Infrastructure Resilience to Disasters

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The Need for Resilient Infrastructures

Urban society depends heavily upon the proper functioning of infrastructure systems such as electric power, potable water, and transportation networks. Normally invisible, this reliance becomes painfully evident when infrastructure systems fail in disaster events. Moreover, because of their network properties, infrastructure damage in one location can disrupt service over an extensive geographic area. The societal disruption caused by infrastructure loss is therefore disproportionately high in relation to the actual amount of physical damage.

Engineers have long sought to design infrastructure to better withstand extreme forces; more recently, however, engineers have begun to articulate the broader need for urban infrastructure systems to be *resilient* to disasters (see, e.g., NIST 2008). Conceptually, resilience entails three interrelated dimensions: reduced failure probabilities; reduced negative consequences when failure does occur; and reduced time required to recover. This suggests that enhancing infrastructure resilience to disasters is not a purely technical problem, but involves societal dimensions.

The consequences of recent disasters demonstrate that urban infrastructure systems in the U.S. and other developed countries (not to mention developing regions of the world) remain highly vulnerable to disasters. A few examples illustrate the problem:

- In the 1994 Northridge earthquake (M_w=6.7), damage to bridges closed portions of 4 major freeway routes in Los Angeles. The disruption from these bridge failures alone accounted for $1.5 billion in business interruption losses, or nearly a quarter of the total (Gordon et al. 1998).
- The 1995 Kobe (Japan) earthquake (M_w=6.9) caused extensive infrastructure failures. Outages of electric power and telecommunications lasted about 1 week; water and natural gas, 2~3 months; passenger railway, up to 7 months; and highway systems and port infrastructure, roughly 2 years (Chang and Nojima 2001).
- The World Trade Center attack on September 11, 2001, caused widespread disruption in lower Manhattan to emergency service facilities, transportation (including subways), telecommunications, electric power, and water (O'Rourke 2003).
- On August 14, 2003, a power outage event beginning in northern Ohio cascaded within the electric power grid to cause the largest blackout in North American history, affecting a region of some 50 million people and causing an estimated $10 billion in losses (U.S.-Canada Power System Outage Task Force 2006). Power outage

caused cities to experience disruption to water supply, telecommunications, transportation, hospitals, and many other dependent infrastructures.

Research on Infrastructure in Disasters

Much of the earlier work on infrastructure in disasters focused on understanding the mechanics of how components of infrastructure systems (e.g., bridge piers, buried pipes, electric power transformers and other substation equipment) perform when subject to extreme forces or conditions. This basic understanding also extends to component assemblages (e.g., bridges, pipelines, substations). Methods ranged from disaster field studies to laboratory simulations with scale models and computer-based analysis. New engineering designs, materials, and retrofit strategies were developed to enhance the ability of infrastructure elements to withstand natural hazards.

While these remain active areas of inquiry, more recently, new research themes have emerged that address some of the additional complexities of infrastructures that are demonstrated in the disaster examples above. These complexities often extend beyond technical domains. How, for instance, will the failure of one bridge affect businesses across the urban area that rely on the transportation system? How will the failure of one infrastructure system disrupt other infrastructures? How can repairs following a disaster be planned so as to optimally restore infrastructure services? Such questions have prompted research that is more collaborative and multi-disciplinary than in the past. It has also required researchers to pay greater attention to issues of time, space, and context. These trends are illustrated below in an example from the field of earthquake engineering.

Example: Water in a Los Angeles Area Earthquake

The Los Angeles Department of Water and Power (LADWP), the largest municipal utility in the U.S., provides potable water to 3.9 million people through 11,700 km of infrastructure in one of the most seismically active regions of the country. Over the last several years, researchers affiliated with the Multidisciplinary Center for Earthquake Engineering Research (MCEER) have been studying the potential consequences of major earthquakes on the LADWP water system. Highlights from three of these studies illustrate some key challenges and breakthroughs.

The first of these, by T. O’Rourke and colleagues, modeled potential physical damage to the network (Romero et al. 2009). Geographic Information Systems (GIS) was essential to visualizing the spatial dimensions of seismic ground waves, peak ground deformation, fault rupture, soil liquefaction, and landslides, as well as the infrastructure network itself. The model estimates damage to network components (pipes, tanks, reservoirs, etc.) and performs hydraulic modeling of water flows through the damaged network. It estimated serviceability -- defined as the ratio of post-earthquake to pre-earthquake water flow -- for each service area. Results for one hypothetical event, a M_w 7.8 earthquake on the southern San Andreas fault, were used in 2008 as part of the largest emergency preparedness exercise in U.S. history. In that scenario, overall water serviceability was estimated to be as low as 34% some 24 hours after the earthquake.

Related work by R. Davidson and colleagues modeled the damage repair process, thereby estimating water outage durations (Brink et al. 2009). A discrete event simulation model was developed that mimics the actual post-earthquake restoration process; in particular, the movements of repair crews over time and their activities, subject to personnel and material constraints. Data were derived from extensive consultation with LADWP engineering staff. The restoration model was run in tandem with O’Rourke’s damage and water flow model, simulating serviceability in 12-hour increments as repairs are made over time and space. Uncertainty was handled through multiple discrete simulations. Results indicated substantial variability in how restoration might proceed; hence the model can help in planning for effective resource allocation following a disaster.

Work by S. Chang and colleagues built on these and other MCEER engineering studies to model the consequences of water outages, including impacts to the economy (Chang et al. 2008). An agent-based simulation model was developed that accounts for how different types of businesses would be affected by water loss. Inputs included water serviceability ratios and restoration times. Data were derived from surveys of business impacts in disasters. Impacts from water outage were estimated in the context of other types of earthquake-related disruption; specifically, building damage and electric power loss. Results for a M_w 6.9 Verdugo Fault scenario indicated that water outage could account for an estimated $467 million in direct business interruption losses, or about 1.5% of the estimated total economic disruption losses from all sources.

Several observations are noteworthy in considering these studies. The entire scope of the complex problem could only be addressed through the coordinated efforts of a multi-disciplinary team. Collaboration with the infrastructure organization itself, LADWP, was essential throughout the research process. GIS helped to bridge the various disparate datasets and models. The concept of *infrastructure services* was also essential in linking damage to societal impacts. Modeling the post-disaster loss and recovery process over time -- an essential dimension in assessing disaster resilience -- is now possible.

Three Challenges on the Horizon

Where is the current frontier in research on infrastructure resilience to disasters? In this author’s opinion, there remains much to be understood and addressed in relation to the performance of engineered elements and systems. The nexus between engineering and social sciences, moreover, has only begun to be explored.

Yet three new challenges are also gaining increasing attention. The first is the challenge of *interdependencies* -- understanding and addressing how failures in one infrastructure system lead to failures in another. The second is the *multi-hazard* challenge, or finding solutions that are effective against the multiple hazards (e.g., wind, ice, earthquake, terrorism, deterioration) that infrastructure systems face. The third is the *sustainability* challenge. Infrastructures are long-lived, facing demands that may change drastically throughout their life cycles (e.g., with population growth). But at the same time, infrastructure decisions also constrain and enable urban changes to take place (e.g., flood control levees can encourage development in hazardous areas). How can infrastructure systems be designed for disaster resilience not only today, but into the future? This question may be at once the most difficult and yet the most important.

References

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