe that organizations first undertake a quick and dirty analysis (Box B, Figure 2.). This preliminary analysis answers several questions that affect how the organization subsequently frames the problem and a response to it:

- Is the message legitimate and credible?
- If legitimate and credible, how salient is the message content for the organization?
- If legitimate, salient, and credible, what are the implications for the organization?
- What is the quality or appropriateness of the solution and the cost and disruption?
- Would acting on the message be congruent with organizational values, goals, and strategy?
- Are there higher priority issues on the agenda that preclude responding to the message at this time?

Organizations framed the challenges posed to them by SB 1953 based on those preliminary scans (Box C, Figure 2). How the individual organization framed the problem conditioned its posture with respect to it and initially limited or focused its choice about how to respond.

In the case of SB 1953, the organizations appear to us to have made a quick assessment of the likely burdens associated with complying and of any benefits that might realistically derive from complying. The analysis proceeds with the organization drawing alternative means for complying being from its repertoire of invented, recalled, or uncovered solutions and, then, comparing that with the organization's available resources.

If no satisfactory solution is immediately apparent from the evoked set, then we believe that organizations consider the consequences of not complying. We call this a "consequence analysis." A consequence analysis may be formal or informal, extensive or done on the back of an envelope. It is, essentially, an exercise in which the organization asks several key questions: How likely is it that the sanctions implicit or explicit in the mandate will be employed if the organization does not comply? If the sanctions are likely, how long before they are imposed? What might be the consequences of not addressing this issue now for organizational viability in terms of its mission? Decision makers think about the likely consequences of inaction for both the organization and its leaders. What are the possible consequences for the administrators and the responsible governing body? Would there be political consequences? How much hassle will complying or not complying generate?

Only rarely does this initial assessment proceed linearly or according to an orderly protocol. Instead, the process seems to move sporadically and iteratively as new ideas occur, as communication takes place with other organizations, and as decision makers struggle to learn what is possible in the environment within which they are operating.

The healthcare organization is faced, continually, with setting priorities. Creating priorities necessitates making tradeoffs between focusing on issues that are both urgent and important and those that are important but not as urgent. Tradeoffs are made between dissimilar goals. California hospitals seek an "optimized" outcome by trading off return on investment in dollar return with return in social (mission) terms and return in regulatory compliance terms. Each organization trades off within its context.

The priority attached to various issues depends on characteristics of the organization itself, including the extent to which decision makers believe they can anticipate what will happen as a consequence of changes in the external environment, cash flows and demands made on those resources, unrelated internal issues, and organizational mission. The context within which priorities and agendas are set changes continually and, sometimes, quickly. Consequently, what might seem like a great idea at one time might be seen as wholly inappropriate at another.

In the case of SB 1953, almost all hospitals with pre-1973 buildings responded to the initial requirement of the regulations: they submitted certifications to the State as to whether specific buildings were subject to SB 1953 provisions. Subsequent action, however, depended on where the organization placed the matter on its agenda (Box D, Figure 2).

Interpreting the Message and Framing the Issues: The Crucial Importance of Organizational Environment

SB 1953 caused most organizations to ascertain the extent to which it was technically possible to retrofit the affected buildings to the required standards. Some buildings could be retrofitted relatively simply and inexpensively, but retrofitting others posed almost intractable problems for engineers and hospital operators alike, especially given the need for the hospital to continue operations during retrofit. Second, the healthcare organizations had to determine whether they had sufficient resources to make the changes. Because 85 percent of California hospitals entered a string of very difficult financial years as SB 1953's clock began to tick, even if it were technically feasible to comply, many, if not most, hospitals simply could not because they did not have enough money, credit, and financial assistance from the federal and state governments.

Within a few years of 1994, when SB 1953 was enacted, the healthcare industry underwent extraordinary structural and financial changes. Rapid changes in healthcare economics and the increasingly bewildering structure of the industry created incredible instability and uncertainty as healthcare decision makers tried to make reasonable business decisions across a broad spectrum of problems and issues.

When SB 1953 was enacted, most California healthcare organizations were generating profits or, in the case of not-for-profits, surpluses. By the late 1990's, however, more than 80 percent of them were losing money (Shattuck Hammond, 2001). What happened and what were the implications for implementing SB 1953?

Two basic changes affected the industry's financial situation. First, managed medical care increased dramatically during the second half of the 1990s, largely as a response to rapidly escalating health insurance premiums. From 1995 to 2005, participation in managed care programs was expected to increase from 12.2 million Californians to 20.1 million (Shattuck Hammond, 2001). Traditionally, hospitals had charged patients for services received on a cost-plus basis. In the managed care environment, they are usually paid a fixed price for a service, regardless of their costs. Competition among HMOs for customers led them to cut payments to hospitals for treatment, often to less than the hospital's cost of providing the service.

At the same time HMOs were experiencing explosive growth, the Federal Medicare program was experiencing explosive cost increases. In 1999, more than 40 percent of California's Medicare population was enrolled in Medicare HMOs. Medical hospital expenses per beneficiary more than doubled from 1970 to 1975 and then doubled again by 1980 (Shattuck Hammond, 2001). The financial problems for hospitals were compounded by the 1997 Federal Balanced Budget Act which called for reducing Medicare expenditures by $215 billion over five years. The number of Medicare patients continued to increase, however, so, to meet that goal, the Medicare program cut reimbursements to hospitals and healthcare professionals for procedures, usually to below the cost of providing the services. While this was happening, hospital costs were escalating. The cost of new medical equipment was skyrocketing and the cost of supplies was increasing much faster than the Consumer Price Index.

Some hospitals, unable to staff themselves with the required number of nurses, had to reduce the number of beds available for acute care. Administrators found themselves with declining revenues per patient, higher direct costs per patient, and allocating fixed overhead costs across fewer patients.

Hospitals responses to this situation were generally rapid and rational. Hospitals and physicians reorganized themselves to gain efficiencies. Hospitals tried to develop integrated delivery systems by aligning themselves with groups of physicians. This way, they thought, they could reduce costs and cope with "capitation," a form of payment to healthcare organizations from insurers that pays a set amount of money per enrolled member per year, regardless of the number or types of treatment required.

Stand-alone hospitals merged with others in hopes of realizing economies of scale. Bigger, stronger corporations with more assets could presumably benefit from integrated management and operations. Hospital mergers swept the nation, peaking between1995 and 1997, during which time there were 680 hospital mergers.

Despite their efforts, most California hospitals could not achieve efficiencies fast enough to make up for the reduction in revenue and the increases in the costs. By 1999, more than half of California's hospitals were losing money.

The financial distress in the second half of the 1990s was not shared equally. Hospitals most likely to have operating losses were small, owned by a local government (municipality, county, or special district), rural, not part of a corporate healthcare organization, and/or serving mostly poor patients. Those hospitals most likely to have positive operating margins were larger, investor-owned, urban, part of a large healthcare organization and not serving a large proportion of poor patients (Shattuck Hammond, 2001).

In 1995, the median operating margin for California hospitals was 1.65% compared with 2.8% nationally. By 1999, the median California hospital operating margin had dropped to negative numbers, 0.33% while the national median operating margin had dropped to 0.4%. In 1999, the top quartile of California hospital corporations experienced positive operating margins of about 5.72%, but the lowest quartile was experiencing a 7.76% operating margin. California's most profitable 25%, almost all of them investor-owned hospitals, were outperforming the top 25% nationally (Shattuck Hammond, 2001).

In the midst of the financial crisis, the California legislature decided that requiring one nurse for every six patients in acute care facilities was insufficient, and, in 2001, it enacted a revised requirement for one nurse for every four patients. It is unlikely that there are enough nurses in California to meet the new requirements. Consequently, healthcare organizations are faced with having to pay nurses enough to attract them from other states and foreign countries or closing portions of their facilities so they can meet standards. Whatever the medical merits of the new nursing requirement, the financial burden will further depress net operating revenues and some facilities will become insolvent.

In this milieu, investor-owned healthcare organizations with many facilities had more flexibility and options than not-for-profit and publicly-owned hospitals. Some readers will leap to the assumption that investor-owned is always more efficient than not-for-profit or public facilities. That is not necessarily the case. Hospitals that trade off meeting shareholder objectives with organizational objectives of service in poor areas or to disadvantaged populations usually find that "efficiency" has more than one meaning. They see themselves as serving society's needs rather than the needs of shareholders, making the question of efficiency more complex. Investor-owned organizations can pick and choose where, how, and to whom to provide service. They are usually in a better position to locate in upscale markets and to provide services with favorable reimbursements from insurance and Medicare. Public hospitals, and many not-for-profit hospitals, rarely have that option. Indeed, they are often located in areas where the population is least able to pay. Local governments, suffering their own fiscal problems, have been parsimonious in providing sufficient funds for capital infrastructure. Not-for-profit hospitals typically have missions to serve particular neighborhoods or communities. They can benefit from some of the same practices used by investor-owned hospitals, but not all of them.

The financial and structural changes in the healthcare industry have much to do with the differing responses of healthcare organizations to SB 1953. Hospitals experiencing financial hemorrhaging can rarely justify spending money on seismic retrofitting. At the same time, healthcare organizations that have been able to remain profitable may be in a position to benefit from the mandated seismic improvements. The costs of retrofits provide legitimate reasons to eliminate unprofitable facilities, either by selling or closing them. Since so many healthcare organizations are in difficult financial straits, this presents well-heeled investor-owned healthcare organizations with the opportunity to strengthen their market position by acquiring desirable facilities and locations from those financially-strapped organizations. The largest and most profitable investor-owned organizations might greatly expand their market share. Unfortunately, one can also expect those organizations to expand their market share by building on the profitable areas of healthcare, leaving those procedures and services with low or below cost reimbursements to public and not-for-profit hospitals.

The upshot is that, depending on their fiscal position and their primary organizational objectives, it makes sense for some healthcare organizations to support SB 1953 and to move forward to comply with its provisions on schedule.

"The financial and structural changes in the healthcare industry have much to do with the differing responses of healthcare organizations to SB 1953."

Compliance is easier for them because they have a variety of options for dealing with inadequate facilities. Other organizations might barely be able to comply and some simply cannot.

Outcomes of the First Iteration

Almost all healthcare organizations complied with SB 1953's first requirement, specifying to OSHPD the classification into which their individual acute care structures fell. Buildings not meeting specified standards were classified as most likely to collapse in an earthquake. A few healthcare organizations moved promptly to comply with the next set of requirements in the OSHPD SB 1953 timetable. Most, however, put SB 1953 on their agenda for later action.

Second Iteration

Issues May or May Not Move up the Agenda

Issues move up the agenda because their priority changes relative to that of other issues. This occurs because the organization has worked its way through other, higher priorities or because internal or external conditions change, making considering the issue more appropriate.

Organizational leaders frequently revisit the ordering of items on their agenda to determine whether they are still placed appropriately (Box E, Figure 2). As an agenda item moves closer to consideration, the organization may also revisit its initial framing of the issue. The reframed issue may have a significantly different priority than it did in its previous configuration (Box F, Figure 2).

Initiating the Primary Analysis

As an item moves up the agenda toward focused consideration, the organization goes through a more careful and detailed analysis of how it relates to the prerequisites for organizational action (Box G, Figure 2).

Initially, the organization revisits the question of whether anything can be done to preclude the adverse event from happening and the expected consequences from occurring (Key Element 2, Figure 2). This decision is often made subconsciously, given that the answer to the question is based primarily on the organization's sense of corporate efficacy and on its sense of locus of control. Some organizations in some cultures might think there is nothing they can do to prevent an event or how a regulator may decide; they believe the matter is out of their hands. Others may perceive the problem as intractable and throw up their hands in resignation. We think that one's belief about whether anything can be done to protect against the likelihood of an extreme event varies by culture and by individual psychological makeup. We visualize a continuum of individuals and organizations ranging from those that believe they can do almost anything to those who believe they are simply pawns in some great game over which they have no influence.

In our model, if the organization believes it cannot do anything to address SB 1953 regulation and avoid the sanctions, the organization cycles back to revisiting the threat (Boxes J and F, Figure 2) and to reframing the issue. The organization would then, we think, seek a fairly radical solution to its dilemma, such as ignoring the legislation and regulations, hoping they will go away, closing the facility, or initiating political action to change the law.

Should the Organization Take Action at This Time?

Assuming the organization believes it can take action to reduce or defer the threatened sanctions, the third element in our prerequisites construct is that the organization has to make a decision as to whether it is in its best interests to take action now (Key Element 3, Figure 2).

As discussed above, many hospital organizations had serious financial problems in the late 1990's and gave those concerns a much higher place on the agenda than they gave to SB 1953. They recycled dealing with SB 1953 back to the agenda, where it was assigned a priority that the organization deemed appropriate (Box D, Figure 2).

By tracking individual organizations through time, we found that how specific organizations attempted to deal with SB 1953 changed through time as financial conditions and the organizational environment changed. SB 1953 moved up the agenda in numerous healthcare organizations simply because they became financially viable. By 2004, about half of California's healthcare organizations had begun to reestablish financial viability in a turbulent environment; they found ways to cope with parsimonious reimbursements from insurance firms, HMOs, and Medicare. Some reorganized so their corporate structure would enable them to get more reimbursements. Some chose to focus on high reimbursement medical procedures and uninsured procedures for private patients instead of procedures for which reimbursements were inadequate to meet costs. Some merged with organizations operating in several states; profits from those other states subsidized the higher costs of doing business in California, but still permitted the not-for-profit to pursue the non-monetary elements of its mission.

What happened during the decade since 1994 is that healthcare organizations learned to be businesses. Some private and not-for-profit healthcare organizations survived because they were in the right place at the right time. Some that didn't survive were simply in the wrong place at the wrong time. Generally, however, the organizations that survived were those that learned to use sophisticated business practices. Even if they did not adopt sophisticated analysis, public hospitals survived because there was no other option; in many cases, they were the hospital of last resort for people in rural areas and inner cities and for the poor and uninsured.

Scanning for Solutions and Selecting a Course of Action

In the preliminary scan of the implications of SB 1953, most healthcare organizations looked at individual buildings that were not in compliance to see what it would take to retrofit them. A ret-

> ***"...decision makers had to find a solution that was congruent with immediate affordability, long term financial viability of the organization, serving the organizational mission, complying with regulations, and fundamental corporate strategy. "***

rofit strategy was virtually implicit in the legislation, but, on further analysis, retrofitting did not make much sense to most healthcare decision makers. Most hospital buildings built before 1973 are not convenient for current medical practice. Moreover, the estimated cost of retrofit was typically high, particularly when one factored indirect costs into the equation. Substantial retrofit would open the doors to having to meet current specialty code provisions for people with disabilities, asbestos, and so forth. Then, after the initial structural retrofit was completed, the hospital would have to do nonstructural retrofit to meet the next deadline, which was likely to require reopening walls and ceilings. Moreover, the costs of shuffling patients from space to space and operating in constant turmoil led hospital decision makers to consider different alternatives.

Individual healthcare organizations considered an array of solutions. First, they could change occupancy of the structure from acute care to something else. If the structure was not used for acute care, it was no longer subject to the Act. It could be used for administration, dorms, chronically ill patients, or out-patient services. Second, the healthcare organization could build a new facility. Third, it could dispose of the structure or structures. Fourth, it could close the facility. This option, of course, appeared more desirable to organizations with many facilities than to those with only one or two. Finally, the organization could choose to not comply with the regulations, choosing instead to seek other ways to ensure that the State would not revoke its license.

Those with resources and numerous facilities decided which facilities to close, which to sell, which to retrofit, and which to convert to non-acute care uses.

Healthcare organizations without the financial wherewithal to emulate their better-off counterparts faced tough problems. Fortunately for them, the SB 1953 compliance dates were several years off, providing them with some time to come up with a plan that was feasible for them individually. In some cases, the organization decided (or hoped fervently) that there really was no serious risk of losing their license because of not complying with SB 1953 and its time line: "If they shut us down, who will provide health care here?" or "They won't do it because the political pressure will be too great." Healthcare organizations that saw their technical, logistical, or financial problems as intractable, at least in the existing milieu, tended to be resentful of the regulation, denied the threat of adverse consequences to them from earthquakes, and sought changes in the law.

If the consequences of not complying with the legislation were deemed sufficiently severe to warrant action, the organization was faced with deciding what to do (Key Element 4, Figure 2). Our model indicates that the organization does additional analysis to learn whether a technical and financial solution to its problem exists.

Rarely did one option appear immediately as superior to all others for an individual organization.

There is not necessarily one best solution. Engineers will have a number of approaches – solutions – to the problem at varying costs and time and complexity and at varying levels of acceptability by the regulator. The regulation is not totally prescriptive as to how to accomplish the objectives. For most healthcare organizations, however, the question of how to respond to SB 1953 was rarely framed as a retrofit problem. Virtually all the organizations we talked with viewed the challenges posed by SB 1953 in the strategic context of their organizational objectives and longer term development, given the unsettled and rapidly-changing economic and financial context in which hospitals found themselves. Decision makers had multiple criteria against which alternatives were considered: an acceptable solution had to meet all of them. The criteria varied by organization, but, generally, decision makers had to find a solution that was congruent with immediate affordability, long term financial viability of the organization, serving the organizational mission, complying with regulations, and fundamental corporate strategy.

Yet another factor complicates the process. Whereas the single facility, stand-alone hospital was commonplace in the 1980s, it all but disappeared by the turn of the century. As a result, relatively few hospital administrators were able to make the final choice about whether and how his or her hospital would respond to SB 1953 or any other issue requiring substantial capital expense. In some instances, the local hospital is required to submit its proposal to the parent organization to compete for budgetary allocations with other hospitals. At the corporate level, officers decide where capital outlays will be made and base those decisions on the well-being of the collective enterprise. Consequently, there are usually two decision processes. The first is at the level of the individual facility, where administrators decide what to ask for and a second is at the corporate level where priorities are set and allocations are made among the individual facilities. This aspect of the decision process has yet to be modeled.

Does the Organization Have the Capacity to Act Now?

If the organization found an acceptable solution, it would then move on to determining whether it has sufficient financial resources, staff, talent, and attention capacity to act at this time (Key Element 5, Figure 2). Organizational capacity is often an issue now that so many organizations have downsized to reduce costs and, in so doing, reduced slack needed to address new issues. If the organization decides it does not have sufficient resources, it would typically add “get more resources” to its agenda and place that on the agenda (Box D, Figure 2). If the organization believes it has, or can obtain, sufficient resources, it moves forward to implementation (Box K, Figure 2).

Next Steps

The next step in the development of the integrated decision support system will take place in MCEER’s Year 7 during 2004. Petak and Alesch will check the behavioral model’s validity by applying it to choices made in a West Coast demonstration hospital. They will attempt to rough out broad quantitative values for several parameters in the model and will attempt to actually couple the behavioral model with both the von Winterfeldt and Dargush models, again using the West Coast demonstration hospital as a test site. The exercises with the single facility will enable us to enhance and refine the behavioral model and to identify and, presumably, overcome difficulties in coupling the model with the normative models being tested by von Winterfeldt and Dargush.

Acknowledgements

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Evolutionary Methodologies for Decision Support

by Gary F. Dargush, Mark L. Green, Yunli Wang and Yufeng Hu

Research Objectives

One of the primary objectives of the MCEER research program is to contribute toward the development of disaster resilient communities. As a result, there is a general need to model, understand and ultimately direct the behavior of a wide variety of complex multi-scale systems. Within the context of a critical care facility, these not only include the structural and nonstructural systems that shape the physical environment, but also the organizational systems that define the social and economic climate. Clearly, the problem does not end at the scale of a single hospital. By expanding our view, we can recognize that local communities and large corporations need to make decisions affecting the performance of a system of critical care facilities. Furthermore, at the regional level, public policy and resource allocation must be based upon the behavior of systems of systems. At each level, there is uncertainty, ambiguity and risk, along with a temporal dimension that must be considered. Evolutionary methodologies (Holland, 1992) may be ideally suited to study and provide guidance for many of these tasks. Here we concentrate on two aspects of the overall problem, namely, *aseismic design and retrofit decision support* and *organizational decision support*. In addition, we attempt to create a theoretical and computational framework that may have applicability for complex decision-making in general.

During the past two decades, there has been increasing interest in the concept of complex adaptive systems, originally formulated by Holland (1992). Physical and social systems often involve the complicated, nonlinear interaction amongst numerous components or agents. In many cases, the agents are free to aggregate at multiple scales in response to an uncertain or changing environment. As a result, such systems may demonstrate an ability to evolve over time and to self-organize. In the process, these complex adaptive systems may display collective attributes acquired through adaptation that could not be achieved either by individual agents acting independently, or by agents under strict top-down control. Standard examples include a rain forest, the human central nervous system, and the local economy. However, from the definition above, a single critical care

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Previous Summaries

2001-2003:
Alesch et al.,
http://mceer.buffalo.edu/publications/resaccom/0103/07alesch.pdf

2000-2001:
Alesch and Petak
http://mceer.buffalo.edu/publications/resaccom/0001/rpa_pdfs/02Alesch_final.pdf

Constantinou et al.,
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1999-2000:
Shinozuka et al.,
http://mceer.buffalo.edu/publications/resaccom/9900/Chapter2.pdf

facility or critical care network also may function as a complex adaptive system.

In some cases, the primary interest is on identifying and understanding system behavior. This is a problem of analysis and several different approaches are available, even when environmental uncertainty must be included. The fragility-based methodologies being developed under MCEER are excellent examples (Shinozuka et al., 2003; Alesch et al., 2003). On the other hand, if we wish to improve performance of a complex adaptive system in some sense, then we should consider the inherent complexity of the underlying system and the decision-making process itself. Effective solutions may require the selection of certain policies from an extensive list of possibilities or the determination of specific parameter values from an available set. Consequently, the decision space of possible solutions is usually quite large and, as noted earlier, there is often a temporal element as well. In essence, here we are faced with a design problem. However, because of the underlying complexity, simple prescriptive solution procedures are typically not available, direct exhaustive search is not feasible and the familiar sequential search strategies have only limited effectiveness. Alternative approaches are needed. For convenience, we shall denote all of these design problems as *complex decision processes*.

Tsypkin (1971) presented perhaps the first major work on adaptation in automated systems. His approach was based primarily on the existing methods of optimal control theory. Holland (1992), on the other hand, developed a unified theory of adaptation for both natural and artificial systems. Ideas from biological evolution were central to his approach. Besides providing a general formalism for studying adaptive systems, this led to the development of evolutionary methods and, more specifically, to *genetic algorithms*.

Within the Holland genetic algorithm formalism, let S be the set of possible solutions, E symbolize the class of realizable environments, μ indicate the performance measure,

> The decision-assisting platforms are intended to help illuminate the consequences of choice for both engineering consultants and their clients. Since clients must consider a wider range of variables than their engineers when making choices about seismic safety, the models are intended to couple organizational and engineering concerns into one or more models to help create recommendations for seismic safety that meet the needs of all the critical stakeholders. Stakeholders may include companies interested in developing markets for new technologies, critical care facility owners required to meet legislated levels of seismic performance, local communities faced with prioritizing rehabilitation projects and/or federal agencies responsible for resource allocation.

and τ represent the adaptive plan. Then by making selections from a set of operators Ω, the adaptive plan τ produces a sequence of potential solutions $s \in S$ based upon the performance measure μ_e associated with environment $e \in E$. In a genetic algorithm, the individual solutions s are encoded as computational chromosomes, often using a binary string representation. The typical genetic operators contained in Ω include selection, crossover, mutation and replacement. At each generation, the best performing solutions are selected for reproduction. The genetic operators then work to increase the frequency of good qualities contained in the population, while continually exploring the space of possible solutions in S. Figure 1 provides the overall flow of a classical genetic algorithm. Notice in particular that there are a number of stages within the algorithm that lend themselves naturally to parallel computing platforms. This is especially true for the fitness evaluation stage, which is often the most computationally demanding task. Further details on genetic algorithms can be found in Holland (1992), Goldberg (1989) and Mitchell (1996).

We should mention that although in the original work by Holland the environment may be uncertain, most implementations and applications of genetic algorithms are limited to fixed environments. However, we find that evolutionary methods are more appropriate for discovering robust solutions to problems involving uncertainty, ambiguity and risk. Of course, these are exactly the types of solutions required for the development of seismically resilient communities.

Genetic Algorithms
Classical Version (Holland, 1992)

Initialize pool of chromosomes [Parallel]
Generation loop [Serial]
    Chromosome loop [Parallel]
        Evaluate chromosome fitness**
    End loop
    Apply genetic operators [Parallel, Serial]
End loop
Select best chromosome(s) [Parallel]

** Often the most computationally intensive operation

Figure 1. Genetic Algorithm Flow Diagram

In the following two sections, we address a pair of specific complex decision processes. The first is an engineering design problem associated with the selection of passive energy dissipation elements for building structures under seismic loading, while the second involves a preliminary look at the broader sociotechnical problem. In the latter case, we present a new framework for organizational decision support.

Aseismic Design and Retrofit Decision Support

Passive energy dissipation systems are now widely used for the seismic control of civil engineering structures and a wide variety of device types are available, including metallic yielding dampers, friction dampers, viscous fluid dampers and viscoelastic dampers (e.g., Soong and Dargush, 1997; Constantinou et al., 1998). While the introduction of these passive energy dissipation concepts and systems presents the structural engineer with considerable freedom in aseismic design and retrofit, further guidance may be needed to help direct the design process. In order to address this issue, several simplified design procedures have been in development over the past decade (e.g., FEMA, 1994, 1997a, 1997b, 2001). These procedures are oriented mostly toward the design of simple uniform structures. Alternatively, one may attempt to develop new computational approaches that can provide insight into seismic performance, as well as design guidance both for simple structural systems and for complex irregular structures.

Here we adopt this latter approach and continue our development of an evolutionary approach for aseismic design and retrofit. Previous research on the application of genetic algorithms to passively damped structures includes the work by Singh and Moreschi (1999, 2000, 2002), Dargush and Sant (2000, 2002) and Dargush and Green (2002). In particular, we extend our previous work by introducing a parallel genetic algorithm for the design of robust passively damped structures within an uncertain seismic environment.

Evolutionary Aseismic Design and Retrofit

```
Initialize pool of structures
Generation loop
        Structures loop [Parallel]
                Evaluate structure fitness via
                transient dynamic analysis**
        End loop
        Apply genetic operators
End loop
Select best structure(s)

** Computationally intensive
```

Figure 2. Evolutionary Aseismic Design and Retrofit Flow Diagram

The overall flow of the genetic algorithm for aseismic design and retrofit is provided in Figure 2. In each generation, a population of individual structures $s \in S$ is defined and evaluated in response to ground motions that are realized in association with an environment $e \in E$. The primary structure may contain a number of metallic yielding dampers, viscous fluid dampers and/or viscoelastic solid dampers over a range of sizes. A binary code in the chromosome of each individual structure $s \in S$ determines the specific design. Cost and structural performance are used to evaluate the fitness of each structure in the population. Then the individual structures compete for survival within the uncertain environment. The fitness values, along with random genetic operators modeling selection, crossover and mutation processes, define the makeup of the next generation of structures. While, in the present implementation, generations must be processed sequentially, evaluations within a generation can be performed in parallel. Furthermore, multiple simulations with different initial seeds can be run simultaneously in a massively parallel computing environment.

In our present system, performance is judged by conducting nonlinear transient dynamic analyses for ground motions that are consistent with the USGS seismicity model for eastern North America (Frankel, 1995; Frankel et al., 1996; Papageorgiou, 2000). The structural analysis utilizes an explicit state-space transient dynamics research code (tda), while the implementation of the genetic algorithm controlling the design evolution is accomplished within Sugal (Hunter, 1995).

Structural Model

For most complicated structures, a nonlinear transient dynamic analysis is needed in order to assess the performance of a given design or retrofit option. In the present work, we employ a lumped parameter representation for both the primary structure and passive elements.

A two-surface cyclic plasticity model in force-displacement space (Constantinou et al., 1998) is used to describe the behavior of the primary structure and metallic dampers. For this model, two distinct, but nested, yield surfaces are defined in one-dimensional force space. The inner or loading surface separates the elastic and inelastic response regimes. This is characterized by its center and radius represented by a back-force F_α and inner yield force F_y^L, respectively. Meanwhile, the outer or bounding surface, which completely contains the smaller inner surface, is always centered at the origin of force space with radius equal to a variable outer yield force F_y^B. Translation of the inner surface corresponds to kinematic hardening, while expansion of the outer surface produces isotropic hardening. A total of six model parameters must be specified, including the stiffness k, inner yield force F_y^L, initial outer yield force F_{y0}^B, and hardening parameters h_0^B, h_1^B, and r.

Viscous dampers are represented as purely linear Newtonian devices, with force proportional to velocity. In a physical sense, this implies that the bracing elements, used to incorporate the viscous dampers into the structural system, are infinitely rigid compared to the stiffness of the primary structure. In some cases, it may be more appropriate to consider more sophisticated models as discussed in Constantinou et al. (1998), however only purely viscous models are utilized here.

The viscoelastic dampers are modeled as nonlinear rate-dependent devices based upon a thermally sensitive generalized Maxwell model. This model is written as a set of coupled first-order ordinary differential equations for the damper force, temperature, intrinsic time and Maxwell element internal variables. This thermally sensitive viscoelastic model is able to account for the typical softening that occurs at elevated ambient temperatures and as the damper temperature increases during seismic excitation.

For any given design or retrofit option s within the set of possible structures S, the properties for the lumped parameter primary structure and passive element models must be defined at each story. The resulting equations of motion for the n-story passively damped structure are written in state-space form and then solved, along with the applicable constitutive models, using an explicit, adaptive step-size Runge-Kutta method (Press et al., 1992).

Links to Current Research

The decision support systems under development in this effort will incorporate the seismic retrofit technologies and response modification methods developed in a parallel effort being carried out by Bruneau, Reinhorn and others in Thrust Area 2.

Geophysical Model

With the structural models defined, we next examine the approach taken to model the seismic environment. One possibility, of course, is to define a small set of historical or synthetic ground motions and attempt to find the best structural design for this set. However, this approach may introduce a bias, particularly if the set is developed with a specific structural frequency in mind. Instead, here we employ the USGS Gutenberg-Richter seismicity database for eastern North America (Frankel, 1995; Frankel et al., 1996) and generate as many ground motions as necessary to evaluate proposed structural design and retrofit options.

Following the USGS model, the entire geographical region of eastern North America is subdivided into bins, with each bin representing 0.1 degrees of longitude and latitude. The USGS database then provides Gutenberg-Richter parameters a and b for each bin such that N the number of earthquakes per year of magnitude greater than or equal to M can be written as $\log N = a\text{-}bM$. We simulate the seismic environment by running Poisson processes in each bin to determine first arrival times T of significant events that may occur during the intended life cycle T_l of the structure. Once magnitude M and epicentral distance R are established for a significant event, the ground motion generation algorithm defined by Papageorgiou (2000) is used to produce an appropriate synthetic accelerogram. This approach is used to simulate n_e environmental realizations independently for each individual structure s at each generation.

Computational Simulations

For illustrative purposes, we will now consider an example of a twelve-story steel frame retrofit with passive energy dissipators. Assume that three different types of dampers are available: metallic plate dampers, linear viscous dampers, and viscoelastic dampers. For each type, four different sizes are possible. Consequently, a 48-bit genetic code is employed to completely specify the dampers used in each story of any particular structure $s \in S$, where for this problem, the set S of attainable structures contains roughly 2^{48} members. Thus, there are over one hundred trillion possible structures.

In some situations, the use of multiple damper types in a single structure may be beneficial. However, it is unlikely that a structure with all three types (i.e., metallic, viscous and viscoelastic) represents a practical design option. In order to restrict the number of distinct damper types, techniques related to gene repair or fitness penalization can be utilized. Instead, we introduce the following recessive gene concept. The chromosome representing each new structure is formed by the standard genetic operations of selection, crossover and mutation. Using biological terms, the resulting binary string represents the structural genotype. However, the actual structural design or phenotype is established by first determining the dominant damper type(s) present in the string. Afterwards the binary string is re-interpreted to convert recessive damper types into dominant ones of the same size. This technique constrains the design space in an appropriate manner, while preserving the diversity of the chromosomes. Results from several simulations will be shown below to illustrate this new approach.

Additional details concerning the relative cost, performance and fitness definition must be specified. For example, in order to establish acceptable performance, we establish the parameters ϕ and β to set limits on interstory drift Δ_i and story acceleration a_i for each story i in relation to the story height H and gravitational acceleration g, respectively. Seismic performance of the structure under a given ground motion is acceptable only if $\Delta_i \leq \phi H$ and $a_i \leq \beta g$ for $i = 1,2,...n$. Further details can be found in Dargush and Sant (2000, 2002) and Dargush and Green (2002).

We now consider a series of examples involving steel frame structures with various retrofit possibilities. The primary purpose of these simulations is to illustrate the methodology, rather than to provide guidance for specific design situations. In each example, a number of parameters must be specified to control the genetic algorithm. Unless otherwise noted, the replacement rate is 50% at each generation. One-point crossover is always activated to form the new structures, followed by random bit mutations with a frequency of 1/24 per bit. Furthermore, the number of generations is set at $n_g = 512$, with $n_p = 32$ structures in the population and $n_e = 128$ environmental realizations per structure at each generation. A life cycle $T_l = 100$ yrs is assumed. Meanwhile, the performance measure μ estimates the fitness U of each structure based upon the relationship $U = (n_e^+ / n_e) B_{\max} - C$, where n_e^+ represents the number of successful environmental realizations for the structure, B_{max} is the maximum benefit obtained from the structure and C is the damper cost.

Twelve Story Steel Frame with Discontinuity

As a first example, we continue with the twelve-story structure discussed above. Let W_i and k_i represent the ith story weight and stiffness, respectively. The baseline steel frame model has story weights, $W_1 = ... = W_6 = W$, $W_7 = W_8 = 3W/4$, $W_9 = ... = W_{12} = W/2$ and stiffness $k_1 = ... = k_6 = k$, $k_7 = ... = k_{12} = k/4$. Notice that there is a strong discontinuity at the seventh story. The parameters W and k are chosen such that the first two natural frequencies are 0.5Hz and 1.10Hz. Additionally, the lumped parameter two-surface cyclic plasticity model discussed above is employed to represent the hysteretic behavior of the primary structure. Within that model, let F_{yi}^L represent the yield force on the inner loading surface for the ith story. Then, $F_{y1}^L = ... = F_{y6}^L = 0.20W$, $F_{y7}^L = ... = F_{y12}^L = 0.05W$. The maximum structure benefit is set at $B_{max} = 2000$. Damper costs vary from 4 to 20 units depending on size.

Assuming that this structure is situated on firm ground in Memphis, TN, we find that the baseline design without passive dampers survives less than 30% of the significant earthquakes, according to our definitions for magnitude and distance cut-offs. Now consider retrofit with metallic (tpea) dampers only. Using the results from four simultaneous simulations, we find a number of robust designs, including those presented in Figure 3. Here and in all subsequent structural diagrams, the size of the rings denotes damper size, while ring color indicates damper type. Notice that the leftmost design has a significant earthquake survival rate of approximately 75% and a fitness of nearly 1300.

However, in these simulations only metallic dampers were permitted. Next we expand the design space to permit all three damper types, including metallic (tpea), viscous (visc) and viscoelastic (ve) devices. The results are presented in Figure 4. Now survival rates have increased to over 90% and the fitness values are well above 1800. These are clearly more robust designs than those presented in Figure 3. Of course, during each simulation, many design configurations are tested. The structures presented are those designs that appear most frequently in the design pool. These designs typically survive over many generations under variable environments and thus can truly be considered as the most robust structures. Notice also that the evolutionary algorithm apparently recognizes the structural discontinuity at the seventh story and designs accordingly.

Although several robust designs are presented in Figure 4, notice that two of the three incorporate all three damper types. As dis-

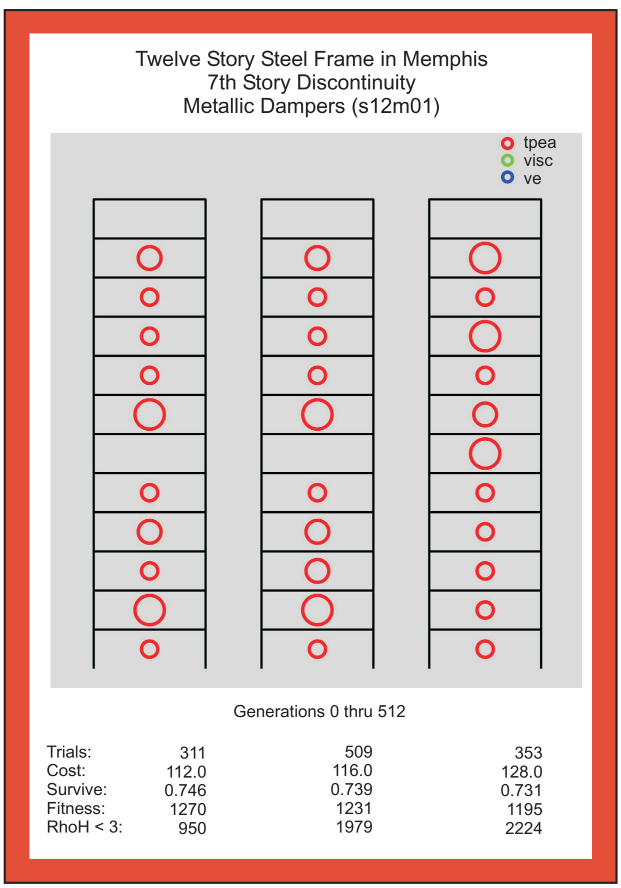


Figure 3. Twelve Story Structure with Metallic Dampers

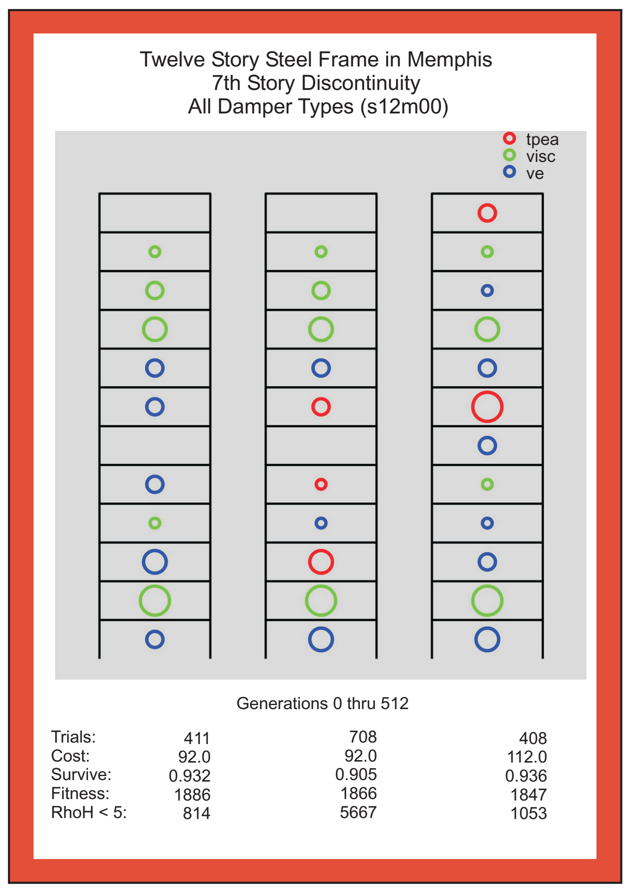
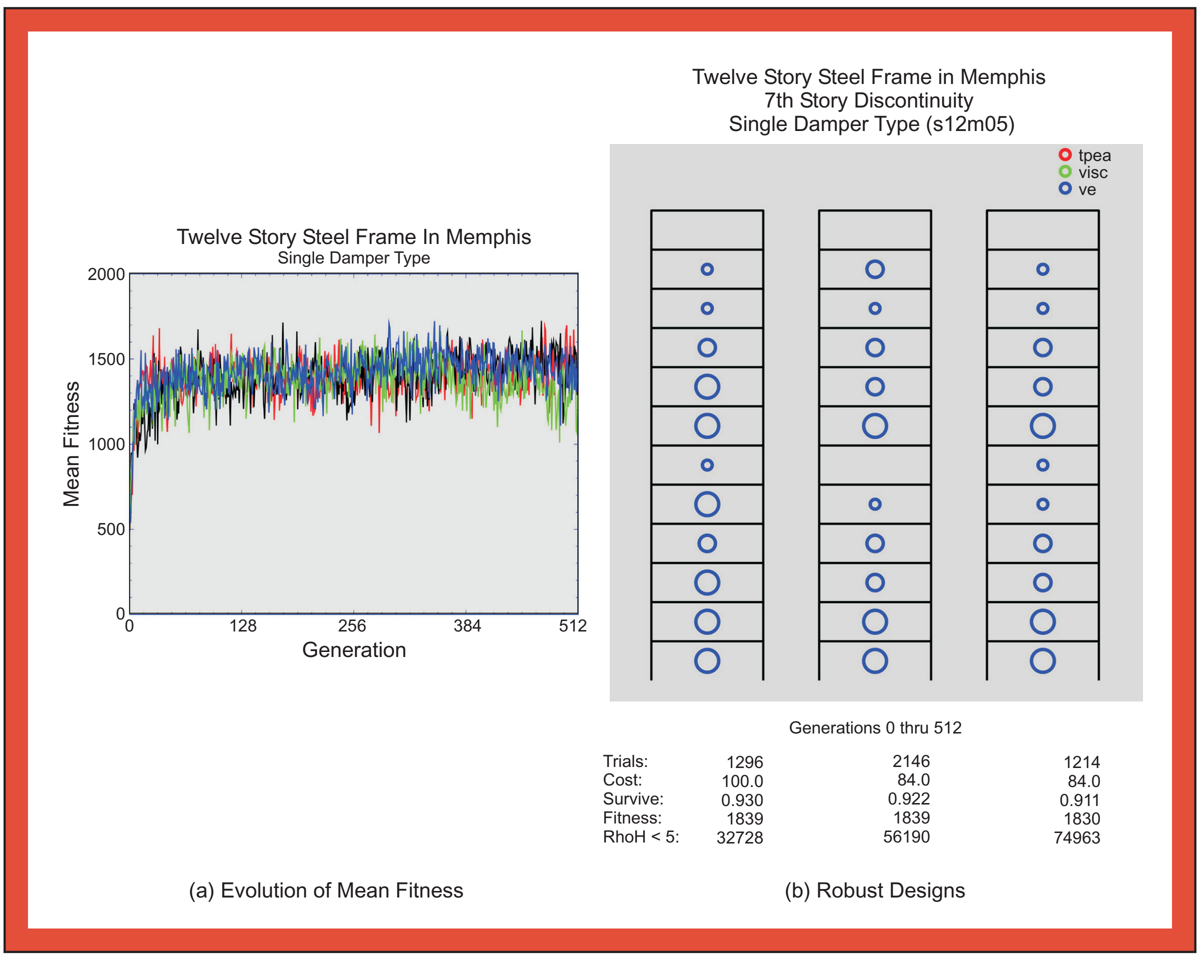


Figure 4. Twelve Story Structure with All Damper Types

cussed previously, this is not likely to yield a practical rehabilitation scenario. Next we constrain the simulations to permit only a single damper type in a given structure. Results are presented in Figure 5. The left-hand plot Figure 5a displays the evolution of mean fitness for four simulations using different initial seeds. The mean fitness tends to increase rather quickly before hovering around 1500. The variability is due to the uncertain environment and the on-going need to explore new regions of the design space. The three robust designs presented in Figure 5b again have survival rates above 90% and fitness values significantly over 1800. Interestingly, viscoelastic (ve) dampers are selected for all of these robust design alternatives.

Uniform Eight Story Steel Frame

In the previous examples, the robust designs resulting from the simulations specified dampers in many of the stories. For a final example, we consider a uniform eight-story structure with metallic dampers as the only retrofit option. In this case, the robust designs obtained after $n_g = 512$ generations are shown in Figure 6. Notice from the figure that the predominant design option involves no dampers.



■ Figure 5. Twelve Story Structure with Single Damper Type

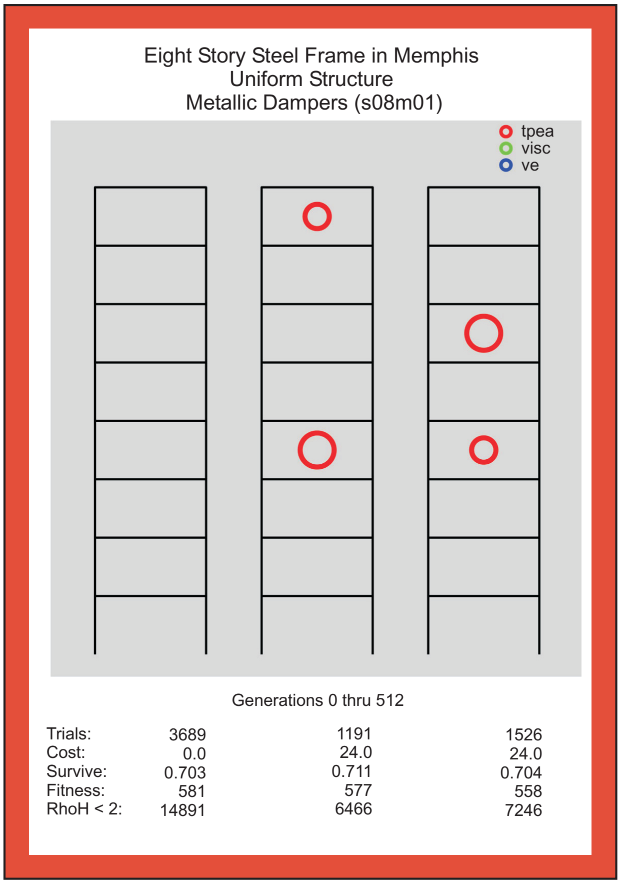


Figure 6. Eight Story Structure with Metallic Dampers

Organizational Decision Support

While the evolutionary approach for aseismic design and retrofit developed here is useful in distinguishing the various design alternatives, decisions regarding whether or not to retrofit an existing structure are seldom based strictly on engineering grounds. The sociotechnical nature of organizational decision-making must be considered. For the general problem, March and Olsen (1973) proposed a garbage can model for organizational decisions. Within that model, decisions are made only if:

- A problem exists
- A credible solution is known
- The organizational agenda can accommodate the solution
- There are advocates within the organization.

Recently, Petak and Alesch (2004) have tailored and augmented the March-Olsen model for earthquake hazard risk reduction in healthcare organizations. There are five prerequisites for organizational action:

- The healthcare organization must perceive the seismic risk
- The organization must believe that it has an internal locus of control regarding the problem
- The organization must feel that implementing the solution is in its best interests
- The organization must believe that a solution exists to reduce that risk
- Organizational capacity must exist to implement the risk reduction measures.

Several of these items correspond to those defined in the general March-Olsen model, however Petak and Alesch (2004) also emphasize the importance of the temporal dimension of decision-making and the need within the organization to actively seek solutions.

This Petak-Alesch descriptive model is very helpful for identifying the prerequisites for organizational action. Additional qualitative and quantitative models of organizational behavior and performance are needed to support the decision-making process. For example, the space of possible solutions must be defined and the impact of potential decisions on the organization must be estimated. Regarding this latter aspect, several different organizational modeling approaches may be appropriate, including systems dynamics formulations (Forrester, 1961, 1969, 1971), interacting species models (May, 1973) and multi-agent complex adaptive systems methods (Holland, 1992; Carley, 2002). The first two of these are closely related. Both represent top-down approaches that primarily attempt to capture global level behavior by formulating and solving sets of ordinary differential (or difference) equations governing the evolution of key organizational variables. On the other hand, the third approach focuses on a bottom-up strategy for model construction based upon the definition of simple interaction rules between many organizational agents.

Although the multi-agent methods arguably have greater long-term potential to represent the true multi-scale behavior of organizations, additional fundamental research is needed. Consequently, within the MCEER Year 7 research program, we are currently concentrating on the development of succinct differential models using ideas from system dynamics and interacting species formulations. For critical care facilities, these models utilize patients, employees, building and equipment stock, and monetary assets as the four key variables characterizing organizational behavior. Ultimately, this organizational model will couple into the overall decision support methodology defined in Figure 7. Notice that this approach also involves the geophysical (Frankel et al., 1996), earthquake (Papageorgiou, 2000) and structural models discussed in the previous section, along with

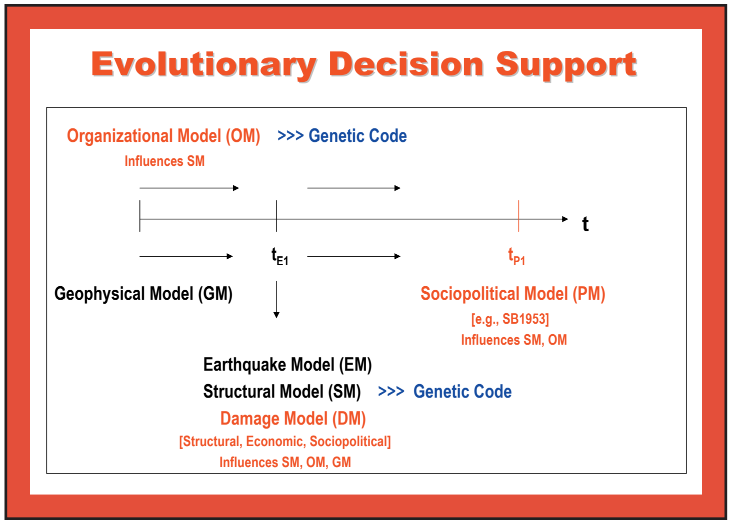


Figure 7. Organizational Decision Support

an extended damage model and possibly a sociotechnical model. In this formulation, which will be developed more fully in Years 7 and 8, genetic algorithms are employed to identify robust structural designs and to evolve effective organizational strategies.

Simulation Network

The evolutionary approaches for aseismic design and retrofit decision support and organizational decision support described in the previous two sections are essentially computational procedures. Although some simulations can be performed on single workstations or personal computers, the full benefit of these methodologies can be better realized within a massively parallel computing environment. In this section, we provide a brief overview of the simulation network that has been developed within MCEER Thrust Area 4 initiatives to support this and other ongoing MCEER research projects.

During Year 7 activities, we installed a powerful server in the University at Buffalo (UB), Center for Computational Research (CCR) to serve as a collaborative platform for MCEER, the Network for Earthquake Engineering Simulation (NEES) and the UB Department of Civil, Structural, and Environmental Engineering (CSEE). Figure 8 provides a schematic of this collaborative platform and the new dedicated server, appropriately named *earth.ccr.buffalo.edu*. The platform was designed to deliver the following high-performance computational and visualization capabilities:

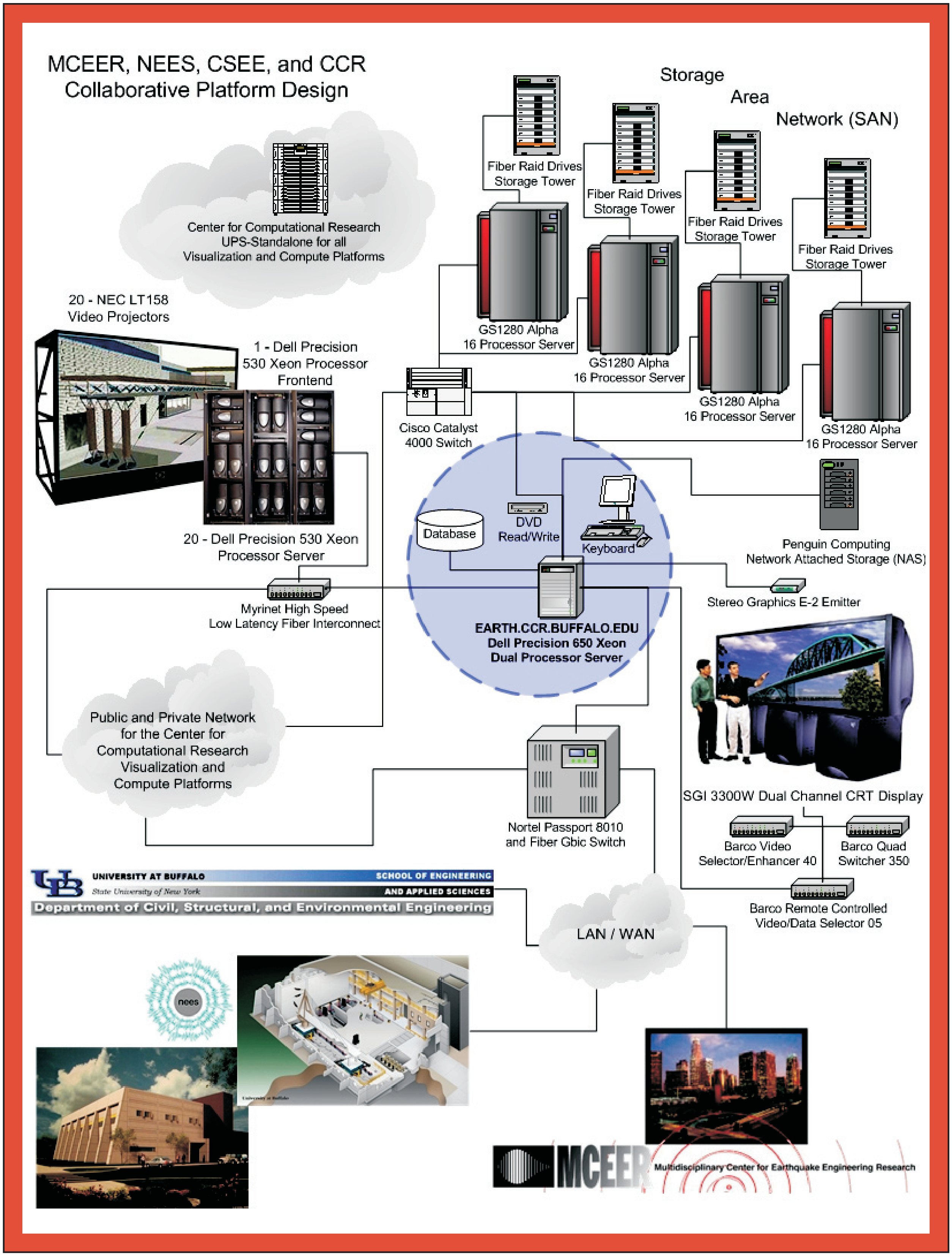
- Serve a custom website with a Gigabit Ethernet connection to the University backbone
- Serve a web accessible MySQL database with SSL connections and authentications
- Serve 3D stereo graphics to the SGI 3300W Visualization Display
- Serve 2D and 3D graphics to the Tiled-Display Wall
- Serve streaming video to the Access Grid for world-wide presentation
- Provide a staging and post-processing platform for the Advanced Computational Data Center - Grid (ACDC-Grid) grid-enabled analysis and result files
- Provide a common platform for exchange of information and visualization between faculty, staff, collaborators, and other researchers
- Provide outreach and education with a descriptive poster depicting the collaboration and website information dissemination

In particular, the addition of this MCEER/NEES/CSEE platform has enabled the development of massively parallel asynchronous implementations of the evolutionary methodologies for decision support discussed above and will greatly enhance our ability to visualize the results of the large-scale simulations.

Conclusions

A general evolutionary framework has been developed to provide support for complex decision processes. Here we concentrate on two specific examples, namely, aseismic design and retrofit decision support and organizational decision support. Within the first domain, we concentrate on the engineering problem associated with the design of passively damped structural systems and present a computational approach based upon genetic algorithms that has significant potential, especially for irregular structures. In numerous case studies, the system is able to discover robust designs in an uncertain seismic environment. In addition, the algorithms scale favorably with increasing problem size and are naturally parallel. Consequently, continued development of the methodology and the associated software appears to be warranted, particularly in light of the anticipated concurrent advancement of massively parallel computing hardware. Furthermore, the extensions of this evolutionary approach to include non-structural components and to address multi-hazard design and retrofit are clearly feasible.

Beyond the engineering aspects of the mitigation problem, there are many associated socioeconomic issues that must enter into the decision-making process. Consequently, in collaboration with



■ Figure 8. MCEER/NEES/CSEE/CCR Collaborative Platform

Professors Petak and Alesch, we focus on developing evolutionary formulations for decision support toward seismic risk reduction in critical care organizations. Our present work is concentrated on the development of quantitative organizational models to approximate the overall behavior and to couple with the existing geophysical and structural models in the evolutionary decision support framework. Although some research challenges remain, we believe that this new approach has considerable potential to provide guidance at the level of a single critical care facility and also for regional planning of critical care networks.

Acknowledgements

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Networks and Resilience in the World Trade Center Disaster

by Kathleen Tierney and Joseph Trainor

Research Objectives

This paper focuses on one aspect of the organized response to the 9-11 attacks: the multi-organizational network that emerged in New York City to carry out emergency response-related tasks. After a discussion of the methods used in this research, the paper focuses on the characteristics of that response network, including its size, composition, and emergent properties, as well as the various tasks that were undertaken during the post-disaster response period. The paper concludes with a discussion of the distinctive strengths of the network as a form of organization and the manner in which networks contribute to resilience in the post-disaster environment.

The September 11, 2001 attack on the World Trade Center was by any measure one of the most damaging and costly disasters in the nation's history. The death toll resulting from the attack has now been finalized at 2,749 (New York Times, 2004). An estimated 790 survivors were treated in area hospitals within 48 hours of the attack; of that number, 139 were hospitalized, the majority due to smoke inhalation (Centers for Disease Control, 2002). This injury total does not include victims who sought assistance from other health care providers and facilities, nor does it include longer-term health impacts resulting from the attacks. The events of September 11 caused significant short-term psychological distress among New York City residents as well as the population outside the areas that were attacked (Galea et al., 2002; Silver et al., 2002; Delisi et al., 2003). Longer-term psychological impacts have yet to be determined.

The economic impacts of 9-11 continue to be assessed nearly three years after the attacks. In 2002, on the basis of eight different studies on short-term economic impacts, the U. S. General Accounting office estimated that the attacks resulted in $83 billion in direct and indirect economic losses in the New York City area alone, $16 billion of which would likely not be compensated by insurance or other forms of assistance (General Accounting Office, 2002a). Recent reports indicate that 9-11 continues to have negative economic impacts on New York City in areas such as gross city product and jobs, and that the disaster is perhaps the single most important factor

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accounting for the city's slow recovery from the last recession (Office of the Comptroller, 2003).

In the fifteen months following the September 11 attacks, the U.S. Small Business Administration approved more than $1 billion in economic injury disaster loans for businesses that experienced revenue losses that were related to the attacks (Small Business Administration, 2003). Assistance provided by the Federal Emergency Management Agency (FEMA) to individuals and households in New York totaled more than $314 million as of 2002, covering services ranging from mortgage and rental assistance for displaced households to the provision of mental health counseling (Federal Emergency Management Agency, 2002). Post-September 11 FEMA funding to public-sector entities has been estimated at $7.4 billion, which includes funding provided for transportation system reconstruction ($2.8 billion), activities associated with debris removal and the provision of insurance for those working on the debris removal operation ($1.7 billion), and other response and recovery-related programs (General Accounting Office, 2003).[1] A February 2004 report from the Insurance Information Institute indicates that insurers expect to pay out approximately $40.2 billion in World Trade Center losses, of which business interruption will constitute approximately 27 percent. About $19 billion in claims had been paid out as of October, 2003 (Insurance Information Institute, 2004). With respect to other impacts of the attacks, the airline industry reported a record loss of $7.7 billion and an increase of $14.4 billion in long-term debt and other liabilities in 2001 (Air Transport Association, 2002).

There has been only one U.S. disaster that resulted in a greater loss of life: the 1900 Galveston Hurricane, which killed 6,000 (see Noji, 1997 for a review of death tolls from 20th century disasters). Prior to 9-11, the most costly natural disasters, in terms of direct losses suffered, were the 1994 Northridge earthquake (with an estimated $44 billion in direct losses), Hurricane Andrew ($30 billion), and the 1993 Midwest floods ($19 billion). The largest insured losses were experienced in Hurricane Andrew—$15 billion—compared with more than $40 billion for the Trade Center disaster. (Estimates based on National Academy of Sciences, 1999).

Users of this research include emergency management agencies at the local, state, and federal level; other organizations charged with planning for and responding to disasters; and network analysts. By showing the complex and diverse networks that emerge and the wide range of tasks responders must address, this study on the World Trade Center provides a realistic perspective on planning and response requirements for large-scale community-wide disasters.

The 9-11 attacks in New York triggered a massive response not only on the part of governmental agencies, but also on the part of the private sector, voluntary and non-governmental organizations, and the general public. Focusing on charitable giving alone, a 2002 report by the General Accounting Office indicated that more than 300 charities requested and received donations for the victims of September 11 and that 34 large charities reported collecting approximately $2.4 billion in donations (General Accounting Office 2002b).

Particularly important for this discussion, the scale of the emergency response to the attacks was commensurate with the size and severity of the event. September 11 was a disaster that greatly exceeded the scope of prior disaster planning in New York City. Although the city had been involved in a range of activities aimed at enhancing preparedness for natural disasters such as hurricanes, as well as planning for terrorist attacks, planners had never envisioned a crisis like the one the city faced on September 11. The attacks occurred without warning, caused widespread death and injury, resulted in the collapse of two of the world's largest buildings, killed hundreds of emergency workers, and caused the collapse of 7 World Trade Center, the building that housed the city's emergency operations center. The city thus had to cope with the loss of its main disaster response coordination facility at the height of the emergency. Planning had similarly never envisioned the need to respond to an event whose impacts resembled those of a major disaster and necessitated a full-scale disaster response, but that was also a crime scene, a national security emergency, and a potential environmental disaster.

Methods and Data Sources

This analysis is based on data that were collected from three sources. First, data were gathered through quick-response field work, which was carried out in the immediate aftermath of the Trade Center attack. Field workers from the University of Delaware Disaster Research Center (DRC) went to New York City three days after the WTC disaster and received permission to observe disaster response operations at the city's reconstituted emergency operations center at Pier 92, at command posts near Ground Zero, and at other sites associated with the emergency response to the 9-11 attack. For two months following the attack, DRC staff remained in those settings, recorded extensive field notes, spoke informally with individuals who were responsible for coordinating various phases of the emergency response, and attended meetings at which decisions were made regarding response and recovery strategies. In all, more than 700 person-hours were spent in the field in direct observation of emergency activities.

Second, a variety of documentary materials containing information on emergency response activities were collected. These data sources included newspaper accounts that were collected systematically for six months following the terrorist attacks; situation reports generated

Links to Current Research

This research focuses on the analysis of emergent disaster response networks. It contributes to basic knowledge on the composition and characteristics of disaster response networks and on the ways in which networks contribute to community resilience following disaster impact. It also highlights the challenges associated with managing emergency response operations in large-scale disaster events.

by responding agencies; and a variety of other materials including maps, meeting rosters, statistical reports, after-action studies, research reports, and book-length journalistic accounts.

Third, just over one year after the WTC disaster, in-depth, face-to-face interviews were conducted with more than sixty individuals representing agencies and organizations that played a key role in emergency response activities. Interviewees were selected based on what had been learned from initial field work about the roles they had played in post-disaster decision making and response coordination. The interviews sought information on such topics as initial perceptions and situation assessments immediately following the attack, tasks undertaken by various organizations and how those tasks changed over time, the extent to which prior planning influenced organizational responses, how multiple organizations coordinated their activities, and key lessons learned.

To date, both qualitative and quantitative techniques have been employed in the analysis of the WTC data. Qualitative analyses have focused on such topics as convergence following the WTC attack (Kendra and Wachtendorf, 2003a); the creative element in crisis response operations (Kendra and Wachtendorf, 2003b), organizational improvisation in response to complex disaster-related demands (Wachtendorf, 2004); the timely restoration of New York City's emergency operations center as an example of organizational resilience (Kendra and Wachtendorf, 2003c); and organizational adaptation under conditions where prior planning did not exist (Kendra, Wachtendorf, and Quarantelli, 2003). What these qualitative analyses have in common is their emphasis on the large-scale mobilization and collective sensemaking activities that accompanied the response to the 9-11 attacks—processes that are characteristic of major disasters. During such events, responding organizations must address unexpected and unplanned-for challenges, often under very severe time constraints, and they do so through their ability to incorporate new members; identify and utilize new resources; develop new organizational forms; compensate for lost personnel, facilities, and other resources; find alternative ways of accomplishing their aims if plans cannot be implemented and discard methods that do not work; and in general develop new action strategies under uncertain and urgent conditions.

Quantitative analyses, which are not yet complete, center on mathematically modeling the response network that emerged following the 9-11 attack. These analyses are based on coded data drawn from all three sources described above. Although all of the data have not been coded, and network modeling has just begun as of this writing, it is possible to draw some preliminary conclusions from currently available data and model outputs. The sections that follow highlight key features of the multi-organizational network that emerged in response to the 9-11 attack and discuss how such networks enhance resilience in the immediate aftermath of disasters.

Preliminary Findings: Characteristics of the WTC Emergency Response Network

It will never be possible to determine definitively how many organizations, groups, and individuals participated in the community response to the WTC disaster. It is clear, however, that in the hours, days, weeks, and months following the attack, emergency response, relief, and supportive activities were carried out by literally thousands of organized entities and many tens of thousands of individuals. This discussion centers on one subset of that response and relief activity: organizations that were directly involved in emergency response activities on September 11 and in the twelve-day period following the attack and whose participation in response activities was documented through DRC's data collection methods. The twelve-day period was focused on for purposes of this study because that time period encompassed the most intense phase of the emergency response. After that period, activities began to shift from emergency operations to post-disaster recovery. One indicator of this transition was the city's carefully-managed movement away from actively searching for victims at Ground Zero and toward demolition and debris removal at the site. The data that have been analyzed to date provide considerable insight into the characteristics of the WTC crisis response network. Chief among those characteristics are size, diversity, decentralization, and emergence.

Network Size and Diversity

The most obvious characteristic of the WTC crisis response network is its sheer size. Even though not all data have been coded and analyzed, it is clear that WTC was a disaster event that triggered organizational mobilization on a massive scale. Figure 1 shows preliminary output from a network analysis[2] that was performed on coded data derived primarily from documentary materials describing organizational activities and interactions

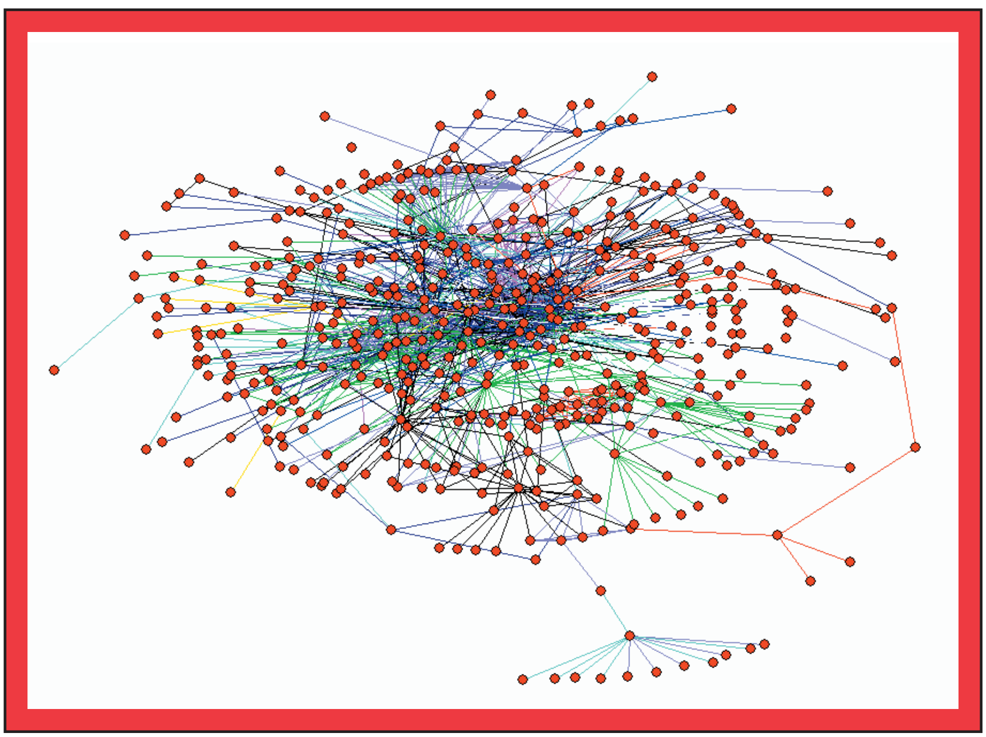


Figure 1. Structure of the World Trade Center Emergency Response Network

over the twelve-day emergency period.[3] This network includes 529 organizations and approximately 4,600 interorganizational interactions.[4] The size and scale of the response were related to the severity and complexity of the demands associated with the 9-11 crisis, the population size and rich organizational ecology of the New York City region, and the strong altruistic emotions the events of 9-11 engendered. Although the impact of the attacks was devastating in the Ground Zero Area, millions of people and hundreds of thousands of organizations in the impact region were largely unaffected and thus available to provide assistance. The attacks coincided with early morning news broadcasts and dominated news coverage throughout the entire country, resulting in rapid dissemination of information on the Trade Center disaster. All of these factors contributed to the massive convergence of aid and volunteers into New York City.

The network that developed to respond to the WTC attack was extremely diverse with respect to the tasks in which responders engaged, as well as the types of organizational entities that were involved. As shown in Table 1, DRC's analyses identified forty-two separate task areas around which emergency response activities were organized during the initial twelve-day period. Those tasks ranged from core emergency management functions such as firefighting, damage assessment, emergency coordination, and building inspection to less obvious support activities, such as the provision of legal services in the response context. The network included entities specializing in particular tasks

Table 1. World Trade Center Disaster Response Activities

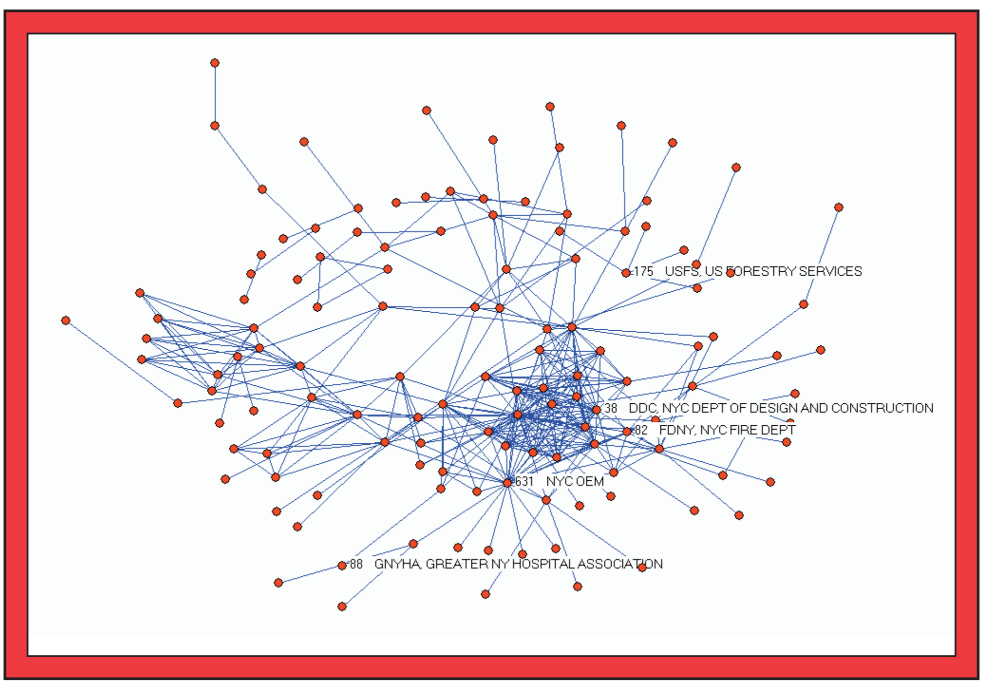
Building Inspection / Repair	Financial Assistance	Remains Recovery
Business Recovery	Fire Suppression	Responder Support Services
Cable Restoration	Food Provision	Response to New Threats
Counseling	Gas Restoration	Search and Rescue
Credentialing	Housing / Shelter Provision	Site and Facility Security
Forensic Investigation	Transportation Infrastructure Restoration	Site Stabilization
Damage and Situation Assessment	Injury Treatment	Space Provision
Debris Management	Law Enforcement	Support to Victims and Victims' Families
Debris Removal	Legal Issues	Technical Support Services
Donations	Logistics	Telecommunications Restoration
Electricity Restoration	Mapping	Victim Transport
Emergency Coordination	Occupational Safety	Volunteer Coordination
Environmental quality	Public Information / Relations	Water Restoration
Evacuation	Remains Identification	Wireless Telecommunications Restoration / Provisions

(e.g., search and rescue) as well as more "generalist" organizations, such as the Mayor's Office of Emergency Management. It consisted of many types of organizations: designated emergency response organizations such as fire, police, and emergency management agencies and the Red Cross; other local government agencies, such as the Department of Information Technology and Telecommunications and the Department of Design and Construction; a broad range of state and federal agencies; and numerous other organizations, including universities, health care organizations, technology firms, food service providers, contractors and construction companies, and organizations and groups providing crisis counseling to victims and first responders.

Decentralization

Although the management of crises is often described in "command-and-control" terms, suggesting that decision making and direction of response operations should be vested in a single individual or group of individuals who are "in charge" of the overall response, analyses of network relationships in the WTC disaster paint a very different picture. Referring again to Figure 1, the WTC response network is not highly centralized. As shown in Figure 2, even the task of coordinating key emergency operations was handled in a relatively decentralized manner, with the Office of Emergency Management, the Department of Design and Construction, and the Fire Department of New York serving as key nodes for overall emergency coordination, site management, stabilization, and debris removal at Ground Zero, and firefighting and search and rescue, respectively.

This decentralized pattern is common in post-disaster responses in the U.S. Disaster response operations are typically decentralized, rather than hierarchically organized, for several reasons. First, many disaster-related tasks, such as firefighting, building inspection, and emergency medical care, require specialized resources, facilitating the formation of semi-autonomous task-oriented subnetworks. Second, for many organizations involved in emergency operations, relationships



■ Figure 2. Emergency Coordination Subnetwork with other responding entities involve coordination, rather than direct control over people and resources. Third, in the U.S. intergovernmental system, with its principle of "shared governance," different levels of government have different disaster-related authorities and responsibilities. Under the Federal Response Plan, for example, federal government agencies provide resources when they are tasked to do so, but they do not take control of the overall response.[5] Instead, local, state, and federal agency officials typically engage in collaborative decision-making. At the same time, both plans and day-to-day practice encourage more interaction within governmental levels than among them. As a consequence, while policy makers and high-level managers set general goals and objectives for response operations, those goals and objectives are pursued through decentralized decision making and collective action. Drabek (2003: 99) describes the process this way:

> Once network priorities are established…functional groups must proceed in a highly decentralized manner in relationship to the network…There is both decentralization of decision making at the tactical level and centralization at the strategic level for each subsystem within each sector of the overall network.

More generally, as will be discussed in more detail below, decentralized networks develop in response to the disaster environment itself. That environment, which is turbulent, ambiguous, and highly demanding, requires organizations to incorporate new information, organizations, and resources and alter their response repertoires on a rapid basis. Centralized decision-making structures are too cumbersome to function effectively in a crisis milieu.

Emergence

Under everyday conditions, individual, group, and organizational behavior is consistent with existing cultural norms and organizational and societal rules and procedures; in other words, such institutionalized features of social life generally provide adequate guidance for organized action. However, under stressful and uncertain circumstances such as those that accompany major disasters, the activities of individuals, groups, and organizations begin increasingly to be characterized by emergence, rather than institutional routines. The concept of emergence refers to social relationships and activities that are new, novel, and non-institutionalized—in other words, different from routine or expected relationships and activities (Marx and McAdam, 1994). Disasters are occasions that stimulate the development of various forms of collective behavior, or behavior directed by emergent norms, as opposed to institutionalized ones. They also set the stage for the formation of emergent groups, or groupings that have no pre-disaster existence but that come together in order to address needs that their members consider vital. The larger the disaster event, the greater the tendency toward emergent activities and social relationships (for additional discussions, see Brouillette and Quarantelli, 1971; Stallings and Quarantelli, 1985).

At the group, organizational, and interorganizational levels, disasters are invariably accompanied by the rapid development of emergent multi-organizational networks (EMONS) (Drabek, 1985; 2003). Emergence occurs along several dimensions within these networks. With respect to network actors, or the nodes comprising the network, while the involvement of some actors is expected (e.g., specified in prior plans), many other actors, including emergent groups, become involved on an as-needed, unplanned basis. Similarly, many of the links or relationships that develop among actors in the network are non-routine and unplanned. The activities in which network actors engage may also be emergent—that is, different from their routine activities, and even different from those specified in disaster plans. Additionally, although EMONS generally stabilize over time, they are very dynamic, with actors entering and leaving the network and new relationships forming on a continuous basis (see, for example, Harrald, Cohn, and Wallace, 1992). It is thus very common in disasters for network actors to be unfamiliar with one another's roles and capabilities and uncertain about the nature of their relationships with one another, especially during the initial phases of the response. The numerous planning and strategy meetings that take place during disasters are needed in order to facilitate the negotiations that must take place among network actors as they attempt to manage emergence. Although such negotiations are often very time consuming, they are absolutely necessary since, as will be discussed in more detail below, emergence is a major source of resilience within disaster response networks.

The WTC EMON possessed the same emergent properties as other networks that develop in response to disasters, encompassing numerous new network actors, interorganizational relationships, and activities. The sheer size of the EMON, which vastly exceeded the scope of prior planning, is one indicator of the degree of emergence that characterized the response. Another is the extent to which numerous organizational actors participated voluntarily, rather than as a result of prior agreements.

Focusing on only one component of the response, the subnetwork that managed the debris removal and remains recovery operation at Ground Zero and the Staten Island Fresh Kills landfill site was almost entirely emergent, involving new network actors and new activities. While debris removal is necessary in all disasters, the WTC debris removal task was distinctive in many ways, necessitating very complex site stabilization operations, the sorting and hauling of enormous volumes of debris, and complex sifting and sorting operations capable of supporting both remains identification and retrieval and a forensic investigation. Responding to the demands associated with these activities, the subnetwork that carried them out developed and evolved "on the fly" as the disaster response progressed. New York City's Department of Design and Construction (DDC) acted rapidly on the day of the attacks to define for itself a key role in the management of site stabilization and debris removal at Ground Zero—a role for

"Planning had similarly never envisioned the need to respond to an event whose impacts resembled those of a major disaster and necessitated a full-scale disaster response, but that was also a crime scene, a national security emergency, and a potential environmental disaster."

which the agency had no pre-disaster authority (Langewiesche, 2002; for more detailed discussions on the emergent and improvisational qualities of this phase of the emergency response, see Wachtendorf, 2004).

This same emergent quality characterized other response subnetworks. For example, as has been documented by Huyck and Adams in their MCEER report (2002), a range of remote sensing technologies were employed by organizations in the aftermath of the 9-11 attacks on an almost entirely emergent basis. Similarly, with respect to mapping for damage assessment and other purposes, while plans had been under way to coordinate mapping activities in the city prior to 9-11, and while some formal data-sharing arrangements did exist among agencies, maps and other GIS products were developed at the reconstituted emergency operations center at Pier 92 by an emergent subnetwork that included city agencies, GIS vendors, and groups from local universities (Thomas et al., 2003). Other key emergency response activities, such as the inspection of Lower Manhattan structures that were damaged by the 9-11 attacks, were also carried out by newly-formed subnetworks. In this case, volunteer engineers worked with city building officials to inspect damaged structures, using the ATC-20 rapid post-earthquake damage screening protocol (for other discussions, see Tierney, 2003). In similar ways, network actors engaged in other response-related tasks actively reached out to partner with organizations and groups they thought possessed needed resources and expertise, even when mechanisms to formalize their participation were not in place.

Emergent Multi-Organizational Networks and Resilience

Part of MCEER's mission consists of conducting fundamental research that can shed light on the conditions that enhance organizational and community resilience following earthquakes and other disasters. This analysis of the WTC crisis response suggests ways in which EMONS contribute to resilience. More specifically, interpreted in light of sociological research on networks, this analysis highlights the characteristics and strengths of emergent networks as *a form of organization that is distinct from other types of organizational arrangements*, such as bureaucracies, markets, and hierarchies. The network as a form of organization can be defined as a set of entities that "pursue repeated, enduring exchange relations with one another and, at the same time, lack a legitimate organizational authority to arbitrate and resolve disputes that may arise during the exchange" (Podolny and Page, 1998).[6] Response networks like the one that developed in the aftermath of 9-11 have many features in common and thus many of the advantages of the "ideal type" network form. One such advantage is enhanced organizational learning (Podolny and Page, 1998; Carley, 1999). Another is the transfer of legitimacy from higher-status actors to other actors in the network, enabling the latter to more readily gain support for their activities (Podolny and Page, 1998). Emergent networks enhance resilience because they raise the probability that needed information and resources will become available through network ties and because they empower even network newcomers within the context of the overall response. Networks are also thought to foster the development and diffusion of innovations (Powell et al., 1996)—a key requirement in the crisis environment.

Networks are better-suited than other organizational forms to detect and respond in appropriate ways to the challenges posed by excessive demands and environmental turbulence, because of their capacity to gather information and identify and mobilize resources. This responsiveness stems in part from their ability to capitalize on diverse information sources and resource pools. In their analysis of the response of financial services organizations following the Trade Center disaster, for example, Beunza and Stark (2003) point to the need for both *replicative and generative* redundancy in crisis response operations. While replicative redundancy refers to the ability to reassemble or reproduce what has been lost in a disaster—for example, by having back-up systems and alternative operational sites or, as happened in the 9-11 disaster, by literally reconstituting a key site—generative redundancy consists of the ability to access new information, resources, and perspectives. This form of redundancy is enhanced through diverse network ties, because (Beunza and Stark, 2003: 153)

> [i]n situations of radical uncertainty, diversity of ties and diversity of means increase the likelihood that interaction will yield unpredictable solutions through 'creative abrasions' and 'generative friction.'

In their view, a key strength of networks is that they give rise to the kind of "laterally distributed intelligence" organizations require in unfamiliar and rapidly changing environments. Along these same lines, networks are capable of transmitting information and responding more rapidly than more highly-structured organizational forms. For network organizations (in this case, strategic interorganizational alliances) in competitive market situations, for example, it has been argued that (Knoke and Guilarte, 1994)

> [a]lthough interfirm alliances may actually increase transaction costs above those of markets and bureaucracies, they offer superior benefits such as swifter response to shifting market conditions, better access to technical know-how and economic information, greater trustworthiness among partners, and reduced uncertainty.

While network organizations may or may not have all these advantages under all circumstances (see, for example, La Porte, 1996, on public organizational networks and the issue of trust), owing to their structural features, they are inherently more capable of rapid adaptation than highly formalized and hierarchical organizations.

Similarly, Comfort (1999) concludes in her multi-national study on system responses to earthquake disasters that the most effective system responses are those that are "auto-adaptive" or "self

"Emergent networks enhance resilience because they raise the probability that needed information and resources will become available through network ties and because they empower even network newcomers within the context of the overall response."

organizing"—that is, (1999: 73) "high on technical structure, high on organizational flexibility and high on cultural openness to new information and new methods of action." EMONS are a key source of this openness and creativity. Networks form the locus for the collective sensemaking (Weick, 1995) and organizational learning that must take place under conditions of ambiguity and uncertainty. To make sense of crisis situations as they unfold, responding organizations need rapid access to information, which is rendered more likely when organizational boundaries are permeable, barriers to information flow are weakened, and many and diverse actors communicate and coordinate with one another. EMONS facilitate this process. To deal with emerging problems as they are identified, responders also require the ability to act without having to adhere to pre-established institutionalized constraints, and EMONs provide this flexibility.

Conclusions

As the preceding discussions indicate, EMONS and the network form of organization contribute to organizational and community resilience in a variety of ways. Focusing first on the redundancy dimension, they help increase redundancies with respect to personnel, facilities and other resources, compensating for resources that are lost in disasters (replicative redundancy). At the same time, they provide the infrastructure for information transfer and the diffusion of novel problem-solving strategies (generative redundancy). Relatedly, they are capable of mobilizing resources of all kinds, which contributes to the resourcefulness dimension of resilience. Because of their diversity, decentralization, and relative lack of formal restrictions on network actors, they are also able to respond rapidly to disaster-generated demands. The advantages of networks over hierarchies can be seen by comparing the response to the 9-11 attacks and other large disasters in the U.S. with the manner in which such events are handled in other political systems that are more highly centralized and less able to accommodate emergence, such as the Japanese system. The slow and initially ineffective response to the 1995 Kobe earthquake can be attributed not only to the size and severity of that disaster but also to the relative inflexibility of the emergency response system, in terms of its ability to allow for emergence and enact structural adaptations that could have enabled the system to perform critical emergency tasks more rapidly and effectively (Comfort, 1999).

Just as it is possible to compare crisis response systems across societies, it is also possible to assess how well EMONs have been managed in different U. S. disasters (see, for example, Drabek, 2003) and, in the pre-event context, how well prepared communities are to manage emergence. Indicators of such capability could include the diversity of organizations and community sectors included in pre-crisis planning; strategies that may exist to incorporate volunteers and emergent groups into the response, including plans for providing space in emergency operations centers for such groups; information-sharing protocols that allow for the expansion of communications networks on an as-needed basis; and mechanisms for establishing interorganizational linkages and enabling new network actors to join response networks rapidly in the event of a disaster (e.g., mutual aid agreements, special contracting provisions, plans for suspending regulations and legal requirements that could slow down response operations). All disasters are accompanied by emergence at the network level, but some communities are likely much more able than others to capitalize on emergence, and hence are more resilient in the face of disasters.

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Endnotes

[1] These funds were expended not only in New York City but also in the greater metropolitan area. An additional $2.4 billion for transportation reconstruction and recovery is being provided through an interagency agreement with the U.S. Department of Transportation. A total of $3.5 billion is also being provided by the Department of Housing and Urban Development for assistance to businesses and individuals and for other recovery-related projects.

[2] UCINET and Pajek were used to analyze and visualize the network.

[3] It should be noted that, because it is based only on a subset—albeit a large one—of the data that were collected, this network model understates the number of organizations involved. Additionally, because more documentary data were available in these data sources on federal agencies than on local groups and agencies, this particular model tends to under-emphasize the participation of those entities.

[4] The different colors denoting network relationships correspond to different tasks around which activities were organized.

[5] The FRP itself provides a framework for response decentralization. The plan structures agency activities around twelve different “emergency support functions” (ESFs) which, while under the general umbrella of FEMA, operate in a more or less autonomous fashion during disasters.

[6] This is not to say that network relationships retain this form over time, or that all participants lack such arrangements, only that network organizations are not as constrained by contracts or other formal agreements than other types of organizations.

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Application of High-Resolution Optical Satellite Imagery for Post-Earthquake Damage Assessment: The 2003 Boumerdes (Algeria) and Bam (Iran) Earthquakes

by Beverley J. Adams, Charles K. Huyck, Babak Mansouri, Ronald T. Eguchi and Masanobu Shinozuka

Research Objectives

The objectives of this research are to develop techniques for post-earthquake urban damage detection, based on the comparative analysis of remote sensing images acquired before and after the event, and to develop the technological infrastructure for integrating these techniques into field-based reconnaissance activities.

Remote sensing technology is increasingly recognized as a valuable post-earthquake damage assessment tool. Recent studies performed by research teams in the U.S., Japan and Europe have demonstrated that building damage sustained in urban environments can be readily identified through the analysis of optical (Matsuoka and Yamazaki, 1998; Chiroiu et al., 2002; Huyck et al., 2002; Mitomi et al., 2002; Yusuf et al., 2002; Shinozuka et al., 2000; Saito and Spence, 2004) and synthetic aperature radar (SAR) (Aoki et al., 1998, Huyck et al., 2002; Yusuf et al., 2002) imagery.

Under the broad aim of identifying ways in which post-earthquake response and recovery activities can be improved through the integration of remote sensing technologies, a Multidisciplinary Center for Earthquake Engineering Research (MCEER) team has been investigating their use for urban damage detection and emergency response (Eguchi et al., 1999; Eguchi et al., 2000a, 2000b; Eguchi et al., 2003; Huyck and Adams, 2002; Huyck et al., 2002). Research to date has focused on various aspects of damage detection, including the development of post-earthquake damage detection algorithms that use optical and SAR data to locate building collapse, and a mapping system to display and disseminate earthquake-related multimodal geospatial data.

This paper describes an extension of the methodology previously developed for the 1999 Marmara (Turkey) earthquake (see Eguchi et al., 2003), to detect building damage caused by the 2003 Boumerdes (Algeria) and Bam (Algeria) earthquakes (see also Adams et al., 2003a, 2003b, 2004). For the Marmara event, change detection algorithms were based on moderate resolution SPOT4 optical and ERS SAR coverage. Following the recent launch of Quickbird and IKONOS commercial satellite systems, a new generation of very high-resolution imagery has become available. The Boumerdes

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Previous Summaries

2001-2003:
Eguchi et al.,
http://mceer.buffalo.edu/publications/resaccom/0103/09eguchi.pdf

2000- 2001:
O'Rourke et al.,
http://mceer.buffalo.edu/publications/resaccom/0001/rpa_pdfs/14orourkegis-4.pdf

1999-2000:
Eguchi et al.,
http://mceer.buffalo.edu/publications/resaccom/9900/Chapter7.pdf

1997-1999:
Eguchi et al.,
http://mceer.buffalo.edu/publications/resaccom/9799/Ch1eguch.pdf

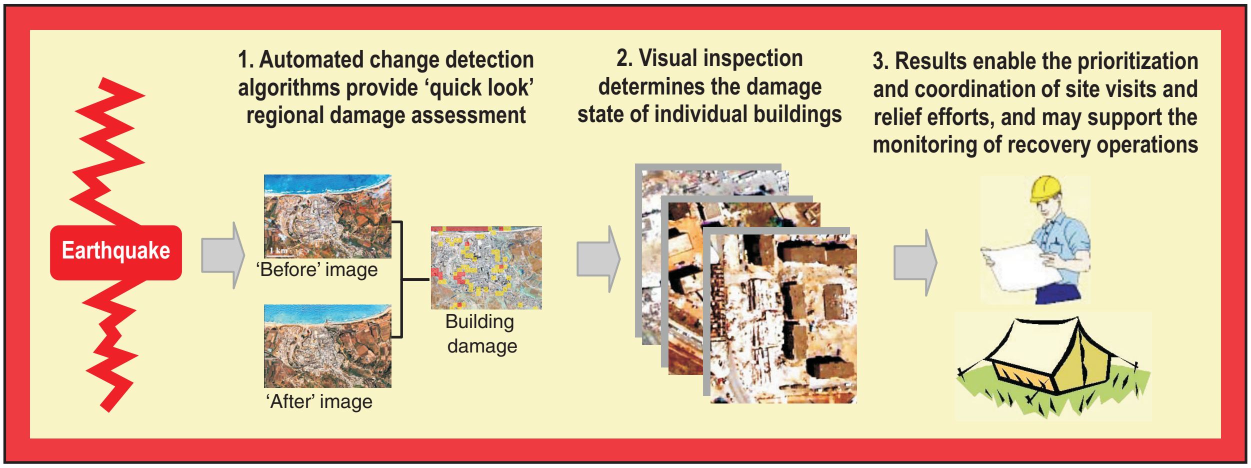
and Bam earthquakes mark the first two occasions for which this imagery was collected before and soon after the event. However, the increase in spatial resolution from 10 meter to sub-meter accuracy calls for a number of methodological refinements. Initially, a 'Tiered Reconnaissance System' (TRS) is conceptualized, which extends the scope of information collected to include damage visualization for individual structures. Following details of a methodological refinement at the pre-processing stage, implementation of the revised methodology is described for the Boumerdes and Bam events. The paper goes on to provide details of its subsequent deployment as a post-earthquake reconnaissance tool within the VIEWS (Visualizing Impacts of Earthquake With Satellites) system, before concluding with a brief discussion of future research directions.

Technical Summary

In the aftermath of extreme earthquakes such as the 2003 Boumerdes and Bam events, remote sensing imagery provides a detailed overview of damage sustained. The location and severity of building collapse can be rapidly determined, facilitating the scaling and prioritization of relief efforts, and potentially the extended monitoring of the recovery operations.

As shown in Figure 1, this reconnaissance process may be conceptualized as a 'Tiered Reconnaissance System' (TRS). First, automated change detection algorithms offer a 'quick-look' city-wide damage assessment. These algorithms compare images acquired before and after the earthquake occurred, according to the methodological approach in Figure 2. Initial pre-processing involves registering the input images and georeferencing them within a common coordinate system. For very high-resolution imagery, an additional image processing step involves edge detection and texture analysis (further details are given in the following section). The theory is that building collapse produces a distinct textural signature compared with non-damaged structures, characterized by dense and irregular edges. This approach was not viable for SPOT4 coverage of the 1999 Marmara earthquake, since the textural characteristics of individual structures are indiscernible at 10m resolution. Damage is then computed in terms of 'changes' between the pre-processed scenes, measured using a simple arithmetic operator, such

Results from this research will bring significant benefits to emergency response personnel in the aftermath of extreme earthquake events. Damage detection techniques will furnish first responders, government officials, international aid agencies and reconnaissance teams with a quick look regional damage assessment and detailed visualization of damage sustained on a per building basis. These tools will enable the prioritization and coordination of relief efforts and site visits.

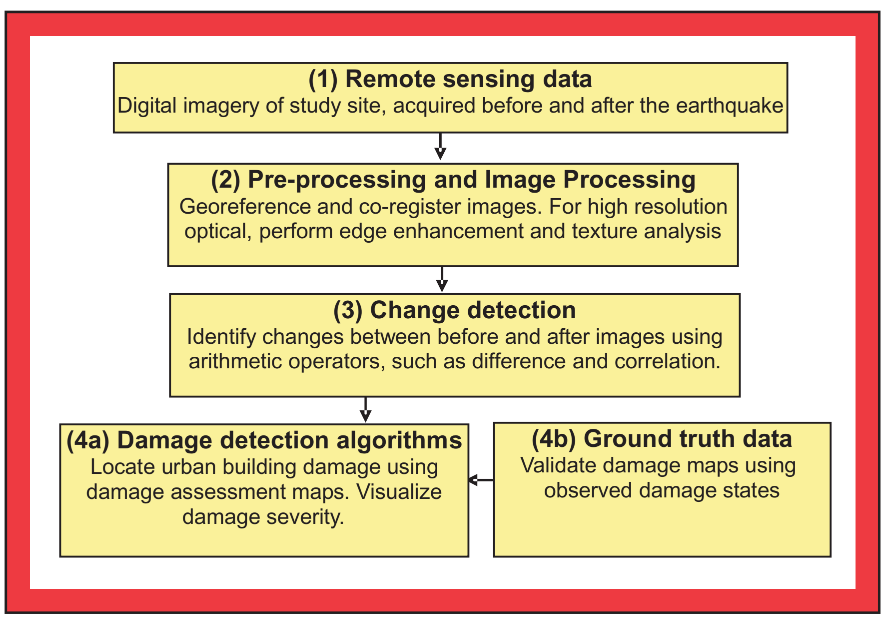


■ Figure 1. Schematic representation of the post-earthquake Tiered Reconnaissance System (TRS), which uses satellite imagery to determine the location, extent and severity of building damage. Output from the TRS guides the scale and prioritization of site visits and relief efforts.

as difference or correlation. Similar change detection algorithms have successfully been used to evaluate damage in cities affected by the 1999 Turkey (Eguchi et al., 2000a, 2000b, 2002, 2003), 1993 Hokkaido, 1995 Kobe (Matsuoka and Yamazaki, 2002), and 2001 Gujurat earthquakes (Matsuoka and Yamazaki, 2002, 2003). Lastly, detected building damage is displayed using a damage assessment map.

This quick-look assessment provides the focus for more detailed inspection of building damage, using visualization techniques. Given the fine detail depicted on very high-resolution imagery, it is possible to interpret the condition of individual structures by comparing enlarged representations from the 'before' and 'after' datasets. This comparative visual analysis is straightforward when the co-registered 'before' and 'after' images can be displayed side by side.

Finally, having performed the initial reconnaissance of damage location and severity, remote sensing imagery may have a longer-term role to play in monitoring clean-up operations. When possible, the acquisition of extended temporal coverage enables progress with debris clearance and reconstruction to be tracked.



■ Figure 2. Building damage detection methodology.

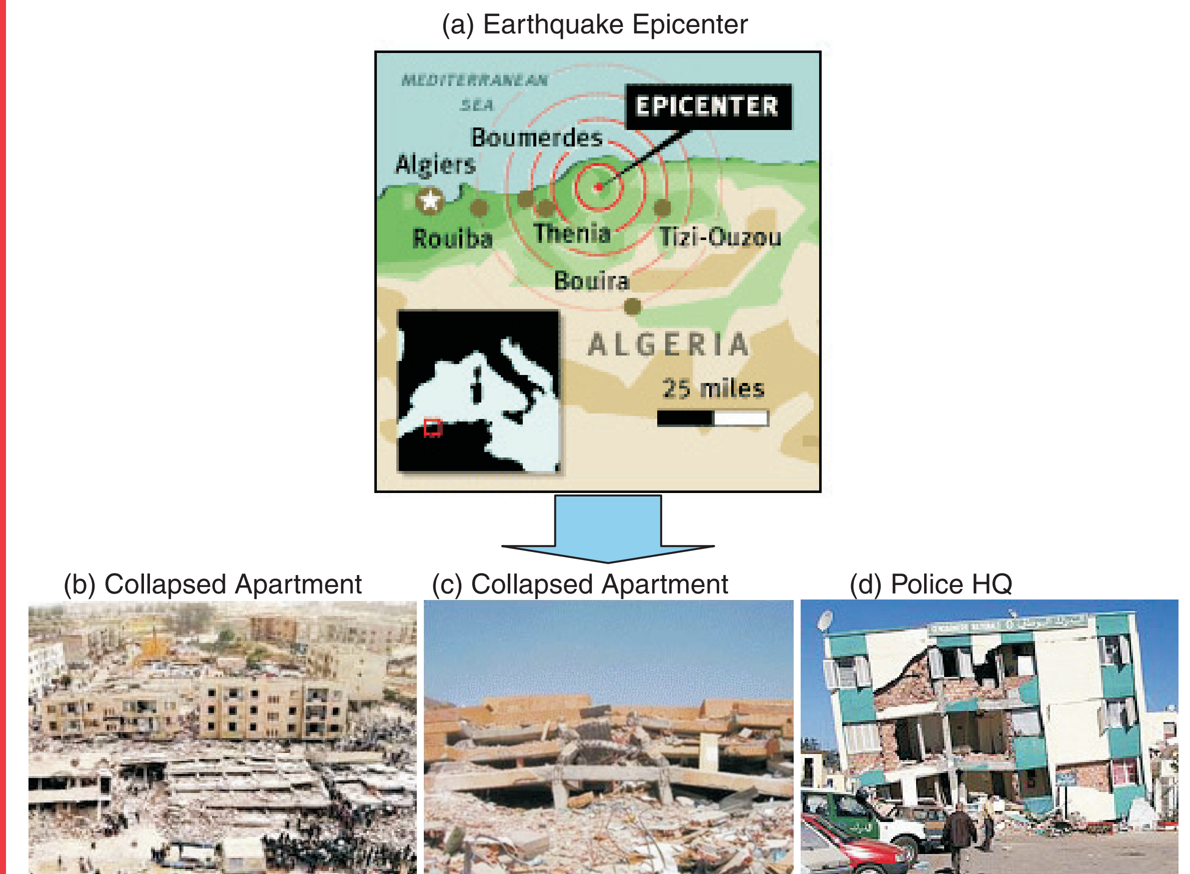
Urban Damage Detection Following the 2003 Boumerdes and Bam Earthquakes

The TRS approach to urban damage detection was implemented following the Boumerdes and Bam earthquakes.

Boumerdes, Algeria Earthquake

At 17:44 local time on May 21, 2003, a magnitude 6.8 earthquake struck Northern Algeria (USGS, 2003). Centered on the Boumerdes province (Figure 3a) some 50 km east of Algiers, the worst-affected urban areas included the cities of Boumerdes, Zemmouri, Thenia, Belouizdad, Rouiba and Reghaia, together with eastern areas of the capital. Deaths totaled 2,266, with a further 10,261 injuries (OCHA, 2003). Structural damage within urban areas was severe. From Figure 3b through Figure 3d, entire apartment blocks were reduced to piles of rubble. Civil structures, such as the police headquarters, were also damaged beyond repair.

Figure 4 shows the high-resolution Quickbird satellite



Photographs courtesy of (b) AP Photo/Claude Paris; (c) Omar Khemici and EERI; and (d) Reuters/Larbi.

■ Figure 3. The May 21 2003 Boumerdes (Algeria) earthquake. Location of the earthquake epicenter; and building damage recorded in Boumerdes.

coverage acquired before and after the Boumerdes earthquake (courtesy of DigitalGlobe, *www.digitalglobe.com*), purchased by the Earthquake Engineering Research Institute (EERI) as part of their Learning from Earthquakes Program. These 'pan-sharpened' images are a fusion of multispectral and panchromatic bands. The dataset includes a time series of imagery. The scene from April 22, 2002 serves as a baseline case, depicting the city as it used to appear before the earthquake struck. The second image is dated May 23, 2003 – just 2 days after the event. Third in the sequence, the coverage of June 18, 2003 records progress made with recovery efforts during the following month.

Constituting the initial TRS phase, Figure 5a shows the spatial distribution of severely damaged and collapsed buildings in Boumerdes, which were identified on the panchromatic Quickbird coverage, using the change detection methodology (see Figure 2). The scenes acquired before (4/22/02) and soon after the earthquake (5/23/03) were analyzed using the image processing software ENVI. In line with the high spatial resolution of 60 cm, an additional texture-based pre-processing step was introduced to the change detection methodology. A 9x9 pixel Laplacian edge detection filter was initially applied to each co-registered scene, followed by a 25x25 dissimilarity texture measure. The resulting images were differenced on a per-pixel basis and the mean standard deviation about the image mean computed. An average standard deviation was then plotted within a 200x200 cell window. Mapping these block statistics in intervals of 1 standard deviation, highlights areas of potential building collapse, where textural change is consistently high. It remains for this city-wide damage map to be formally verified against ground based observations. This future work will draw on the building damage interpretation performed by Chiba University, Japan (see Yamazaki et al., 2003), as shown in Figure 5b.

In the meantime, a broad scale comparison can be drawn between observations and the damage map. Areas depicted in red and yellow in Figure 5a generally correspond with extreme textural changes accompanying building collapse.

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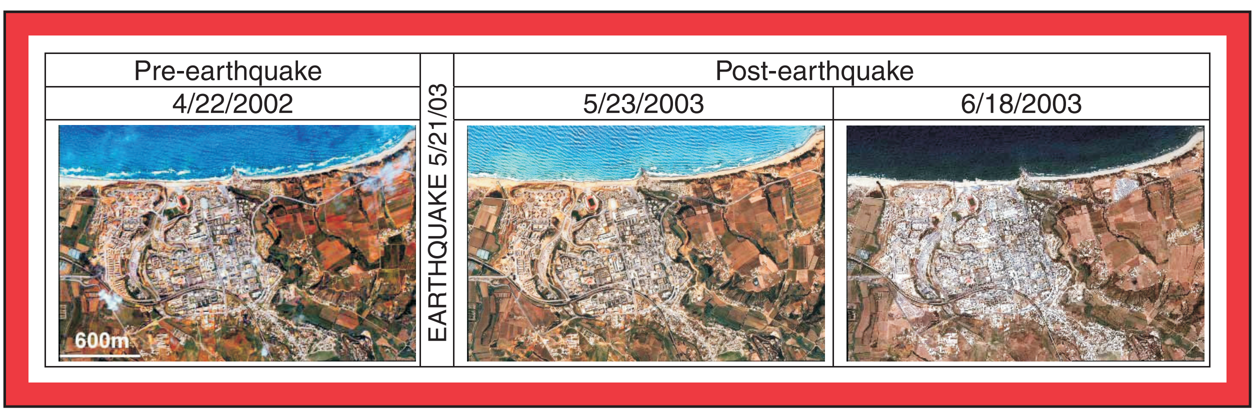
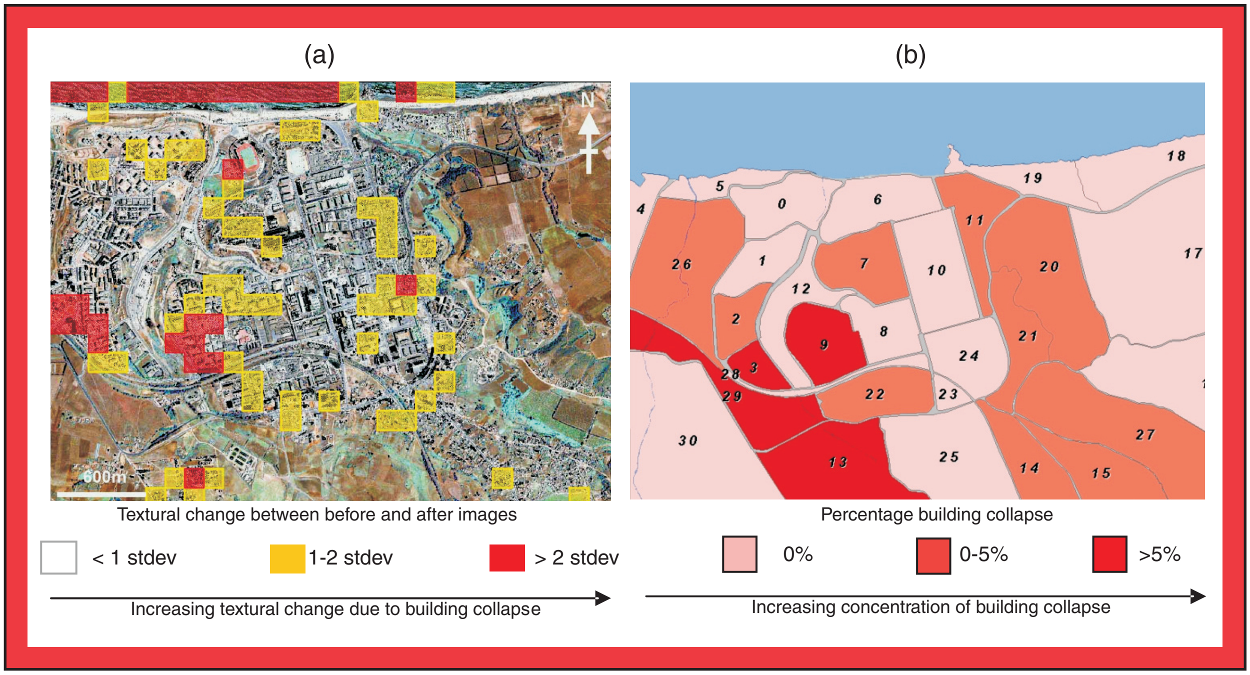


Images courtesy of DigitalGlobe, www.digitalglobe.com

■ Figure 4. Quickbird satellite imagery of Boumerdes, acquired before and after the May 23, 2003 earthquake.



courtesy of F. Yamazaki

Figure 5. (a) Quickbird damage map for Boumerdes. High average block standard deviation from the image mean corresponds with extreme textural changes caused by building collapse. (b) Distribution of building collapse in Boumerdes

Concentrated damage in the south-west of the city aligns with zones 3 and 9 in the Chiba results (Figure 5b), where >5% of buildings collapsed. Extreme change within the coastal waters is probably attributable to textural variations in sea surface conditions.

Moving on to the second TRS phase, Figure 6 offers a detailed representation of neighborhoods sustaining severe building damage. From visual inspection of the 'before' and 'after' scenes, significant structural and geometric irregularities are apparent. Collapsed apartment blocks are readily distinguished by the bright yet chaotic appearance of debris. Where buildings have pancaked or toppled sideways, changes in shape and position are also evident. In the case of Boumerdes, a temporal sequence of 'after' images was available. In terms of monitoring progress with recovery operations, Figure 7 shows the full temporal sequence for an area of apartment blocks in western Boumerdes. The first image illustrates the buildings prior to the earthquake. The second shows their collapsed state, surrounded by debris. The third scene tracks recovery efforts, indicating that the site has largely been cleared.

Bam, Iran Earthquake

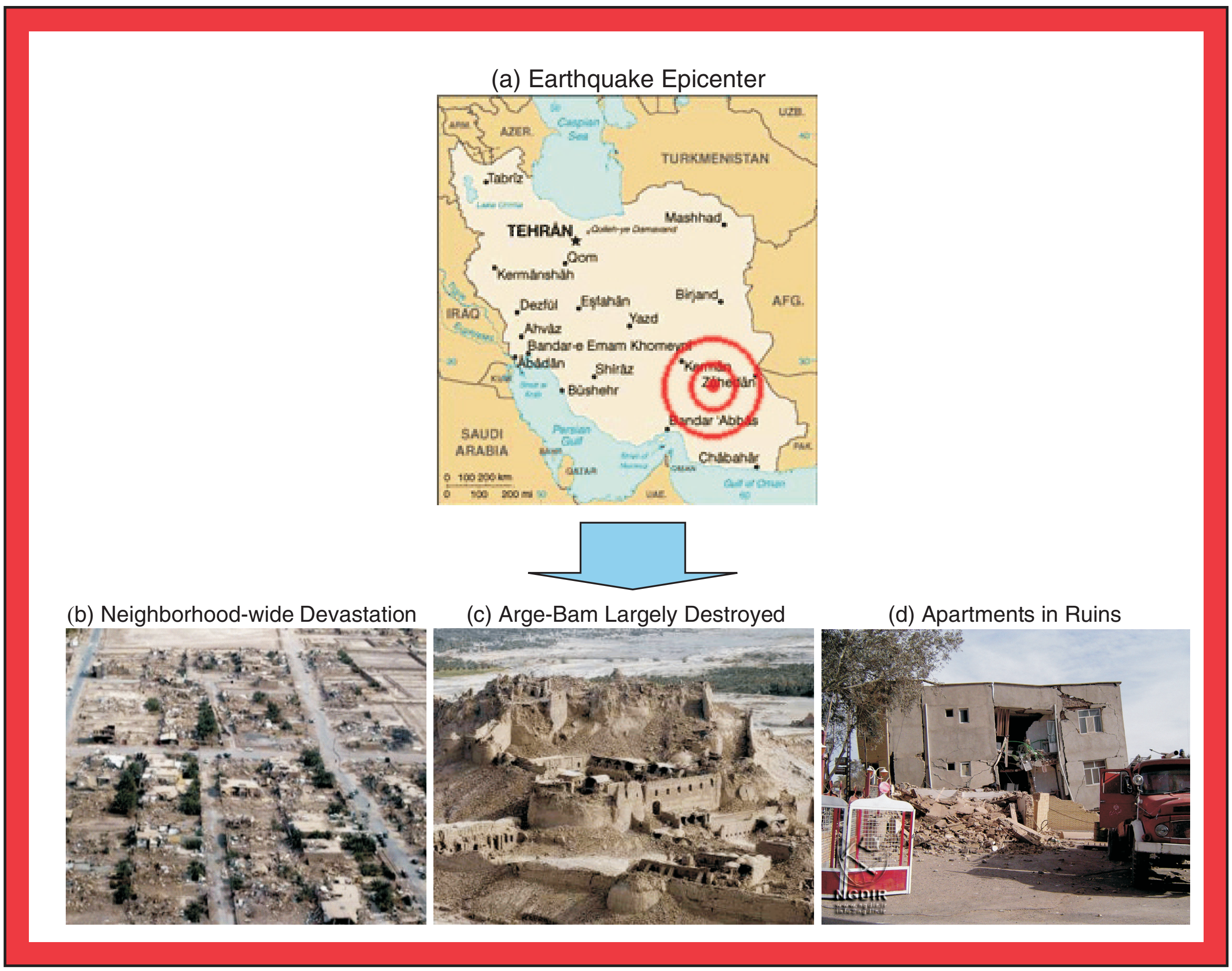
At 05:26 on December 26 2003, a magnitude 6.6 (USGS, 2004) earthquake struck the historic city of Bam, in the Iranian province of Kerman (Figure 8a). The earthquake was centered approximately 10 km to the south-west of Bam. Damage was concentrated in a 16 km radius around the city, which is famed for its 2,500 year old citadel Arge-Bam. In terms of human cost, the Bam earthquake ranks as the worst recorded disas-

■ Figure 6. Visualization of building collapse in Boumerdes. The selected neighborhoods were identified as regions of extreme textural change in the damage map (Figure 5a)

■ Figure 7. Time sequence of Quickbird images, showing apartments in western Boumerdes (1) prior to and (2) soon after the earthquake. Scene (3) acquired on 6/18/03, shows progress made with clean-up operations ter in Iranian history. According to recent reports, the death toll has reached 26,200 (IFRC, 2004) with a further 75, 600 left homeless. Initial reports from aid organizations in Bam estimated that between 70-95% of buildings were destroyed. Figure 8b through Figure 8d illustrate the nature and extent of damage: annihilation across entire city blocks; the historic city center and fortress in ruins; the main hospitals effectively destroyed, together with health homes, rural and urban health centers; 131 schools and 3 universities severely damaged.

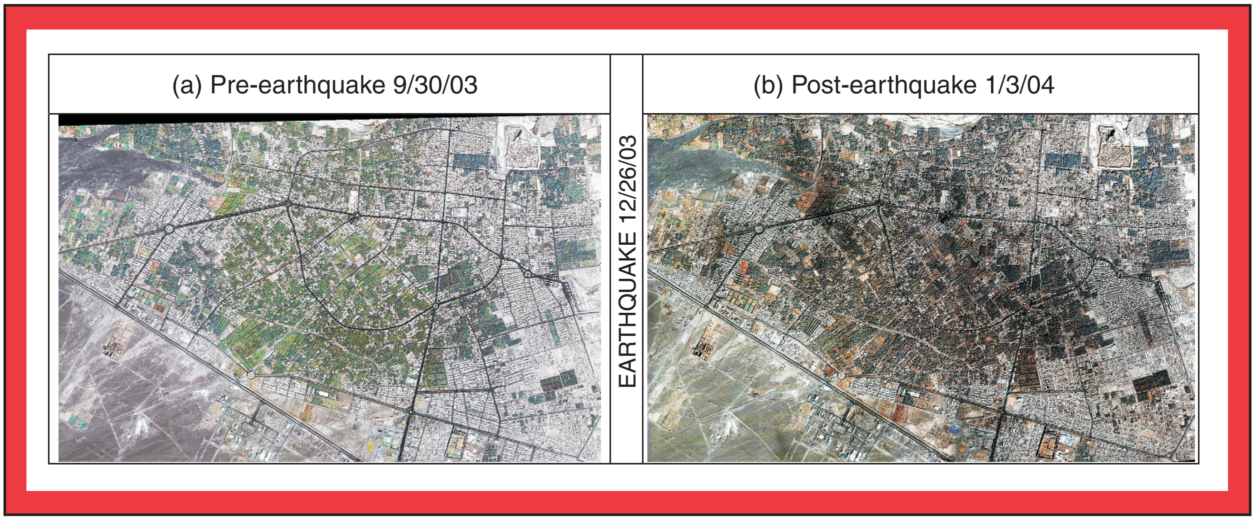
Figure 9 shows the extent of Quickbird satellite coverage of Bam (courtesy of DigitalGlobe, *www.digitalglobe.com*), acquired by the University of California at Irvine, and the EERI as part of their Learning from Earthquakes Program. The first image is dated September 30, 2003 – approximately 3 months before the earthquake struck. The second, taken just over one week after the earthquake on January 3, 2004, shows widespread changes associated with building collapse.

For the initial TRS phase (see Figure 1), the same methodol-



Photographs courtesy of http://activistchat.com/gallery/albums.php

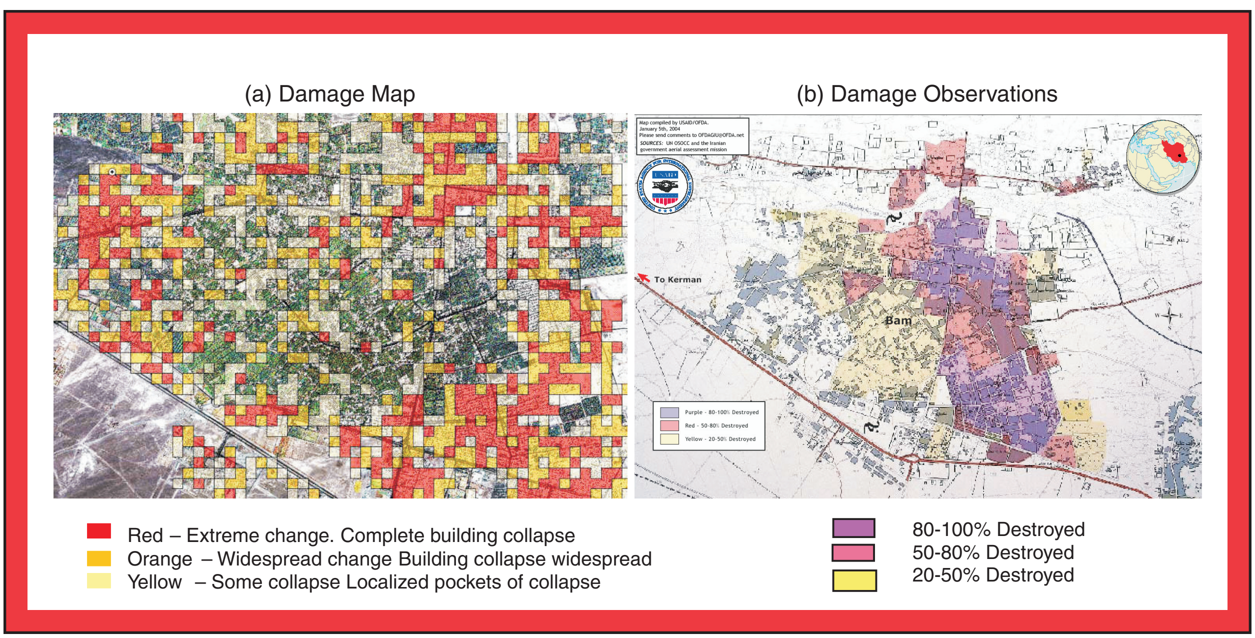
■ Figure 8. The December 26 2003 Bam (Iran) earthquake. Location of the earthquake epicenter; and examples of building damage recorded in the city and historic citadel Arge-Bam.



Images courtesy of DigitalGlobe, www.digitalglobe.com

■ Figure 9. Quickbird satellite imagery of Bam, acquired before and after the December 26th 2003 earthquake.

ogy was employed here as for the Boumerdes event, with damage detected in terms of textural changes between the 'before' and 'after' scenes. The resulting city-wide damage map in Figure 10a shows the widespread occurrence of extreme changes (manifest as a high standard deviation about the image mean) throughout Bam. The red and orange blocks corresponding with the highest concentration of collapsed structures, are widespread through eastern areas of the city and the Arge-Bam citadel. Visual comparison with the USAID damage map in Figure 10b, published in early January, indicates



courtesy of USAID

■ Figure 10. Quickbird damage map for Bam. Extreme textural changes caused by building collapse relate to a high average block standard deviation from the image mean (see also Figure 5) (b) Distribution of building collapse in Bam.

that 80-100% of buildings were destroyed in these areas. Formal verification of the damage map against these ground-based observations is a focus of ongoing research.

In terms of visual inspection, Figure 11 provides a close-up view of damage within a selection of areas on the damage map that record extreme changes. Collapsed buildings are evident throughout the ancient citadel. The eastern wall of the fortress appears to have collapsed. Many of the surrounding structures are no longer clearly defined as the walls and roofs have fallen in. In surrounding residential areas, building collapse is widespread; entire blocks of family homes have been destroyed. Their distinct footprint and white roofs in the 'before' image, have been replaced by chaotic piles of brown rubble. Constructed from local material, the sand-colored debris is difficult to distinguish from the surrounding sandy ground surface.

■ Figure 11. Visualization of building collapse in Bam. The selected neighborhoods were identified as regions of extreme damage (80-100% collapse) on the USAID damage map (Figure 10b)

Deployment for Field Reconnaissance through VIEWS

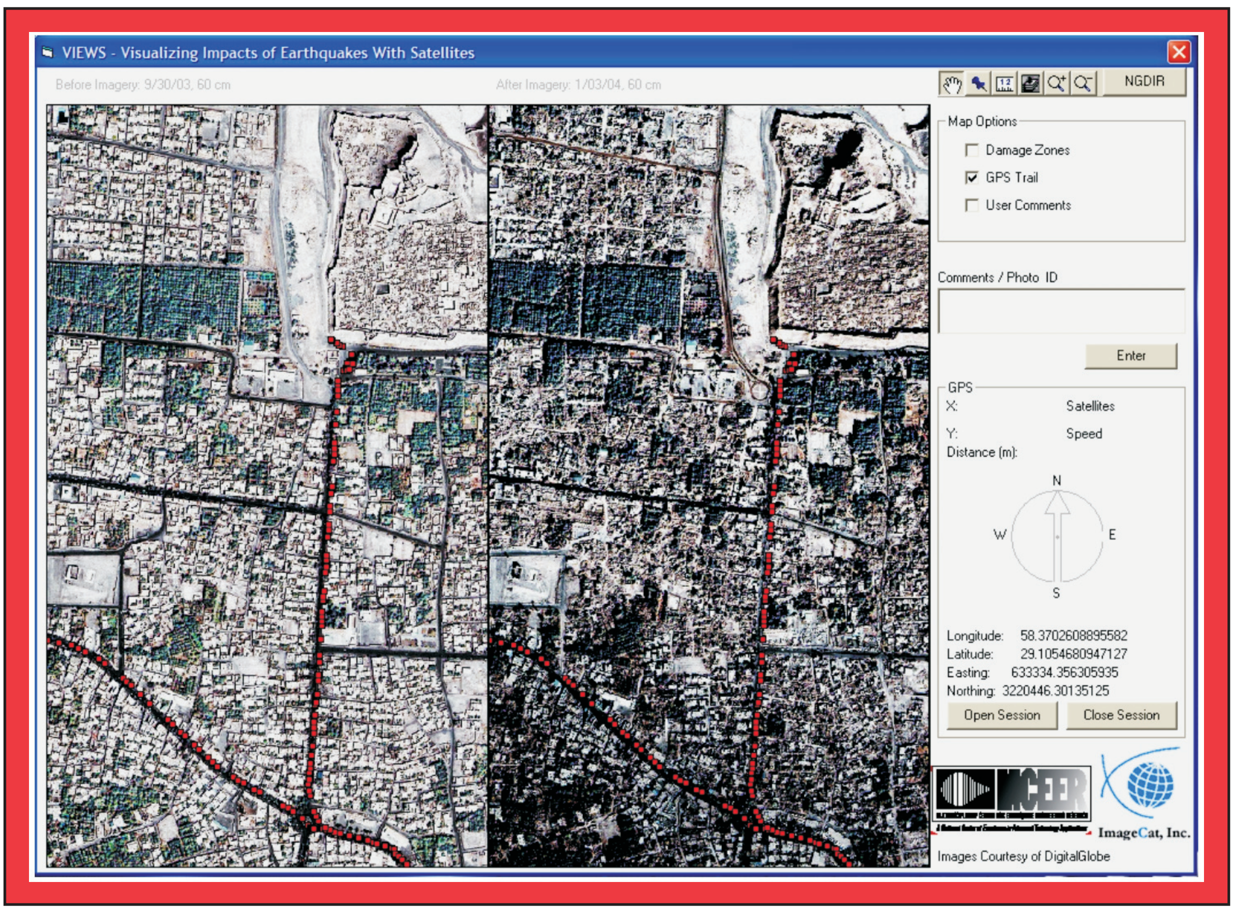
Through MCEER funding, considerable effort has been invested in developing automated building damage detection methods, together with techniques for visualizing damage. The Bam earthquake marks their first deployment as a post-earthquake reconnaissance tool, within the VIEWS (Visualizing Impacts of Earthquakes With Satellites) system. Figure 12 shows the VIEWS interface, displaying 'before' and 'after' imagery of Bam.

Running on a notebook for portability, VIEWS enables reconnaissance teams to compare satellite images acquired before and after an earthquake. The system directs responders to the hardest hit areas, using the damage assessment map (Figure 10a). For more detailed damage information, collapsed buildings are easily identified on the high-resolution satellite coverage. This also serves as a basemap and orientation device for teams deployed to unfamiliar cities. To help users gain and maintain their bearings, VIEWS tracks their current position using a real-time GPS feed. The system also provides easy recall for observations made in the field. As users enter comments such as building damage descriptions and the ID number of their photographs, all information is automatically linked to the current GPS location. Back in the office, VIEWS datasets are readily transferred to a GIS environment, for further analysis.

The VIEWS system was deployed by the EERI reconnaissance team. During the course of reconnaissance activities in Bam, the GPS functionality was used to track routes followed through the city. Figure 12 illustrates one of the routes taken towards the citadel. The location of digital photographs was also recorded and their identification numbers and associated comments added as attributes. Following this initial trial, important lessons have been learned that will improve logistical and technical aspects of VIEWS deployment for future earthquakes.

Conclusion and Further Research

Results from the multitemporal change detection methodologies presented in this paper demonstrate that high-resolution Quickbird satellite imagery can be used to successfully determine the location and severity of post-earthquake building collapse. Compared with previous research completed for the 1999 Marmara (Turkey) earthquake (see Eguchi et al., 2003) using SPOT 4 optical data, the increase in spatial resolution to 60 cm necessitated additional



■ Figure 12. Screen-grab of the VIEWS (Visualizing Impacts of Earthquakes with Satellites) system, deployed in Bam with the EERI reconnaissance team. The GPS trail (red symbols) is shown for a route taken by the team during reconnaissance activities.

processing to distinguish damage associated with building collapse. When plotted as a damage map, the differenced edge detection and textural dissimilarity results successfully located blocks of extreme change. In this case, change was measured relatively rather than absolutely, in terms of the standard deviation about the image mean. The spectral signature of earthquake building damage differs around the World, as the building stock and construction materials vary. As such, devising universally applicable measures of change poses a considerable challenge.

While working towards an end goal of robust damage detection algorithms that can be rapidly deployed in future earthquakes to aid response and recovery efforts, this research program will concentrate on standardizing the methodology, so that building damage can be detected, irrespective of urban setting. From a methodological perspective, findings from the 1999 Turkey, and 2003 Algerian and Iranian events, will be consolidated and existing optical damage detection algorithms refined and augmented with new capabilities. For example, the integration of higher resolution Radarsat SAR satellite imagery would enable 24/7, all-weather damage assessment. The use of unmanned airborne vehicles (UAVs) such as the MLB 'Bat' as part of reconnaissance activities, would enable the collection of imagery from remote locations with poor accessibility, or sites that are cut-off after an earthquake. The processing and integration of resulting high-resolution optical coverage will pose an exciting new research challenge.

In terms of research implementation, VIEWS technology will be extended to include these refinements, and on the basis of feedback from field reconnaissance teams, enhanced to optimize performance during future deployments. In achieving these objectives, collaboration will continue with U.S. and International research partners.

Acknowledgements

This work was supported primarily by the Earthquake Engineering Research Centers Program of the National Science Foundation, under NSF Award Number EEC-9701471. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect those of the National Science Foundation. The help and support of Professor Fumio Yamazaki, from the University of Chiba and Dr. Masashi Matsuoka of the Earthquake Disaster Mitigation Research Center (EDM) is acknowledged. The authors would also like to the Earthquake Engineering Research Institute for their generous support in purchasing the images for the Boumerdes and Bam earthquakes.

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Java-Powered Virtual Laboratories for Earthquake Engineering Education

by Yong Gao, Guangqiang Yang, Billie F. Spencer, Jr. and George C. Lee

Research Objectives

The objective of this MCEER educational project is to develop Java-based Virtual Laboratories for Earthquake Engineering (VLEE) as a Tri-Center collaborative effort to produce online resources for earthquake engineering education. This task is a part of MCEER's Center-wide effort to develop educational modules, in which various Java-Powered Virtual Laboratories (VLs) have been developed to provide a means for on-line interactive experiments. They are intended to provide a conceptual understanding of a wide range of topics related to earthquake engineering, including structural control using the tuned mass damper (TMD) and the hybrid mass damper (HMD), linear and nonlinear base isolation system, and nonlinear structural dynamic analysis of multi-story buildings. The VLEEs are available on-line at *http://cee.uiuc.edu/sst/java/* and have been incorporated as a reference implementation of educational modules in the NEESgrid software (*http://www.neesgrid.org/*).

Educators must always strive to better prepare the next generation of structural engineers so that they may better understand and effectively deal with the design of earthquake resilient structures to reduce the loss of human lives and the negative impacts to society. One of the challenges of teaching students about the fundamentals of earthquake engineering is to give them an intuitive understanding of the dynamics of structures. Demonstrating the concepts of dynamics using static chalk boards or books is difficult. The best approach is through hands-on laboratories. Unfortunately, few instructors have the necessary facilities readily available to demonstrate structural dynamic concepts. To overcome this difficulty, a series of Java-Powered Virtual Laboratories (VLs) have been developed, as part of the MCEER Education Module Development task, in the Smart Structures Technology Laboratory (SSTL) of the University of Illinois at Urbana-Champaign.

To date, a total of five VLs have been published on the internet. The structural control VL allows users to compare the effect of using two different control systems to reduce structural response of an "uncontrolled" structure subject to earthquake excitations. The linear and nonlinear base isolation VLs allow users to study the effectiveness of base isolation to

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Previous Summaries

2001-2003:
Dargush et al.,
http://mceer.buffalo.edu/publications/resaccom/0103/12dargush.pdf

reduce the seismic demands on a structure. The focus of our 2003-04 efforts was the extension of a two degree-of-freedom nonlinear dynamic analysis VL to accommodate multi-story buildings with an arbitrary number of degrees-of-freedom. These VLs provide users with wide flexibility to understand the dynamic performance of building structures subject to earthquake loading.

Technical Summary

The virtual laboratories were programmed using Java. The Java programming language (Newman, 1996) offers significant advantages because of its minimal dependence on the operational platform. Therefore, these Java-powered VLs can be accessed universally through the Internet. Using the Java language minimizes administration maintenance for the VL once it has been developed and published on the Internet. If additional updating is required, it can be made locally and updated on the Internet. When remote users access the VL the next time, the updated version will be automatically downloaded and executed. In addition, these VLs' interactive interface, optimized with Java programming, significantly increases the efficiency of presenting and, in turn, of understanding a wide range of topics in earthquake engineering.

Computational analysis of the dynamic problems in these virtual simulations utilizes several state-of-the-art numerical algorithms. In the structural control VL, the linear dynamic analysis problems are solved by the Runge-Kutta method. The algebraic Ricatti equation associated with the LQR controller design was solved using the Generalized Eigenproblem Algorithms given by Arnold and Laub (1984). In the base isolation and nonlinear dynamic analysis VLs, the Generalized α – method was employed to solve the hysteretic bilinear stiffness problem, and the Runge-Kutta method was applied to handle all other linear and nonlinear analysis (Tedesco et al., 1998; Belytschko and Hughes, 1983; Berg, 1989).

In the subsequent sections of this paper, an overview of each VL is provided, followed by examples on how these VLs can be utilized to facilitate understanding of different special topics. Finally, conclusions and future research are presented.

Structural Control Virtual Laboratory

This structural control VL allows users to compare the effect of using two different control systems

These virtual laboratories constitute one of the first efforts in the U.S. to develop on-line interactive educational tools to illustrate structural dynamic concepts for earthquake engineering. Graduate students and professional engineers will find these modules useful in understanding the cutting edge techniques used to design earthquake resilient structures. About 500 visitors per month from around the world access the five modules currently available on the Internet.

to reduce the structural response of an "uncontrolled" structure subjected to earthquake excitation. The two control systems, chosen because of the widespread interest in this class of systems (Soong, 1990; Housner et al., 1994; Fujino et al., 1996), are the tuned mass damper (TMD) and the hybrid mass damper (HMD).

This virtual laboratory allows users to vary the control system properties and control objectives and to perform "what if" studies so as to better understand the control design process to mitigate the earthquake response. This VL can calculate and animate the structural responses under the El Centro, Hachinohe, Northridge and Kobe earthquakes, as well as determine the transfer functions of the uncontrolled and controlled systems. Three cases are considered: (i) TMD/HMD Locked: the auxiliary mass is rigidly attached to the structure; (ii) Tuned Mass Damper (TMD): the auxiliary mass is attached to the structure by a spring and damper; and (iii) Hybrid Mass Damper (HMD): in addition to spring and damper utilized in the previous case, a control actuator is installed between the auxiliary mass and the structure. In all of these cases, the structure is modeled as a single-degree-of-freedom linear system.

The interface for this control VL is provided in Figure 1. There are four frames: the animation frame, excitation frame, bode plot frame,

Links to Current Research

The Virtual Laboratories are based on the platform independent Java programming language and are being integrated into the framework of MCEER member-institution coordinated graduate professional educational program in earthquake engineering.

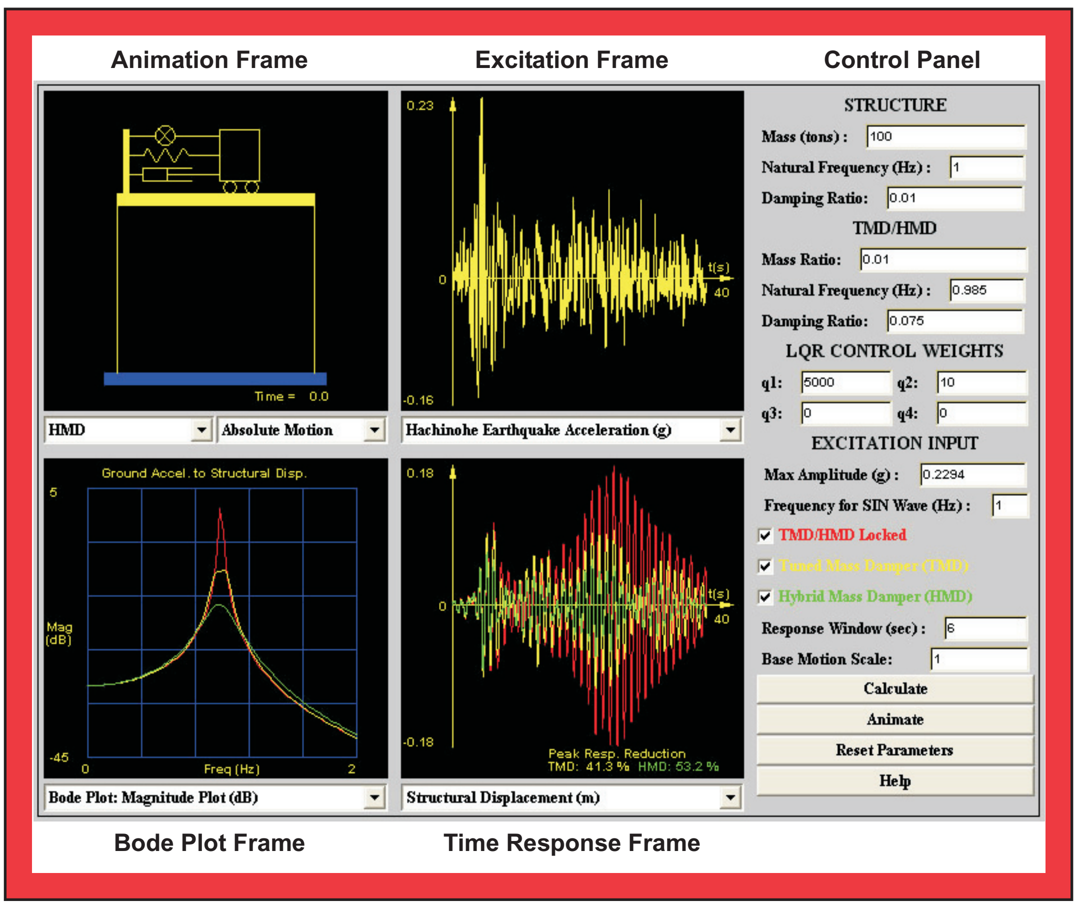


Figure 1. Structural Control Virtual Laboratory

and time response frame on the left of the user interface. On the right, the control panel is utilized to conduct structural analysis and input parameters. A description of each of these components is given below.

The control panel on the right of the interface has the following information:

- *Mass*: total mass of the structure.
- *Natural Frequency*: natural frequency of the structure.
- *Damping Ratio*: damping ratio of the structure.
- *TMD/HMD Mass Ratio*: ratio between the auxiliary mass to the structure mass.
- *TMD/HMD Frequency*: natural frequency of the TMD/HMD system.
- *TMD/HMD Damping Ratio*: damping ratio of the TMD/HMD system.
- *LQR Control Weights*: an LQR controller for HMD system is calculated based on a quadratic performance index that weights the responses. The parameters q1 - q4 weight the following responses: q1 is the structure displacement, q2 is the HMD displacement, q3 is the structure velocity and q4 is the HMD velocity.
- *Checkboxes*: click the checkbox to select/deselect the response to be displayed.
- *Response Window*: width of the excitation/time response frames (in seconds) used during the animation.
- *Base Motion Scale*: scale used for the ground motion during the animation. The ground displacements are multiplied by this value before being displayed in the animation. This scale factor does not affect the animation when the "Relative Motion" option is selected, nor does it affect any response calculation.
- *Calculate*: conduct calculation according to the current input parameters. When structure parameters, TMD/HMD parameters or LQR control weights are changed, this button must be pushed to recalculate response.
- *Animate*: start/stop animation of the response.
- *Reset Parameters*: reset all the parameters to the default values.
- *Help*: pop up the help page when this button is pushed.

On the left side of the interface, the animation frame allows the user to view the actual motion (either absolute or relative motion of the structure) under current excitation. The excitation frame displays the time history of the excitation. The bode plot frame shows the transfer function between the ground acceleration and the response selected in the time response frame. The relationship between the magnitude/phase of the transfer function and frequency can be displayed in this frame.

Various analytical results can be shown in the time response frame, including displacement, velocity and acceleration of the structure and TMD/HMD. The actuator force in the HMD system can be displayed as well. A peak reduction factor, which reflects the reduced percentage of the maximum response compared to the "uncontrolled" case, is displayed for both the TMD and HMD control system in the lower portion of this frame. As shown in this frame, not surprisingly, both TMD and HMD control systems can significantly reduce the earthquake response in this case with appropriate design.

Linear and Nonlinear Base Isolation Virtual Laboratories

Base isolation is another important strategy for protecting structures from earthquakes. It attempts to isolate a structure from the external ground excitations instead of dissipating the earthquake energy within the structure. As a testament to this strategy, buildings in the Kansai region of Japan with base isolation devices survived the devastating 1995 Kobe earthquake with little or no damage. This event has prompted great interest in base isolation for seismic protection of civil structures.

To facilitate the understanding of a base isolation system, two virtual laboratories have been developed. A linear base isolation VL was first developed as illustrated in Figure 2. A nonlinear base isolation VL, which includes the linear isolation case, was then developed for better understanding the behaviors of different isolation systems. There is another difference between the linear and nonlinear base isolation VLs: the linear base isolation VL can display transfer functions between the excitation acceleration and responses while the nonlinear base isolation VL can't. In this section, only the nonlinear base isolation VL will be carefully reviewed.

This nonlinear base isolation VL considers five cases: (i) a conventional structure fixed directly to

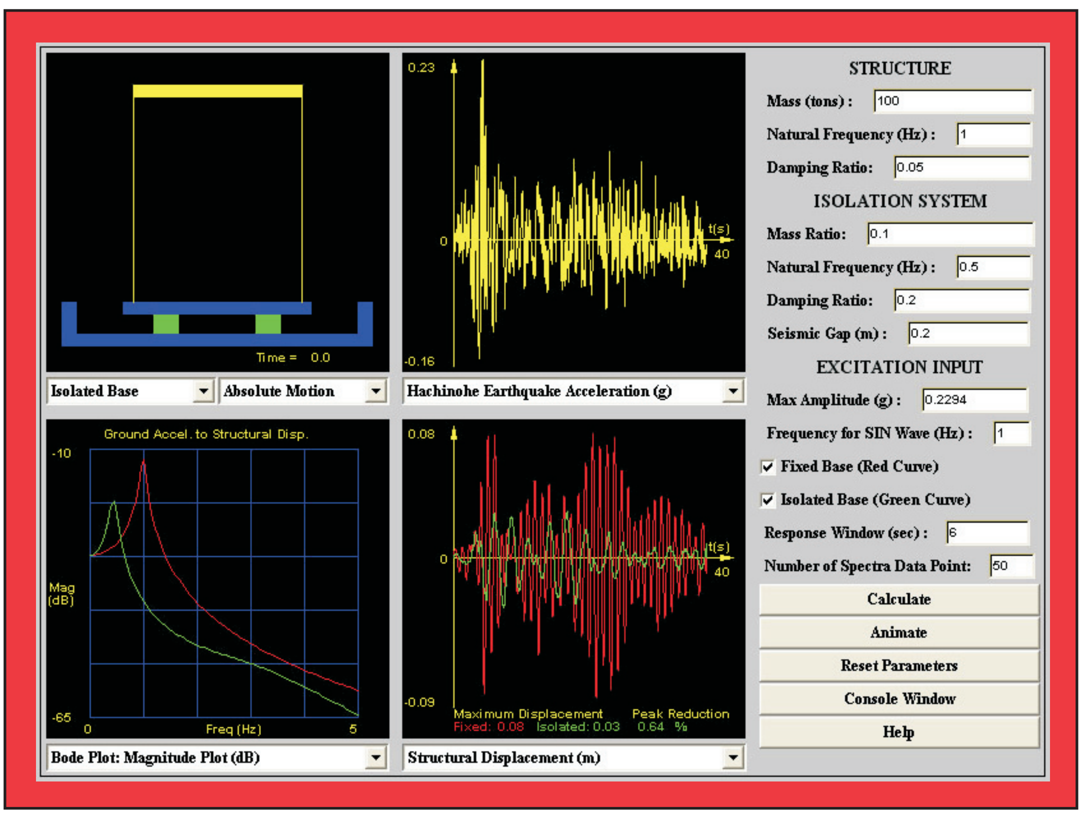


Figure 2. Linear Base Isolation Virtual Laboratory

the ground; (ii) ~ (v) base isolated structures where the isolation system is installed between the structure and the ground to isolate the earthquake energy. In all of these five cases, the structure is modeled as a single-degree-of-freedom linear system. For cases (ii) ~ (v), four types of models are provided in this VL to describe the behavior of the isolator. These models (shown in Figure 3) are: (a) linear stiffness and linear viscous damping; (b) linear stiffness and nonlinear power-law damping; (c) hysteretic stiffness using the Bouc-Wen model and linear viscous damping; and (d) hysteretic bilinear stiffness and linear viscous damping. For types (a) and (b), buildings behave as linear elastic structures. The damping force remains linear for type (a), and follows the nonlinear power-law with respect to the velocity for type (b). The Bouc-Wen model and hysteretic bilinear model in types (c) and (d) are widely employed for modeling nonlinear behavior of isolators. By choosing various models describing the isolator, users are able to analyze the structure response with different types of isolation systems.

The interface of the nonlinear base isolation VL is provided in Figure 4. Similar to the structural control VL, there are four frames on the left of the user interface, namely the animation frame, excitation frame, response spectra frame, and time response frame. On the right, there is a panel to control the structural analysis and input parameters. A description of each of these components is given below.

The control panel has the following information:

- *Mass*: total mass of the structure.
- *Natural Frequency*: natural frequency of the structure.
- *Damping Ratio*: damping ratio of the structure.
- *Mass Ratio*: ratio between the base floor mass and structure mass.
- *Isolation System Natural Frequency*: natural frequency of the linear and nonlinear damping isolators assuming the structure is rigid. This is also the natural frequency for the hysteretic isolators when the displacement exceeds the yielding displacement.
- *Seismic Gap*: the gap between the base slab and ground, as indicated in Figure 5. It should be greater than the maximum displacement of base slab.

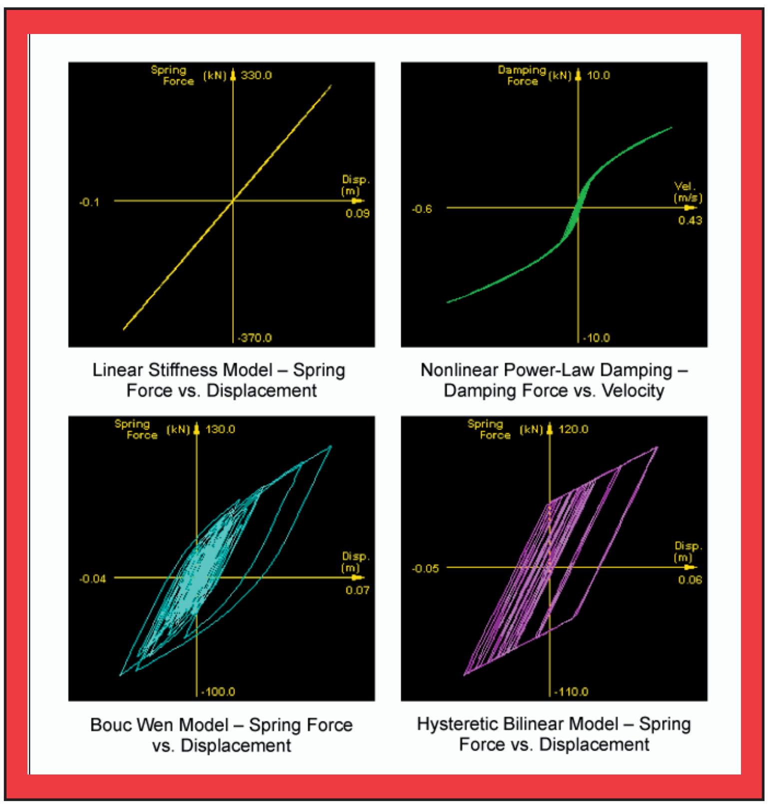


Figure 3. Typical Relationship Between Force and Response for Different Nonlinearities

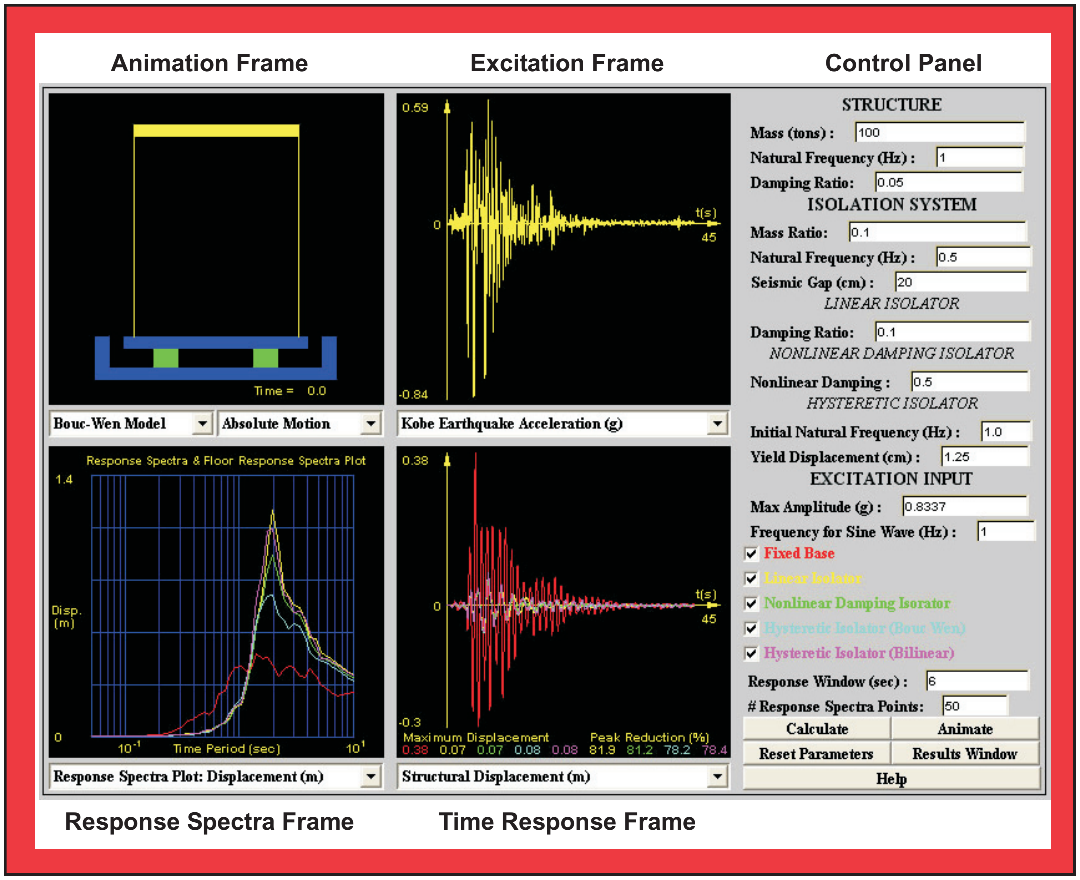
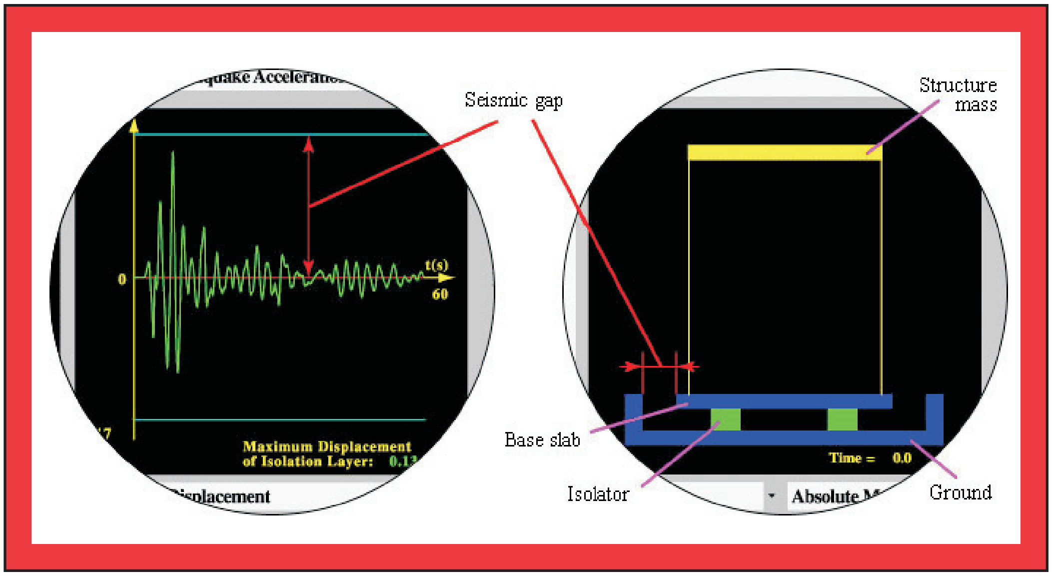


Figure 4. Nonlinear Base Isolation Virtual Laboratory

- *Linear Isolator Damping Ratio*: damping ratio of the linear and nonlinear damping isolation system assuming the structure is rigid.
- *Nonlinear Damping*: involution coefficient for nonlinear damping isolator.
- *Initial Natural Frequency*: natural frequency of the hysteretic isolators (Bouc-Wen and bilinear model) assuming the structure is rigid. This value is used to calculate the elastic stiffness of these two nonlinear stiffness models. The post yielding stiffness is computed based on the natural frequency under "Isolation System."
- *Yield Displacement*: displacement when exceeded, the hysteretic isolators (Bouc-Wen model and bilinear model) change from elastic to plastic region.
- *Max Amplitude*: maximum amplitude of the earthquake acceleration. By changing this value, excitation can be scaled.
- *Frequency for Sine Wave*: frequency component of the sinusoid excitation.
- *Checkboxes*: by checking one or more of the following check boxes, desired analysis results can be displayed.
- *Response Window*: width of the excitation/time response frames (in seconds) used during the animation.
- *# Response Spectra Points*: number of points used to draw response spectra curve.



■ Figure 5. Diagram of Seismic Gap

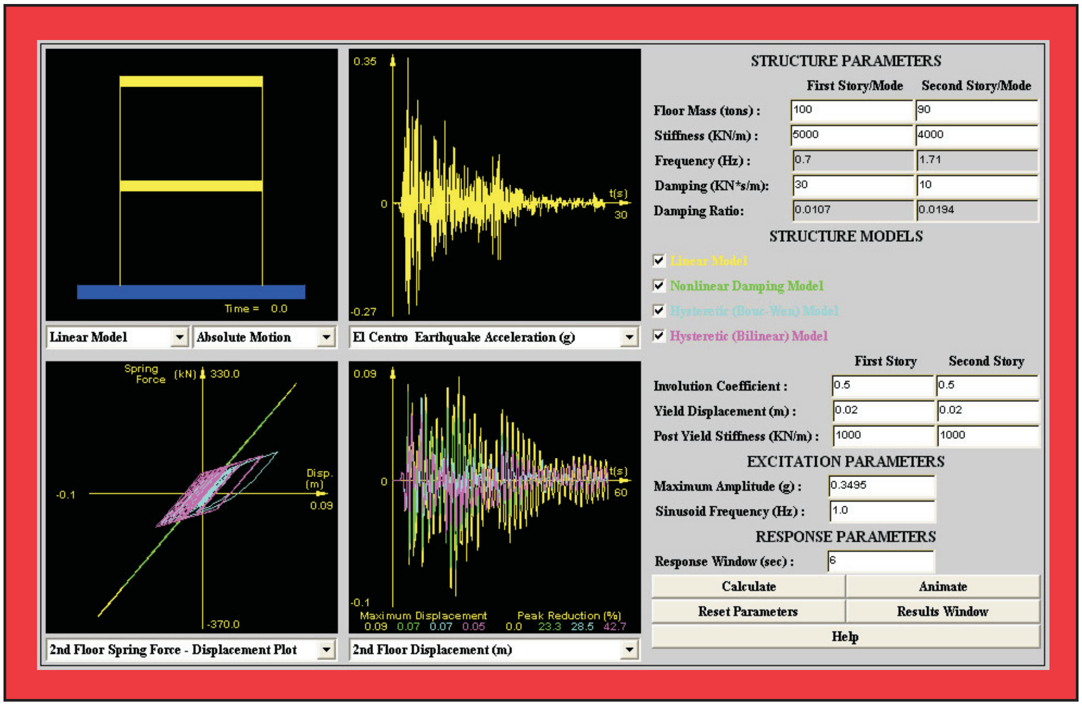
- *Calculate*: conduct the calculation.
- *Animate*: start/stop animation.
- *Reset Parameters*: reset all the parameters
- *Results Window*: display important analysis results after calculation.
- *Help*: pop up help page when pushed.

On the left side of the interface, the animation frame allows users to view the actual motion, either the absolute or the relative motion of the structure. The excitation frame displays the time history of the excitation. The response spectra frame shows the response spectra of the structure's displacement, velocity and acceleration.

Computational results can be displayed in the time response frame. A time history of the relative displacement, relative velocity and absolute acceleration of the structure and base floor can be plotted. A time history of the shear force for the structure is also ready to be displayed. Other plots in this frame include the relationship between damping force and relative displacement/relative velocity. Similar plots for restoring (spring) force and total (shear) force are available. A peak reduction factor, which reflects the reduced percentage compared to the fixed case, is displayed at the lower portion of the frame. As observed from Figure 4, a base isolation system can significantly reduce the structure's seismic demand.

Nonlinear Dynamic Analysis Virtual Laboratories

It is common to design structures to behave nonlinearly under extreme load conditions, e.g. earthquakes and hurricanes. To instruct students or practitioners to better understand the effect of the nonlinear behavior of buildings, our research effort recently has focused on the development of the nonlinear dynamic analysis virtual laboratories. In 2002, a two-story nonlinear dynamic analysis VL was developed for this purpose and is show in Figure 6. Based on



■ Figure 6. Two-Story Nonlinear Dynamic Analysis Virtual Laboratory

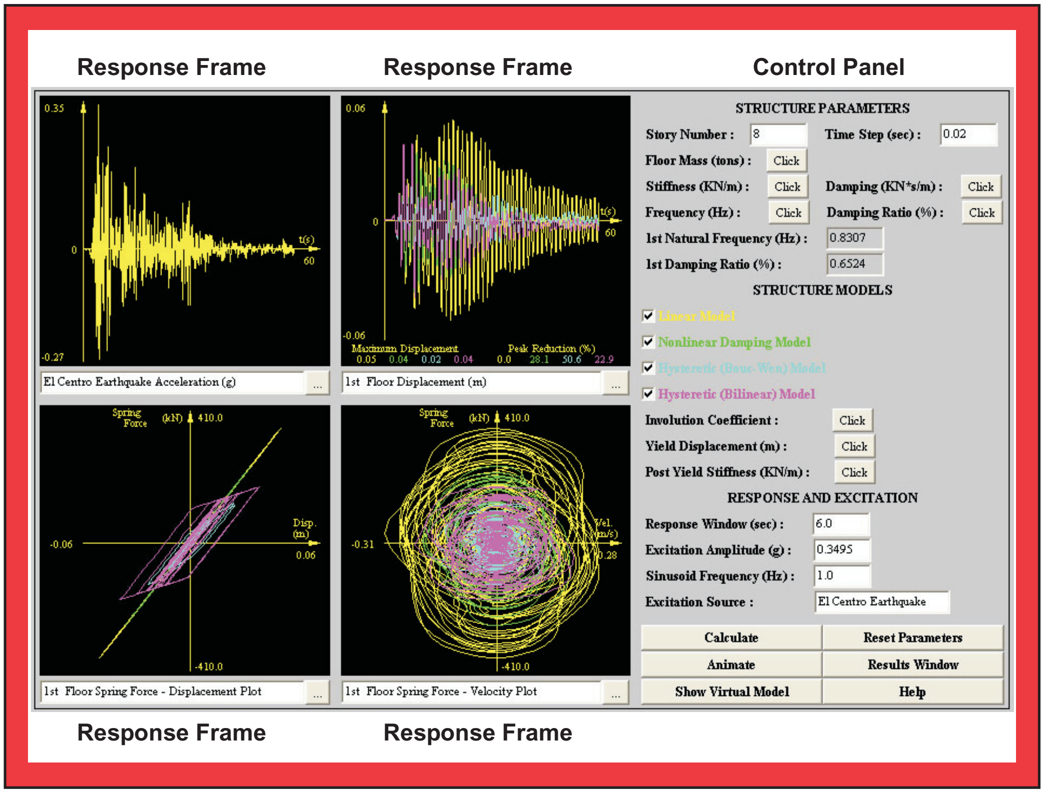
this VL, a nonlinear dynamic analysis VL for multi-story buildings has been developed in 2003 and will be carefully reviewed in this section.

The interface of this multi-story nonlinear dynamic analysis VL is provided in Figure 7. In this VL, users are given wide flexibility to perform dynamic analysis. Users can choose the number of stories, as well as select the floor mass, stiffness, and damping coefficients for each story. Four models, as shown in Figure 3, are provided to portray the behavior of the structure. The same type of model is employed for all columns, but the parameters defining this model can be varied for each story. Sinusoidal and four historical earthquake excitations can be chosen for conducting the dynamic analysis.

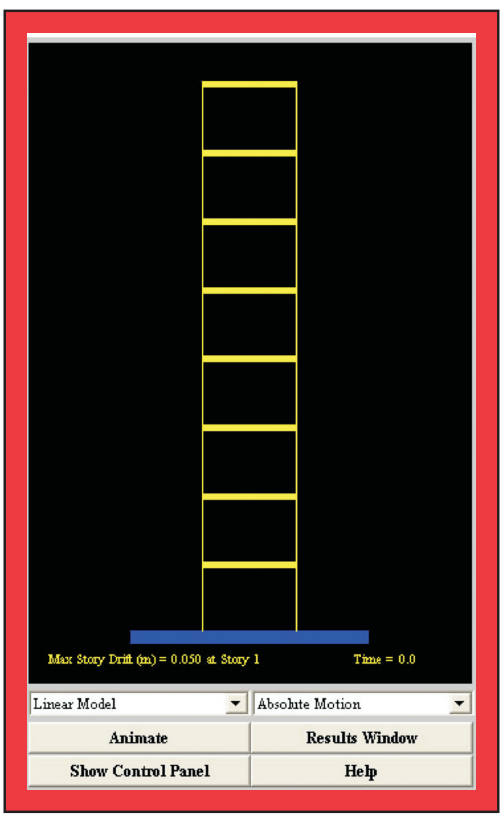
As shown in Figure 7, there are four response frames on the left of the user interface. On the right, there is a control panel for conducting structural analysis and changing parameters. There is also an animation panel which provides the animated response through a virtual building model. This panel is shown in Figure 8. The control panel and animation panel are interchanged with each other by clicking the "Show Virtual Model" or "Show Control Panel" button located at the lower corner of their panels. A description of each of these components is given below.

The control panel has the following information:

- *Story Number*: total number of stories.
- *Time Step*: time step for numerical computation. A smaller time step is expected when the structure is stiffer.
- *Floor Mass*: a dialogue box (Figure 9) will open when the selection button is pushed, which allows users to input floor mass for each floor.



■ Figure 7. Multi-Story Nonlinear Dynamic Analysis Virtual Laboratory



■ Figure 8. Animation Panel

- *Stiffness*: linear stiffness for each story.
- *Damping*: viscous damping coefficient for each story.
- *Frequency*: natural frequencies associated with the structural parameters.
- *Damping Ratio*: damping ratio associated with the structural parameters.
- *1st Natural Frequency*: for convenience, the first natural frequency is displayed.
- *1st Damping Ratio*: for convenience, the first damping ratio is displayed.
- *Structure Models*: by checking one or more of the following checkboxes, desired analysis results can be displayed.
- *Involution Coefficient*: parameters associated with the nonlinear damping model.

- *Yield Displacement*: displacement when exceeded, the Bouc-Wen model and the bilinear model change from elastic to plastic region.
- *Post Yield Stiffness*: stiffness of the structural member after the displacement exceeds the yield displacement.
- *Response Window*: width of the response frames (in sec) during the animation.
- *Excitation Amplitude*: by changing this value, the excitation magnitude can be scaled.
- *Sinusoid Frequency*: frequency component for the sinusoid excitation.
- *Excitation Source*: display the name of the current excitation.
- *Calculate*: conduct calculation.
- *Reset Parameters*: resets all the parameters to default values.
- *Animate*: start/stop animation.
- *Results Window*: display important analysis results after computation.
- *Show Virtual Model*: by clicking this button, the control panel and animation panel are interchanged with each other.
- *Help*: pop up the help page when pushed.

Calculated results are shown in the response frames. The functions of these response frames are identical, except that the top left frame can also display the earthquake excitation. There is a selection button at the lower right corner of each frame. For the top left frame, this selection button brings up a dialogue box (shown in Figure 10) for user to select the earthquake excitation or response to display. For the other three response frames, the selection button brings up a similar dialogue box for a response selection only. The currently displayed signal in the response frame is shown in the text field under the plot.

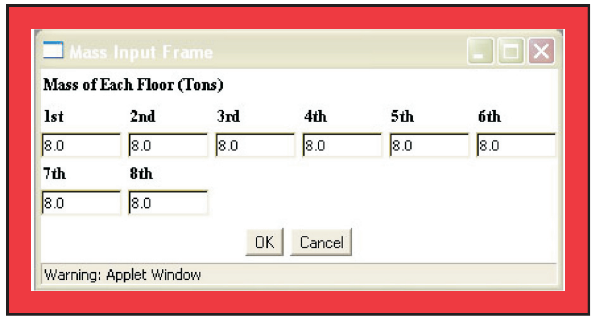


Figure 9. Floor Mass Input Dialogue Box

Various analytical results can be displayed in these response frames. The top right response frame shows an example of the time history response. In this example, the 1st floor inter-story drifts for all the selected structural models are displayed simultaneously. It also shows the maximum response values and the corresponding peak reduction factors, which is a reduction compared with the linear elastic case. By seeing the time history and peak reduction factor for

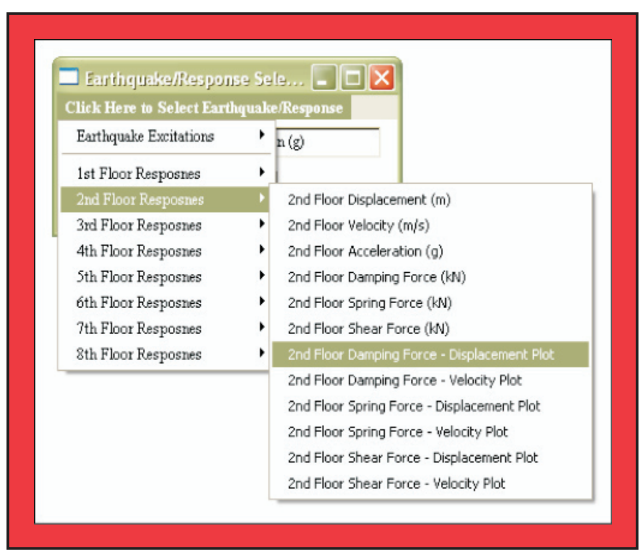


Figure 10. Response Selection Dialogue Box

Related Web Sites

Virtual Laboratory for Earthquake Engineering:
http://cee.uiuc.edu/sstl/java/

Multidisciplinary Center for Earthquake Engineering Research, Education:
http://mceer.buffalo.edu/education/default.asp#vl

different models simultaneously, users can easily appreciate the difference among these models under the current excitation. Similar time history plots for relative velocity, absolute acceleration, spring force, damping force and shear force are also readily displayed by clicking the selection button in each of the four frames. In this example, the bottom two response frames demonstrate relationships between spring force and displacement, and between spring force and velocity. Similar plots for spring force and damping force can also be shown by clicking the selection button in any one of these four frames. As can be seen from the overview, this nonlinear dynamic analysis VL grants users wide flexibly of the control over describing the structure, conducting analysis and viewing the results.

Verification of the Virtual Laboratories

The computation engines for all five VLs were first programmed in Matlab and then converted into Java. The calculations were verified by programming in two different ways with Matlab. One way is to program all the algorithms in Matlab language to numerically solve the dynamic equations. The other method is to utilize the exsiting algorithms in the Simulink Toolbox to solve the dynamic equations. By comparing results from these two approaches, the errors of computation have been minimized. The programming was then translated into Java language. The book, Numerical Recipes (Press et al., 1987), was very helpful for this translation. Accurate results have been obtained for these dynamic problems.

Use of the Virtual Laboratories

These interactive VLs have been well developed to fit various purposes. They are unique tools to introduce various advanced earthquake engineering topics to senior undergraduates, graduate students and junior engineers. If an Internet connection is available during lectures, these VLs can be utilized to demonstrate different ideas and designs during the lectures, which will enhance the efficiency of lecturing. These VLs can also be used as homework assignments regarding specific earthquake engineering topics. Young researchers are also expected to find these VLs handy and helpful to gain extra experience on these advanced topics.

To demonstrate the concepts of these VLs, three sample laboratory sessions are included in this paper. Sample laboratory session A gives an example of how the structural control VL can be used to reduce earthquake response. Sample laboratory session B demonstrates the design of an isolator which can be described by a hysteretic bilinear model to reduce the structural response. Sample laboratory session C illustrates the nonlinear dynamic behavior of an 11-story building under the Kobe earthquake excitation.

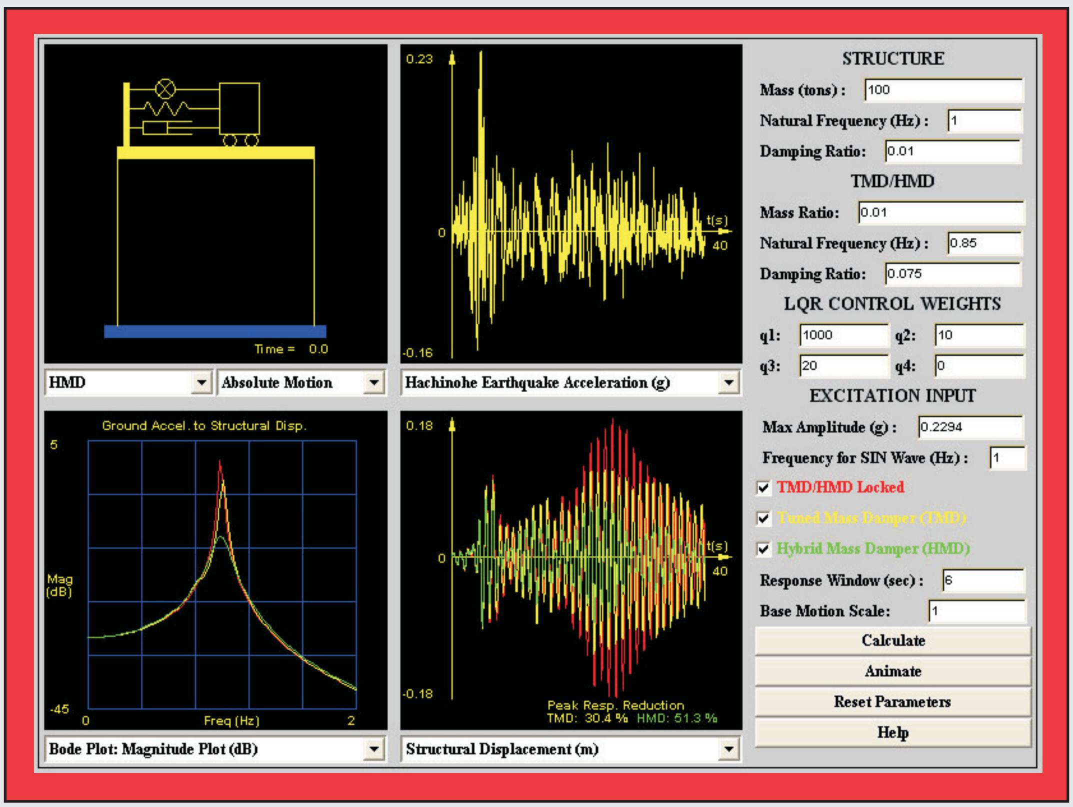
Sample Laboratory Session A

Problem

For a structure with 100 tons of mass, 1.0 Hz natural frequency, and 1% viscous damping ratio subject to Hachinohi earthquake excitation with a peak acceleration of 0.2294 g, design a TMD passive control system with a damping ratio of 7.5% to achieve a 30% reduction for the peak displacement response. Using the same parameters for the TMD system for HMD control system, could we achieve a reduction of 50% for the peak displacement response by appropriately designing a LQR controller?

Solution

Obviously, this problem does not have a unique solution. A sample result is shown in Figure 11. This figure shows that the TMD has achieved a 30.4% peak displacement reduction by designing the mass ratio as 1% and natural frequency of the TMD as 0.85 Hz. Not surprisingly, as an active control system, HMD achieves better results in this case. By setting the design parameters for the LQR controller as 1000, 10, 20 and 0 separately, the HMD system obtains a reduction of 51.3% with a peak actuator force of 10.7 KN. More complicated problems can be easily set to achieve several goals simultaneously, e.g. 30% and 20% reduction of peak displacement and velocity.



■ Figure 11. Sample Laboratory Session A

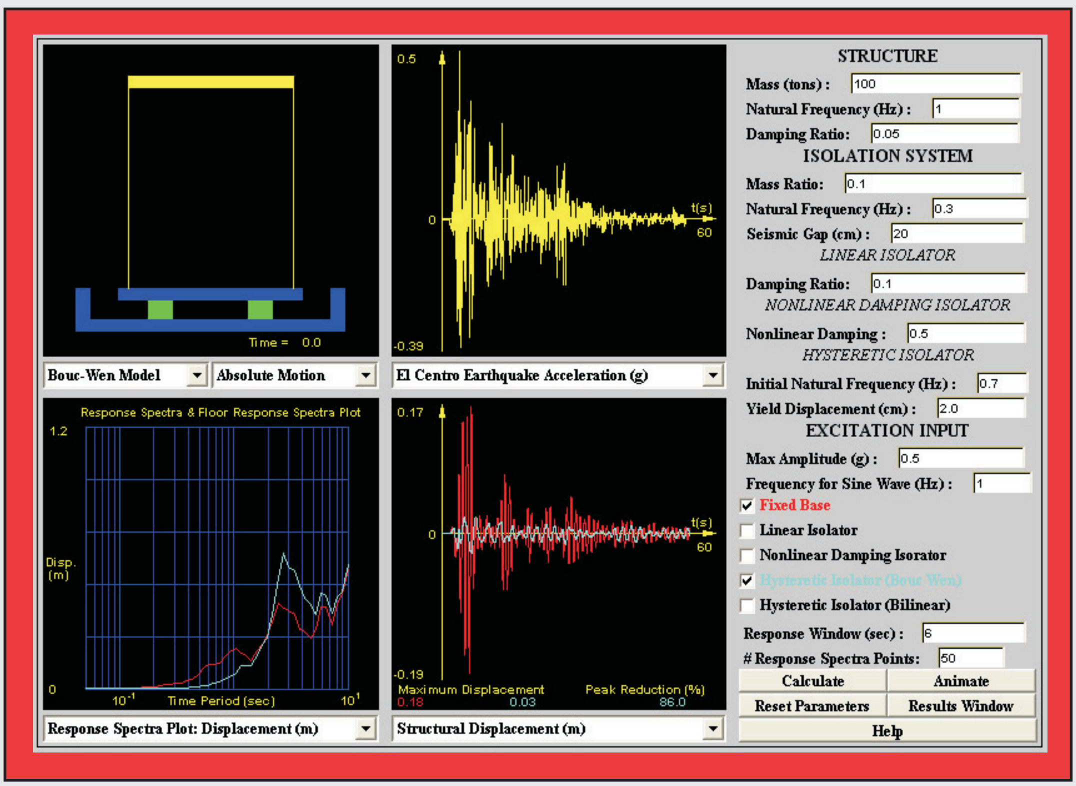
Sample Laboratory Session B

Problem

For a structure with 100 tons of mass, a natural frequency of 1.0 Hz, and viscous damping ratio of 1%, under El Centro earthquake excitation with a peak acceleration of 0.5 g, design an isolation system with mass ration of base floor to structure as 0.1 to achieve an 80% reduction of the structural peak displacement response. Note that the isolator can be described by the hysteretic Bouc-Wen model with a maximum allowable deformation of 20.0 cm.

Solution

One sample result is displayed in Figure 12. This figure shows that the isolation system achieves an 83.3% peak displacement reduction by designing initial natural frequency of 0.7 Hz, post yield stiffness of 0.3 Hz and a yield displacement of 2.0 cm. The maximum displacement of the base floor is 19.0 cm which is within the deformation limit of the isolator. It is impressive to see that the base isolation system reduces the seismic demand dramatically in the example.



■ Figure 12. Sample Laboratory Session B

Sample Laboratory Session C

Problem

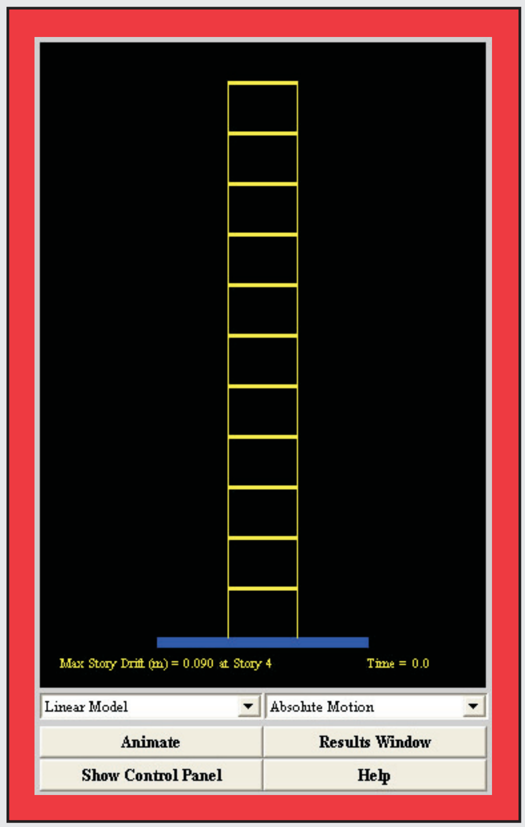
An 11-story building with equivalent mass, stiffness and damping coefficient distributions as given in Table 1 is subjected to the Kobe ground motion record with peak ground acceleration of 0.8337 g. The elastic maximum base shear and inter-story displacement are considered excessive and not suitable for design purposes. It is therefore required to determine the yield force and displacement of each story which is described by hysteretic bilinear model, preserving the given stiffness distribution, such that the ensuing maximum base shear and maximum inter-story displacements are 65% and 45% of the elastic values.

■ Table 1. Session C Structure Parameters

Story Number	1	2	3	4	5	6	7	8	9	10	11
Mass (tons)	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Stiffness (KN/m)	10000	9500	9000	8500	8000	7500	7000	6500	6500	6500	6500
Damping (KN s/m)	50	50	50	50	50	50	50	50	50	50	50

Solution

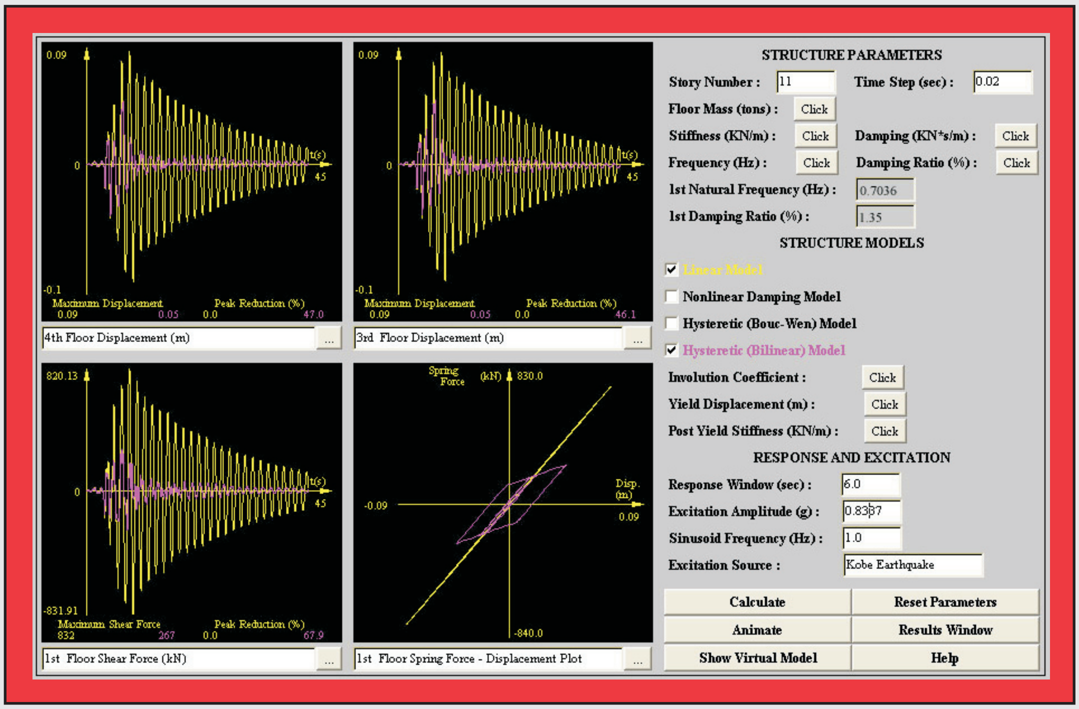
One of the designs with the hysteretic model parameters shown in Table 2 achieves the objective. The associated virtual building model is shown in Figure 13 and the results are shown in Figure 14. As shown in the Figure 13, the maximum inter-story displacement for linear structure is 0.09 m and happens at story 4. By selecting the hysteretic bilinear model on Figure 13, the maximum inter-story displacement was found to be 0.048 m and happens at story 3. Top left frame of Figure 14 indicates that for the 4th story, the displacement has been reduced by 47.0%, which is better than the target requirement. The top middle frame shows that a 46.1% reduction has been obtained for story 3, which is the location of the maximum inter-story displacement for the nonlinear structure. More importantly, a 67.9% reduction has been obtained for the base shear, which is a significant improvement of the design. Of course, a better result can be achieved by changing the parameters.



■ Figure 13. Virtual Building Model

■ Table 2. Session C Bilinear Model Parameters

Story Number	1	2	3	4	5	6	7	8	9	10	11
Initial Stiffness (KN/m)	10000	9500	9000	8500	8000	7500	7000	6500	6500	6500	6500
Post-yield Stiffness (KN/m)	3000	3000	3000	3000	3000	3000	3000	2500	2500	2500	2500
Yield Displacement (cm)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0



■ Figure 14. Sample Laboratory Session C

Conclusions and Future Research

A series of unique Java-Powered Virtual Laboratories have been developed to facilitate the understanding of a wide range of topics in earthquake engineering and dynamic analysis. Participants are expected to gain fundamental understanding of these topics by conducting on-line numerical experiments using these interactive VLs. These on-line VLs provide an excellent alternative way for students and practitioners to develop their knowledge of earthquake engineering. By designing these VLs using Java programming, they can be accessed universally through the Internet and provide users with wide flexibility to configure system parameters, conduct analysis, and view results. A total of five VLs, including a structural control VL, two base isolation VLs using linear and nonlinear devices, and two nonlinear dynamic analysis VLs for buildings have been published.

Current and continuing efforts emphasize the development of more realistic virtual laboratories which allow users to imitate real dynamic experiments step by step, including selecting sensor locations, collecting data from sensors, designing anti-aliasing filters, and conducting FFT analysis, etc. The intention is to provide the users with a more realistic feeling of conducting a real experiment without dealing with wires and experimental setups. These VLs are expected to be an effective complement to the teaching of structural dynamics and earthquake engineering analysis at institutions which lack the facilities to conduct dynamic experiments.

Acknowledgements

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Liquefaction Mitigation in Silty Soils Using Composite Stone Columns and Dynamic Compaction

by Thevachandran Shenthan, Rafeek G. Nashed, Sabanayagam Thevanayagam and Geoffrey R. Martin

Research Objectives

The objective of this study is to develop an analytical methodology to evaluate the effectiveness of vibro-stone column (SC) and dynamic compaction (DC) techniques supplemented with wick drains to densify and mitigate liquefaction in saturated sands and non-plastic silty soils. It includes the following: (i) develop numerical models to simulate and analyze soil densification during SC installation and DC process, and (ii) identify parameters controlling post-improvement soil density in both cases, and (iii) develop design guidelines for densification of silty soils using the above techniques. An analytical procedure was developed and used to simulate soil response during SC and DC installations, and the results were compared with available case history data. Important construction design parameters and soil properties that affect the effectiveness of these techniques, and construction design choices suitable for sands and non-plastic silty soils were identified. The methodology is expected to advance the use of SC and DC in silty soils reducing the reliance on expensive field trials as a design tool. The ultimate outcome of this research will be design charts and design guidelines for using composite stone columns and composite dynamic compaction techniques in liquefaction mitigation of saturated silty soils.

Sponsors

Federal Highway Administration

Research Team

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Liquefaction is one of the primary causes of lateral spreading, failures of bridge foundations, embankments, and ports and harbor facilities during earthquakes (e.g., 1964 Alaska earthquake, 1995 Kobe earthquake). Soil densification techniques using vibro-stone column (Figure 1a) and deep dynamic compaction (Figure 2a) are proven ground improvement methods for liquefaction mitigation in loose saturated sands containing less than 15% non-plastic silts and less than 2% of clay particles (FHWA, 2001, Mitchell et al., 1995, Andrus and Chung, 1995). Silty sands containing excessive fines have been considered difficult to densify using the above densification methods. However, recent case histories show that provision of pre-installed supplementary wick drains around the vibro-stone columns (Figures 1b) and impact locations (Figure 2b) help densification of silty soils during vibro-stone column installation or dynamic compaction (Andrews, 1998, Dise et al., 1994, and Luehring et al., 2001).

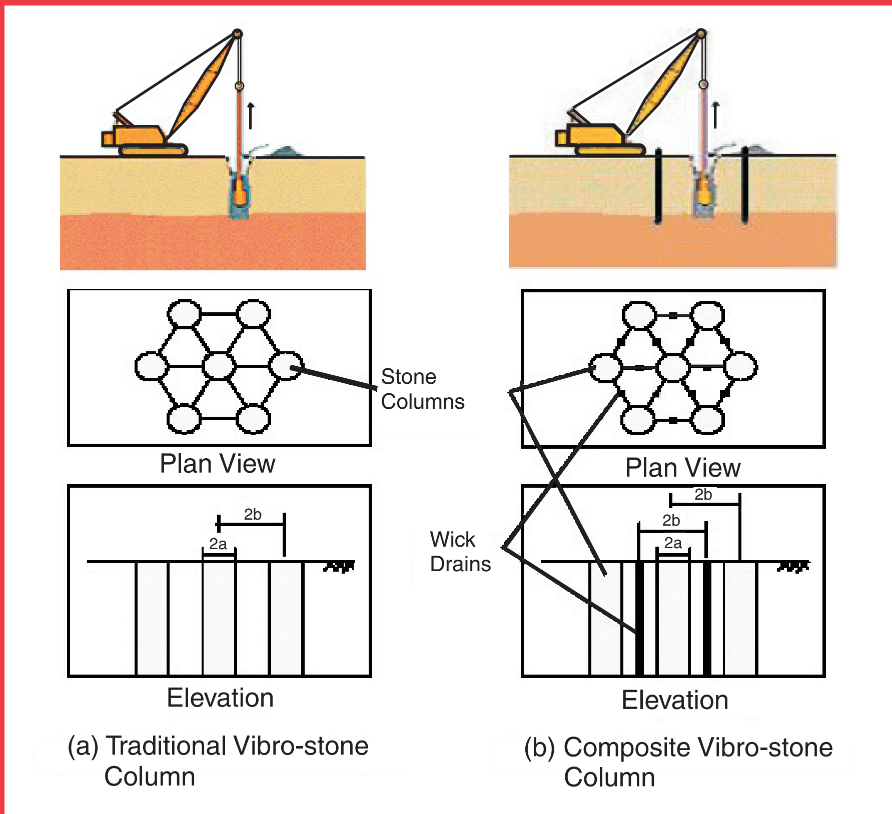
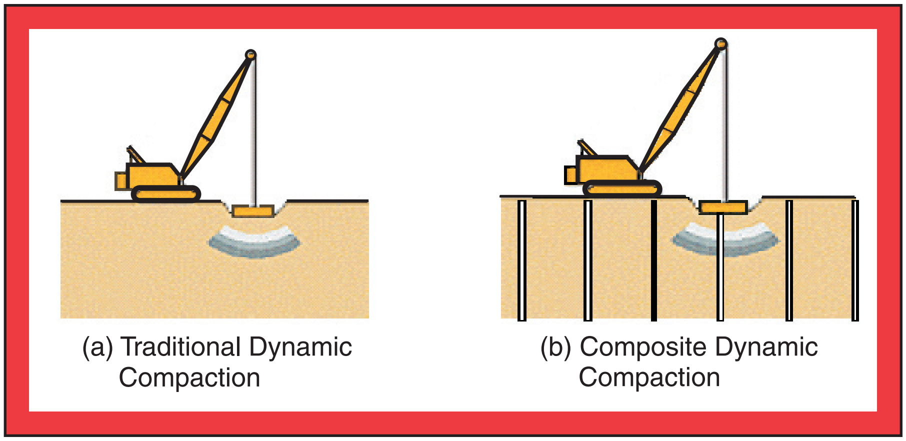


Figure 1. Vibro-Stone Columns and Composite Vibro-Stone Column

The vibro-stone column installation process involves insertion of a vibratory probe with rotating eccentric mass. The probe plunges into the ground due to its self-weight and vibratory energy, which facilitates penetration of the probe. Once the specified depth (depth of stone column) is reached, the probe is withdrawn in steps (lifts) of about 1 m. During withdrawal of the probe, the hole is backfilled with gravel. During each lift, the probe is reinserted, expanding the stone column diameter. This process is repeated several times until a limiting condition is achieved. No detailed analytical procedures are available to determine the densification achievable during stone column installation or the effects of various construction choices such as stone column spacing, diameter, and wick drain size and spacing on the degree of improvement. The current state of practice depends mainly on previous experience or field test programs to determine the applicability of the technique and choice of stone column spacing, etc., at a given site. Based on field data, Baez (1995) outlines an empirical approach (Figure 8, introduced later) for design of vibro-stone columns, without wick drains, to improve sandy soils containing less than 15% silt.

This research provides an analytical methodology to simulate and evaluate the effectiveness of vibro-stone columns and dynamic compaction supplemented with wick drains, to densify and mitigate liquefaction in saturated silty soils. This methodology and the design charts resulting from this work will help geotechnical engineers from transportation agencies and construction companies in designing an appropriate ground improvement technique to densify loose, saturated silty soil deposits, without solely relying on expensive field trials.

The DC technique involves high-energy impacts to the ground surface by systematically dropping heavy weights of 6 to 35 tons from heights ranging from 12 to 40 m to compact the underlying ground using heavy crawler cranes. Based on previous field experience (Lukas 1986, 1995), for an average cumulative applied energy in the range of 1 to 3 MJ/m^2, the maximum depth of improvement (d_{max}) that can be achieved due to DC is given by:



■ Figure 2. Dynamic Compaction

$$d_{max} = n\ (WH)^{1/2} \qquad (1)$$

where W is the dropped weight in tonnes, and H is the height of drop in m. The value of n depends on soil type, and decreases with an increase in degree of saturation. Although Eq.1 is a useful guide, design choices such as impact weight, height of drop, impact grid spacing, time lag between impacts, total number of passes required to achieve a specified level of relative density or SPT/CPT penetration resistance are made based on field trials. Again, no detailed analytical procedures are available to determine the densification achievable or to analyze the effects of various operational parameters on the degree of improvement.

This paper presents a brief summary of recent work conducted to develop a simple analytical methodology to simulate soil response during vibro-stone column installation and dynamic compaction, quantify soil densification during vibro-stone column installation and dynamic compaction in saturated sands and silty soils, and assess the effect of various construction/design choices and soil parameters on the degree of improvement that can be achieved.

Semi-Theoretical Framework

Densification of saturated sands and silty soils by vibro-stone column and dynamic compaction is essentially a process involving vibration of the soil causing excess pore pressure development, liquefaction, and consolidation of the soil leading to concurrent densification. Vibro-stone column also involves expansion of a zero cavity and associated pore pressures and densification of the soil. This paper presents a methodology to simulate pore pressure developments in the soil due to vibratory energy imparted during installation, and subsequent consolidation of the soil and densification. Simple attenuation relationships are used to estimate the energy dissipated in the soil. Experimental data based on energy principles is used to estimate the pore pressures generated as a function of the energy dissipated. Coupled consolidation

Links to Current Research

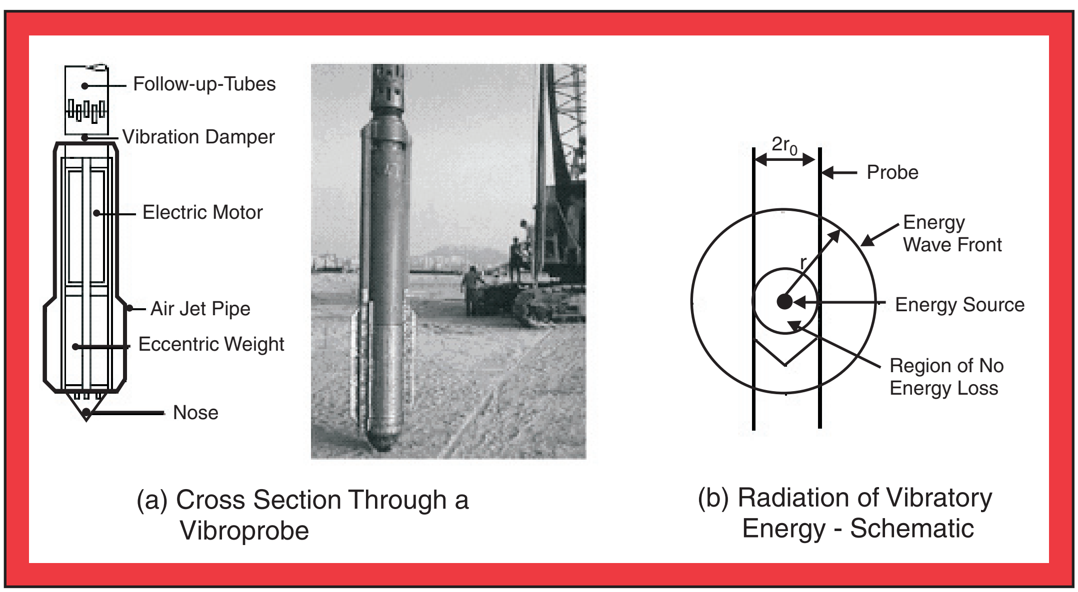
This study is a part of the project 'seismic vulnerability of the national highway system'. This work is to improve understanding of the liquefaction hazards to highways and to improve and develop analysis methods and design criteria for ground improvement techniques in order to reduce seismic vulnerability of existing and future highway infrastructure.

equations are used to quantify densification and study the effects of various soil parameters and design/construction choices on the degree of improvement that can be achieved.

Energy Radiation and Attenuation

Consider vibro-stone column (SC) (Figure 3) and dynamic compaction (DC) impact (Figure 4) processes. The energy delivered at the source by the vibratory probe and by a falling weight propagates through the surrounding soil as body waves (compressional and shear waves) in the case of SC and body waves and surface waves (Rayleigh waves) in the case of DC, respectively. Field observations indicate that the ground vibrations caused by SC are in the range of 30 to 50 Hz (FHWA, 2001) and between 2 to 20 Hz (Mayne, 1985) for DC. A solution for energy dissipated (per unit volume of soil), the associated pore water pressures, and densification at any point in the soil requires a reasonably accurate quantification of energy partitions in the above three categories and their spatial attenuation relationships. The problem is complex due to non-uniformity in stress field, stress and density dependent soil properties, and changes in the stress field, pore water pressures, and soil densities in the ground during and immediately following the energy delivery. In order to circumvent this problem, as a first order approximation, models for energy partition in elastic half space coupled with field-observation based attenuation models are used herein.

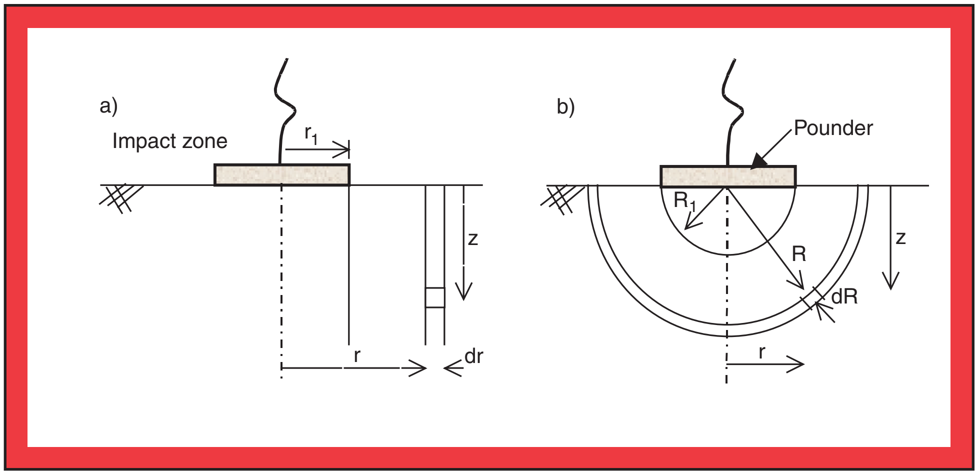
Past studies indicate that the energy partitioning in the form of shear, compressional, and Raleigh waves due to a harmonic uniform vertical stress on a flexible disk of radius r_0 acting on an elastic half-space is dependent on frequency parameter a_0 (= $\omega r_0/c_s$, where, ω = angular frequency in Hz., and c_s = shear wave velocity in m/s) (Figure 5a) and Poisson's ratio (Miller and



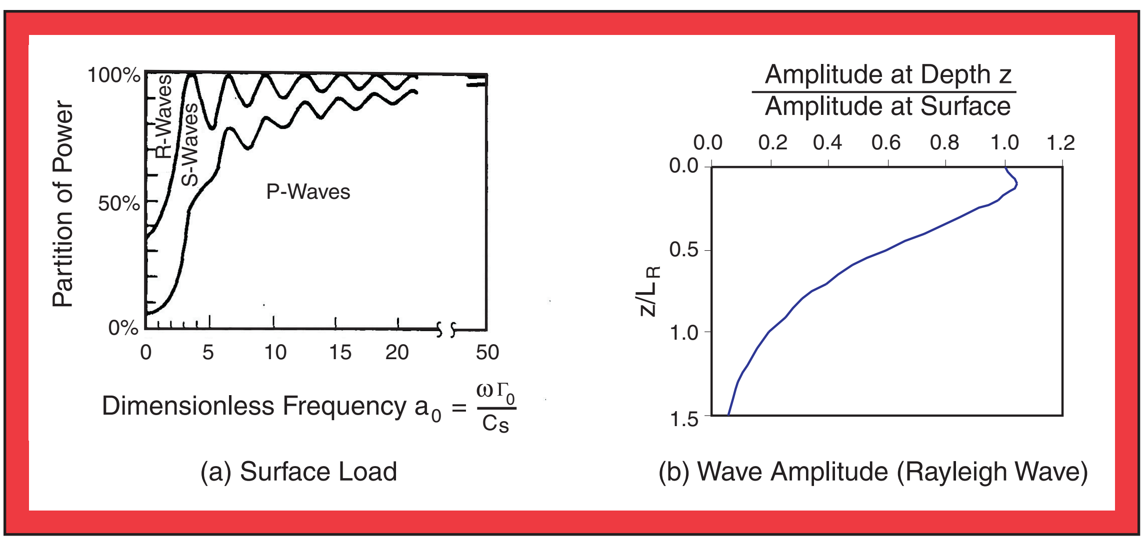
■ Figure 3. Vibratory Probe and Energy Propagation

Pursey, 1955, Meek and Wolf, 1993). Further, Richart et al.(1970) show that Raleigh wave amplitude varies with dimensionless depth (depth/L_R) as shown in Figure 5b where L_R is the wavelength of the Rayleigh wave. The Rayleigh wave amplitude ratio attenuates with depth very rapidly to about 10% at a depth of about 1.6 L_R. As a first order approximation, if the above model is used to determine the energy partitioning for DC, the frequency parameter a_0 tends to be less than 1 for typical values of r_o corresponding to impact weights used in dynamic compaction, c_s, of soils, and frequencies in the range of 2 to 20 Hz. Hence, Rayleigh waves account for about two thirds of the impact energy transfer and body waves account for the remaining one third. For DC, further, considering radiation damping, the energy content of the body wave is assumed to be uniformly distributed on a hemispherical surface of the wave front, while the energy content of the Rayleigh wave is assumed to be spreading radially along a cylindrical surface, and is also assumed to attenuate with depth as shown in Figure 5b for Poisson's ratio ν = 0.25.

Material damping occurs as a result of energy loss due to hysteresis damping and internal sliding of soil particles. The energy loss depends



■ Figure 4. Energy Partitioning – Dynamic Compaction



■ Figure 5. Partition of Energy

Collaborative Partners

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on frequency of loading, soil type, stress conditions, and strain level. Field observations indicate surface wave attenuation due to material damping is given by (Dowding 1996):

$$a = a_1 . e^{-\alpha(r-r_1)} \tag{2}$$

where a_1 is the amplitude of vibration at distance r_1 from the source, a is the amplitude of vibration at distance r, and α is the attenuation coefficient due to material damping. Energy attenuation is related to the square of the amplitude of vibration; the corresponding energy attenuation relationship is given by

$$E = E_1 . e^{-2\alpha(r-r_1)} \tag{3}$$

where E_1 is the energy content at a distance r_1 from the source, and E is the energy content at a distance r.

Based on the above considerations, the energy loss per unit volume of soil due to Rayleigh waves w_R and body waves w_B, respectively, in the case of DC, are given by

$$w_R(r,z) = F(0.67WH)\frac{\alpha e^{-2\alpha r}}{\pi r} \tag{4}$$

$$F = \frac{f^2\left(\frac{z}{L_R}\right)}{\int_0^\infty f^2\left(\frac{z}{L_R}\right)dz} \tag{5}$$

$$w_B(r,z) = (0.33WH)\frac{\alpha e^{-2\alpha R}}{\pi R^2} \tag{6}$$

where R is the $\sqrt{(r^2+z^2)}$, f is the amplitude ratio given by Figure 5b, and r and z are radial and vertical coordinates, respectively.

In the case of SC, assuming that radiation damping is due to body waves spreading along a spherical wave front and it is uniformly distributed on a spherical surface of the wave front, the energy loss per unit time per unit volume of soil takes the form:

$$w = W_0 \frac{\alpha e^{-2\alpha(r-r_0)}}{2\pi r^2} \tag{7}$$

where W_0 is the $\eta_0 P_0$, P_0 is the power rating of the vibratory probe, and η_0 is the probe efficiency. As excess pore pressure develops due to vibration during the SC process, the soil becomes weak. Since the amplitude of vibration of the probe is limited (FHWA, 2001), the energy imparted to the surrounding soil would decrease, resulting in a reduced efficiency. When the pore pressures dissipate, and the soil is sufficiently densified, the energy transfer rate would increase. In this paper, this phenomenon was taken into account considering the energy transfer rate to decay with increasing excess pore pressure:

$$w = W_0 \frac{\alpha e^{-2\alpha(r-r_0)}}{2\pi r^2} . e^{-\beta(r_e)_{av}} \tag{8}$$

where $(r_u)_{av}$ is the the average excess pore pressure ratio within the soil surrounding the probe up to an effective radial distance r_e, and β is a constant. A detailed discussion on the applicability and limitations of the above attenuation relationships, and ongoing further work on attenuation relationships, are reported in Shenthan (2004) and Nashed (2004).

Pore Pressure Generation

Based on a large experimental database and theoretical considerations, excess pore water pressure generated due to undrained cyclic loading has been related to frictional energy loss in the soil by Thevanayagam et al. (2002) as:

$$r_u = 0.5\log_{10}\left(100\frac{w_c}{w_L}\right), \quad \frac{w_c}{w_L} \rangle\ 0.05 \tag{9}$$

where r_u is the excess pore pressure ratio (u/σ_0'), σ_0' is the initial mean effective confining pressure, w_c is the cumulative energy loss per unit volume of soil, and w_L is the energy per unit volume required to cause liquefaction.

In the case of the SC process, in addition to vibration-induced excess pore pressure, a significant amount of pore pressure is generated due to cavity expansion as well. Initial insertion of the probe into the ground can be considered as expanding a zero cavity to a diameter the same as that of the probe. Filling of this cavity by stones and inserting the probe further expands the cavity by pushing the stone backfill radially outwards. Lifting the probe causes slight contraction of the cavity. Repeated lifting, filling, and insertion of the probe cause repeated cavity expansions. Shenthan et al. (2004) outline a simplified approach to estimate excess pore pressures induced during such cavity expansions and contractions.

Pore Pressure Dissipation and Densification

The governing equation for pore pressure dissipation in the soil is:

$$\frac{\partial u}{\partial t} = \frac{k_b}{\gamma_w m_v}\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} + \frac{1}{r^2}\frac{\partial^2 u}{\partial \theta^2}\right) + \frac{k_v}{\gamma_w m_v}\frac{\partial^2 u}{\partial z^2} + \frac{\partial u_g}{\partial t} \tag{10}$$

where k_b and k_v are hydraulic conductivity of the soil in the horizontal and vertical directions, respectively; m_v is the volume compressibility of the soil; u is the excess pore water pressure at coordinates (r, θ, z); u_g is the excess pore pressure generated due to vibration and cavity expansion (in the case of SC); t is the time; γ_w is the unit weight of water; and r, θ, and z are radial, angular, and vertical coordinates, respectively. In the case of the vibro-stone column, the term u_g stands for time dependent pore pressure generation as in the case due to vibratory energy during SC installation. In the case of cavity expansion/contraction and DC, excess pore pressures are assumed to be induced instantaneously.

Volumetric densification of a soil element due to excess pore pressure dissipation may be obtained by:

$$\varepsilon_v = \int m_v . d\sigma' \tag{11}$$

where ε_v is the volumetric strain, and σ' is the mean effective confining pressure. Seed et al. (1975) suggest that m_v values for sand increases from its initial value according to the following relationship, and does not decrease from the highest value obtained:

$$\frac{m_v}{m_{v0}} = \frac{\exp(y)}{1 + y + y^2/2} \geq 1; \;\; y = a.r_u^b;$$
$$a = 5\,(1.5 - D_r); \qquad b = 3\,(4)^{-D_r} \tag{12}$$

where m_v and D_r are initial volume compressibility and relative density of soils, respectively. For silty sands, the above equation is modified to use $(D_{rc})_{eq}$ instead of D_r to take into account the effects of fines on volume compressibility (Shenthan, 2004). Typical values for m_{v0} are adopted from Thevanayagam and Martin (2001).

Simulations and Field Comparisons

Vibro-Stone Column

Two sets of numerical simulations were conducted to study the densification process of soils during stone column installation. In the first set of simulations, the effect of cavity expansion was neglected and the effect of vibration-induced pore pressure generation and dissipation was considered. Based on available experimental data, hydraulic conductivity *k* was obtained as a function of silt content. In the second set of simulations, the effect of cavity expansion was included and the vibration-induced pore pressures were neglected. In both sets of simulations, vertical dissipation was neglected in order to reduce the computational time. These simulations are presented below.

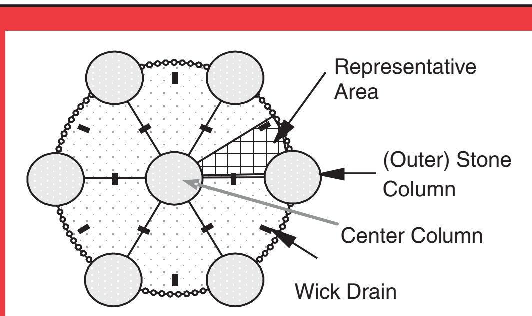


Figure 6. Composite Stone Column Layout

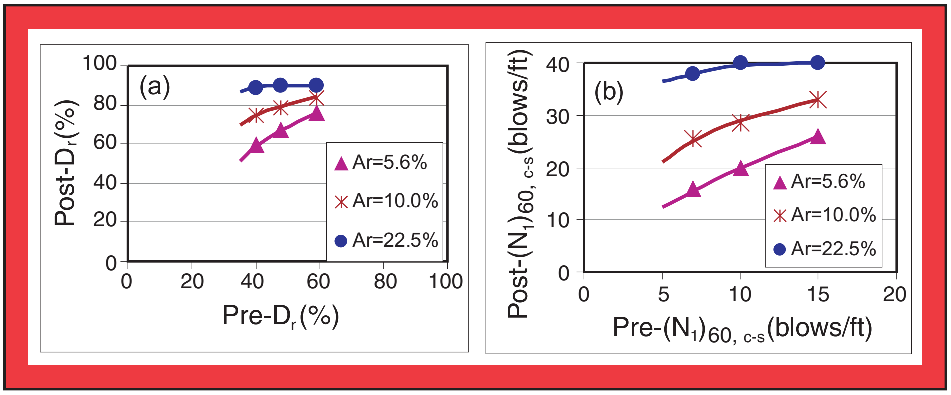
Energy Dissipation and Densification

The simulations presented herein consider soil densification due to dissipation of vibration-induced pore pressures only. Figure 6 shows a composite vibro-stone column layout. The radii of the stone columns and wick drains are a and r_w, respectively. The spacing between stone columns is 2b. The spacing between wick drains is b. The wick drains are installed first, and the surrounding stone-columns are installed next followed by installation of the center column. The numerical simulation presented in the following sections pertains to densification of the soil during installation of the center column. Using the semi-theoretical background introduced earlier, a finite-difference numerical scheme was developed to simulate this densification process in the soil surrounding the center column. Boundaries of symmetry allow the computational time to be reduced by requiring calculations to be done for only the representative area shown in Figure 6.

Vibro-stone Columns without Wicks

The simulations herein consider installation of vibro-stone columns in clean sand with no wick drains (Figure 1a). Three different initial densities were used: (a) D_r = 40%, (b) D_r = 48%, and (c) D_r = 59%. Three different area replacement ratios (A_r = 5.6, 10.0, and 22.5%) were assumed for each initial density, where $A_r = (A_c/A_e)*100\%$, A_c is area of the stone-column, A_e

is the tributary area (= $\pi * D_e^2/4$), and D_e = equivalent diameter of the tributary area = 1.05 times the center-to-center spacing between stone columns installed in a triangular pattern. These A_r values correspond to center-to-center stone column spacing of 4 diameters, 3 diameters, and 2 diameters, respectively. The hydraulic conductivity was assumed to be 5x10^{-6} m/s. Table 1 summarizes the probe characteristics used for the simulation. Table 2 summarizes simulation parameters. The post-improvement densification results are shown in Figure 7a.



■ Figure 7. Vibro-Stone Column Simulation Results

■ Table 1. Vibratory Probe Specifications

Length	Frequency	Power Rating P_0	η_0	β	Avg. Penetration Rate
m	Hz	kW	%		cm/s
3	50	120	50	4	3

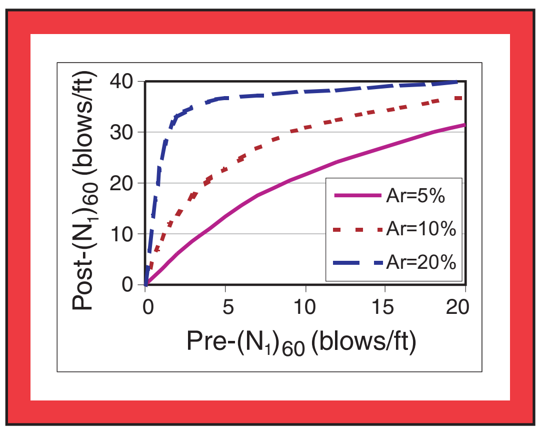
■ Table 2. Simulation Parameters – Stone Column

Column Dia. (m)	Column Spacing (m)			k (m/s)
	A_r = 5.6%	10.0%	22.5%	
0.9	3.6	2.7	1.8	5x10^{-6}

Note: Initial effective confining pressure at the depth considered is about 100 kPa.

The area replacement ratio has a significant influence on post-improvement density. This influence diminishes as the initial density increases. Although not shown in this paper, it was also found that hydraulic conductivity plays an important role and higher hydraulic conductivity leads to higher densification for the same vibratory duration (Shenthan, 2004, Thevanayagam et al., 2001).

For qualitative comparison purposes, the data in Figure 7a may be converted to equivalent SPT blow counts $(N_1)_{60,c\text{-}s}$ using the Tokimatsu and Seed (1984) relationship for clean sands, as shown in Figure 7b. This can be compared with the field case history database for pre- and post-improvement SPT blow counts compiled by Baez (1995) shown in Figure 8. The regression curves for post-improvement SPT blow counts obtained by Baez (1995) were based on an analysis of a number of case histories, where vibro-stone columns were used to improve sandy soil sites with less than 15% silts. Although direct comparisons are not possible, due to lack of site-specific data, the trend found in Figure 7b agrees well with the trend in Figure 8. Further work is underway to verify simulation results with field trials.

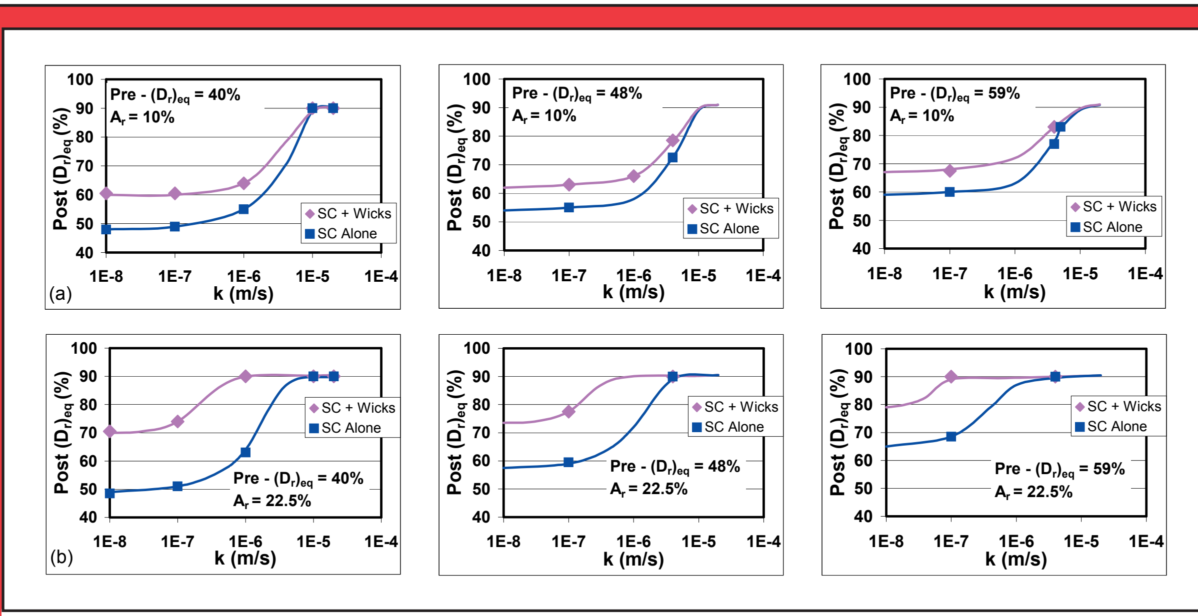


Baez 1995

■ Figure 8. Regression Design Curves

Composite Vibro-Stone Column

A number of simulations were conducted to assess the effects of silt content, and area replacement ratio A_r on post improvement density of silty soils supplemented by wick drains (Figure 1b). Three different initial equivalent relative densities ($(D_r)_{eq}$ = 40, 48 and 59%, Shenthan, 2004) were considered. Silt content-dependent soil input parameters m_v, k, E_L were obtained from an experimental database for silty soils (Shenthan, 2001, and Thevanayagam et al., 2001). For direct comparison purposes, the same simulations were repeated for stone columns in the same soil without wick drains (Figure 1a). Figure 9 shows the simulation results for post-improvement relative densities for A_r = 10, and 22.5%, respectively, for the three different initial relative densities $(D_r)_{eq}$ considered. Without wick drains, no significant improvement is achieved for soils with hydraulic conductivity less than about 10^{-6} m/s. Although not shown in this paper, at low A_r, wick drains do not contribute to any further increase in post-improvement density for all initial densities (Shenthan et al., 2004). In this case, the spacing of stone columns and wick drains is too large and wick drains are far from the stone columns to be effective in relieving the pore pressures during installation and to facilitate repeated cycles of densification. As the area replacement ratio increases, the influence of wick drains increases. At high area replacement ratio of about 20% or above (Figure 9b), wick drains significantly contribute to the drainage and repeated densification of silty soils with hydraulic conductivity as low as 10^{-8}m/s. However, the degree of improvement is dependent on hydraulic conductivity.



(SC=Vibro-Stone Column without Wicks, SC + Wicks=Composite Vibro-Stone Column)

Figure 9. Composite Vibro-Stone Columns – Simulation Results

Cavity Expansion and Densification

The simulations presented herein consider soil densification due to dissipation of cavity expansion-induced pore pressures only. These simulations involved two cases: (i) stone columns with wick drains, and (ii) without wick drains. The initial density of soils was $(D_r)_{eq}$ = 40%. Three different area replacement ratios (A_r = 10, 15, and 25%) were considered. Probe characteristics used for the simulation are the same as those summarized in the Table 1. Table 3 summarizes simulation parameters relevant to this analysis. The vibratory probe diameter is 0.36 m. In lifts of 1 m, the probe is reinserted seven times to build a stone column of 0.95 m diameter at any given depth. Field observations indicate that this process takes about 4 to 5 minutes per lift of 1 m.

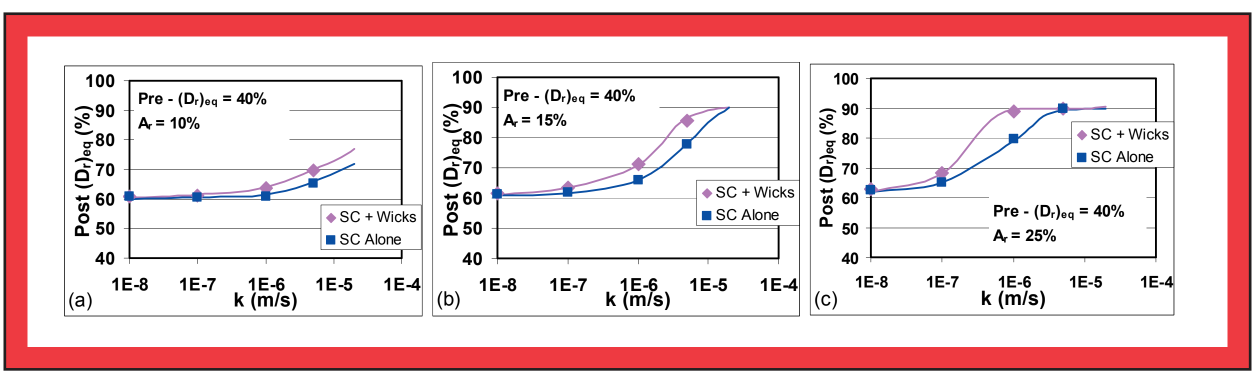
The post-improvement densification results are shown in Figure 10 for A_r = 10, 15, and 25, respectively. Without wick drains, the highest improvement is achieved for highly permeable soils at or above 10^{-5} m/s. The post-improvement density depends on hydraulic conductivity and the area replacement ratio. The addition of wick drains does not significantly affect the degree of improvement. It appears that the cavity expansion-induced pore pressures do not extend far enough from the stone column and hence, wick drains do not significantly contribute to drainage in this case, except for large A_r (Figure 10c).

The above results, shown in Figures 9 and 10, indicate that both the cavity expansion process and ground vibration contribute to densification. Post-improvement densities due to the coupled effect of both cavity expansion and vibratory energy should be higher than those obtained by considering cavity expansion only. Further work is underway to couple these two phenomena.

■ Table 3. Simulation Parameters - Cavity Expansion

Column Diameter (m)	Column Depth (m)	Column Spacing (m)			Depth Simulated (m)
		A_r = 10%	15%	25%	
0.95	15	2.85	2.3	1.8	12

Note: Initial effective confining pressure at the depth considered is about 100 kPa.



■ Figure 10. Post-Improvement Densification - Due to Pore Pressures Induced by Cavity Expansion

Dynamic Compaction

The above model given by Eqs. 2 through 6 and 9 through 12 was used to simulate soil response during the dynamic compaction process and quantify soil densification in sands and silty soils. First, for the DC process, two case history sites were analyzed: (a) Kampung Pakar site, Malaysia (Chow et al., 1992), and (b) Steinaker dam modification project (Dise et al., 1994). The results were compared with field measurements. This was followed by a parametric study.

Kampung Pakar Site, Malaysia

The Kampung Pakar site is a development site consisting of 14 m of relatively uniform and homogeneous loose sand, with a water table at about 3 m below the surface. The dynamic compaction program involved two high-energy passes carried out on a 6 m x 6 m grid pattern using a 1.83 meter square pounder weighing 15 tonnes. The design parameters are summarized in Table 4. The post-improvement simulation results are compared with the field density measurements, deduced from CPT data, in Figure 11. The profile corresponds to the center in the six-meter square grid pattern. Considering the approximate, first-order nature of the numerical simulations, the simulation results agree reasonably well with the measured data.

Steinaker Dam Modification Project, Utah

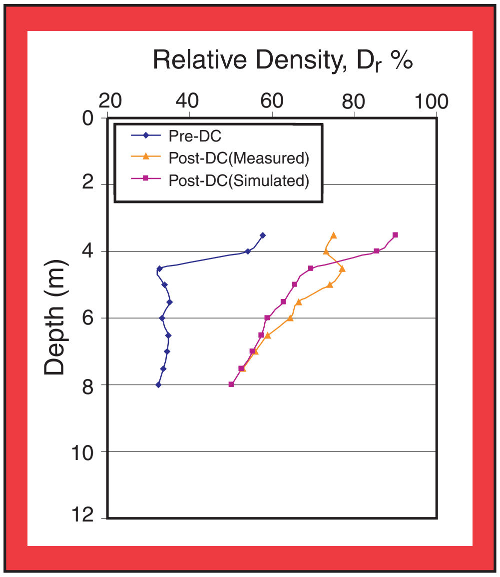
In this case, the soil profile data and compaction parameters were obtained from Hayward Baker, Inc., and is reported by Nashed (2004). Briefly, the treated sandy silt contains an average fines content of 45%. Wick drains were installed on 1.5 m centers to a depth of 9 m and a 1.5 m thick compaction pad was constructed. Perimeter well points were installed to lower the water table at least 3.7 m below the top of the compaction pad. The dynamic compaction program involved three high-energy passes (Table 4). The impact grid pattern is shown in Figure 13. Because of the expected buildup of excess pore pressures, the drop sequence was tightly controlled. The primary pass was completed before drops were allowed at secondary locations. Similarly, this was the case for the secondary and tertiary passes as well. Measured data consisted of pre- and post-improvement SPT profiles. Figure 12 shows the pre- and post-improvement SPT field data along with the equivalent SPT profiles obtained based on density profile results from numerical simulations (Nashed, 2004). The simulation results follow the

Table 4. Impact Parameters – Dynamic Compaction

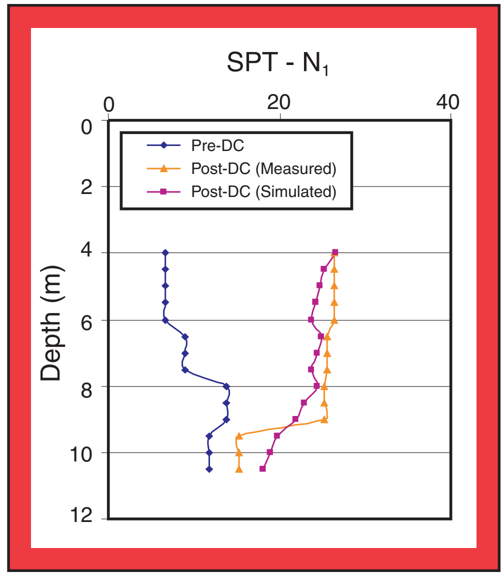
Parameters	Kampung Paker Site, Malaysia		Steinaker Dam Modification Project, Utah			
	1st pass	2nd pass	Initial ironing	1st pass	2nd pass	3rd pass
Pounder weight (tonne)	15.0	15.0	30.0	30.0	30.0	30.0
Drop height (m)	20.0	25.0	18.0	30.0	30.0	30.0
No. of impacts at each grid point	10	6	2	30	30	20

trend observed in the field.

Following reasonable comparisons with case history data described above for both sand (without drains) and silty soils with wick drains, the above computational simulation model was used to assess the effect of the following parameters on densification by dynamic compaction in sands and silty sands: (i) hydraulic conductivity k and fines content FC, (ii) impact grid pattern, (iii) impact print spacing, (iv) number of impacts, (v) time cycle between passes/impacts, (vi) wick drains spacing, and (vii) initial relative density. The results from this study are presented in Nashed (2004). The following section presents a brief summary of the effect of some of these parameters.



■ Figure 11. Pre- and post-DC Relative Density (Kampung Pakar site, Malaysia)



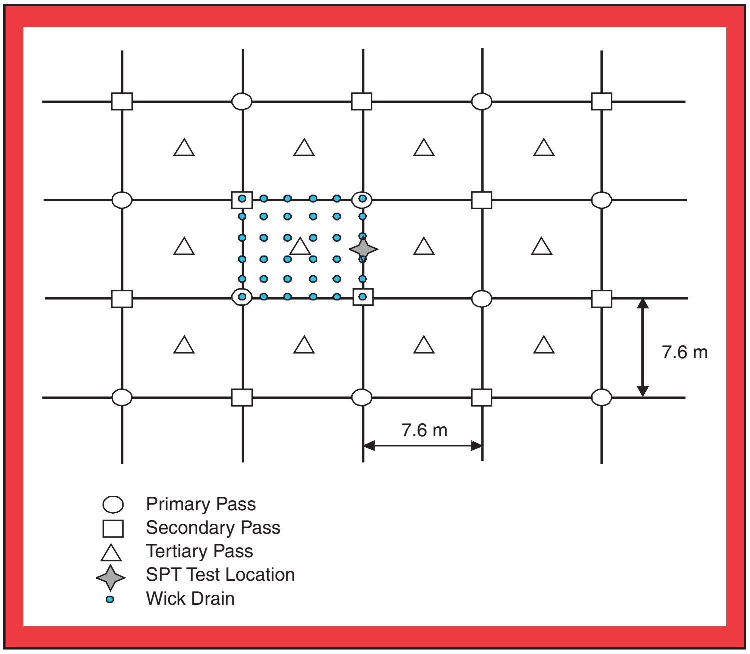
■ Figure 12. Pre- and Post-DC SPT Blow Counts (Steinaker Dam Modification Project, Utah)

Effect of Hydraulic Conductivity and Fines Content on Depth of Influence

In this case, numerical simulations were carried out on two silty soils with the same equivalent relative density of 40% but different hydraulic conductivities (a silty sand at $k = 10^{-7}$ m/s at fines content FC of 25%; and a sandy silt at $k = 10^{-8}$ m/s at FC = 40%). The deposit was supplemented with wick drains of an equivalent diameter of 5 cm installed at a center-to-center spacing of 1.5 m in a square pattern. The ground water table was assumed to be at 2 m depth, and the time cycle between subsequent impacts was selected as two minutes. The same impact grid pattern used for the Steinaker dam project (Figure 13) was adopted. Three energy-delivery passes (primary, secondary, and tertiary) were made. Each grid point received a total of 12 impacts. The cumulative energy applied ranged from 1 to 3 MJ/m^2.

For comparison purposes, a second set of simulations was done for a sand deposit with k of 10^{-5} m/s at an initial relative density of 40%, without wick drains. A typical impact grid pattern for sand with 6.0 m spacing between the impact points was used. Each grid point received a total of 12 impacts.

The simulation results for depth of improvement d_{max} versus energy/impact for the silty soils with wick drains are shown in Figure 14a, and for sand without

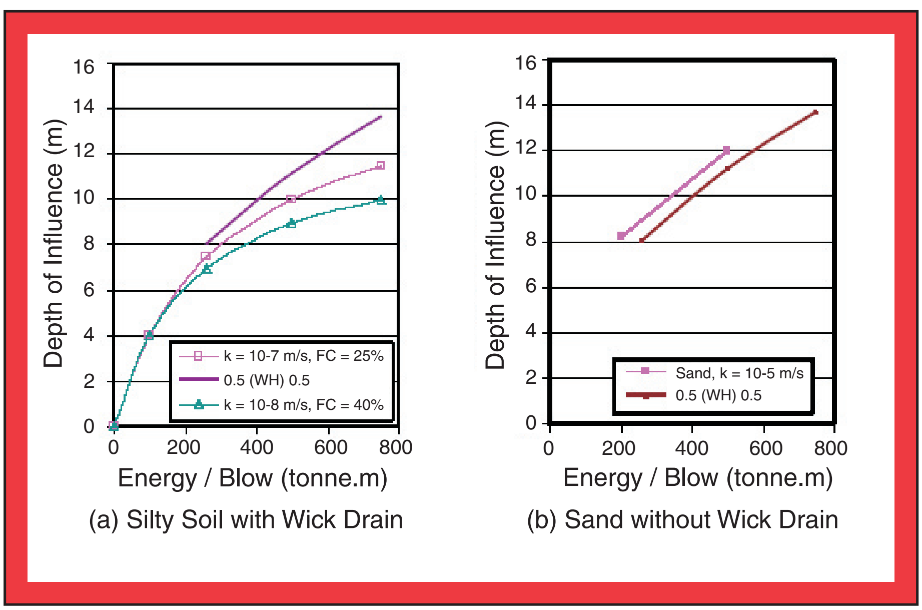


■ Figure 13. Impact Grid Pattern - Steinaker Dam

wick drains are shown in Figure 14b. Also shown in these figures is Eq. 1 for highly pervious sands (n = 0.5), without wick drains. It is interesting to note the effects of fines and hydraulic conductivity on d_{max} in silty soils. A decrease in hydraulic conductivity reduces the effective depth of influence d_{max} (Nashed, 2004). When compared with Figure 14b, the results indicate that, with the provision of wick drains, silty soils can be improved up to depths comparable for sands without wick drains.

Although further details of the study are not shown here, results indicate that DC is ineffective in silty soils with hydraulic conductivity less than 10^{-6} m/s, without wick drains. With wick drains, however, silty soils with hydraulic conductivities as low as 10^{-8} m/s could be densified using DC by pre-installing wick drains at a spacing of 1 m to 1.5 m.

The numerical simulation tool presented herein allows a designer or a contractor to study the effects of various site conditions and construction/design choices on the efficiency of DC process and arrive at an optimum design choice beyond what is currently possible with the use of Eq. 1. Final guidelines for using DC to densify saturated silty soils supplemented with wick drains will be presented in Nashed (2004).



■ Figure 14. Effect of Hydraulic Conductivity and Fines Content on Depth of Influence

Conclusions

A semi-theoretical framework was developed to simulate ground response and analyze the densification process in saturated sands and non-plastic silty soils during vibro-stone column installation and dynamic compaction operations.

For the vibro-stone column technique, the analysis includes two phenomena, (a) vibration-induced excess pore pressure development and concurrent dissipation and densification, and (b) cavity expansion-induced excess pore pressure development and concurrent dissipation and densification. Two factors have been identified as important: (i) Area replacement ratio A_r, and (ii) hydraulic conductivity and silt content. For dynamic compaction, effects of site conditions, and the operational parameters of the technique were studied.

The results indicate that silty soils with hydraulic conductivities as low as 10^{-8} m/s could be densified using stone columns at a close spacing of about 2 diameters or less with an area replacement ratio of about 20% or more supplemented with wick drains. Also for DC, using wick drains in such low permeable soils improves the drainage rate and decreases consolidation time, making it possible to achieve depth of improvement as high as possible in sand deposits. Soils at hydraulic conductivities higher than about 10^{-6} m/s may be densified using either technique, without supplementary drainage systems.

The computational methodology presented herein is a powerful tool for design analyses of stone columns and dynamic compaction taking into account the site conditions and operational parameters for different deposits. The model is expected to advance the use of SC and DC in silty soils, and reduce the reliance on expensive field trials as a design tool. Ongoing further work focuses on developing design charts and design guidelines for both composite SC and composite DC techniques.

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New Developments in Seismic Risk Analysis of Highway Systems

by Stuart D. Werner, Craig E. Taylor, Sungbin Cho, Jean-Paul Lavoie, Charles K. Huyck, Chip Eitzel, Ronald T. Eguchi, and James E. Moore II

Research Objectives

A new methodology has been developed for probabilistic or deterministic seismic risk analysis (SRA) of highway systems. This methodology is multidisciplinary and modular, and includes new and improved procedures and models for scenario earthquakes, seismic hazards, bridge fragility, and transportation network analysis. It has been applied to actual highway systems in the United States, and is now being programmed into a public-domain software package named REDARS 2. This paper summarizes the technical features of the SRA methodology, its application to the Shelby County, Tennessee highway system, and recent improvements to the methodology and its models.

Over the past several years, the Federal Highway Administration (FHWA) has been sponsoring a multi-year research project titled "Seismic Vulnerability of the Highway System," which is being carried out through MCEER. This project includes a task to enhance current procedures for seismic risk analysis (SRA) of highway systems, and to program these enhancements into a public domain software package named REDARS 2.

Early efforts under this task included: (a) development of the framework of the SRA methodology; and (b) initial deterministic application of the methodology to the highway-roadway network in Shelby County, Tennessee using then-available models, in order to demonstrate the use of the methodology and to prioritize further research under the FHWA-MCEER project. This research led to improved models for scenario earthquakes, seismic hazards, bridge fragility, and transportation network analysis. These updated models were then used to carry out a fully probabilistic SRA of the Shelby County roadway network.

Recent work on the SRA methodology has focused on validation of the various models, improvement of the network analysis procedure to include post-earthquake congestion-dependent trip demands, development of an "import wizard" to ease input data preparation, and addition of a "decision-guidance" model to facilitate use of the methodology to guide seismic risk reduction decision making. These features are now being programmed into a public-domain software package named REDARS (Risks from Earthquake

Sponsors

Federal Highway Administration

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Previous Summaries

2001-2003:
Werner et al.,
http://mceer.buffalo.edu/publications/resaccom/0103/02werner.pdf

2000-2001:
Werner,
http://mceer.buffalo.edu/publications/resaccom/0001/rpa_pdfs/07werner_f.pdf

1997-1999:
Friedland et al.,
http://mceer.buffalo.edu/publications/resaccom/9799/Ch12frie.pdf

DAmage to Roadway Systems), which is scheduled for release at the end of 2005.

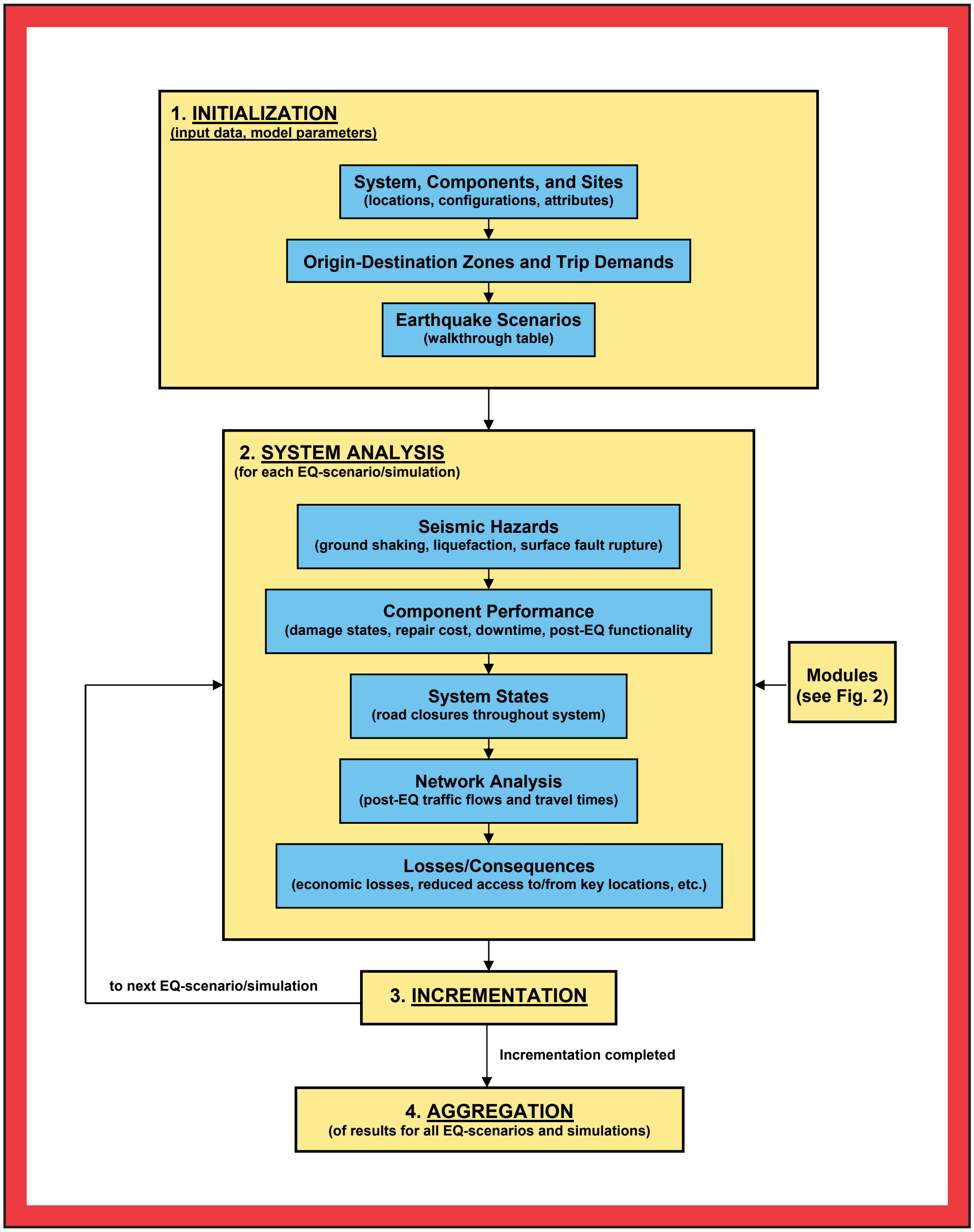
SRA Methodology

The REDARS SRA methodology (Werner et al., 2000) is shown in Figure 1. It consists of input data and analysis setup (Step 1), seismic analysis of the highway system for multiple scenario earthquakes and simulations, (Steps 2 and 3), and aggregation of the results from each analysis (Step 4). In this, a simulation is defined as a complete set of system SRA results for one set of uncertain input and model parameters. The numerical values of these parameters for one simulation may differ from those of other simulations because of random and systematic uncertainties. Features of the methodology are summarized below.

- *Modular.* The heart of the methodology is a series of modules that contain the input data and analytical models needed to characterize the highway system, the seismic hazards, the fragility of the components within the system, and the economic losses due to earthquake-induced damage and traffic disruption (Figure 2). This modular structure will facilitate the inclusion of new improvements to REDARS' hazards, component, and network models, as they are developed from future research.
- *Multidisciplinary.* The SRA methodology is a synthesis of models developed by earth scientists, geotechnical and structural earthquake engineers, transportation engineers/planners, and economists.
- *Wide Range of Results.* The methodology can develop multiple types/forms of results from deterministic or probabilistic SRA, in order to meet needs of a wide range of possible future users.

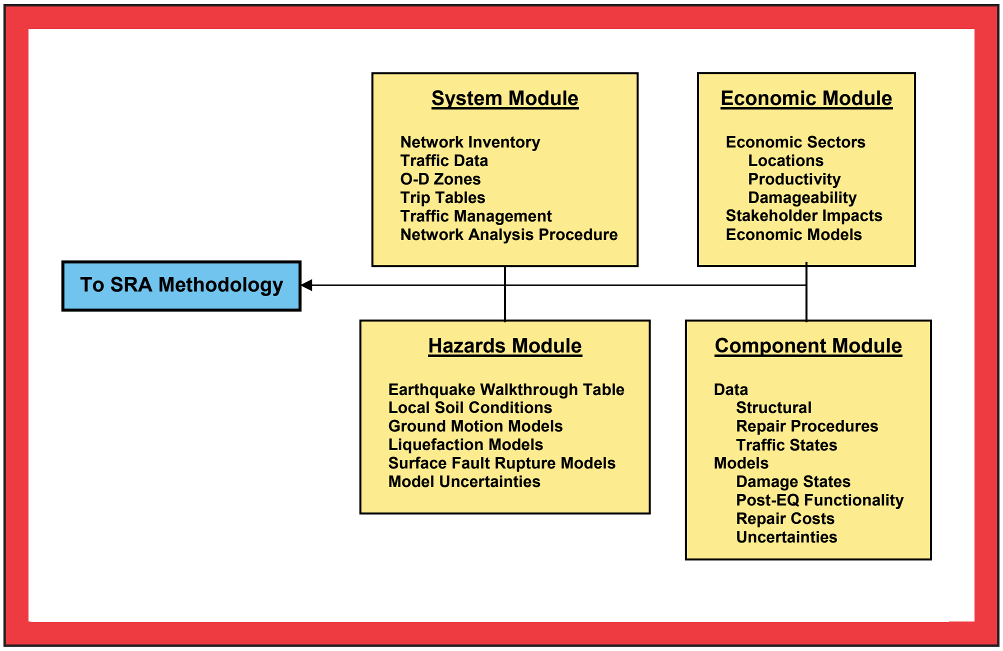
The SRA methodology uses a walk-through process (Taylor et

This SRA methodology for highway-roadway systems will provide cost and risk information pertaining to how alternative seismic risk reduction strategies will affect post-earthquake traffic flows and travel times. This information will facilitate rational and informed evaluation of these alternative strategies by decision makers from federal, state, county, or local transportation agencies who are involved with upgrading highway-roadway infrastructure, emergency response planning, and transportation planning. Such strategies can include prioritization and seismic strengthening measures for existing bridges and other components, establishment of design criteria for new bridges and other components, construction of additional roadways to expand system redundancy, and post-earthquake traffic management planning. The methodology can also be used in real time after an actual earthquake by staff from government agencies and transportation departments, in order to facilitate and coordinate their deployment of effective post-earthquake emergency response strategies.



■ Figure 1. Methodology for Seismic Risk Analysis of Highway Systems *Werner et al., 2000*

al., 2001) that considers earthquake occurrences over a specified walk-through duration (which may be in hundreds or thousands of years). For each year of the walk-through, random samplings of a regional earthquake model are used to establish the number of earthquakes (i.e., zero, one, or more earthquakes) occurring during that year, along with each earthquake's magnitude and location. These results are stored in a "walk-through table" which contains a year-by-year tabulation of these earthquake occurrences. Then, the following SRA steps are carried out for each earthquake



Werner et al., 2000

■ Figure 2. SRA Modules

(and simulation) occurring during each year of the walk-through:

- *Uncertain Parameters.* Values of all uncertain parameters are randomly selected.
- *Seismic Hazards.* Seismic hazard models from the Hazards Module are used to estimate the ground shaking and permanent ground displacement hazards at the site of each component in the system.
- *Component Performance.* Fragility models from the Component Module are used to estimate each component's damage state due to the above hazards, and the component's repair cost, downtime, and traffic state (ability to carry traffic during repairs) at various post-earthquake times. The time-dependence of the traffic states reflect the estimated rate of repair of the component damage.
- *Network Analysis.* The component traffic states are included into the highway system model, in order to develop the overall post-earthquake "system states" (roadway closures throughout the system at various post-earthquake times). Then, network analysis procedures from the System Module are applied to each system state in order to estimate how the closures affect post-earthquake travel times.
- *Economic Losses.* Models from the Economic Module are used to estimate economic losses due to earthquake-induced travel time delays estimated from the network analysis.

The above walk-through process that is key to the SRA methodology facilitates the consideration of all quantifiable model and input parameter uncertainties, the calculation of nominal confidence levels and limits (CLLs) of the SRA loss estimates, and the consideration of changing trip demands and time value of money over time frames of importance to decision makers responsible for highway seismic improvement programs. Variance-reduction techniques summarized later in this paper have been found to dramatically reduce the walk-through duration needed to achieve target CLLs.

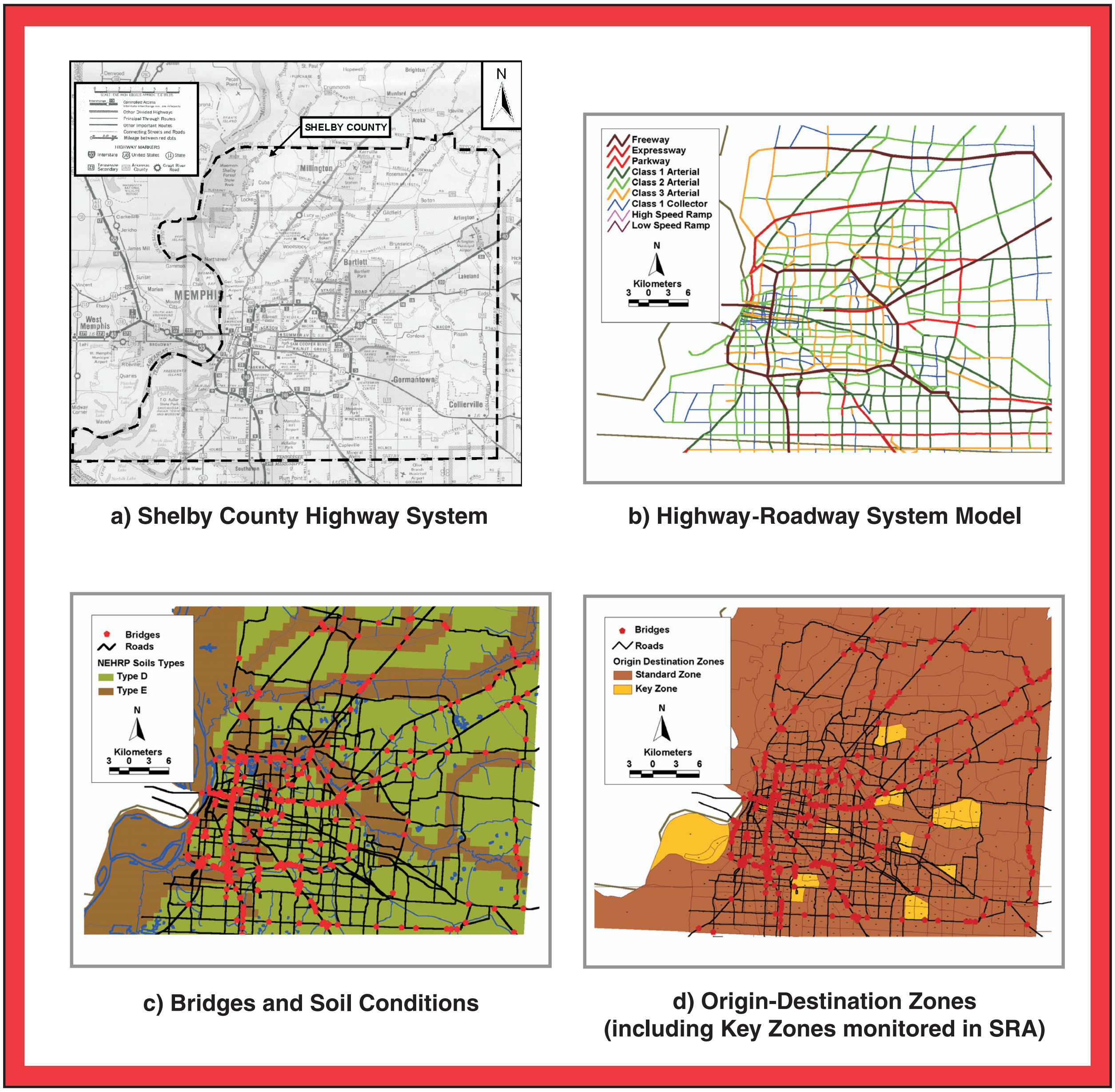
Another feature of the SRA methodology is its use of either a simplified default fragility model or a user-specified set of fragility curves to characterize the seismic performance of any bridge in the highway system. In view of the large number of bridges contained in highway systems, the simplified default model for SRA applications was motivated by the need: (a) for rapid analysis; and (b) to accommodate the limited seismic-performance-related attribute data for bridges contained in most federal or state computerized databases (Mander and Basoz, 1999). This model is practical for application to most of the bridges in the highway system. The user-specified fragility curves (which can be based on more detailed bridge analysis implemented outside of REDARS) are most suitable for modeling of bridges that have a unique configuration not well represented by the default model, or whose damageability could have a major impact on system-wide post-earthquake travel times.

Demonstration Application

This probabilistic SRA methodology was applied to the highway system in Shelby County, which is located in the southwestern corner of Tennessee alongside the Mississippi River (Figure 3a). This application shows how the methodology can be used to analyze an actual highway system, and the types of results it can provide. It is described in detail in Werner et al., 2000, and is summarized below.

Input Data

SRA input data includes: (a) a highway-roadway network model, that includes the network's geometry, and each roadway's lanes traffic carrying capacities, and free-flow speeds (Figure 3b); (b) for each component (bridge, roadway, tunnel, etc.) a fragility model for each component in the system (bridge, roadway, tunnel, etc.) that characterizes its damageability and post-earthquake functionality; (c) soil conditions throughout the network, as needed to estimate site-specific ground motions (Figure 3c) and permanent ground displacement hazards at each component site; (d) trip demands on the network, in the form of origin-destination (O-D) zones (Figure 3d), and trip tables that define the number of pre-earthquake trips from each zone to all other zones in the region; and (e) economic parameters needed to estimate economic losses due to travel time delays that result from earthquake damage to the highway network. The O-D zones and trip tables used in this demonstration application (Item (d) above) correspond to projections for the year 2020 as provided by the Shelby County Office of Planning and Development (Werner et al., 2000).



Werner et al., 2000

■ Figure 3. Input Data for SRA of Shelby County, Tennessee Highway System

Analysis

This SRA was conducted by using a walk-through with a duration of 50,000 years. Earthquakes occurring during each year of the walk-through were estimated by applying the then-current U.S. Geological Survey models for the Central United States (Frankel et al., 1996). This generated 2,321 earthquakes with moment magnitudes ranging from 5.0 to 8.0. The network model included 7,807 links, 15,614 nodes, and 384 bridges. The system analysis for each simulation followed the steps shown in Figure 1. It used a ground shaking model for the Central United States developed by Hwang and Huo (1997), a liquefaction hazard model developed by Youd (1998), fragility models for conventional bridges in Shelby County that were developed by Jernigan and Hwang (1997), special user-specified fragility models for the major crossings of the Mississippi River along Interstate Highways 40 and 55 (Werner et al., 2000), a first-order bridge repair model documented in Werner et al. (2000), an approach-fill settlement model by Youd (1999), and a network analysis procedure developed by Moore et al. (1997) that is based on a user-equilibrium model in which pre- and post-earthquake trip demands are assumed to be identical (see Werner et al., 2000).

Results

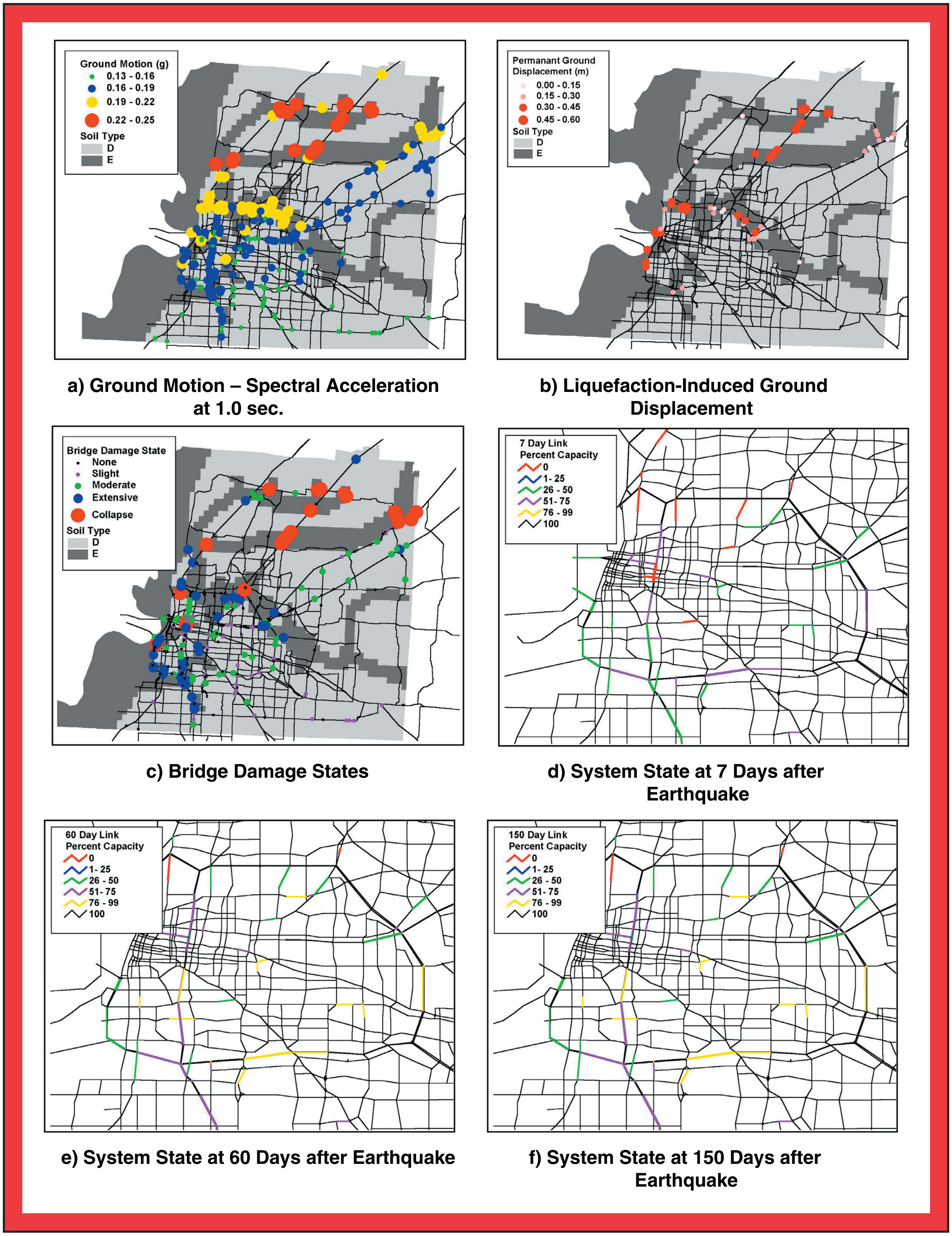
The analysis results for any simulation included: (a) GIS displays of region-wide ground shaking and liquefaction hazards, and bridge damage states (Figures 4a-4c); (b) for selected times after the earthquake, GIS displays of post-earthquake system states that reflect the estimated rate of repair of the earthquake damage (Figures 4d-4f), minimum-time travel paths between any two locations, and traffic volumes along selected roadways; and (c) tabulations of economic losses and effects of earthquake damage on access and egress times to/from selected locations in the region (Table 1). Then, after results from all simulations were aggregated, probabilistic estimates of economic losses for various exposure times were developed (Figure 5).

New Developments

Since the above demonstration application was completed, a validation application of the SRA methodology was carried out and new technological and usability improvements to the methodology were added. These developments are summarized below.

■ Table 1. Percent Increase in Access Time to Selected Locations in Shelby County, Tennessee (Relative to Pre-Earthquake Access Times) due to Earthquake Damage to Highway System

Origin-Destination Zone (see Key Zones in Figure 3d)	Post-Earthquake Access Time		
	7 Days after EQ	60 Days after EQ	150 Days after EQ
9 (Government Center in downtown Memphis)	43.8%	5.8%	2.0%
28 (Major Hospital Center, just east of downtown Memphis)	44.6%	6.7%	2.0%
205 (Memphis Airport and Federal Express transportation center, south of beltway)	53.7%	4.0%	1.6%
73 (University of Memphis campus in central Memphis)	21.6%	4.3%	1.5%
310 (Germantown, residential area east of beltway)	2.9%	0.9%	0.4%
160 (President's Island, Port of Memphis at Mississippi River)	34.9%	6.1%	1.6%
246 (Hickory Hill, commercial area southeast of beltway)	3.9%	1.9%	1.1%
335 (Shelby Farms residential area northeast of beltway)	28.4%	4.8%	1.6%
412 (Bartlett, residential area north of beltway)	13.2%	3.0%	1.3%



a) Ground Motion – Spectral Acceleration at 1.0 sec.

b) Liquefaction-Induced Ground Displacement

c) Bridge Damage States

d) System State at 7 Days after Earthquake

e) System State at 60 Days after Earthquake

f) System State at 150 Days after Earthquake

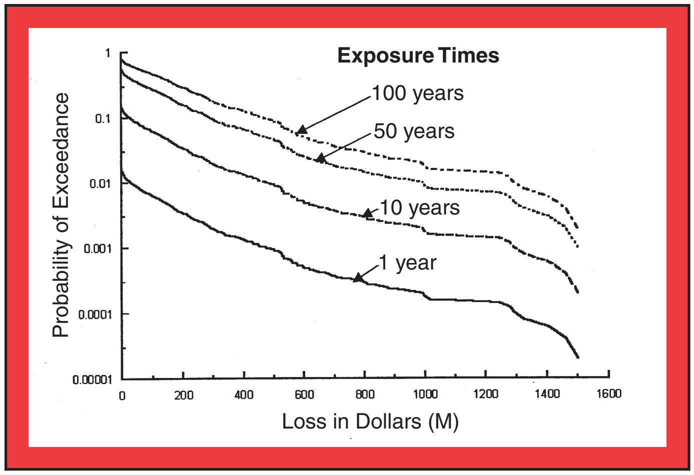
Werner et al., 2000

■ Figure 4. System Response to Magnitude 8.0 Earthquake 142 km North of Shelby County

Validation Application

Prior to developing improvements to the methodology, it was independently reviewed and validated using the early (pre-beta) version the REDARS software that was used to carry out the above demonstration SRA of the Shelby County highway system (Cho et al., 2003a). This consisted of: (a) review of the basic SRA methodology; (b) creation of input data for a case study of the Los Angeles area highway system; (c) deterministic predictions of the system's seismic performance during the Northridge earthquake, and comparison of these predictions to the system's observed performance; and (d) performance of sensitivity studies to identify key parameters for loss estimation. The validation focused on the models used to estimate bridge damage states, corresponding traffic states, and post-earthquake travel times.

Comparisons of predicted vs. observed seismic performance showed that: (a) the number of damaged bridges was overestimated by a factor of about 2 – probably because of model simplifications noted earlier in this paper (see Bridge Research Recommendations later in the paper); (b) bridge closure times for a given damage state were overestimated – which was expected because the bridge repair estimates in this pre-beta REDARS software were intended to simulate Tennessee repair resources, and did not account for the rapid rate of bridge repair after the Northridge earthquake that resulted from California Department of Transportation repair experience and special repair incentives; and (c) traffic volume predictions for roadways near collapsed bridge sites overestimated observed traffic volumes by factors of 1.3 to 2.5 – which can be attributed, at least in part, to the ignoring of effects of increased congestion on post-earthquake trip demands in these predictions. These comparisons were incentives for the planning of several of the recent model improvements summarized in the following sections of this paper.



Werner et al., 2000

■ Figure 5. Economic Losses due to Travel Time Increases caused by Earthquake Damage to Shelby County, Tennessee Highway-Roadway System

Transportation Module Improvements

Variable Demand Model

In prior versions of the REDARS SRA methodology, a user-equilibrium network flow model with trip demands that are fixed at their pre-earthquake levels was used to estimate post-earthquake traffic flows and travel times (Moore et al., 1997). In this model, a commuter's selection of a travel route will depend on route congestion, but the propensity to travel will not. However, more realistically, trip rates/demands will also de-

Links to Current Research

There has been considerable interest among the other national earthquake research centers, PEER and MAE, in possibly using REDARS as a platform for SRA of highway systems. Toward this end, two workshops involving the national earthquake centers as well as FHWA and representatives from several state transportation departments nationwide were held during the past year to begin planning collaborative research along these lines. In addition, fragility models for retrofitted bridges being developed by Shinozuka and others will be incorporated into the REDARS 2 software.

pend on the congestion level. This will be particularly true after a damaging earthquake that closes major roadway links within a highway-roadway system and results in substantial congestion. Under such conditions, post-earthquake trip demands can be expected to be much lower than pre-earthquake trip demands. This will affect estimates of post-earthquake travel times and corresponding economic losses due to post-earthquake travel time delays, as well as post-earthquake access and egress times to/from key locations in the region (e.g., medical centers, airports, and fire departments).

To account for this, the REDARS network analysis procedure has been upgraded to include a "variable demand" model that estimates how trip demands will vary with post-earthquake congestion level (Cho et al., 2003b). This model accounts for the fact that economic losses due to highway network damage will depend not only on travel time delays, but also on the economic value of trips foregone due to earthquake-induced highway-system damage and traffic congestion.

Freight Flows

The modeling of earthquake effects on post-earthquake intra-urban freight flows is important to the estimation of economic losses caused by earthquake damage to the highway system. However, REDARS' earlier treatment of freight flows was constrained by an absence of intra-urban freight origin-destination (O-D) trip-table data. This made it necessary to assume that freight traffic is simply a user specified fraction of automobile traffic, which limited the quality of REDARS' estimates of post-earthquake highway-system performance.

To address this issue, improved methods for estimating freight O-D trip demands are being developed under related research sponsored by the California Department of Transportation (Caltrans). These methods involve adaptation of a freight O-D estimation algorithm that was previously applied to the Los Angeles highway-roadway system (Cho et al., 2001). Instead of relying on a freight O-D survey, this algorithm estimates truck trip movement based on intra- and inter-regional commodity flow data by industrial sectors. The algorithm is now being used to estimate truck trip movement in the San Francisco Bay area by compiling input from various regional freight data sources. This work will guide future applications of the algorithm in other regions of the country where REDARS SRA applications are carried out.

Hazard and Component Modules

Hazards Module

The SRA Hazards Module is being updated to enable the methodology to: (a) accommodate multiple ground motion models for various regions of the United States; (b) compute source-site distances according to a wide range of distance definitions, in order to facilitate REDARS' accommodation of other ground motion models in the future; (c) check the consistency of probabilistic estimates of ground motions from the walk-through approach with those estimated using conventional seismic hazard analysis procedures; (d) include the four-parameter liquefaction-induced lateral spread displacement model by Bardet and his associates (Bardet et al., 2002); and (e) adapt the Youngs et al. probabilistic model for site-specific surface fault displacements (Youngs et al., 2003) to apply to probabilistic system-based evaluations carried out by the REDARS SRA methodology.

Component Module

The SRA Component Module is being updated to modify the process for modeling bridge repairs as a function of bridge damage state, and to extend default bridge fragility models to account for the beneficial effects of seismic retrofit. The repair model is being modified to: (a) encourage user modeling of repair costs, downtimes, and traffic state; and (b) include repair guidelines based on Caltrans experience. The encouragement for users to develop their own repair model was motivated by the fact that bridge post-earthquake repair rates will vary from region to region throughout the United States, because of regional differences in bridge construction practices, repair resources, and earthquake repair experience. Therefore, it is not plausible to specify a single default repair model in REDARS that will apply to bridges nationwide. Inclusion of repair guidelines based on Caltrans experience was motivated by their extensive post-earthquake bridge repair experience. Repair modeling of bridges outside of California can use these experience-based guidelines as a starting point, after which user adjustments to account for regional differences in bridge construction and repair practices can be included.

The default bridge fragility model used in the previously-noted validation analyses applies to un-retrofitted bridges only; i.e., they do not account for the beneficial effects of bridge retrofit. Because statewide bridge retrofit was in progress at the time of the Northridge earthquake, this limitation of the default model probably contributed to some extent to the model's overestimation of observed bridge damage. Therefore, as a first step for including retrofit effects into the default model, results of research by Shinozuka and his associates are being incorporated (Kim and Shinozuka, 2003). This research has used analytical investigations of the longitudinal response of several typical California bridge configurations in order to characterize the effects of column-jacket and cable-restrainer retrofitting on seismic performance of these bridges. The research is now being extended to also consider transverse bridge response.

Computation-Time-Reduction Improvements

Computational times required for REDARS probabilistic SRA applications are affected by the number of simulations used (which can be large), and by the time required to implement network analysis for post-earthquake system states at several times after each earthquake. Steps being taken to reduce REDARS computation times by addressing these issues are summarized below.

Related Web Sites

Seismic System for Southern California:
http://trinet.org/shake

Caltrans' Division of Research and Innovation:
http://www.dot.ca.gov/research/operations/redars/redars.htm

Variance Reduction

The number of simulations and earthquake scenarios considered for probabilistic SRA should be chosen to achieve target confidence levels and limits (CLLs) in the loss results. In the demonstration SRA of the Shelby County highway system summarized earlier in this paper, a binomial distribution was used to estimate CLLs in the average annual loss (AAL) caused by earthquake damage to the system. This SRA was based on a walk-through duration of 50,000 years, which included 760 simulations with non-zero losses. The resulting CLLs were judged to be acceptable (95 percent confidence that the true value of the AAL was within ±12.6 percent of the computed AAL); however, the computer run time needed to carry out the SRA for this long walk-through duration and large number of simulations was extensive.

This issue has been addressed by considering that the number of simulations needed to achieve a target CLL will decrease as the variance of the loss distribution decreases. This led to the investigation of variance reduction methods, which use advanced statistical analysis techniques to reduce the variance in the estimate of some selected parameter (here the AAL). When applied to the SRA of the Shelby County, Tennessee highway system, it turned out that these methods led to nearly a 70 percent reduction in the number of simulations needed to achieve the CLLs indicated in the previous paragraph. Therefore, a post-processor is being added to REDARS that will use variance-reduction methods to estimate CLLs for a given number of simulations. These methods, and their application within REDARS, are further described in Perkins and Taylor, 2003.

Improved Time-Efficiency of Network Analysis

The most time-consuming step of the SRA for each simulation is the network analysis for estimating post-earthquake traffic flows. This analysis has used a user-equilibrium model, which assumes that roadway system users will always choose travel paths that minimize their travel times. A key element of this model is a minimum time-path searching algorithm, which searches many possible paths between various O-D zone pairs to find the path that has the shortest travel time. Originally, a Moore-Pipe algorithm was used for this purpose. However, to reduce network-analysis run times, a much more efficient Dual-Simplex searching algorithm has since been included into REDARS. This algorithm has been shown to reduce network analysis run times by factors ranging from about 20 percent (for small networks) to nearly 60 percent (for large networks with many links and nodes).

Decision Guidance

The REDARS SRA methodology is not only being structured as a tool to estimate losses due to effects of highway system earthquake damage on post-earthquake travel times and traffic flows. Rather, it is also being developed to guide highway transportation agency decision-makers during their evaluation of various seismic-risk-reduction options (such as alternative bridge strengthening or highway system improvement strategies), and their selection of a preferred option that reduces these losses to an acceptable level.

Use of REDARS as a decision-guidance tool will involve the following steps: (a) developing multiple models of the highway network, in which each model includes one of the seismic-risk-reduction options under consideration; (b) performing a SRA for each model, and estimating relative implementation-costs and losses (risks) for each risk-reduction option; and (c) structuring these cost and losses into several decision models that facilitate the quantitative comparison of the various options. The latter step will be accomplished through a new REDARS post-processor that will include both deterministic and probabilistic decision models (to accommodate either deterministic or probabilistic SRA applications). The deterministic decision models will be the principle of dominance, the maxi-min principle, and the min-max principle, and the probabilistic decision models will consist of benefit-cost, least mean total cost, mean-variance, and first-order stochastic dominance methods.

Import Wizard

The development of input data for REDARS SRA applications requires the use of several publicly-available databases, including: (a) the National Highway Performance Network (NHPN) database for defining network topology only (spatial coordinates); (b) the Highway Performance Monitoring System (HPMS) database for defining highway network attributes only (e.g., number of lanes, functional class, etc.); (c) the National Bridge Inventory (NBI) database which defines certain bridge attributes; and (d) regional databases for defining O-D zones and associated trip tables, NEHRP soil conditions, etc. Unfortunately, the information contained in these various databases is not always compatible. For example, the segmentation of the links in the NHPN database (network topology) is not always consistent with that of the HPMS database (link attributes). In addition, bridge coordinates from the NBI database are not always consistent with the corresponding roadway link location given in the NHPN database. The resolution of these issues in order to develop consistent input data for a REDARS SRA application can be time consuming.

To reduce these user time requirements, an Import Wizard is being developed to interface with REDARS. This Wizard will guide the user through each step of the input-data development process, and will automate the resolution of many of the above inconsistencies. It will consist of a series of prototype user interfaces (graphical user interfaces and dialogue windows) that are successively activated by users and will guide them through each step of the development of the input data. Such interfaces will enable users to locate publicly available databases within the Wizard, define study region boundaries, establish the various network, soil, and bridge input databases within REDARS, define boundary conditions (e.g., trip demands on the highway network from outside of the study region), and check network-model connectivity and continuity of O-D zones.

"The REDARS SRA Methodology is being developed to guide highway transportation agency decision-makers during their evaluation of various seismic risk reduction options (such as alternative bridge strengthening or highway system improvement strategies), and their selection of a preferred option that reduces these losses to an acceptable level."

Software Development

In addition to the foregoing new improvements directed toward enhanced technical capabilities and usability of the SRA methodology, this SRA research is now focusing on the programming of the methodology into what will be a public-domain software package. This programming work has led to completion of an initial demonstration software package (REDARS 1), and is now developing the public-domain software (REDARS 2).

REDARS 1

REDARS 1 is demonstration software that performs deterministic SRA of the Los Angeles, California highway-roadway system subjected to scenario earthquakes for which ShakeMap ground motion data (Wald et al., 2003) are available. It is a simplified version of the REDARS SRA methodology, in that it considers ground shaking hazards only, and does not include any of the new improvements summarized in the foregoing paragraphs. Development of REDARS 1 was motivated by early interest in REDARS by several state highway transportation agencies, and the need to: (a) provide a simplified tool to familiarize these agencies with basic SRA concepts while the more extensive public-domain software (REDARS 2) is being developed; and (b) enable these agencies to provide early feedback regarding particular features that would be desirable to include in the forthcoming REDARS 2 software.

For the Los Angeles highway system and ShakeMap ground motion cases that can be analyzed, REDARS 1 enables users to: (a) compute and display system-wide bridge damage states and highway-roadway system states at various post-earthquake times; (b) perform network analysis to estimate effects of earthquake damage on post-earthquake travel times; and (c) estimate economic losses due to travel time delays, and effects of earthquake damage on access-egress time to/from any O-D zone in the model. In addition, the user can simulate seismic upgrades to bridges and highway system improvements, and then rerun REDARS 1 to compute the effects of these improvements on post-earthquake travel times (Werner et al., 2003).

REDARS 2

REDARS 2 will be public domain software for deterministic or probabilistic SRA of highway-roadway systems nationwide. This software will start with features and structure summarized for REDARS 1, and will then be extended to include technical and user-oriented features and improvements summarized earlier in this paper. REDARS 2 will be programmed as a stand-alone Microsoft Windows desktop application, and will include several process-flow and general-application changes (relative to REDARS 1) that are described in detailed REDARS 2 draft software specifications (SSEC, 2004). These specifications also include priorities, budgets, and schedules for completion of all software development tasks pertaining to general applications development, programming of SRA capabilities, software documentation, release, support, and administration.

During the remainder of this year (2004), a beta version of the RE-

DARS 2 software will be prepared and tested, and programming of the software and Import Wizard will be completed. Preparation of user and technical documentation, implementation of a new demonstration application, and public release of the software are scheduled to be completed by the end of the following year (2005).

Future Directions

This section addresses recommended future research directions for further improving the REDARS SRA methodology. These pertain to bridge modeling, network analysis, and economic loss estimation.

Bridge Modeling

As previously noted, REDARS' default procedure for fragility modeling of bridges subjected to ground shaking hazards was constrained by the need to carry out rapid estimates of the seismic performance of the large number of bridges in a highway system, and to use the limited bridge attribute data contained in current federal and state computerized databases (Werner et al., 2000). In view of these constraints, bridge performance predictions by the default procedure suffer from certain limitations, e.g., (a) they use qualitative descriptors of bridge damage that do not provide sufficient information on the extent, locations, and types of earthquake-induced bridge damage that would ordinarily be needed to estimate repair requirements; (b) they do not include certain key elements of bridge seismic performance, such as foundation and abutment performance, overall bridge system characteristics, effects of bridge retrofit, and certain structural details that can have important effects on seismic performance. Other key limitations of current bridge modeling procedures for SRA applications are: (c) limited information is available to guide the estimation of bridge repair requirements; and (d) procedures to estimate the seismic performance of bridges subjected to permanent ground displacement hazards (in addition to ground shaking hazards) are limited. Therefore, research to address the following bridge modeling issues is recommended:

- What should be the next-generation default bridge modeling procedures that lead to improved seismic performance predictions, while also being practical for SRA applications?
- How can current computerized bridge attribute databases be expanded to provide the input data needed to apply these procedures?
- How can bridge damage states be defined to better facilitate the estimation of bridge repair costs, downtimes, and functionality (traffic carrying capacity during repair) after an earthquake?
- What guidance can be provided for modeling of bridge repair costs, times, and functionality (ability to carry at least partial traffic while repairs are proceeding) for various damage states?
- How can fragility models be developed for bridges subjected to both ground shaking and permanent ground displacement hazards (e.g., due to liquefaction, landslide, or surface fault rupture)?

Network Analysis

As noted earlier in this paper, the network analysis procedure included in the REDARS SRA methodology is based on an idealized model for estimating traveler route choice, which assumes that travelers have perfect information on traffic congestion conditions along possible alternate routes between their origin and their destination. In addition, the procedure does not account for the so-called "boundary problem," i.e., effects of earthquake damage on trips whose routes would ordinarily pass through the system being analyzed, but whose origins or destinations are located outside of that system. Therefore, research is recommended to address the following questions:

- Can stochastic route-choice models be developed to simulate effects of uncertainties in route choice because of imperfect traveler information on traffic conditions along candidate alternative routes?
- How might SRA be carried out for a larger region that surrounds the particular region under investigation, in order to estimate effects of earthquake damage on trips through the system that originate or end outside of the system?

Economic Losses

The REDARS SRA methodology currently uses a first-order model to estimate economic losses due to earthquake-induced travel time delays (Caltrans, 1994). This procedure accounts for the percentage of the total traffic that is automotive vs. freight, estimated vehicle-occupancy rates and associated unit costs, and estimated costs per gallon of excess fuel used because of travel time delays. Possible improvements in economic loss predictions may be realized through: (a) integration of spatial models of the region's economic activity system with the transportation network analysis (including improvements summarized earlier in this paper); and (b) modeling of higher order economic impacts. Research to investigate the feasibility of including these improvements in future versions of the REDARS SRA methodology is recommended.

Concluding Comments

The REDARS SRA methodology summarized in this paper estimates how earthquake damage to a highway-roadway system will affect post-earthquake traffic flows and travel times, and the corresponding economic losses and other consequences of this damage (e.g., reduced access to key emergency response facilities). It also can be used to enable decision makers to assess how various seismic risk reduction options under consideration affect post-earthquake system-wide travel times, and to therefore make a more informed selection of a preferred option to implement.

In closing, a central focus of this SRA research and development program has been the needs of potential future users from federal, state, and local transportation agencies nationwide. Vehicles for user feedback have included: (a) meetings/mini-workshops at various Caltrans district offices; (b) Highway Seismic Research Council (HSRC) meetings conducted as part of the FHWA-MCEER highway research project; and (c) Tri-Center research-collaboration workshops involving highway-transportation agencies nationwide as well as the three national earthquake research centers (MCEER, the Pacific Earthquake Engineering Research Center, and the Mid-America Earthquake Center). During these interactions, users have identified the benefits of SRA in enabling them to more effectively address key user needs related to: (a) pre-earthquake planning of bridge design/retrofit programs, assessment of seismic performance of critical lifeline routes, and assessment of the adequacy of available repair resources; and (b) post-earthquake (real-time) assessment of alternative traffic management strategies and coordination of emergency-response activities between agencies. The meeting of these user needs will continue to be a major focus of future SRA research under this program.

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