Effective Seismic Risk Reduction Through Integrated Interdisciplinary Research

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ABSTRACT :

In spite of significant technical advances in understanding seismic effects on structures, improved design and construction over the past 30 years, the losses in each major earthquake event around the world continue to escalate. The prime reason for this is the lack of systems level approach to understand vulnerability to seismic hazard. Technical discipline –driven research has dominated the earthquake engineering research and has significantly improved our understanding of structural behavior, however, an integrated and interdisciplinary methodology in this research is missing. It is necessary to integrate disciplines such as social sciences, economics, emergency management, and public policy in *research design* to assess the vulnerability of the entire system. The framework of *cause* and *effect* has not served well as the dynamic in the society changes constantly. It is argued in this paper that a *systems level* approach needs to be developed integrating various disciplines and creating a continuous *feedback loop* providing input on the behavior of the whole system. This *systems level* approach provides a cost effective and efficient holistic solution to minimize seismic risk to society as it takes into account the impact of sub-systems on the overall system considering their interdependent characteristics.

KEYWORDS: Systems level, cause and effect, research design, feedback loop, interdependent, vulnerability

1. INTRODUCTION

Considerations of seismic risk have been influenced by two aspects: *uncertainty in the occurrence of a major seismic event; and life safety*. The code provisions and other regulatory mechanisms are based on the life safety aspect of seismic risk. For critical facilities, an added provision related to their functionality during and after a major seismic event is also a criterion. There has been no meaningful progress in reducing the uncertainty for a major seismic event occurrence but considerable progress has been made in understanding the behavior of structural systems subjected to major seismic events. Loss of life in the last two significant seismic events in California: Loma Prieta, 1989 and Northridge, 1994 has been low as compared to a similar magnitude seismic event in Kobe, Japan in 1995. While less than 70 persons died in each of the California events, the loss of life toll in Japan was over 5000. The loss of life in subsequent similar magnitude seismic events in India, Iran, and Pakistan has been significantly higher primarily due to poor construction quality and materials.

Two important findings from the seismic events in California are worth noting: 1) damage to non-structural systems in buildings in California was significantly higher than the damage to structural systems thus causing serious disruptions in business operations resulting in considerable economic losses, and 2) global economic interconnectedness caused economic and societal disruptions and losses beyond the borders of individual countries due to increased global interdependence. Similarly Chi-Chi earthquake in Taiwan in 1999 where US companies manufacture electronic components for worldwide use, and in the Kobe earthquake in Japan where 15% of the Japanese export are shipped through Osaka port that had to be closed following the earthquake, impacted availability of goods worldwide. These types of impacts to society are beyond the assumptions of code provisions, based on life safety considerations alone as they are developed primarily to prevent major damage to structures or to prevent the collapse of structures thus allowing safe exit of occupants (life safety). The reason why the loss of life and damage to physical facilities varies significantly across the globe for similar magnitude earthquakes is that the *vulnerability* in each location is significantly different.

2. SYSTEMS APPROACH

A system can be defined as a connected group of independent but interrelated components or subsystems forming a unified whole, that interact coherently and synergistically to achieve a beneficial purpose. In earthquake hazard risk the system requires feedback and contribution from diverse disciplines such as social sciences, economics, emergency management, and public policy because of the multidisciplinary nature of seismic hazard risk. Total seismic risk is shown is shown in figure 1. To reduce the seismic risk requires consideration of all three components which act interdependently.

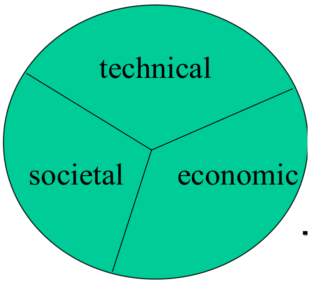

Figure 1 - Total Seismic Risk

In 2004, the Subcommittee on Disaster Reduction stated in a report to the US President " Protecting American communities from disasters ---- depends on policy makers adopting an *integrated approach* to disaster risk reduction, drawing on existing knowledge ----- combined with new information on risks –".

To address the problem of assessing overall impact necessarily requires an interdisciplinary research which is inherently complex as interaction among system components is neither well understood nor well defined. A new framework that uses input from various divergent disciplinary subsystems is needed. These subsystems interact and influence the outcome of the behavior of the entire *system*. A system suitable to deal with earthquake hazard is shown in figure 2. The components of a system could be connected in *series*, in *parallel* or a combination of the two. Most civil physical infrastructure systems are connected in *series,* whereas networks such as information systems operate in *parallel.* The societal networks on the other hand are connected in a random way and some systems in them operate in series but other in a parallel mode. That is one of the prime reasons, these systems are difficult to analyze.

Studying figure 2, several specifics can be noted. The impact of the seismic event on the built environment is depicted by a rigid connection as there is no modified response. The link is rigid. The link between the event and the economic infrastructure is non-linear. Consider a seismic hazard that is capable of a major disruption to a community. Its impact on various subsystems can be judged by the type of linkage it has with a particular subsystem. The impact on the built environment results in damages and possibly loss of life depending on the severity of damage and the type of damaged structure. This type of link is usually linear and rigid as it does not allow any different modified behavior of the structure due seismic impact. The link to economic infrastructure is non-linear and also somewhat flexible. The non-linearity results from varying degrees of economic damage depending on the type of economic activity where the seismic impact has been greatest. e. g. if the seismic event is located close to a major financial center such as Tokyo, the disruption would result in financial and economic market disruptions with repercussions throughout the world. On the other hand, if the seismic event is close to location such as Los Angeles, the repercussions to financial markets worldwide would be limited and the economic damage would be regional rather than national or international. The link is also flexible because the economic infrastructure is global and can respond to disruptions with support through alternate links providing some resiliency. Examples of this type of resiliency can be found in response to terrorist attacks in Mumbai (2005), London (2003), and Tokyo (2004). Although these are not seismic activities, the impact on society is similar. In all these cases, financial markets were open within 48 hours and economic repercussions were limited in degree and extent. Societal links are also non-linear and flexible.

Finally, the link between the community and the impact due to seismic hazard is shown by a flexible link (spring) which has the characteristics to absorb shocks. Depending on the degree of resiliency in a community, the damage and disruption to a community can be modified for a similar event. It is extremely important to understand the type of linkages with various subsystems within a system to understand the overall behavior of a larger system. Seismic research to date has been dominated by making subsystems robust without due consideration to larger seismic hazard minimization system.

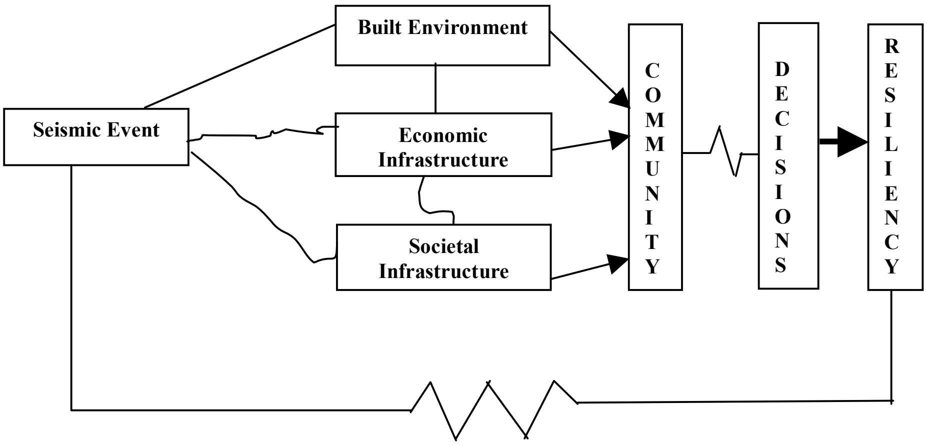

Figure 2 - Larger System and linkages of sub-systems

2.1 System Types and Characteristics

Systems can be classified in two basic types: *static; and dynamic. Static* systems are non-adaptive as they rarely have feedback loops. *Dynamic* systems on the other hand are adaptive and generally have feedback loops. Possibly, a third type of system can also be classified; a *hybrid* system. This type of system combines the characteristics of both static and dynamic systems. Components of a system can be connected in series, parallel, hybrid (combining series and parallel), or in a random way. Robustness of a system is governed by the robustness of the weakest link in the system, particularly when the components are connected in *series*. The type of connection between components is very important. Linkages between components must be flexible to allow modified behavior based on the input from subsystems through feedback loops. These feedback loops play an important role in making the system behavior *adaptable*. The connections between components can be linear or non-linear and can be flexible, semi-rigid or rigid.

2.1.1 Static Systems

Many civil physical infrastructure systems and building structures are static with components connected in series with linear rigid type connectors. Examples of such systems are shown in Fig.3. Both the building system and the bridge system are composed of components or sub-systems which rely on connections in *series* that are also rigid, e. g. in the bridge system, if the substructure fails or is badly damaged, the superstructure resting on it will be damaged. Consequently, any structural or non-structural systems supported on the superstructure will not be usable when the superstructure fails. This is a classic example of a system connected in series linearly. Similar situation exists in the building structure.

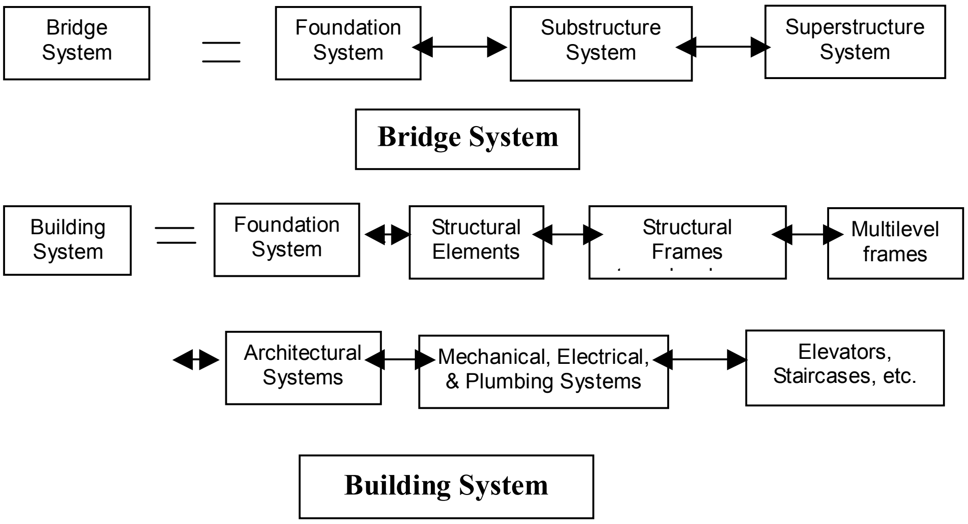

Figure 3 - Static Systems connected in Series

Utilities such as water supply networks, electrical networks and gas distribution lines may have hybrid connections, i.e. some major parts are connected in series but the network may also be connected in parallel with other similar networks providing vital service in case of disruption in the service due to a major earthquake event (added redundancy). Utility networks are interdependent, e.g. water supply networks rely on pump stations which need uninterrupted electrical service. If the electrical network is disrupted, water supply is impacted although there may not be damage to its pipelines. The disruption in electrical power may also impact several other systems as shown in figure 4. In general these systems are also static but may provide robustness due to hybrid connections.

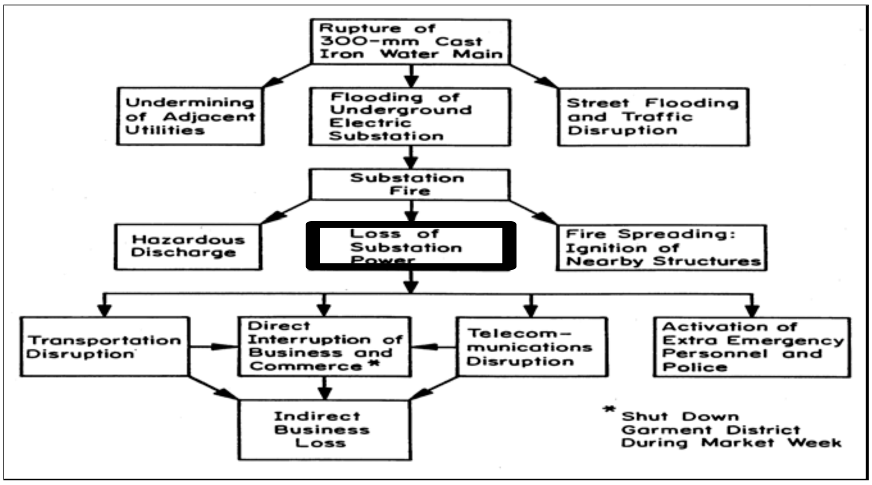

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Figure 4 – Interdependence of various utilities

2.1.2. Interdependency

The interdependency between systems is extremely difficult to quantify. Some attempts have been made to quantify this parameter, however much work remains to be done. One way to quantify is to go on experience basis and determine how long a particular service was out due to problems with another service. For example, if the power was out for 2 hrs resulting in a 3 hrs outage for the dependent water system, it can be stated that the interdependency coefficient between these two systems is 1.5. Although this is not an absolute measure, it is a relative measure of interdependency. Once the outage time for a service is determined, it is possible to quantify the economic impact. Another measure that could be helpful in determining societal impact is the number of households, and number of businesses that are affected by the outage. These are indicators of vulnerabilities in the system and although cannot be quantified for economic purposes, decisions on alternatives can be made based on this information.

2.1.3 Dynamic Systems

Most societal network systems are dynamic by nature as they adapt and respond to changing conditions. The linkages between various components of these systems are flexible and non-linear. Some of the connections also tend to be random and present difficulties in determining their connection paths. This very aspect presents the difficulty in combining societal systems with engineering systems to determine the overall impact of a major seismic event on society. However, recent advances in quantifying societal impacts as consequences of major seismic events have led to development of their inclusion in the research design at the fundamental level, although at an extremely limited level. This paper essentially argues that inclusion of all subsystems is necessary to reliably estimate the impact of a major seismic event and thus design of appropriate steps for seismic hazard impact minimization.

3. SYSTEM VULNERABILITY (Vs)

Although many definitions of vulnerability exist, this author would like to adopt a more general definition in the narrow context of seismic hazard. *Vulnerability* of a system to seismic hazard can be defined as a resulting adverse aggregate outcome due to degree of exposure, system sensitivity, and system resiliency. When human interventions in a system are involved, the system becomes dynamic and can be considered a loosely coupled Human-Environment system. Vulnerability has three dimensions:

a. Degree of exposure
b. System sensitivity

c. System resiliency

Vulnerability is contextual and due to dynamic nature of human-environment coupled systems, it is also temporal. Components of a system are: *physical systems; and societal systems.*

3.1 Degree of Exposure(Se)

For damage or loss of life to be a meaningful effect, the impacted systems must be exposed to the hazard. More the exposure to hazard, the larger the impact and greater the potential damage. For example, same magnitude earthquake in a sparsely populated area will have much less effect as compared to a populated area. Similarly the impact of an earthquake near its epicenter generally, would be greater than the impact away from the epicenter, as the exposure is smaller. Degree of exposure could also be modified due to subsurface conditions. In a geographic area, geological conditions could vary significantly and could modify the impact of a seismic event. This is particularly true near coastal areas where the subsurface conditions near the coast may be quite different than those only a few kilometers away from the coast. Vulnerability depends on the degree of exposure. Different exposure categories or numerical scores can be assigned to different areas, such as 100 for the most exposed to o for the least exposed.

3.2 System Sensitivity(Ss)

Given a specific degree of exposure, vulnerability is a function of the sensitivity of the system to the seismic hazard. Certain structural systems are inherently more vulnerable to seismic hazard than others. For example, low-ductile systems such as masonry, and poorly detailed concrete wall systems are more damage prone than properly detailed structural concrete frame systems .Beyond this generalization, the system behavior primarily depends on the behavior of its components or sub-systems. It can be surmised in general that the system sensitivity is a function of the behavior and placement of the weakest component; WC, in the system. Two specific examples are cited to illustrate this concept. In the first example, in a multistory building structural frame system, suppose the beam is a weak member. The sensitivity of the system depends on the location of the beam. Should this member be at the first level there is a greater chance that the entire system will fail as the columns at first level may become unstable. However if the beam is at the top floor location, the chances are that the entire system may not fail as the damage is likely be localized. The entire system sensitivity is different in each case. In the second example, let us consider a water supply system and let us assume that the primary pipe is a weak component. This would impact the entire system and potentially a large number of customers. On the other hand if the pipe at the end of a piping system were to fail, it would impact only a limited number of customers. Although both are parts of the same water supply system, their locations are extremely important in determining the sensitivity of a system. Sensitivity scores can be assigned to different structural and infrastructure systems, such as 8 being the most sensitive to 1 being the least sensitive.

$$Ss = f\,[WCs, \text{location in the system}] \tag{3.1}$$

WCs is weakest component sensitivity.

3.3 System Resiliency(Sr)

Most general definition of resiliency is the ability to recover from a changed state. The concept of resiliency is equally applied to social systems and physical systems although their dimensions are different. More specifically as applied to seismic hazard: in physical systems, resiliency can be viewed as the ability of a structural or an infrastructural system to withstand the effects of a seismic event without major or un-repairable damage. Some systems can remain elastic and thus bounce back to their original state although that is usually not the case for most systems. In social systems, it is the ability of various social systems either to continue to function or recover to their former stage quickly. Multidisciplinary Center for Earthquake Engineering Research (MCEER) at University at Buffalo, NY, a NSF funded Center has defined four dimensions of resiliency: Robustness; Redundancy; Resourcefulness; and Rapidity. Since restoration of a system to full functionality occurs over time, a measure of resilience can be defined as the area under the curve ABCDE as shown in figure 5. Point B is where the seismic event occurred and E is where full functionality was restored. The steeper the lines BCD the smaller the area indicating a rapid recovery.

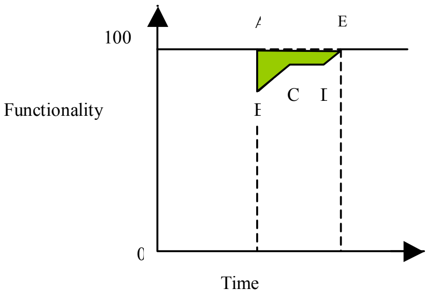

Figure 5 - Measure of Resiliency

For a given impact, the flatter the lines the longer the recovery indicating lesser resiliency. The smaller the area the greater the resiliency and vice-versa. The overall vulnerability is reduced with smaller area under the curve. The time dimension is important here because one can make the areas equal but with different times for recovery and different impact to original functionality. Numerical scores can be assigned to resiliency, such as 1 being the least resilient to 4 being the most resilient.

The overall Vulnerability equation can be written as:

$$Vs = F\ [Se, Ss, Sr] \qquad (3.2)$$

Vulnerability scores can be assigned and different systems can be compared on a relative basis to make decisions. For example, for a structural system that has most exposure but is least sensitive and extremely resilient would have a score of (100x1x4 = 400). This score can be compared with another system and relative vulnerabilities can be assessed.

4. INTEGRATED INTERDISCIPLINARY SYSTEMS

Although the societal component of the overall interdisciplinary system for seismic vulnerability cannot be appropriately quantified, measures of relative vulnerability can be developed to assess the behavior of different sub-systems likely to be impacted by a major seismic event. These measures need to be considered along with the quantifiable measures for the technical and economic components of the system. An overall decision making process then will assign different importance factors to different components to make a seismic mitigation decision. The three components that interact with each other to influence decision are shown in figure 6. It should be kept in mind that the interaction is not linear. In the engineering community, focus has been on developing structural systems that are seismic resistant. Although this is an important achievement, it is not sufficient to address the overall seismic risk. There has been significantly less attention given to networks of lifeline systems, economic systems and societal systems. One of the critical issues is to determine the overall vulnerability of the entire system subjected to a major seismic hazard event.

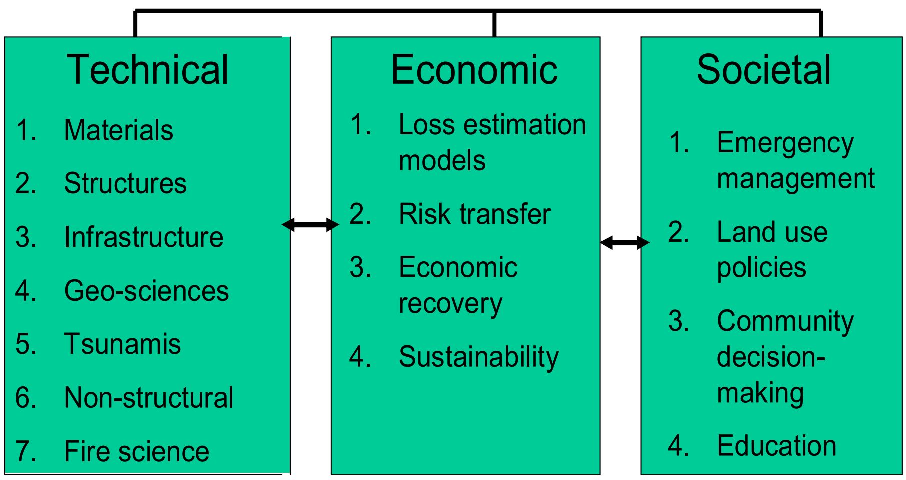

Figure 6 – Seismic Hazard Reduction System Framework

5. SUMMARY

This paper has argued that a culture of collaborative integrated and interdisciplinary research in the academic institutions needs to be developed. For reduction of seismic hazard risk to society, integrated research involving engineering, social sciences such as, decision science & public policy disciplines is essential. New integrated risk assessment models for improved vulnerability analyses of system interdependencies are required. As an integral part of seismic risk reduction to society, integrated models of mitigation, preparedness, and evacuation planning needs to be developed. There are quantifiable components of a seismic risk and others are non-quantifiable. However, relative measures can be developed in those non-quantifiable areas. Such measures along with the quantifiable measures can be successfully used to make appropriate decisions.

Finally, from a public policy perspective, when an earthquake occurs, decisions have to be made by various officials located remotely from each other. This process of distributed decision-making is not well understood. Distributed decision-making models specifically addressing seismic hazard risk need to be developed.

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