ENGINEERING AND SOCIOECONOMIC IMPACTS OF EARTHQUAKES: 
AN ANALYSIS OF ELECTRICITY LIFELINE DISRUPTIONS IN THE NEW MADRID AREA

Edited by
Masanobu Shinozuka
Adam Rose
Ronald T. Eguchi
Earthquakes are potentially devastating natural events which threaten lives, destroy property, and disrupt life-sustaining services and societal functions. In 1986, the National Science Foundation established the National Center for Earthquake Engineering Research to carry out systems integrated research to mitigate earthquake hazards in vulnerable communities and to enhance implementation efforts through technology transfer, outreach, and education. Since that time, our Center has engaged in a wide variety of multidisciplinary studies to develop solutions to the complex array of problems associated with the development of earthquake-resistant communities.

Our series of monographs is a step toward meeting this formidable challenge. Over the past 12 years, we have investigated how buildings and their nonstructural components, lifelines, and highway structures behave and are affected by earthquakes, how damage to these structures impacts society, and how these damages can be mitigated through innovative means. Our researchers have joined together to share their expertise in seismology, geotechnical engineering, structural engineering, risk and reliability, protective systems, and social and economic systems to begin to define and delineate the best methods to mitigate the losses caused by these natural events.

Each monograph describes these research efforts in detail. Each is meant to be read by a wide variety of stakeholders, including academicians, engineers, government officials, insurance and financial experts, and others who are involved in developing earthquake loss mitigation measures. They supplement the Center’s technical report series by broadening the topics studied.

As we begin our next phase of research as the Multidisciplinary Center for Earthquake Engineering Research, we intend to focus our efforts on applying advanced technologies to quantifying building and lifeline performance through the estimation of expected losses; developing cost-effective, performance-based rehabilitation technologies; and improving response and recovery through strategic planning and crisis management. These subjects are expected to result in a new monograph series in the future.

I would like to take this opportunity to thank the National Science Foundation, the State of New York, the State University of New
York at Buffalo, and our institutional and industrial affiliates for their continued support and involvement with the Center. I thank all the authors who contributed their time and talents to conducting the research portrayed in the monograph series and for their commitment to furthering our common goals. I would also like to thank the peer reviewers of each monograph for their comments and constructive advice.

It is my hope that this monograph series will serve as an important tool toward making research results more accessible to those who are in a position to implement them, thus furthering our goal to reduce loss of life and protect property from the damage caused by earthquakes.

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

Foreword ................................................................. vii
Preface ....................................................................... xiii
Acknowledgments ....................................................... xix
Abbreviations .......................................................... xxi

1 Introduction .......................................................... 1
by Adam Rose, Ronald T. Eguchi, and Masanobu Shinozuka
1.1 Background ............................................................ 4
  1.1.1 Brief History of Lifeline Earthquake Developments in the United States ................................................. 5
  1.1.2 Federal and Industry Lifeline Initiatives ..................10
1.2 Overview .............................................................. 10

2 Modeling the Memphis Economy ............................. 13
by Adam Rose and Philip A. Szczesniak
2.1 History ..................................................................... 13
2.2 Major Sectors of the Memphis Economy .................. 14
2.3 Economic Indicators ................................................. 17
2.4 Economic Interdependence and Interindustry Analysis .... 18
2.5 Memphis Input-Output Model ................................... 22
2.6 Regional Analysis of the Role of Utility Lifelines .......... 23
2.7 Conclusion .............................................................. 29

3 Seismic Performance of Electric Power Systems 33
by Masanobu Shinozuka and Howard H. M. Hwang
3.1 Electric Power System .............................................. 34
  3.1.1 Conditions for System Failure .................................. 34
  3.1.2 Substation Model ................................................ 35
  3.1.3 Monte Carlo Simulation ...................................... 38
3.2 Conclusion .............................................................. 43
4  **Spatial Analysis Techniques for Linking Physical Damage to Economic Functions** .......................... 45  
by Steven P. French  
4.1  Describing the Local Economy .............................................................. 47  
4.2  Spatial Analysis ........................................................................... 49  
4.3  Conclusion ............................................................................... 51  

5  **Earthquake Vulnerability and Emergency Preparedness Among Businesses** ............................ 53  
by Kathleen J. Tierney and James M. Dahlhamer  
5.1  Memphis/Shelby County Business Survey .................................. 57  
5.2  Business Vulnerability ................................................................. 58  
5.2.1  Building Type and Business Location ..................................... 59  
5.2.2  Lifeline Dependency .......................................................... 60  
5.2.3  Perceptions of the Earthquake Threat .................................. 64  
5.3  Business Preparedness ................................................................. 65  
5.3.1  Adoption of Preparedness Measures .................................. 65  
5.3.2  Explaining Business Preparedness ................................... 67  
5.4  Conclusion ............................................................................... 70  

6  **Direct Economic Impacts** .......................................................... 75  
by Stephanie E. Chang  
6.1  Scope of Direct Economic Impacts ............................................. 75  
6.2  Current Estimation Methodologies ........................................... 78  
6.3  Conceptual Framework .............................................................. 80  
6.4  Case Study: Electricity Disruption in NMSZ Earthquake .......... 81  
6.4.1  Business Resiliency to Lifeline Disruption .......................... 81  
6.4.2  Location of Economic Activity .......................................... 85  
6.4.3  Lifeline Service Disruption and Restoration ...................... 86  
6.4.4  Deterministic vs. Probabilistic Analysis .............................. 88  
6.4.5  Results .............................................................................. 91  
6.5  Conclusion ............................................................................... 92  

7  **Regional Economic Impacts** ....................................................... 95  
by Adam Rose and Juan Benavides  
7.1  Estimation of Total Regional Impacts .......................................... 96  
7.1.1  Input-Output Impact Analysis ............................................ 96  
7.1.2  Analysis of Simulation Results ........................................ 99  
7.2  Optimal Rationing of Scarce Electricity .................................. 102  
7.2.1  Linear Programming .......................................................... 102  
7.2.2  Analysis of Simulation Results ........................................ 106
8 Decision Support for Calamity Preparedness: Socioeconomic and Interregional Impacts ...... 125

by Sam Cole

8.1 Modeling Economic Disasters .............................................................. 127
8.2 Construction of the Many-Region Accounts ........................................ 128
  8.2.1 Development of the Model ............................................................ 129
  8.2.2 Representation as a Virtual GIS-based Model .............................. 131
8.3 Model Solution .................................................................................. 134
  8.3.1 Distributed Disruptions, Transaction Costs and Uncertainty ........ 134
8.4 Memphis-Mississippi Valley Model .................................................... 135
  8.4.1 Memphis Region ......................................................................... 135
  8.4.2 Memphis Accounts ..................................................................... 137
8.5 Application of the Decision Support System ........................................ 141
  8.5.1 Event Accounting Matrix ............................................................... 141
  8.5.2 Base Scenario .............................................................................. 141
  8.5.3 Income Distribution and Interregional Impacts ............................. 148
  8.5.4 Reallocation of Resources ......................................................... 149
8.6 Integration into Policy Making ............................................................ 150
  8.6.1 Decision Support Systems Versus Expert Systems ....................... 151

9 Implications for Effective Lifeline Risk Reduction Policy Formulation and Implementation 155

by Laurie A. Johnson and Ronald T. Eguchi

9.1 Study Implications ............................................................................. 157
9.2 Towards Effective Lifeline Risk Reduction Policy Formulation and Implementation ....................................................... 162
  9.2.1 Policy Formulation Model ............................................................ 162
9.3 Conclusion ........................................................................................ 168

References ............................................................................................. 171
Index ....................................................................................................... 183
Contributors .......................................................................................... 189
The potential losses from natural hazards, in terms of both lives and property, are increasing. On the one hand, human action is now so pervasive as to intrude in a major way on the environment, even to the extent of causing climate change. This may manifest itself not only in terms of warming, but also climate variability that increases the prevalence of strong winds and floods. In contrast, our potential to affect the frequency of earthquakes is rather limited. Here the main concern is the other side of the ledger—the continued population and economic build-up, which makes us increasingly more vulnerable even if the frequency of ground shaking does not increase.

Our ability to cope with these issues thus requires an Integrated Assessment, ranging from geology and engineering to economics and policy. In-depth studies of this kind are, however, lacking in the earthquake field, and, for the most part, with respect to other natural hazards. Our study is the first that has attempted such an assessment of urban lifeline systems in relation to earthquakes.

This monograph is a first-of-its-kind effort to remedy the situation by developing and applying a multidisciplinary methodology that traces the impacts of a catastrophic earthquake through a curtailment of utility lifeline services to its host regional economy and beyond. The New Madrid Seismic Zone is an appropriate case study because it is the site of the largest earthquakes to hit North America in recorded history. It has been the focal point of extensive research, especially by scientists, engineers, and social scientists affiliated with the National Center for Earthquake Engineering Research over the first ten years of its existence. The study represents the culmination of many of these efforts, which have often involved not only researchers but also public officials, utility managers, company executives, and the public at large.
Our objective is to improve the understanding of the detailed aspects and overall complexity of the problem. This monograph examines and connects the role of an electric utility and its host economy, the vulnerability of the lifeline network to a catastrophic earthquake, the business response to physical damage and production losses, the estimation of direct economic losses, the estimation of indirect losses in the immediate region, and the manner in which these losses cause further ripple effects to a broader metropolitan area and the rest of the U.S., as well as the policy implications of all these interactions. The presentation of this monograph appears multidisciplinary rather than interdisciplinary—it is more like a relay race where each member has picked up the baton from his or her predecessor. However, each hand-off heightens our interdisciplinary understanding of the problem, and the effort as a whole is an integrated assessment.

The ultimate aim of our study is to heighten awareness of earthquake vulnerability and the interconnected nature of human actions. Our methods should help analysts sharpen their vulnerability and loss estimates. It should also help private and public decision-makers make wiser choices about putting themselves at risk and about coping measures ranging from pre-disaster mitigation to post-disaster recovery. Obviously, the analysis is readily generalizable to both other types of lifelines and other natural hazards.

In addition to its practical usefulness, we also take pride as researchers in our ability to advance the state-of-the-art in several areas, both in terms of theory and empirical work. Examples include:

- An advanced vulnerability analysis of a major municipal electric utility system.
- The results of a major survey of perceived business disruptions.
- A GIS overlay of a major socioeconomic database and an electric utility grid, capturing engineering features of electric utility lifelines and their linkages to the economy.
- Neglected features of input-output impact analysis relating to the estimation of indirect effects, general input supply bottlenecks, resilience of production technology to electricity curtailment, and spatial differentials in electricity utilization.
- Formal optimization of scarce lifeline services across sectors
and sub-regions.

- A methodology to telescope economic impacts from the neighborhood to the national level.
- A new set of policy recommendations only ascertainable from an integrated assessment.

The number of integrated assessment models of natural hazards is on the rise. A major initiative was recently sponsored by the National Institute of Building Sciences on behalf of the Federal Emergency Management Agency to develop an Earthquake Loss Estimation Methodology, referred to as HAZUS, and related efforts are currently underway to supplement this effort with wind damage and flood damages modules. HAZUS is a computerized system primarily for use by government agencies at all levels to evaluate hazard mitigation, response, and recovery. System components range from ground-shaking through physical damage to the built environment to a translation into direct dollar damage and then direct and indirect business disruption losses. Although HAZUS represents a major advance, for it to be operational it had to sacrifice modeling sophistication of the type presented in this monograph. Also, more specifically, it is very limited in its treatment of lifelines, including only direct physical damage to lifeline structural components. It omits direct impacts on lifeline customers and ensuing economy-wide ripple effects, as well as omitting considerations of optimal reallocation of scarce lifeline resources so as to minimize production and employment losses. We hope that our monograph will prove useful in remedying these omissions in the HAZUS software and other practical approaches to emergency management in the future. At the same time, we intend that our work will provide engineering and socioeconomic insights that will help streamline loss estimation methods for complex systems in general.

This study will prove useful to several categories of readers. While the probabilities of large earthquakes are highly uncertain, the potentially overwhelming economic impacts (both regionally and nationally) cannot be ignored. This study should prove provocative to even experienced public utility managers. It provides compelling evidence for considering a long-term risk management strategy to reduce earthquake vulnerability. Further, it demonstrates the significance of economic impacts induced by lifeline damage and the importance of considering them in designing socially responsible risk management strategies.
Insurance companies might also be interested in our methodologies to quantify indirect losses. There may be a market demand for insurance riders that cover business interruption losses resulting from both direct damage to a facility or building, and from external factors, such as loss of electric power service or unavailability of other inputs. This coverage is not generally offered because of the lack of actuarial experience to assess risk. The methods developed in this study could be used to calculate the potential magnitude of these losses, and then used in establishing a credible insurance structure. As a result, insurance companies might be better able to offer business interruption coverage on a broader basis.

Business executives could gain insight to earthquake preparedness from their counterparts in Memphis in terms of an assessment of vulnerability and identification of coping measures. They might also gain a greater appreciation of the interconnectedness of the economy in which they operate and its ramifications. For example, paying a premium for non-interruptible electricity service may not insure continued operation if a supplier of another critical input opts not to pay the premium and is not able to produce and hence deliver its product.

We also hope that the analysis will be useful to our fellow researchers in the earthquake field, as well as other hazards. We make no pretense that we have exhausted research advances needed to adequately address these issues, and hence encourage others to build on our work.

The research in this monograph has endeavored to improve our perspectives on time and space in relation to hazards. It has imparted spatial dimensions to economic models, where these are usually lacking. This is a key link between the physical world and the human settlement system. On a temporal side, the research emphasis on production losses helps heighten awareness that an earthquake event is not confined to the period of ground shaking and structural damage, but to the longer period during which the socioeconomic system is unable to prevail at pre-earthquake levels. This is key in making the transition from structural to nonstructural (societal) aspects of earthquakes.

Finally, an overall theme of this monograph is that natural hazards accentuate scarcity, thus making resources even more valuable than before. Our limited resources must be balanced wisely between pre-disaster mitigation and post-disaster recov-
ery. Just as emergency medical, fire, and other safety services must be well managed in the aftermath of a disaster, so too should lifeline services. This calls for major reallocations of resources, which may be controversial from a political standpoint. However, our analysis indicates that savings from prioritizing electricity service among those with the lowest intensities of electricity use directly and indirectly (after safeguarding for health, safety, and essential industry) can reduce losses of goods and services several-fold. As the author of one of the chapters notes, not taking advantage of such opportunities results in an outcome as devastating as if the earthquake had actually toppled the buildings in which the lost production would have originated.
The papers in this monograph resulted from multi-year, multidisciplinary research sponsored by the National Center for Earthquake Engineering Research. The researchers gratefully acknowledge the assistance of many individuals who contributed to the project. In particular, we would like to thank Dr. Woody Savage, Pacific Gas and Electric Company; Mr. Tom Durham, Central United States Earthquake Consortium; Dr. Anshel Schiff, Stanford University; Dr. Satoshi Tanaka, Kyoto University; and Mr. Tommy Whitlow and Mr. Bill Sipe, Memphis Light, Gas and Water (MLGW) Division, City of Memphis, for their helpful suggestions. We are also indebted to MLGW and the Shelby County Planning Department for access to their data.

We owe a great debt to the staff of the National Center for Earthquake Engineering Research, especially its Director, Dr. George Lee, and its Publication Manager, Jane Stoyle, who did such a fine job during the various stages of this monograph’s production. We benefitted greatly from the helpful suggestions of several anonymous reviewers contacted by NCEER to assess the suitability of our manuscript for publication. The financial support of NCEER’s sponsors, the National Science Foundation and the State of New York, is also gratefully acknowledged. Several of the authors also benefitted from supplemental finding from related NSF grants and other sources.

Many of the authors benefitted from clerical support at their institutions/organizations. However, the word processing and coordination efforts of Jan Moyer of The Pennsylvania State University deserve special mention.

Perhaps our greatest debt is to our departed friend and colleague, Barclay Jones, who was a stalwart among NCEER researchers for many years. Barclay, perhaps more than anyone, worked to bridge the gap between engineers and social scientists. Without his pioneering efforts, this interdisciplinary monograph would not have been possible.