This paper lays out a basic approach to link physical earthquake damage to its social and economic impacts. Linking physical damage to social and economic impacts is difficult for several reasons. First, and fortunately, there are relatively few damaging earthquakes to provide actual data that can be used for understanding and modeling social and economic impacts. Second, there is not a simple deterministic relationship between physical damage and resultant impacts, and a number of contributing and confounding factors mediate this relationship. There is considerable uncertainty in the incidence of impacts across populations. There are also complex social interactions that can amplify or reduce the impacts. And finally, social and economic impacts develop and change over time. Some impacts do not manifest themselves immediately and many are not resolved in the short term. This extended temporal dimension adds complexity to linking social and economic impacts to physical damage, which occurs within a very short time period.

Early social science research on earthquakes consisted of post-event case studies. More recently studies have collected more comprehensive statistical data that more fully describe the character and incidence of the impacts. Several studies have been able to collect longitudinal data that documents how these impacts develop and evolve over time (Zhang and Peacock, 2005; Tierney, 1997). These more comprehensive studies show how impacts vary across the area affected by the earthquake and can be linked to the spatial pattern of physical damage. These studies serve as a foundation to build quantitative models of social and economic impacts that are driven by physical damage.

Conceptual Model

Figure 1 depicts a conceptual model of the relationship between an earthquake, the physical damage it produces and the resulting social and economic impacts.

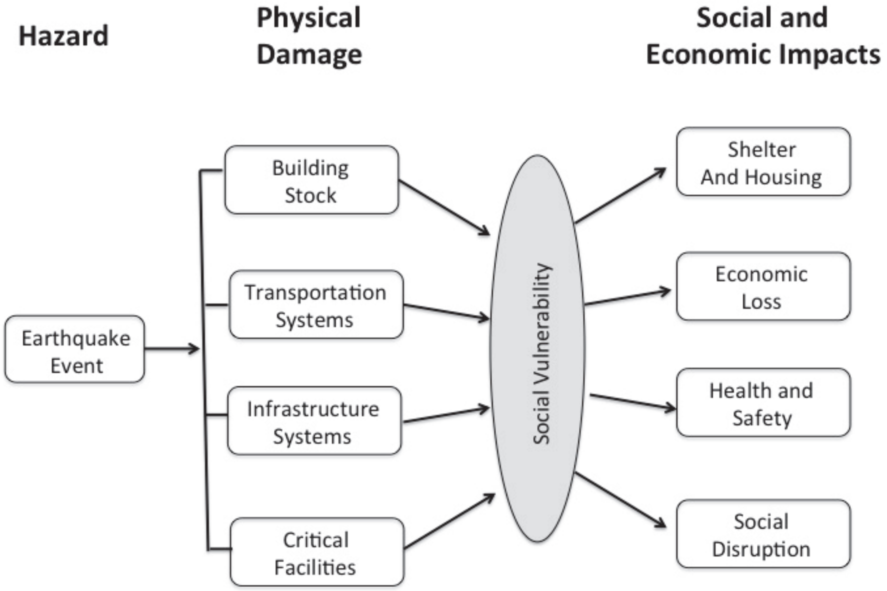

Figure1. Conceptual model links hazard, damage and impacts.

It shows how the earthquake hazard produces physical damage, which results in a variety of social and economic impacts. These impacts are, however, focused by the lens of social vulnerability.

With respect to the earthquake hazard, scientists have made little progress toward real time prediction of earthquake events, however seismologists are able to provide reasonable estimates of the likelihood of events of a given magnitude occurring in a region within a defined time period (e.g., 20 to 50 years).

Earthquakes typically produce four types of physical damage: damage to the building stock, damage to transportation systems, damage to infrastructure systems and damage to critical facilities. Existing engineering models can estimate how various classes of buildings and infrastructure components will respond to earthquakes of various magnitudes. Critical facilities, such as hospitals and fire stations, are often housed in buildings, but are given special attention because they play a critical role in responding to the earthquake. In addition to the buildings that house these critical facilities, damage to their nonstructural systems can prevent them from being fully operational after an earthquake.

This physical damage produces a variety of social and economic consequences. The consequences that have been observed following an earthquake result from a complex interaction of damage with these interdependent social and economic systems. Part of the challenge in creating quantitative models of social and economic consequences is disentangling the maze of effects that stem from this assortment of physical damage effects. Our model identifies four types of social and economic consequences that can result from an earthquake event: (1) shelter and housing, (2) direct and indirect economic losses, (3) health, including deaths and casualties, and (4) social disruption. Each of these impacts can occur in both the short term immediately following the earthquake and over the longer term potentially lasting for years.

Earthquake ground motion, physical damage and social and economic impacts all vary over space. Geographic location has long been recognized as the key to linking hazard, physical damage and resulting impacts (French and Jia, 1997). As more and more detailed social and economic impact data is collected, advanced spatial analysis tools provide a key mechanism to help understand the relationship between physical damage and social and economic impacts.

Physical damage to buildings is the most common form of damage. Building damage includes not only damage to the structural system, but also damage to nonstructural systems, such as piping, partition walls and heating and lighting systems. Building damage produces direct economic damages that include the costs of repair and reconstruction, but is also closely linked to business interruption, casualties and social disruption.

Because residential buildings comprise the majority of the building stock in most urban areas, damage to housing is usually the largest component of all losses in terms of the number of buildings damaged. Damage to the residential building stock produces an immediate need for emergency shelter just after the earthquake event. It may also reduce the availability of affordable rental housing long term. Comerio (1998) found that the impacts on shelter and housing are linked with conditions of pre-disaster housing markets and physical damages of housing. Bolin and Stanford (1998) found that the Loma Prieta earthquake exacerbated the pre-existing shortage of affordable housing. Homeowners may experience significant economic losses, especially if they are not covered by earthquake insurance.

Damage to transportation systems not only produce significant repair costs associated with direct damage, but can also disrupt the movement of people and goods. Disruption of the transportation network can have significant economic impacts. Several studies have shown that damage to transportation systems can contribute to business and economic losses following an earthquake (Gordon et al., 1998; Boarnet, 1998). Damage to the transportation network makes it difficult for firms to get the raw materials they need or distribute the goods they produce. It may also be difficult for employees and customers to get to the business. Damage to transportation network can create long-term disruption, sometimes taking years to fully restore.

Damage to infrastructure systems (e.g., gas, electricity and water systems) can produce similar economic losses. A number of studies have shown that disruptions to these services produce not only facility repair costs, but also revenue loss to the service provider, direct economic loss to consumers and indirect economic loss to the region as a whole (i.e., Chang et al., 1996; Rose et al., 1997). Research conducted after the Northridge earthquake confirmed the high costs of infrastructure damage. Businesses reported utility service disruption as an important cause of closure. Of the five most widely reported reasons for business closure, loss of electricity ranked two and loss of telephone service ranked fourth (Tierney, 1997).

Critical facilities are important in a region's ability to respond to the earthquake. They include hospitals, police and fire stations and potential emergency shelters. Typically, physical damage to these facilities is modeled much like other buildings. However, since these facilities are needed in the immediate post-disaster period, more attention is given to their ability to continue functioning after a hazard event. As a result more attention must be paid to non-structural damage. In the early 1980s the California Division of Mines and Geology undertook a series of studies that looked at the impact of major earthquakes on lifelines and critical facilities in California's metropolitan areas (Davis et al., 1982).

Earthquakes can also produce a significant health impacts, including deaths, injuries, and psychological distress. Decades of structural engineering focus on life safety have greatly reduced the number of deaths and casualties caused by earthquakes in most developed countries. However earthquakes in areas with less stringent building standards can still produce large numbers of deaths and casualties.

Damage to residential buildings and infrastructure systems can force families to relocate from their neighborhoods and communities. The hazard literature suggests that relocation forced by earthquakes and other natural hazard events can separate families and disrupt existing the social structure of neighborhoods (Girard and Peacock, 1997; Smith, 1996). This relocation can destroy the social support networks of friends and families that support these populations. The limited resources of vulnerable populations make it more likely that they will be relocated after a damaging earthquake. As a result, vulnerable populations are more likely to suffer increased neighborhood disruption.

Social scientists portray earthquakes and other natural disasters as social events, because social and economic impacts are shaped by the underlying social structure (Fothergill and Peek, 2004). They have documented that some individuals and groups are particularly vulnerable to the consequences of earthquakes and other natural hazards. Those social groups include the low-income families, the elderly, the disabled, women, children, and renters. Vulnerable populations suffer a disproportionate share of the social and economic impacts of an earthquake. As such, vulnerability to an earthquake is not determined solely by the event itself, but instead by the pre-existing social, economic and political conditions of the populations subjected to the event.

There have been several efforts to assess social vulnerability of natural hazards (Tierney, 2006; Cutter et al., 2003). Social vulnerability can be measured by socio-demographic characteristics, experience with hazards, and financial and social capacity to respond to the earthquake (Peacock et al., 1997). In our conceptual model, social vulnerability is characterized as a lens that focuses the effects of an earthquake on those groups that are most at risk and least able to recover from the event.

This conceptual model provides a basis to develop quantitative models of social and economic consequences. The model views the earthquake as an initiating event that produces damage to the built environment. This physical damage is filtered through a lens of social vulnerability to produce social and economic consequences. These impacted vary with the intensity of the earthquake, the severity of the resulting physical damage and the characteristics of the population and firms affected by the event.

Modeling Social and Economic Impacts

Most existing modeling efforts have focused on relating the intensity of the earthquake event (e.g., level of ground motion) to the probability of physical damage to different types of buildings. These intensity-damage relationships are generally depicted in the form of fragility curves that relate different levels of one or more intensity parameters (e.g., peak ground acceleration) to the probability of one or more damage states (i.e., Bai et al., 2007). Many existing models follow this basic approach to produce estimates of damage to urban scale building inventories.

There have been a number of attempts to model the social and economic impacts of earthquakes. Most of them focus on a limited range of impacts. Dowrick and Rhodes (1993) estimated damage costs for commercial and industrial property as a function of earthquake intensity. Perkins et al. (1996) developed a model for estimating shelter demands based on the Loma Prieta earthquake data.

The best known and most widely used model is the earthquake module included in the HAZUS-MH loss assessment system developed by the Federal Emergency Management Agency (FEMA). HAZUS-MH is designed to provide general estimates of the kinds of damage and impacts to expect when natural hazard events strike particular areas of the United States. This risk assessment model combines data that describes the hazard with aggregated information on the building stock, population, household characteristics, the types of local economic activity and employment. It is a GIS-based model that was primarily developed to plan for emergency response. Based on local ground motion HAZUS places buildings into one of five damage states: none, slight, moderate, heavy and complete. These damage state metrics were translated into economic losses based on the average percentage of the value destroyed associated with each damage state. Direct economic losses and emergency shelter needs were estimated based on these damage states. Business interruption and other indirect economic losses were estimated based on historical loss data.

HAZUS operates on groups of buildings, population and employment aggregated at the census tract level. Census tracts can vary widely in size from tens of city blocks to many square miles depending on their population. The decennial census provides very detailed information on the population residing within each census tract. Small area business and employment statistics that are necessary to estimate economic impacts are more difficult to obtain. HAZUS has aggregated data from a variety of sources to provide local economic data. HAZUS uses estimates damage to the general building stock, direct and indirect economic losses and household displacement, including short-term shelter needs, and casualties. HAZUS-MH represented a reasonable modeling approach given the technology and data available at the time it was developed some twenty years ago.

The world has recently moved from an environment of data scarcity to one on data abundance. More and more detailed data is being produced on the function of urban areas. This detailed data provides a more complete view of the behavior of urban residents before, during and after an earthquake event. This data has high spatial resolution and is collected repeatedly over time, so it also has high temporal resolution. This new data is often referred to as "Urban Big Data."

It is now possible to combine traditional data sources, such as tax assessor records, census demographic data and remote sensing imagery, with newer streams of digital data, including cell phone location data, crowd sourced observations, online business directories (e.g., Yelp, Trip Advisor), Google Streetview images, video from drones and surveillance cameras and instrumented infrastructure sensor feeds. This new data provides a better means to determine the characteristics of the people and firms at risk and dynamic data on their location. Effective investments in mitigation measures, emergency response plans and reconstruction strategies require better estimates of social and economic impacts, not just physical damage to the built environment. The abundance of digital data on human activities provides an opportunity to create much richer models of social and economic impacts.

Infrastructure systems are rapidly joining the Internet of Things (IoT). Data from these instrumented systems describe the performance of these systems under both normal conditions and under periods of severe stress caused by earthquakes and other natural hazards. This newly available data provides a unique opportunity to understand the dynamic interactions between human and physical systems. The data on urban infrastructure systems can be combined with massive amounts of cell phone location data, social media postings, transit access card swipes, drone and surveillance video and credit card transaction records that depict the activities of urban residents. Together this rich confluence of data provides a dynamic, comprehensive view of the functioning of the city and the activity patterns of urban populations. Urban Big Data provides a truly unique opportunity to investigate and understand the dynamic interactions between urban residents and built environment systems.

Over the past generation cities and counties have developed extensive base data that in the form of traditional geographic information systems (GIS) and relational databases. These data sets include parcel-level land records, infrastructure systems, street networks and ecosystem inventories as well as traditional census information. In addition to that rich set of traditional data a wide variety of unstructured data is now being created from infrastructure sensors, video cameras, drones and social media. Urban infrastructure systems and smart buildings are rapidly joining the Internet of Things (IoT). In addition, social media postings (Facebook, Twitter, FourSquare, etc.), surveillance cameras, drones, cell phone location data, license plate readers, transit access cards and credit card transaction records provide a dynamic view of the function of the city and the activity of its inhabitants. Combining this rich and diverse amalgam of unstructured data with more traditional data produces a more complete, highly detailed, real time view of the city, including the built environment and the behavior of urban inhabitants. Urban Big Data provides a much more comprehensive understanding of the city and provides the foundation for developing the next generation of social and economic impact models.

Conclusion

Significant strides have been made in modeling the response of buildings and infrastructure systems to earthquake hazards. However, many public and private decision makers need to understand the social and economic impacts of earthquakes to evaluate mitigation and emergency response policies and investments. There have been some initial attempts to model social and economic impacts and progress has been made. New forms of digital data, known as Urban Big Data, provides the opportunity to build more detailed and accurate models of the social and economic impacts of earthquakes.

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