

Improving Earthquake Loss Estimation: Review, Assessment and Extension of Loss Estimation Methodologies

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Research Objectives

The overall goals of the research are to link engineering system vulnerability analysis with the best-available techniques of economic analysis, to produce integrated models of physical and economic loss, and to improve the efficiency and effectiveness of loss estimation methods through the application of advanced and emerging technologies. This program of research focuses both on general methodological refinements and model improvement and on applications that will support MCEER's power and water lifeline and hospital demonstration projects.



MCEER/NSF

Spurred in part by the rising economic costs of natural disasters, there has been a dramatic increase in efforts aimed at estimating the direct and indirect losses caused by earthquakes. For example, in 1997 the journal *Earthquake Spectra* devoted a special issue to loss estimation. Papers appearing in that publication ranged from cost-benefit analyses of structural rehabilitation strategies (D'Ayala et al., 1997) to the development of real-time earthquake damage assessment tools (Eguchi et al., 1997). In 1998, MCEER published a monograph addressing the physical and socio-economic impacts of earthquake-induced electrical power disruption in the central U.S. (Shinozuka, Rose, and Eguchi, 1998). More recently, the National Research Council Committee on Assessing the Costs of Natural Disasters published a report outlining a framework for loss estimation (National Research Council, 1999). The HAZUS methodology, developed by the National Institute of Building Sciences with funding from the Federal Emergency Management Agency, is currently one of the best-known set of loss estimation techniques (National Institute of Building Sciences, 1997). Further advances in loss estimation research have been facilitated by new geographic information system (GIS) mapping techniques, as well as by the growing body of empirical data on the physical and economic effects of recent earthquakes.

Providing better estimates of potential earthquake losses is extremely challenging, because of shortages in the kinds of empirical data that are

- MCEER investigator **Ronald Eguchi** has established close working relationships with the California Governor's Office of Emergency Services and with the City of Los Angeles, which have used damage assessment and decision support systems developed by EQE in responding to the 1994 Northridge earthquake, in emergency response training, and in mitigation decision making.
- In related work, with funding from the joint federal-state TriNet program, EQE, the University of Delaware Disaster Research Center, and the University of California, Los Angeles have recently begun to undertake research on the feasibility of implementing a real-time earthquake warning system for the southern California region.
- MCEER investigator **Adam Rose** has been working with Colorado State University economist **Harold Cochran** on improving methods for indirect loss modeling.
- Members of the loss estimation group also work closely with **Howard Kunreuther**, an MCEER investigator at the Wharton School, who will be undertaking benefit/cost analyses for alternative mitigation measures.

needed for more accurate estimates, our limited understanding of the mechanisms through which losses are generated and of the risk factors associated with loss, and the uncertainties that enter into loss calculations at various stages. The MCEER loss estimation research team has attempted to address these problems by systematically reviewing selected loss estimation methodologies, identifying areas where improvements are needed, and conducting new research on earthquake losses. These investigations center on four inter-related topics:

- use of advanced technologies for real-time damage and loss estimation;
- measurement and estimation of direct physical and economic losses;
- identification of risk factors for business losses, including both physical and business interruption losses; and
- estimation of indirect or induced economic losses

This paper briefly summarizes work that has been undertaken to date in each of these four areas.

Advanced Technologies in Real-Time Damage Assessment

This phase of MCEER's research focuses on improving loss estimation for earthquake preparedness, response, and mitigation through the application of new technologies that collect and analyze information on the built environment more efficiently, rapidly, and economically. The availability of accurate and timely information on post-event damage is one of the most critical factors influencing the effectiveness of post-disaster response efforts. The rapid deployment of resources where they are most needed cannot take place unless a comprehensive picture of damage is available. The concept of real-time damage assessment in the U.S. began roughly eight years ago with the introduction of the CUBE (Caltech-USGS-Broadcast of Earthquakes) system in southern California (see CUBE, 1992). About four years ago, a similar system, REDI (Rapid Earthquake Data Integration) was set up in northern California.

Both probabilistic and scenario-based loss estimates are being used as planning tools in the pre-earthquake context, e.g., to provide forecasts of likely physical impacts. Loss estimation methodologies are also being applied to aid mitigation decision making through making it possible to determine the cost-effectiveness of alternative mitigation strategies. With the advent of real-time damage- and loss-estimation tools, loss estimation methodologies also have the potential for use in guiding emergency response and early recovery activities, such as search and rescue, the provision of emergency shelter, and decision making with respect to lifeline restoration. Users of loss estimation research and techniques include federal, state, and local policy makers and planners, the emergency management community, and various private-sector groups, particularly those in the financial, insurance, and real estate sectors.

Future developments, as part of the CUBE/TriNet program, will include real-time ground motion maps and a real-time warning system based on early detection of earthquakes.

Although they provide valuable earthquake information, the CUBE and REDI systems stop short of estimating the damaging effects of earthquakes. To fill this need, a number of earthquake researchers have developed software tools based on conventional loss estimation methodologies that can generate loss estimates from earthquake magnitude data (Eguchi et al., 1997). However, in the last several years, a new set of technologies based on remote sensing methods have found their way into disaster management. One of the first examples of a remote sensing application to earthquake hazards was provided by Dr. Robert Crippen of the Jet Propulsion Laboratory (JPL) in Pasadena (Crippen, 1992; Crippen and Blom, 1993). Using SPOT¹ satellite images acquired approximately one month after the 1992 Landers earthquake, JPL captured the spatial details of terrain movements along fault breaks associated with the earthquake that were virtually undetectable by any other means. These changes, seen in Figure 1, allowed displays of fault location, patterns of drag and block rotation, and pull-apart zones to be revealed. Additionally, separate applications of correlation analysis (i.e., image matching) on each side of the fault provided a comprehensive and quantitative estimate of

the total slip (magnitude and direction) across all strands, warps, and other areas across the fault zone.

Synthetic Aperture Radar (SAR) is another promising technology that extends the applicability of satellite-based or airborne systems to post-earthquake analysis. When used to compare before and after radar images of earthquake impacted areas, these methods have been effective in identifying regions of widespread ground displacement. Figure 2 presents colored images of the co-seismic displacements that were observed after the 1994 Northridge, California, and 1995 Kobe, Japan, earthquakes. In the Northridge image, an interferometric method known as repeat pass interferometry (Gabriel and Goldstein, 1988) was used to quantify the amount of relative displacement recorded after the Northridge earthquake. Figure 2a shows that the highest rates, approximately 60 cm of relative displacement, occurred in the northwestern part of the San Fernando Valley.

Related MCEER Research Activities

- *Los Angeles Water and Power Demonstration Project*
- *Hospital Demonstration Project*
- *Advanced Technologies for Loss Estimation, Development of Damage Functions using Remote Sensing and Real-time Decision Support Systems, R.T. Eguchi, EQE International and D.M. Tralli, MCEER Consultant*
- *Cost-Benefit Studies of Rehabilitation Using Advanced Technologies, R. Eguchi, EQE International, P. Kleindorfer and H. Kunreuther, University of Pennsylvania, M. Shinozuka, University of Southern California and K. Tierney, University of Delaware*

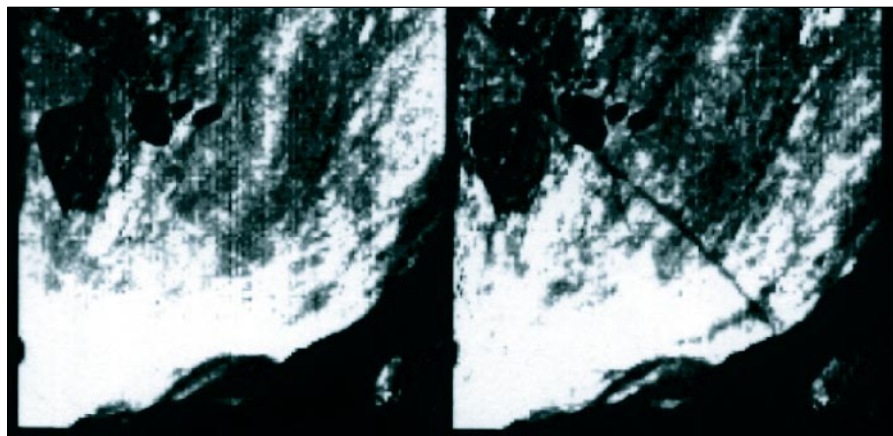


Image produced by Dr. Robert Crippen, Jet Propulsion Laboratory, Pasadena.

■ **Figure 1.** Landers Earthquake Ground Cracks, Emerson Fault, SW of Galway Lake, Mojave Desert, California. Before Satellite Image (Left) 27 July 1991; After Satellite Image (Right) 25 July 1992. Scale: 1.28 km across fault (upper left to lower right).

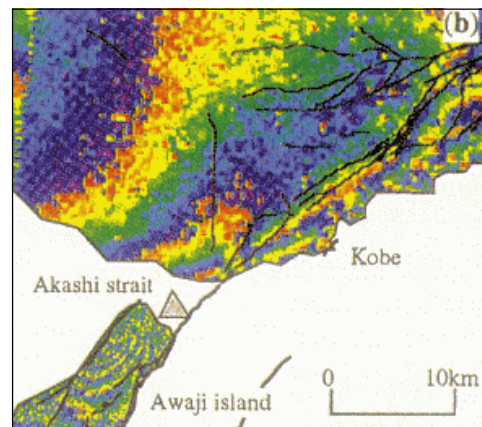
“Synthetic Aperature Radar is another promising technology that extends the applicability of satellite-based or airborne systems to post-earthquake analysis.”

In the Kobe earthquake, a similar interferometric image was constructed using pre- and post-earthquake SAR images. In Figure 2b, each cycle of color corresponds to about 12 cm change in distance between the satellite and the ground surface. Both studies used images obtained by JERS²-1. SAR also has the advantage of imaging through cloud cover and during nighttime conditions, thus making it applicable in real-time.

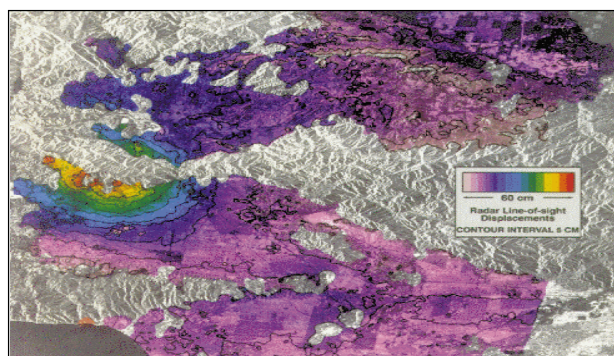
MCEER investigator Ronald Eguchi is currently exploring the application of remote sensing methods for real-time post-impact damage assessment (see *A New Application for Remotely Sensed Data: Construction of Building Inventories Using Synthetic Aperature Radar Technology* in this report). While the applications described above provide useful post-earthquake data, they fail to explain fully the changes in the post-earthquake images. Data are limited to differential measurements of elevation and scattering³ based on repeat passes (pre- and post-event) over the subject area. In general, the observer does not know whether these changes are due to surface displacement, building damage, or a combination of these two effects. MCEER’s research focuses on differentiating between these effects by introducing other independent data and

models that allow a validation/calibration of SAR parameters. For example, GPS measurements can provide site or regional validations that surface displacement has occurred. Optical images created by aerial photographs or satellite imaging (e.g., SPOT) can provide important verification that damage has or has not occurred. In addition, new simulation models that replicate SAR images through analytical techniques can be used to help quantify building damage on a local level. In combination, these technologies will provide a powerful tool that can quickly and reliably assess damage on a large regional scale. With such systems in place, emergency responders can act more decisively after a major event, reducing overall response times, saving lives, and containing property losses.

Complementing this work, which is designed to detect damage at a



Kobe Image from Ozawa et al., 1997



Northridge Earthquake image provided by Dr. Paul Rosen (JPL)

■ Figure 2. Interferograms Showing Relative Ground Displacements Measured After the 1994 Northridge and 1995 Kobe Earthquakes. Each color change reflects an increase or decrease in constant ground displacement. Note that the color scales are different in each figure.

more macro-level, MCEER investigator Masanobu Shinozuka has been using SAR imaging to focus more closely on specific structures. In his research, several buildings on the University of Southern California's main campus are being modeled using Auto-CAD and MATLAB, with possible future use of ARC/INFO's 3D Analyst. SAR approaches will be applied in simulation and completed for some buildings. Computations are currently being carried out for a grouping of buildings, introducing changes that resemble earthquake damage.

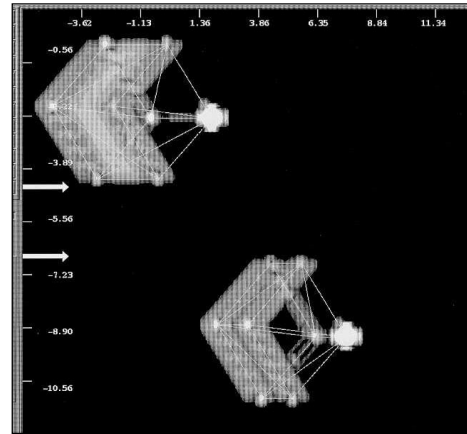
SAR operates by shooting a bundle of many thousand rays at an object. The rays interact with the structure at its boundaries, with attendant reflections and refractions. Rays penetrate the material and may bounce several times before exiting an object. Thus, structures and their edges are usually readily detectable using this technology. Simulated SAR images can be projected on a slant plane, ground plane, and on a plane vertical to the slant plane. The vertical image projection, which is used for diagnostic purposes, reveals height changes most directly. Due to "layover," the fact that higher objects appear closer in a radar image but further away in a photograph, buildings are skewed in a predictable manner. Geometrical changes, such as tilting, overturning, or pancaking can be observed and measured through the use of SAR, as shown in Figure 3. The height and straightness of buildings can be deduced using these measures. Taller buildings cast longer shadows, and thicker horizontal contour edges at the front of structures are another indication of building height, as indicated in Figure 4. This type of analytic research on individual

structures is an essential step in developing macro-level or regional damage models, because in the absence of SAR-derived empirical data, it is necessary to compile catalogues of images that accurately depict a range of possible damage states.

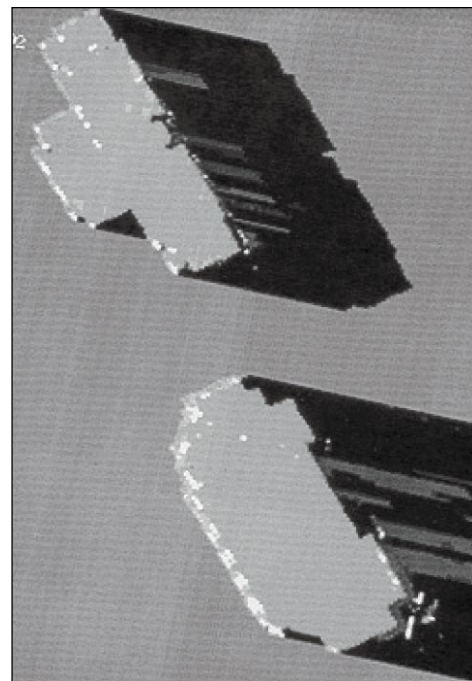
This new approach to loss estimation is consistent with two of MCEER's primary program goals: its emphasis on advanced technology and its commitment to multidisciplinary research. For the first time, a combination of advanced technologies (satellite imaging, Global Positioning Systems, real-time ground motion mapping, advanced simulations, and geographic information systems) is being employed to develop a real-time damage assessment system. This research not only represents an integrated interdisciplinary effort, but it also serves as an example of effective and coordinated technology transfer—in this case, transfer of NASA technology and products.

Direct Losses

Recent disasters such as the Northridge and Kobe earthquakes have demonstrated the importance of evaluating not only the physical



■ Figure 3. Simulated SAR image of two boxes in a slant plane (15 cm resolution)



■ Figure 4. Simulated SAR images of two buildings on the University of Southern California Campus

damage that future earthquakes may cause, but also the losses to urban and regional economies caused by that damage, particularly those resulting from damage to urban lifeline systems. In its Los Angeles Department of Water and Power (LADWP) demonstration project, MCEER will be developing an innovative loss estimation methodology for urban lifeline systems that pays particular attention to assessing disruption to the economies of affected areas. This methodology will build on MCEER's previous multidisciplinary work on Memphis Light, Gas and Water (MLGW) Division's utility systems (Shinozuka, Rose, and Eguchi, 1998). Initial efforts have focused on reviewing recent developments in earthquake loss estimation,

developing a "benchmark" dataset of empirical loss data in recent disasters, and developing an improved methodology that can be applied in the LADWP project (see *Seismic Performance Analyses of Electric Power Systems* in this report). These investigations focus in particular on the direct economic loss component of an integrated loss estimation methodology. In this research, the term direct economic loss refers to the disruption to economic activity that is caused by lifeline service outage at the site of production.

MCEER investigator Stephanie Chang has conducted a systematic review of twelve methodologies that evaluate losses related to water lifeline systems and that have made innovations in predicting water service disruption ("outage") and/or the ensuing economic impacts. This group of studies ranges from consulting projects for individual utility systems to nationally applicable, fully software-implemented methodologies. Table 1 summarizes major noteworthy innovations and remaining methodological gaps identified in this review, according to various technical areas within a comprehensive loss estimation methodology. The specific methodologies included in the review are listed in the footnote to the table. Innovations made in the MCEER Memphis lifeline loss estimation methodology are identified in italics.

The review found that among current loss estimation methodologies, the approach taken in the

■ **Table 1.** Lifeline Loss Estimation State-of-the-Art: Innovations and Gaps^(a)

Methodological Area	Noteworthy Innovations ^(b)	Remaining Gaps
Uses of Loss Estimation	Service goals and priorities introduced; <i>GIS</i>	Service goals and priorities rigorously integrated
Repair Cost		Standardized repair cost data/method
Systems Analysis and Outage	<i>Flow analysis for damaged system; variable demand</i>	Lifeline interaction; full integration with socio-economic analysis
Restoration	Repair demand/capacity method; optimized restoration sequencing	Standardized demand/capacity data
Secondary Loss	Fire-fighting capacity (preliminary)	Water serviceability link to fire following earthquake
Social Impacts	Populations affected; critical facilities served	Link to economic impacts
Economic Impacts	<i>Utility revenue loss; direct and indirect regional economic loss; reconstruction stimulus</i>	Integration with engineering systems analysis
Uncertainty	<i>Monte Carlo simulation of damage</i>	Quantification of uncertainty throughout methodology

Notes: (a) Based on review of the following 12 methodologies: HAZUS (NIBS, 1997; Whitman et al., 1997), CUREe model (Kiremidjian et al., 1997), PIPELINE-FIX (French and Jia, 1997), NCEER model (Rose et al., 1997; Chang et al., 1996; Shinozuka, 1994; Koiwa et al., 1993), IRAS (RMS, 1995), EBMUD study (G&E, 1994), VRWater (Cassaro et al., 1993), ATC-25-1 (ATC, 1992), ASCE/TCLÉE methodology (Taylor, 1991), K/J/C Everett study (Ballantyne and Heubach, 1991), K/J/C Seattle study (Ballantyne, 1990), and Boston study (URS/Blume, 1989);

(b) *Italics* identify innovations made in the MCEER Memphis model.

MCEER Memphis study incorporated numerous innovations in terms of modeling water outage and associated regional economic impacts. That approach thus provides an excellent basis for further development in the LADWP demonstration project. However, several significant improvements can be made by learning from other current methodologies, in particular by introducing explicit system service goals/priorities, adopting current models of post-disaster system restoration, and evaluating social impacts and implications for fire following earthquake. Furthermore, many gaps remain, even in state-of-the-art approaches. One of the most critical economic loss modeling shortfalls that will need to be addressed in MCEER's LADWP project is full integration of engineering systems analysis with economic analysis. While the Memphis study made important contributions toward such integration, improvements are still needed. For example, in that model, lifeline outage is modeled probabilistically, while economic loss is modeled deterministically.

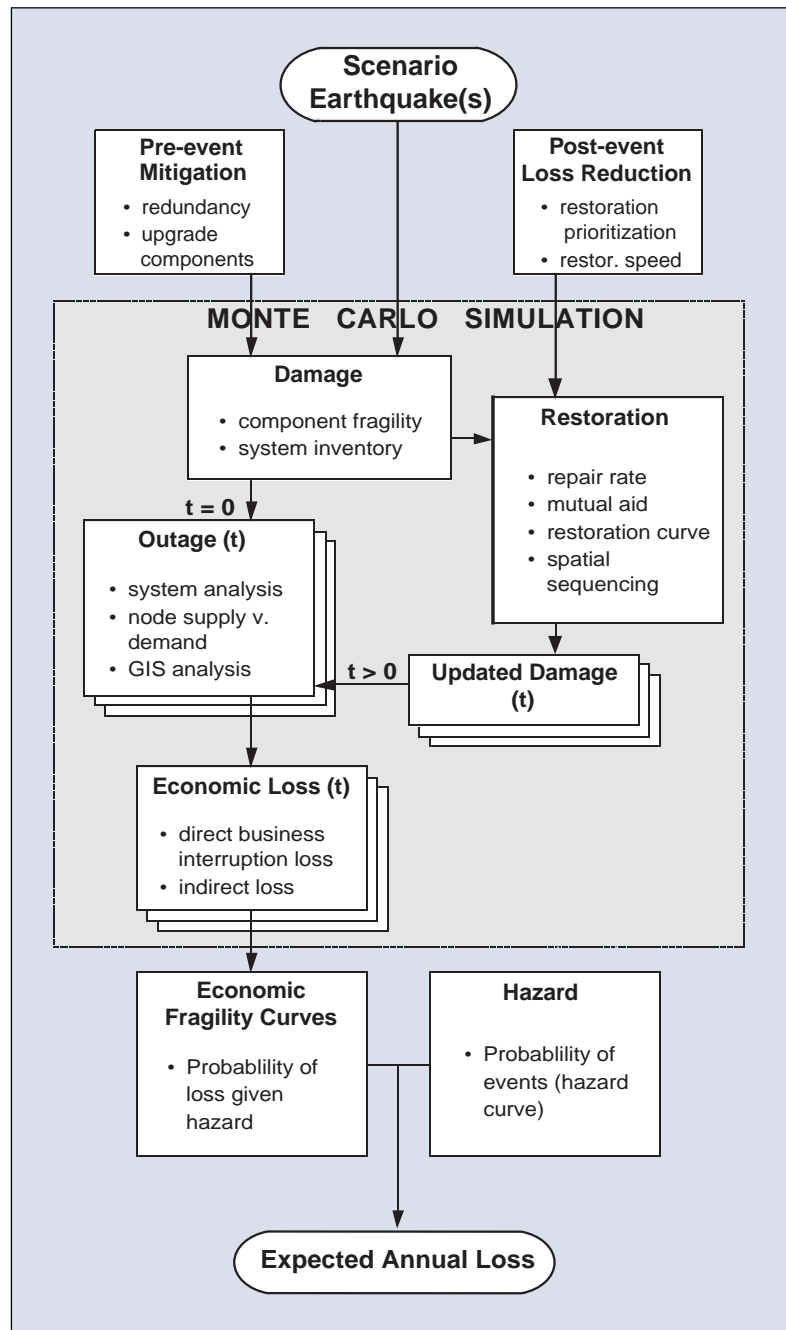
As a first step in further refining direct loss estimates, MCEER is conducting further analyses on the Memphis lifeline system. This approach takes advantage of existing data while allowing time for the development of databases for the LADWP demonstration project. Figure 5 outlines the refined methodology for estimating direct losses that is currently under development.

The enhancements incorporated into this new approach to modeling direct losses include the following:

- Integration of economic loss modeling within the Monte Carlo simulation process. This

allows not only damage, but also economic loss, to be estimated on a probabilistic basis, producing a “seamless” loss estimation model.

- Incorporation of the spatial and temporal dimensions of loss through improved restoration



■ Figure 5. Flowchart of Refined Methodology for Estimating Direct Losses Due to Lifeline Disruption

“This new approach to loss estimation is consistent with two of MCEER’s primary program goals: its emphasis on advanced technology and its commitment to multidisciplinary research.”

modeling. This approach makes it possible to explore how post-event strategies such as spatially prioritizing restoration using GIS methods can reduce total economic loss.

- Development of “economic fragility curves.” As with component fragility curves, which indicate the probability of exceeding a given damage state for various levels of ground motion, an economic fragility curve would indicate the probability of exceeding a given level of loss for various earthquake magnitudes. Results can be integrated with probabilistic hazard information to derive expected annual loss estimates, which are necessary for cost/benefit analysis of loss reduction measures.

This approach parallels the methodology developed by Shinozuka and Eguchi (1998). The refined model will be applied to simulating and comparing the direct loss-reduction benefits of various mitigation strategies, ranging from pre-disaster system upgrading through post-disaster mutual aid and optimized restoration.

Finally, in this phase of MCEER’s work on loss estimation, efforts are also being made to develop a benchmark dataset of losses from historic disasters that can be used in the validation and calibration of future loss estimation methodologies. To date, disaster loss data have been fragmented, inconsistently defined, and incomplete, and the goal of MCEER’s research is to collect, reconcile, and compare empirical data on the regional economic impacts of earthquakes, focusing primarily on the U.S. and Japan.

Business-Level Losses

Research to identify and quantify the factors that predict earthquake-related business losses can enhance our understanding of the processes leading to economic loss and can also point to ways of reducing losses through appropriate mitigation, response, and recovery measures. Existing loss estimation methodologies have by and large not concentrated on investigating firm-level earthquake impacts or on isolating the most significant contributors to business loss. Most efforts at estimating losses focus on the aggregate or regional level, rather than on populations of business firms. Research in this area, which is being conducted at the University of Delaware’s Disaster Research Center (DRC), builds upon the Center’s earlier work on business vulnerability and earthquake-induced business losses (Tierney, 1997; Dahlhamer and Tierney, 1998; Tierney and Dahlhamer, 1998a, 1998b).

DRC’s most recent analyses on risk factors for business loss have focused on predicting dollar losses due to both physical damage and business interruption using data collected from large samples of businesses affected by the 1989 Loma Prieta and 1994 Northridge earthquakes. These analyses use several types of predictor variables: business-level characteristics, including business size and economic sector; measures of lifeline service disruption; peak ground acceleration (PGA); and the age of the structure housing the business. (Data on PGA and building age are currently available only for Los Angeles and Santa Monica; those data will be incorporated into Santa Cruz County analyses when they become available.)

■ Table 2. Regression (OLS) Results for Total Dollar Losses

Variable	Santa Cruz			Northridge (initial)			Northridge (full)		
	Unstd. Coeff.	SE	Std. Coeff.	Unstd. Coeff.	SE	Std. Coeff.	Unstd. Coeff.	SE	Std. Coeff.
Full-time Employees (ln)	.27***	.04	.24	.15***	.03	.15	.16***	.03	.17
Wholesale or Retail	.41**	.13	.13	.57***	.13	.16	.54***	.13	.15
Finance, Insurance, or Real Estate	.12	.20	.02	.62***	.16	.13	.57**	.17	.12
Services	.27*	.13	.09	.39**	.12	.12	.31*	.13	.10
Loss of Electricity	.40*	.19	.08	.88***	.12	.28	.85***	.13	.28
Loss of Telephones	.17	.13	.05	.27*	.12	.09	.19	.12	.06
Loss of Water	.57***	.11	.20	1.02***	.12	.27	.77***	.13	.20
Peak Ground Acceleration	--	--	--	--	--	--	1.62***	.25	.22
Year Built (1960-76)	--	--	--	--	--	--	.11	.11	.03
Year Built (Post-1976)	--	--	--	--	--	--	.22	.12	.07
N	725			852			719		
R ²	.14			.29			.33		
F-value	16.69***			48.20***			35.55***		

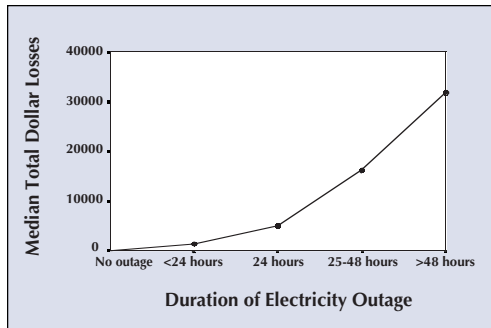
*p<.05 **p<.01 ***p<.001

Table 2 presents the results of analyses that have been conducted to assess the differential impact of this group of factors on business losses. The table summarizes findings for three regression analyses: separate models for Northridge and Santa Cruz using business-level and lifeline disruption variables, and a more complete model for the Northridge data that incorporates PGA and building data. Five significant predictors of business losses have been identified in this series of analyses. In both study areas, business size is a significant predictor of total dollar loss, with larger firms reporting greater losses than their smaller counterparts. However, the relationship was more pronounced among Santa Cruz County businesses.⁴

Business sector also plays an important role in predicting total dollar losses, with wholesale and retail businesses and service firms reporting greater losses following both

earthquakes than manufacturing and “other” establishments. Lifeline outages also had a significant influence on total dollar losses. Businesses that lost electricity reported significantly greater losses in both study communities, as did firms losing water service. This relationship was particularly pronounced in the Northridge sample. Telephone service disruption was also an important predictor of losses among Northridge firms, with businesses losing telephones incurring significantly higher losses.

Another way of looking at the relationship between the interruption of lifelines and dollar losses is to consider the duration of outage and its impact on loss. While the initial impact of lifeline disruption may not be felt immediately, MCEER’s analyses show that there is a ramping up of dollar losses as lifeline outages continue. As illustrated in Figure 6, among Northridge businesses, losses remained fairly low up to



■ Figure 6. Median Total Dollar Losses by Duration of Electricity Outage (Northridge)

twenty-four hours of electricity outage, but after that time losses began to escalate. Similar patterns were observed for telephone and water loss following the Northridge event, although the data also suggest that any interruption of water

service tends to be costly for businesses. These findings point to the importance of mitigation and rapid restoration measures for lifeline systems as strategies for containing economic losses.

Returning to Table 2, additional analyses were conducted with the Northridge data, incorporating data on PGA as a measure of earthquake shaking, as well as on the time period in which the buildings housing businesses were constructed, to take into account structural vulnerabilities. PGA emerged as the second strongest predictor of total dollar loss. Not surprisingly, firms located in areas experiencing more intense shaking reported overall greater losses. While almost nonexistent at low levels, losses substantially increase with higher ground acceleration levels.

While not reaching statistical significance, the relationship between building age and total dollar losses is interesting and somewhat counterintuitive. Firms housed in buildings constructed after 1976 reported much greater losses than those located in building constructed between 1960 and 1976 or prior to 1960. Contrary to what might be expected, businesses operating in newer structures sustained the highest losses among all firms in the sample. This relationship is likely due to the fact that

structures in the area near the epicenter of the Northridge earthquake, which experienced the strongest shaking, tended to be of relatively recent vintage. Parts of the impact region that had a greater concentration of older buildings experienced less shaking in this particular event.

Studies that focus on risk factors for loss at the firm level contribute to loss estimation methodologies in several ways. First, they identify variables that need to be taken into account in the development of aggregate regional direct and indirect loss models. Second, they provide insights into the relative importance of different factors that contribute to losses, such as ground motion and lifeline disruption. And relatedly, they provide data that can be used to better calibrate the assumptions made in regional loss models. More generally, they serve as a bridge between modeling efforts that focus on direct physical impacts and those that attempt to estimate indirect or induced economic losses, which are discussed in the section that follows.

Indirect Economic Losses

Indirect losses, defined here as the difference between total business interruption losses that propagate through the economy and the direct losses stemming from physical damage caused by ground shaking, are usually measured in terms of the interruption of flows in the production of goods or services. Such losses are typically distinguished from indirect physical damage and ensuing business disruption, due, for example, to fires in the aftermath of an earthquake. While property damage is generally immediate, business

interruption losses can last months and even years. Whether indirect losses proliferate depends considerably on the speed and extent of recovery and reconstruction efforts.

Input-output (I-O) analysis is the most widely used approach to estimating indirect losses resulting from earthquakes and other hazards. In its most basic form, I-O is a static, linear model of all purchases and sales between sectors of an economy, based on the technical relations of production (Rose and Miernyk, 1989). I-O models are especially adept at calculating multiplier effects (Kawashima and Kanoh, 1990; Gordon, et al., 1998), and empirical models are widely available for any county or county grouping of the U.S. through the Impact Analysis for Planning (IMPLAN) System, developed by FEMA and several other federal government agencies (see Minnesota IMPLAN Group, 1998). However, in its more basic forms, I-O is extremely rigid, incapable of incorporating the resiliency often observed in the aftermath of hazard events, and lacking in behavioral content.

There are several alternatives to I-O analysis. One alternative, mathematical programming models of an entire economy, adds to an I-O table an objective function to be optimized, as well as various resource constraints (Rose, 1981; Cole, 1995). This framework, which is able to incorporate substitution possibilities on both the supply and demand sides, has proved to be especially useful in analyses of how to minimize indirect losses (see, e.g., Rose et al., 1997). However, like I-O analysis, it fails to incorporate behavioral considerations associated with decision making.

Another modeling approach, econometric estimation, ranges from studies of individual sectors, such as the real estate market (Ellson et al., 1984), to the entire economy (Guimares et al., 1993). Econometric models have much sounder statistical properties than other modeling approaches. However, since these analyses are typically based on time series data, they often represent extrapolations of past behavior and thus are not especially adept at modeling the disjointed nature of hazard impacts.

MCEER is currently investigating another category of approaches, computable general equilibrium (CGE) models. CGE analyses employ multi-market simulation models based on the simultaneous optimizing behavior of individual consumers and firms, subject to economic account balances and resource constraints (see Shoven and Whalley, 1992). Prior to research by MCEER investigator Adam Rose, the only applications of CGE models to hazard analysis were pedagogical overviews or pilot applications (see, e.g., Boisvert, 1992; Brookshire and McKee, 1992).

CGE models can incorporate the best features of the other modeling approaches. They are typically based on an I-O table of detailed production data and a social accounting matrix (SAM) extension of double entry accounts of institutions such as households, corporations, and trade balances. CGE models have an optimizing feature, but it is based on the interaction of individual firms and consumers. Moreover, the major parameters of CGE models can be statistically estimated or can be based on engineering studies.

Constructing and Applying a CGE Model

In modeling the effects of natural hazards, analysts must first set the stage by identifying key characteristics, which provide the basis for specifying assumptions and causal relationships of the analytical model. The characteristics for two different contexts are enumerated in Table 3. For example, characteristics 1 through 3 have implications for the extent and aggregation of capital asset variables in the model. They also identify the conduit through which impacts manifest themselves, or, more practically, indicate which variables are affected by the event. The capital asset variables also raise an important distinction. The terms *short run* and *long run* pertain to the standard economic distinction between the period when some inputs (usually capital) are fixed and the period when all inputs are variable. In relation to hazards, the former refers to the time of the hazard event and its immediate

aftermath, while the latter pertains to the period of reconstruction.

A prototype CGE model has been constructed for Shelby County, Tennessee, in order to simulate the impacts of a New Madrid earthquake on the city of Memphis. The model is patterned after a similar construct for the Susquehanna River Basin developed by MCEER investigator Adam Rose to analyze the indirect economic impacts of flooding (Rose et al., 1998) and structured to be comparable to input-output and linear programming models previously used by Rose to estimate the indirect impacts of a New Madrid earthquake (see Rose et al., 1997). The model consists of 22 production sectors, with an emphasis on those that are major users of electricity lifelines and those that are most crucial to the functioning of the regional economy.

The model is currently being applied to the simulation of direct and indirect economic impacts from a 7.5 magnitude earthquake in the New Madrid area, using data on electricity lifeline system vulnerability

■ Table 3. Key Considerations in Modeling the Economic Impacts of Earthquakes

Short Run	Long Run
1. Capital stock is reduced immediately.	1. Rebuilding of capital stock takes time.
2. Loss is concentrated in man-made capital.	2. Rebuilding often includes mitigation measures.
3. Damage manifests itself through capacity reduction.	3. Damage stops when capacity is rebuilt or institutions are rearranged.
4. Disequilibrium is pervasive.	4. Equilibrium is re-established.
5. Losses are usually regionally isolated.	5. Other regions lose if aid is not repaid.
6. Production is curtailed.	6. Some or all of production can be recaptured.
7. Some prices may rise.	7. Prices are likely to return to previous levels.
8. New input combinations are used.	8. Some input combination changes may persist.
9. Imports are a major stop gap.	9. Imports return to pre-disaster norm or revised pattern.
10. Use of savings provides an economic boost.	10. Use of savings in short run is a long run drain.
11. Gov't recovery aid provides an economic boost.	11. Gov't reconstruction aid provides an economic boost.
12. Insurance payments provide a boost.	12. Insurance options will decline if losses increase.
13. Recovery may require some central planning.	13. Reconstruction is helped by planning (including incentive based).
14. Modest uncertainty exists.	14. Uncertainty declines.
15. Decision-making is myopic because of immediate needs.	15. Decision-making somewhat myopic because of infrequency of events.

and direct economic losses from previous MCEER research (Shinozuka, Rose, and Eguchi, 1998). Additionally, data from MCEER's earlier Loss Assessment of Memphis Buildings (LAMB) study (Chang and Eguchi, 1997) are being used as the basis for estimates of broader business interruption and ensuing direct effects. Sensitivity tests will be performed related to assumptions on the main parameters of input and import substitution, factor mobility, recovery timing, and insurance/aid payment levels.

Future Research Activities

Two new research activities are being undertaken as part of this component of MCEER's research program. The first is a meta-analysis of factors influencing direct and indirect losses from natural hazards. Meta-analysis is a statistical technique that summarizes and synthesizes the results of individual studies. The literature is being reviewed to identify causal factors, and additional data are being collected. Multiple regression estimates will yield prime determinants, which in turn will be used to specify important relationships in future computable general equilibrium models.

In addition, a CGE model for Los Angeles will be constructed and will be applied to analyzing the direct and indirect economic impacts of disruptions of utility lifeline services as part of MCEER's Los Angeles lifeline demonstration project. This multidisciplinary research will also incorporate mitigation considerations so as to fit into the overall cost-benefit analysis framework that MCEER investigator Howard Kunreuther is developing (see Kunreuther, 1999).

Conclusion

MCEER's research on earthquake loss estimation builds upon collaborations among engineers and social scientists that were initiated during its first ten years as the National Center for Earthquake Engineering Research. This multidisciplinary approach, which is demonstrated in the 1998 MCEER monograph on the economic impacts of lifeline disruption in the central U.S. (Shinozuka, Rose and Eguchi, 1998), begins with an understanding of seismic hazards and continues with analyses that quantify the vulnerability of engineered systems and the ways in which the physical impacts of earthquakes on those systems subsequently affect economic activity, producing losses that ripple outward through affected regional economies. Consistent with its emphasis on the use of advanced technologies in earthquake loss reduction, a second major theme in MCEER's groundbreaking loss estimation research centers on the ways in which technologies originally developed for other purposes—in this case, remote-sensing technologies—can be used to assess the vulnerability of the built environment and to improve the speed and quality of crisis decision making.

Future research will focus on collecting additional data, systematizing what is known about earthquake-related losses, and further refining and calibrating loss models. The methods developed by loss estimation researchers will be applied in MCEER's demonstration projects and linked with other investigations that focus on assessing the costs and benefits of mitigation strategies for critical facilities and lifelines.

Endnotes

- ¹ SPOT is a company that provides satellite imagery data throughout the world. SPOT stands for Satellite Pour l'Observation de la Terra.
- ² JERS is the satellite system operated in Japan.
- ³ Scattering describes the physical process that occurs when radar signals are reflected back from the earth's surface to the sensor. The degree of scattering depends on the surface cover, e.g., type of vegetation, and the type of development.
- ⁴ While larger firms sustained greater overall financial losses, the impacts are more devastating to smaller businesses when losses are calculated on a per-employee basis. Standardized in this manner, small businesses report greater median losses than larger ones. Small Santa Cruz firms reported median per employee losses of \$1,000, as compared with their larger counterparts, whose per capita losses were \$352. The figures for Northridge for small and large firms were \$851 and \$31, respectively.

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