ALL-HAZARDS PREPAREDNESS, RESPONSE, AND RECOVERY

Conceptualizing and Measuring Resilience

A Key to Disaster Loss Reduction

KATHLEEN TIERNEY AND MICHEL BRUNEAU

Tierney is Professor of Sociology and Director of the Natural Hazards Research Center, Institute of Behavioral Science, University of Colorado, Boulder. Bruneau is Director, Multidisciplinary Center for Earthquake Engineering Research, and Professor of Civil, Structural, and Environmental Engineering, University at Buffalo.

In recent years, particularly after the catastrophe of Hurricane Katrina in August 2005, resilience has gained prominence as a topic in the field of disaster research, supplanting the concept of disaster resistance.

◆ Disaster resistance emphasizes the importance of predisaster mitigation measures that enhance the performance of structures, infrastructure elements, and institutions in reducing losses from a disaster.

◆ Resilience reflects a concern for improving the capacity of physical and human systems to respond to and recover from extreme events.

For the past seven years, researchers affiliated with the Multidisciplinary Center for Earthquake Engineering Research (MCEER), sponsored by the National Science Foundation and headquartered at the University at Buffalo, have collaborated on studies to conceptualize and measure disaster resilience. The resilience-related projects have involved researchers from a range of disciplines, including civil, structural, and lifeline engineering; sociology, economics, and regional science; policy research; and decision science. The goals of the multiyear effort were to define disaster resilience, develop measures appropriate for assessing resilience, and then demonstrate the utility of the concept through empirical research.

To develop a framework, the MCEER research team drew on various literatures and research traditions that have focused on resilience and related concepts, including ecology, economics, engineering, organizational research, and psychology. The literature revealed consistent cross-disciplinary treatments in which resilience was viewed as both inherent strength and the ability to be flexible and adaptable after environmental shocks and disruptive events.

PHOTO: NOAA

Hurricane Katrina made landfall near Bay St. Louis, Mississippi, at the mouth of the Pearl River, during high tide, causing a storm tide approximately 30 feet deep, and toppling segments of the I-90 bridge.

R4 Framework

MCEER researchers defined disaster 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 effects of future disasters. (*1*)

Critical infrastructure systems—including transportation and utility lifeline systems—play an essential role in communitywide disaster mitigation, response, and recovery and therefore are high-priority targets for resilience enhancement.

Resilient systems reduce the probabilities of failure; the consequences of failure—such as deaths and injuries, physical damage, and negative economic and social effects; and the time for recovery. Resilience can be measured by the functionality of an infrastructure system after a disaster and also by the time it takes for a system to return to predisaster levels of performance.

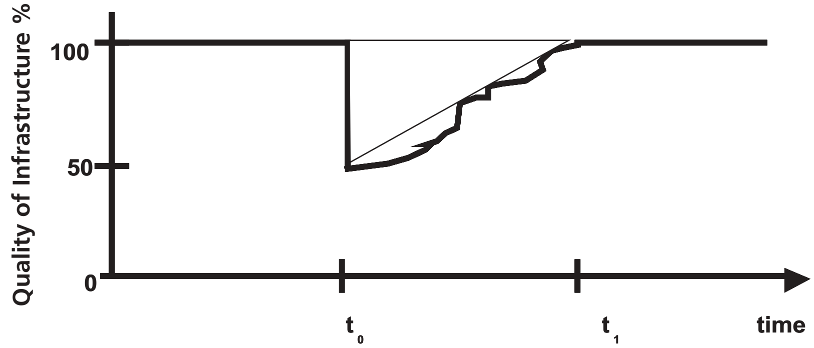
Figure 1 plots the quality or functionality and the performance of infrastructure after a 50 percent loss. The “resilience triangle” in the figure represents the loss of functionality from damage and disruption, as well as the pattern of restoration and recovery over time.

Resilience-enhancing measures aim at reducing the size of the resilience triangle through strategies that improve the infrastructure’s functionality and performance (the vertical axis in the figure) and that decrease the time to full recovery (the horizontal axis). For example, mitigation measures can improve both infrastructure performance and time to recovery. The time to recovery can be shortened by improving measures to restore and replace damaged infrastructure.

In examining the attributes and determinants of resilience, MCEER investigators developed the R4 framework of resilience:

- **Robustness**—the ability of systems, system elements, and other units of analysis to withstand disaster forces without significant degradation or loss of performance;
- **Redundancy**—the extent to which systems, system elements, or other units are substitutable, that is, capable of satisfying functional requirements, if significant degradation or loss of functionality occurs;
- **Resourcefulness**—the ability to diagnose and prioritize problems and to initiate solutions by identifying and mobilizing material, monetary, informational, technological, and human resources; and
- **Rapidity**—the capacity to restore functionality in a timely way, containing losses and avoiding disruptions.

FIGURE 1 The Resilience Triangle



In transportation systems, robustness reflects the ability of the entire system—including the most critical elements—to withstand disaster-induced damage and disruption. Redundancy can be measured by the extent that alternative routes and modes of transportation can be employed if some elements lose function. After the 1989 Loma Prieta earthquake, for example, expanded use of the Bay Area Rapid Transit system and the trans-Bay ferries overcame to some extent the loss of the San Francisco Bay Bridge.

Resourcefulness reflects the availability of materials, supplies, repair crews, and other resources to restore functionality. Hurricane Katrina was a catastrophe because of the extent and severity of the physical damage and the inability to move critical resources into the disaster-stricken region.

Rapidity is a consequence or outcome of

Ferry *Marissa Mae Nicole* carries local traffic across the Bay of St. Louis, Mississippi, during construction of the new I-90 bridge.

Photo: Hornblower Marine Services

Improving Resilience with Remote Sensing Technologies

RONALD T. EGUCHI AND BEVERLEY J. ADAMS

The performance of highway bridges is a major concern after earthquakes and other extreme events. Serious damage can impede critical emergency response, and the failure to detect collapsed bridge spans—particularly during the first few minutes of an earthquake—can result in serious injuries and fatalities.

During the past five years, a group of researchers from the Multidisciplinary Center for Earthquake Engineering Research in Buffalo, New York, has investigated the use of remote sensing technologies to detect urban damage and to assist in emergency response. The research has focused on damage detection, including the development of algorithms for using optical and synthetic aperture radar data to locate highway and building collapses, as well as a mapping scheme to display and disseminate earthquake-related geospatial data.

Another technology is a tiered reconnaissance system (TRS), which uses satellite images to determine the location, extent, and severity of building damage after an earthquake; the accompanying photographs offer a schematic representation. Output from the TRS can assist in determining the scale of site visits and of relief efforts and in setting priorities.

A second major effort in postdisaster damage assessment was completed recently under the Joint Program on Remote Sensing and Spatial Information Technologies of the U.S. Department of Transportation and NASA. As part of the Safety, Hazards, and Disasters Consortium led by the University of New Mexico, ImageCat, Inc., developed innovative methods for near real-time damage assessment of highway bridges. The methods employ remote sensing technology. The products from the research were Bridge Hunter, which produces a catalogue of key bridge attributes and images from a range of airborne and satellite sensors, and Bridge Doctor, which assesses the damage state of bridges by evaluating changes between images acquired before and after an earthquake.

Eguchi is CEO, ImageCat, Inc., Long Beach, California; Adams is Managing Director, ImageCat Ltd., London, United Kingdom.

(*a*)

(*b*)

(*c*)

Schematic Representation of the Postearthquake Tiered Reconnaissance System

Note: Color in original images (*a*) and (*b*) indicates severity of damage.

(*a*) Tier 1: Regional—moderate-resolution imagery detects changes and allows a quick assessment of regional damage.

(*b*) Tier 2: Neighborhood—high-resolution imagery allows detailed analysis for determining the level of damage within communities.

(*c*) Tier 3: Per building—supports the prioritization and coordination of field-based response and recovery and of field reconnaissance.

improvements in robustness, redundancy, and resourcefulness. The slow pace of restoration and recovery in the Gulf Region after Hurricane Katrina indicates low levels of resilience throughout the area. At the same time, some states, communities, and infrastructure systems have proved more resilient than others.

The literature and the MCEER research consider resilience to comprise both inherent and adaptive properties (*2–3*). Inherent resilience refers to an entity's ability to function well during noncrisis times. Adaptive resilience refers to an entity's demonstrated flexibility during and after disasters—the ability to adapt behavior and exercise creativity in addressing disaster-induced problems. These two properties of resilience may be correlated; entities with inherent resilience also may be better able to develop and implement adaptive coping strategies.

Resilience Domains

MCEER investigators identified four dimensions or domains of resilience: the technical, organizational, social, and economic (TOSE):

◆ The **technical** domain refers primarily to the physical properties of systems, including the ability to resist damage and loss of function and to fail gracefully. The technical domain also includes the physical components that add redundancy.

◆ **Organizational** resilience relates to the organizations and institutions that manage the physical components of the systems. This domain encompasses measures of organizational capacity, planning, training, leadership, experience, and information management that improve disaster-related organizational performance and problem solving. The resilience of an emergency management system, therefore, is based on both the physical components of the system—such as emergency operations centers, communications technology, and emergency vehicles—and on the properties of the emergency management organization itself—such as the quality of the disaster plans, the ability to incorporate lessons learned from past disasters, and the training and experience of emergency management personnel.

◆ The **social** dimension encompasses population and community characteristics that render social groups either more vulnerable or more adaptable to hazards and disasters. Social vulnerability indicators include poverty, low levels of education, linguistic isolation, and a lack of access to resources for protective action, such as evacuation.

◆ Local and regional **economies** and business firms exhibit different levels of resilience. Economic resilience has been analyzed both in terms of the inherent properties of local economies—such as the ability of firms to make adjustments and adaptations during nondisaster times—and in terms of their capacity for postdisaster improvisation, innovation, and resource substitution (*3*). In general, social and economic resilience relate to the ability to identify and access a range of options for coping with a disaster—the more limited the options of individuals and social groups, the lower their resiliency.

Resilience Metrics

Understanding the attributes and dimensions of resilience provides guidance for defining and achieving acceptable levels of loss, disruption, and system performance. The R4 approach highlights the multiple paths to resilience. Investments can improve all four resilience components—robustness, redundancy, resourcefulness, and rapidity. The TOSE framework emphasizes a holistic approach to community and societal resilience, looking beyond physical and organizational systems to the impact of the disruptions on social and economic systems.

The MCEER perspective suggests a range of approaches to enhance resilience, including mitigation-based strategies, the development of a robust organizational and community capacity to respond to disasters, and improving the coping capabilities of households and businesses. In conjunction with disaster loss estimation techniques and other types of decision support tools, the MCEER resilience framework can help community officials, transportation and utility lifeline service organizations, and other stakeholders to explore the outcomes and trade-offs associated with different resilience-enhancing strategies. For example, MCEER investigators are now collaborating with officials of the Los Angeles Department of Water and Power to assess the resilience of the electric power and the water systems after earthquake-induced damage and disruption.

References

1. Bruneau, M., S. E. Chang, R. T. Eguchi, G. C. Lee, T. D. O'Rourke, A. M. Reinhorn, M. Shinozuka, K. Tierney, W. A. Wallace, and D. von Winterfeldt. A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra,* Vol. 19, No. 4, 2003, pp. 733–752.
2. Rose, A. Defining and Measuring Economic Resilience to Earthquakes. In *Research Progress and Accomplishments, 2003–2004*. Multidisciplinary Center for Earthquake Engineering Research, State University of New York at Buffalo, 2004, pp. 41–54.
3. Rose, A., and S.-Y. Liao. Modeling Regional Economic Resilience to Disasters: A Computable General Equilibrium Model of Water Service Disruptions. *Journal of Regional Science*, Vol. 48, No. 1, 2005, pp. 75–112.

ALL-HAZARDS PREPAREDNESS, RESPONSE, AND RECOVERY

The Prague Subway's New Flood Protection System

Lessons from the Disaster of 2002

TOMAS JILEK, ANTONIN FEDORKO, AND JIŘÍ ŠUBRT

(*Above*:) Prague Castle and the Vltava River at ordinary high water level. (*Right:*) Removable flood walls deployed in the city center, August 2002.

Jilek is General Manager, Fedorko is Security Director, and Šubrt is Safety and Security Manager, Prague Public Transit Co., Inc., Czech Republic.

The Vltava River passes through the city of Prague in the Czech Republic. The river has several dams upstream, and two major tributaries run into the Vltava just before it reaches the city.

Because of the proximity of the river, the city's subway system has included protections against flooding, based on the probability of occurrence once every 100 years. Flood levels have been recorded since 1827, and the highest summer floods occurred in 1890. The 100-year flood level was established at 50 centimeters above the 1890 flood levels.

In August 2002, disastrous floods struck the city. The unexpected surge was likely a once-every-500-years occurrence; some experts have theorized about river floods on a 1,000-year cycle, but historic records are not available to verify the possibility.

The 2002 floods affected parts of the city situated at lower levels, as well as the transportation system and public transit system, which comprises tram, bus, and subway services. Because the subway is deep underground, subway tunnels were flooded to a greater extent than other affected parts of the city.

Since then, Prague has worked to address its flood protections, with particular attention to the underground stations. The solutions are not simple but can apply to other subway systems that face similar dangers.