INFRASTRUCTURE RISK MANAGEMENT IN PREPAREDNESS OF EXTREME EVENTS

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Abstract: Natural disasters, such as the recent floods in the Midwest, Hurricane Ike in the Gulf coast region (U.S.), and the earthquake in Sichuan (China), cause severe damage to the infrastructure as well as the associated industries and communities that rely on the infrastructure. The estimated damages due to Hurricane Ike in 2008 were a staggering $27 billion, the third worst in U.S. history. In addition, the worst earthquake in three decades in Sichuan resulted in about 90,000 people dead or missing and $20 billion of the estimated loss. A common observation in the analyses of these natural disaster events is the inadequacy of critical infrastructure to withstand the forces of natural calamities and the lack of mitigation strategies when they occur on the part of emergency-related organizations, industries, and communities. If the emergency-related agencies could identify and fortify the vulnerable critical infrastructure in the preparedness stage, the damage and impacts can be significantly reduced.

Therefore, it is important to develop a decision support system (DSS) for identifying region-specific mitigation strategies based on the inter-relationships between the infrastructure and associated industries and communities in the affected region. To establish effective mitigation strategies, relevant data were collected from the affected areas with respect to the technical, social, and economic impact levels. The data analysis facilitated identifying the major factors, such as vulnerability, criticality, and severity, for developing a DSS. Customized mitigation strategies that will help agencies prepare, respond, and recover according to the disaster response were suggested.

1. Natural Disasters and Critical Infrastructure

Natural disasters, such as the recent floods in the Midwest, Hurricane Ike in the Gulf coast region, and the earthquake in Sichuan, China, cause severe damage to critical infrastructure as well as associated industries and communities. The estimated damages due to Hurricane Ike (Figure 1) are a staggering $27 billion, third worst in the U.S. after Hurricane Andrew (1992) and Hurricane Katrina (2005).

Figure 1: Flooded Neighborhood in Galveston, Texas after Hurricane Ike (2008)

Similarly, South Korea is affected by typhoons that normally occur in late summer; and almost 60 percent of the damage of natural disasters in South Korea is caused by typhoons. Typhoons are generated on the south Asian oceans (tropical oceans in low latitude areas from five degrees to 25 degrees) and proceed to the northwest (or northeast). Typhoon Rusa, for example, was recorded as the most destructive natural calamity in Korean history with respect to the amount of loss. The estimated loss was over $5Million and the recovery cost was around $8Million (YTN.com 2009) (Figure 2).

Every region comprises of communities and industries, which function and sustain on a closely-knit infrastructure network. A need arises to identify important or critical infrastructure. Critical infrastructure has been defined as "the infrastructure whose incapacity or destruction would have a debilitating impact on our defense and economic security" by the President's Commission on Critical Infrastructure Protection (United State 1997).

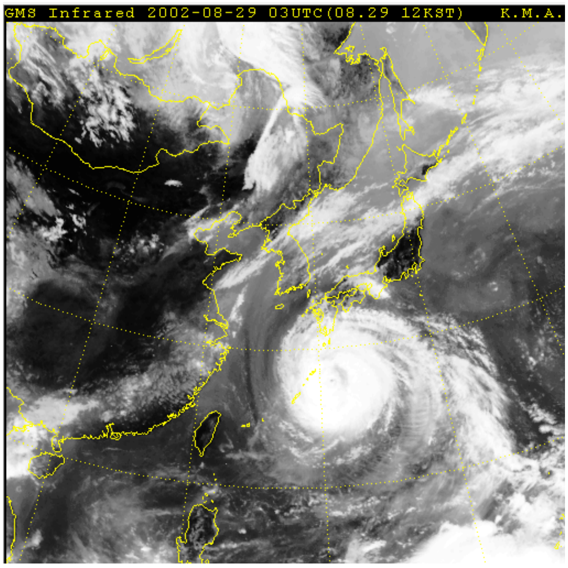

Figure 2: The Satellite Image of Typhoon Rusa, 2002 (www.typhoon.or.kr 2009)

The Critical Infrastructure Assurance Office (CIAO) has also defined the critical infrastructure as "the framework of interdependent networks and systems comprising identifiable industries, institutions (including people and procedures), and distribution capabilities that provide a reliable flow of products and services essential to the defense and economic security of the United States, the smooth functioning of governments at all levels, and society as a whole." In addition, Robert et al (2008) modified the definition as "critical infrastructure are also lifeline facilities to support industries and communities as life support networks."

For this research, **critical infrastructure** is defined as infrastructure (e.g., roads, water, wastewater, electricity, schools, etc.) that is considered essential for the sustenance of the normal activities of the impacted industry or community (activities such as, production, delivery, and supply chain issues for an industry, as well as commuting to work, school, church, healthcare, etc. for a community). Based on these definitions, thirteen lifeline infrastructures were identified as the most critical ones to sustain services and activities of industries and communities. Those are telecommunications, electric power systems, natural gas and oil, transportation, water supply systems, banking and finance, government services, emergency services (including medical, police, fire and rescue systems), food & agriculture (including production, storage, and distribution), space, numerous commodities (including iron and steel, aluminum, finished goods, etc.), the health care industry, and the educational system.

The impact of natural disasters affects not only people and property, but also the services and activities of industries and communities. Recently, the worst flooding in the Midwest in 15 years swamped vast areas of the U.S. and caused widespread damage in cities and towns in Iowa, Illinois, Missouri, and Indiana. This slow-rolling disaster killed 24 people and injured about 150 people. It swallowed up huge farm belts in the affected areas, resulting in over a billion dollar in losses and feeding global food inflation fears. While the massive floods were triggered by heavy rains, the fundamental reason for the widespread damage was infrastructure failures, such as broken levees along the rivers and the railroad bridge in Cedar Rapids (Figure 3). The Midwest levees, roads, water, and transport systems have proven vulnerable to natural disasters on several occasions (ASCE 2005 Report Card for America's Infrastructure). Many experts feel that the recent disaster could have been prevented if infrastructure had been consistently a top priority (People's Weekly World Newspaper, June 19, 2008).

Figure 3: Midwest Floods and Infrastructure Failure (2008)

The affected areas have been historically vulnerable with respect to floods. However, it became apparent that the critical infrastructure were not sufficiently fortified and maintained to resist the impact of floods. This was also an issue after the landfall of Hurricane Katrina. The emergency agencies and industries had failed to sustain their roles properly due to the damaged infrastructure (Oh and Hastak, 2008). A common outcome of the analyses of these disaster events is the inadequacy of critical infrastructure to withstand the forces of natural calamities and the lack of mitigation strategies under these circumstances on the part of emergency-related organizations, industries, and communities.

For example, if the emergency-related agencies in Sichuan, China had identified and fortified the vulnerable critical infrastructure ahead of time, the damage and impacts could have been significantly mitigated. Similarly, Aceh, Indonesia had more than 190,000 fatalities on December 26, 2004 due to an 8.9 magnitude undersea quake and a subsequent tsunami (the Indian Ocean Tsunami). Since then, more earthquakes (or undersea quakes) have occurred in Aceh: 2005 (eight times), 2006 (four times), 2007 (seven times), and 2008 (two times). The death toll and loss of property continue to be enormous (Chinaview, Post Online Magazine, USGS, etc., 2008), which implies that Aceh failed to prepare for the natural catastrophes that followed the earthquake of 2004. The lack of preparedness brought about increased damage, especially with respect to critical but vulnerable infrastructure.

Therefore, identifying and fortifying vulnerable critical infrastructure ahead of time will protect and support communities and industrial activities during the occurrence of disasters and provide emergency agencies and associated industries better strategies for preparedness. Thus, it is important for the governing agencies to understand more about the disaster itself and its impacts on infrastructure and industries and to identify such vulnerable infrastructure for mitigating the impact of the next possible natural disaster such as hurricane, typhoon, flood, earthquake, etc. To address the issues, we need to understand what the mechanism of disaster and its impacts are; what inter-relationships infrastructure and industries (or communities) have; how the impacts spread out on infrastructure and industries; and, how the governing agencies respond before, during, and after the disaster occurrence. Therefore, the purpose of this research is to develop a Disaster Impact Analysis Model as a framework to support more understanding of natural disaster events with respect to inter-relation of infrastructure and associated industries.

2. Methodology

Inter-relationship

Since critical infrastructure plays a significant role during the occurrence of natural disasters, preparedness and mitigation strategies should include identifying and fortifying vulnerable infrastructure based on their interrelationship with the associated industries and communities. In a previous research conducted by Oh and Hastak (2008), a disaster impact mechanism was defined through a basic cell model (Figure 4). The flow of impact by a natural disaster can be divided into two stages: the primary impact and the secondary impact. Primary impact refers to direct impact from a natural disaster itself on infrastructure with physical damages and losses. For example, a hurricane brings a few destructive powers such as winds, rain, flood, hail, tornado, etc. Infrastructure in the influenced territory would get damaged or collapse directly due to the impact of the hurricane. The results could be outage of electricity, break in communications, collapse of levees, roads and bridges, etc. After these direct impacts or during the disaster impact on infrastructure, secondary impact will be on the services of associated industries. These service failures occur due to damaged infrastructure.

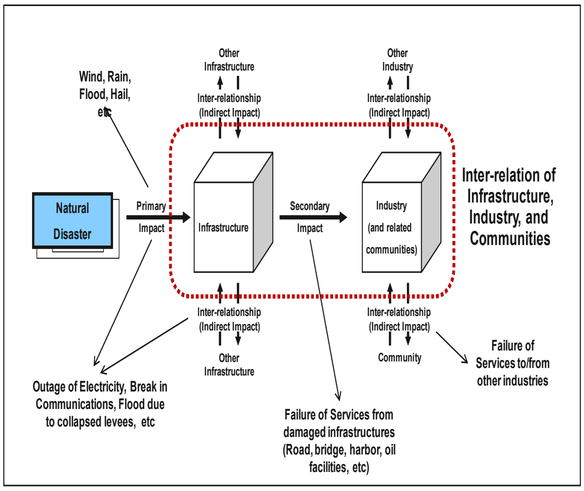

Figure 4: Disaster Impact Mechanism (Basic Cell Model) (Oh and Hastak 2008)

As defined in the disaster impact mechanism, there are many relations such as between infrastructure, between industries, and between infrastructure and industries. It is important to define all these inter-relationships to establish the disaster impact mechanism and to structure a disaster impact analysis model. The main components of establishing inter-relationships of infrastructure and associated industries are critical infrastructure (as defined earlier), associated industries and communities. Associated industries are the industries that depend on the conditions of the critical infrastructure to sustain their services and production where as supporting industries are mainly related to lifeline infrastructure, such as communications, transportation, electricity, gas and oil, and water supply systems. Supporting industries are also the industries that have a major responsibility to support, operate, and maintain lifeline/essential infrastructure. Oh and Hastak (2008) have identified twelve main industries that are associated with the thirteen critical infrastructure. The main industries have been divided into two groups, the supporting and the affected industries. Affected industries are the primary industries that provide essential services, such as banking & insurance, food, agriculture, construction, manufacture, health care (including emergency health care), and education which are affected by the condition of both the critical infrastructure and the supporting industries.

Data collection

To analyze the impact of natural disasters in the various spectrums, it is important to collect relevant data from the affected areas without losing the characteristics of the data. For this reason, the significant data are best collected soon after the occurrence of disasters (Oh and Hastak, 2008). As the floodwaters recede and rehabilitation commences, a lot of evidence of destruction and damage is removed, making it difficult to establish the extent of the impact and the inter-relationship between the infrastructure, industries, and communities (Figure 5).

Data regarding the affected infrastructure can be interpreted as impacts on industries and communities in terms of technical, social, and economic aspects. Thus, early site investigation is important to gather the ephemeral data that in the end would support the development of a more robust disaster impact analysis model. Such a model would facilitate the identification of vulnerable infrastructure and its impact on related industries and communities as well as in developing relevant mitigation strategies.

Figure 5: Flooded Road in Oakville, IA (Chicagotribune.com, 2008)

Three modes of data collection were used in this research: interviews, site investigations, and questionnaire survey with respect to technical, social, and economic impacts. The characteristics of the data can be explained as:

- Demographical information (i.e., population, gender, employment, income, etc.)
- Critical infrastructure (roads, bridges, office buildings, hospitals, manufacturing plants, wastewater treatment plants, etc.) and the conditions (deteriorations, maintenance, etc)

- Affected infrastructure (locations, reported damages, adjacent facilities, industrial activities or services that rely on the affected infrastructure, etc.)
- The level of damage of infrastructure, duration of service failure (i.e., hours, days, weeks, months, and years), and description of details
- Main functions and services that are disrupted for specific industries in the affected area (distribution center, corporation office, manufacturing, retail center, warehouse, etc.)

3. Measurement Factors for Decision Support System (DSS)

Measurement Factors

Plans and mitigation strategies for reducing the impact from natural disasters can be prepared using the data collected from the affected areas as mentioned above. However, there are levels of preparedness in disaster management from the city, industry, and community perspectives. The goal or expectation can vary according to which view is used. For example, the purpose of disaster preparedness for a city manager, who is in charge of planning, design, construction, and maintenance of public infrastructure, can be to protect entire communities and industries so that he may want to know the critical or vulnerable infrastructure from the viewpoint of the whole city. However, a manager in a company will be interested in protecting the needs of their own facilities and employees in a limited area. In this paper, the measurement factors were derived from the viewpoint of a city manager, who has responsibilities to protect the city and to provide measures for sustaining the activities in the city. A prime question that a city government or associated parties can raise before preparing plans and strategies would be how much (or how relevant) information is available about the city in terms of the infrastructure and the impacts of natural disasters The information for developing disaster mitigation strategies and plans can be the followings.

- Identification of critical infrastructure for industries and communities in terms of the technical, social, and economic aspects (criticality)
- Identification of vulnerable infrastructure or vulnerable parts and sections of the critical infrastructure (vulnerability)
- Establishment of priority to retrofit vulnerable infrastructure
- Impacts on industries and communities if vulnerable infrastructure fail during a disaster (severity or level of impact).
- Mitigation plans to protect industries and communities.

Therefore, the data for the technical, social, and economic aspects can be interpreted in terms of criticality, vulnerability, and severity to identify the inter-relationships based on the characteristics. For example, criticality implies how much a company is critically inter-related with (or depends on) critical infrastructure. Vulnerability addresses the threats or real hazards to industries or communities in disaster situations and can vary according to the condition of infrastructure. Severity implies the extent of damage or impact when a disaster occurs in communities or near industries. Therefore, criticality, vulnerability, and severity can be key metrics to understand how critical infrastructure, industries, and communities are inter-related in terms of the impacts of natural disasters and how the natural impact can be measured (Figure 6).

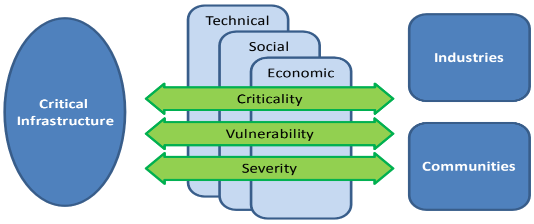

Figure 6: Metrics of Inter-relationships

Modeling Approach to develop a Decision Support System (DSS)

A modeling approach needs specific characteristics to be considered. The flow of natural disaster impacts must be described and simulated in a simple manner. Thus, the model should start simple and rely on the available data and be expandable to benefit from additional data. The model should be dynamic to cope with the nature of the disasters impacts, which are inter-related to each other. Also the model should provide a way to represent the feedback mechanism to handle counterintuitive processes and provide the ability to test different policy or management scenarios for better decision-making (Amin et al., 2005). The System Dynamics simulation approach relies on understanding complex inter-relationships between main entities, such as infrastructure, industries, and communities. The entities in turn will be affected by major factors that control or represent the nature of impacts. For example, levee, a critical infrastructure, can be affected by influencing factors, such as the rising river water and the creek water due to heavy precipitation. The entities and factors can be structured in a simulation model using variables in System Dynamics Method, such as box variables (stocks and levels), flows, variables (constant, auxiliary, and data), causal loop that describe the behavior of the system. Figure 7 shows how the flood water impacts related infrastructure and community. River water (an auxiliary variable) could be rising due to heavy precipitation (a constant variable) making the collected water in the river reach up to the flood stage (an auxiliary box variable) at some point. This could significantly increase the vulnerability of a part of levee (a stock variable). Inter-relationships should be identified ahead of this modeling and it will show the level of criticality, which means how a community activities or daily life depends on the levee. Finally, the vulnerability from the levee can be transferred to community and serve an aid to increase the vulnerability of community with a fixed rate of criticality (the vulnerability can be a factor to measure the level of threat caused by a disaster).

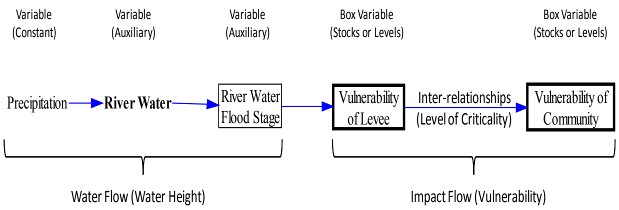

Figure 7: Basic Flow of Flood Impacts from Precipitation

4. Disaster Mitigation Strategies

The collected data in terms of technical, social, and economic aspects can be analyzed by the three metrics, criticality, vulnerability, and severity in the decision support system (DSS). DSS can support emergency agencies and industries to prepare their mitigation strategies using the criticality analysis, the vulnerability analysis, and severity analysis (Figure 8). The mitigation strategies can be established into three stages: preparedness, response, and recovery (DHS, 2004). Prior to floods, actions are necessary to ensure that people and equipment are organized and emergency personnel are trained to know how to respond during floods. According to the Department of Homeland Security (USA), preparedness includes wide range of activities to prevent/mitigate the impact of disasters. Commonly, the activities include hazard assessment, planning, and training personnel, however, in this context, we can assess the condition of critical infrastructure from the viewpoint of an city manager. The main infrastructure that should be considered in the planning stage are transportation, main routes, bridges, etc. Especially, main routes should be examined ahead of disaster occurrence to provide evacuation methods during the disaster. In addition, the condition of critical infrastructure, such as levees, flood walls, dams, etc., should be considered in the protection plans because those infrastructures are critical to protect industries and communities. The analyses of criticality, vulnerability, and severity will facilitate emergency agencies and industries to prepare better plans and strategies in the preparedness stage.

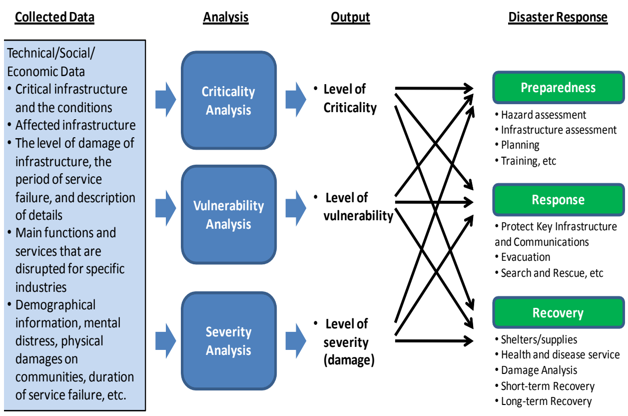

Figure 8: Decision Support System and Disaster Mitigation Strategies in Disaster Response

Response is defined as “activities that address the short-term, direct effects of an incident.” It includes immediate actions to preserve life, property, and the environment; meet basic human needs; and maintain the social, economic, and political structure of the affected community (DHS 2004). Voluntary or mandatory evacuation is declared in accordance with the level of disasters. State Coast Guard or volunteers start the search and rescue activities as well as protecting critical infrastructure such as power plants, wells, wastewater treatment plants, etc. The first responders, such as, emergency agencies and the city government, should be able to identify which infrastructure can be sustaining and supporting the evacuations prior to and during the disaster (flood) through the vulnerability analysis.

After the flood water has receded, recovery or rehabilitation of damaged industries/communities/ infrastructure will follow. The recovery implies activities and programs designed to return the entity to an acceptable condition (or pre-disaster condition). The priority of recovery of damaged infrastructure will be decided based on the result of the criticality analysis. Besides, the magnitude of impact will be measured through the severity analysis.

5. Conclusion

It is indeed difficult to have an optimal solution for mitigating the impacts of natural disasters on infrastructure, properties, and communities due to their overwhelming power and unpredictable characteristics. However, this research was conducted, based on the thesis that a better understanding of natural calamities and measuring the magnitude of disaster impacts through a disaster impact analysis model, using the concept of the inter-relationship between the critical infrastructure and the associated industries, will provide emergency management agencies and associated industries with more effective guidelines for disaster preparedness and fortified cooperation between the infrastructure and industries. The inter-relationships of the critical infrastructure and the associated industries will give the experts, who are related to the planning, design, construction, and maintenance of infrastructure, a better insight to improving the functions of infrastructure in terms of the mitigation of disaster impacts. Identification of vulnerable infrastructure for certain industries will help the people who are involved in risk management in terms of disaster events to improve their manuals and processes when a disaster occurs. When the model is applied to a certain area to analyze a disaster impact, the impact of the possibly vulnerable infrastructure in the area and the main industries can be found. Then, it will be possible to determine a disaster mitigation strategy to protect the infrastructure and the services of the associated industries. This strategy will be established based on the cooperation of representatives from emergency management (federal, state, and local levels), city infrastructure management, and the associated industries. If the governing agencies succeed to achieve their goals or mitigate the impacts, the loss of human life and properties will be decreased.

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