ASSESSMENT OF INFRASTRUCTURE RESILIENCE TO DISASTERS: CASE STUDY OF THE 2015 GORKHA EARTHQUAKE

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Assessment of Infrastructure Resilience to Disasters: Case Study of the 2015 Gorkha Earthquake

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Natural disasters, such as earthquake, flood, hurricane and tornado, cause disruptions and damages in different infrastructure systems (e.g., water, electricity, road), and thus, greatly affect the quality of life. Despite the existing studies on infrastructure disaster resilience, an integrated framework for resilience assessment of interconnected infrastructure systems, especially in developing countries, is still missing. To this end, we proposed an integrated framework for assessment of resilience in interconnected infrastructure systems. The proposed framework includes eight indicators of infrastructure resilience: vulnerability, anticipation, redundancy, adaptive capacity, rapidity, resourcefulness, cross-scale interactions, and learning culture. In addition, three different types of infrastructure interdependencies that could affect the resilience of interconnected infrastructure systems are identified in the proposed framework. The proposed framework was used to examine the resilience performance of three infrastructure sectors (i.e., water, electricity, and road) in a case study of 2015 Gorkha Earthquake in Nepal. Using qualitative data collected from 45 in-depth interviews conducted with subject matter experts who were involved in the response and recovery process of Gorkha earthquake, key factors contributing to different resilience indicators as well as interdependencies between infrastructure

sectors were identified. The data analysis results show that in general, the infrastructure systems in Nepal have inherent vulnerability even before the earthquake. There was anticipation of the occurrence of the earthquake. However, not enough preparation effort was made. After the earthquake, preliminary assessment and response were conducted in different infrastructure sectors. However, there was a severe delay in long-term reconstruction planning. The redundancy in water and electricity sectors developed over time (e.g., water tanks and privately-owned generators) due to the supply-demand disparity has helped the infrastructure systems to cope with the effects of the earthquake. The research findings also reveal how the interdependencies between different infrastructure sectors affected the disaster response and recovery in Nepal. For example, in some parts of Nepal, roads were narrow and when buildings collapsed, many roads were inaccessible, which affected the recovery process in electricity and water sectors. The study has important implications for engineers and decision-makers as it identified the characteristics of infrastructure systems in Nepal that contribute to different resilience indicators. In addition, the systematic qualitative data analysis method and the resilience assessment framework proposed in this study provide new opportunities for disaster resilience studies in the future.

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CHAPTER I

INTRODUCTION

Natural disasters are often unpredictable and can cause loss of life, poverty issues, and damages to infrastructure systems which halts developments of a country (Hillier et al., 2013). Nowadays infrastructure systems, including water, power, transportation, and communication infrastructures, are exposed to an increasing number of natural disasters. As a community greatly relies on those critical infrastructure systems, the damages of fundamental infrastructures due to disasters could significantly affect the quality of life and economic prosperity (Berkeley III et al., 2010; Rinaldi et al., 2001). The issue is becoming more serious with the increase in the frequency of natural disasters caused by global climate change (Bouwer, 2011). Literature suggests that the level of infrastructure resilience affects the severity of impacts from disasters (Escaleras & Register, 2016). With this in mind, improving infrastructure resilience against natural disasters will lessen the repercussions.

Although there are many existing literatures on infrastructure resilience (e.g. Matthews, 2016; Berkeley III et al., 2010), there are two important knowledge gaps in this research filed. First, there is a lack of an integrated framework that includes different resilience indicators of infrastructure systems, which can facilitate the assessment of infrastructure resilience using qualitative data. This kind of framework is extremely important in providing a better understanding of infrastructure resilience in developing countries. Many of the existing studies of infrastructure resilience are in the context of well-designed and well-maintained infrastructure systems with adequate serviceability in business-as-usual conditions in developed countries. For this kind of infrastructure systems, large amount of quantitative data related to the operation and restoration of infrastructure is available, and thus, outcome-based assessment can be conducted. However, in many developing countries where quantitative data of infrastructures are not available or reliable, an integrated framework for resilience assessment based on qualitative data is needed. Another knowledge gap in existing studies is the understanding on infrastructure interdependencies and how they affect infrastructure performance. Urban infrastructures are interdependent systems (Yazdani & Azizi, 2016). A collapse in one sector of infrastructure may lead to a failure in another sector. An example is the California energy crisis, where the shortage of electricity supply affected production and operation of gas and fuel as well as the operation of few pumps in water distribution (Chen et al, 2009). It is important to view the system as a whole, where improving one sector leads to the another's operating success. Different types of interdependencies in infrastructure systems have been investigated in existing studies (e.g., functional, physical, resource, technical information, input-output) (Yazdani & Azizi, 2016; Zhang & Peeta, 2010). However, an integrated framework for identification and analysis of interdependencies between different infrastructure systems based on qualitative data is still missing.

To address the abovementioned knowledge gaps, an integrated framework for assessment of resilience in interconnected infrastructure systems is proposed and examined in a case study of 2015 Gorka Earthquake in Nepal. In the next few sections, this paper outlines the research context, framework, methodology, research findings, and conclusion.

CHAPTER II

RESEARCH CONTEXT

Nepal is situated on the Mediterranean-Himalayan seismic zone, making it susceptible to earthquakes (Zhao, 2016). On April 25, 2015 Nepal experienced a 7.6 magnitude earthquake resulting over 8,790 casualties and 22,300 injuries (as of June 2015) followed by more than 300 aftershocks greater than a 4.0 magnitude (National Planning Commission, 2015). The earthquake impacted almost one-third of the population and more than half a million houses were destroyed (National Planning Commission, 2015).

In the infrastructure sectors the most affected ones based on damages and losses costs are: electricity, transport, and water and sanitation (Table 1). This paper focuses on these three sectors.

Table 1: Disaster Effects of Gorkha Earthquake on Nepal Infrastructures (Source: National Planning Commission 2015)

Infrastructure Sectors	Disaster Effects (NPR million)		
	Damages	Losses	Total
Electricity	17,807	3,435	21,242
Transport	17,188	4,930	22,118
Water and Sanitation	10,506	873	11,379
Communication	3,610	5,085	8,695
Community Infrastructure	3,349	-	3,349
Total	**52,460**	**14,323**	**66,783**

CHAPTER III

FRAMEWORK

In this study, we proposed an integrated framework to assess resilience in interconnected infrastructure systems. The proposed framework includes two components: (1) indicators of infrastructure resilience; and (2) interdependencies between infrastructure systems.

Indicators of Infrastructure Resilience

The main indicators of resilience used to link the data found in Nepal are: vulnerability, anticipation, adaptive capacity, redundancy, adaptive capacity, resourcefulness, cross-scale interaction, learning culture, and rapidity (Table 2). The eight indicators were identified and selected from a range of existing studies (Bruneau et al., 2003; Berkeley III and Wallace, 2010; Cabinet Office, 2011; Francis and Bekera, 2014; Shirali et al., 2016) with the aim to develop a set of indicators that can effectively capture and categorize important characteristics that contribute to resilience performance of infrastructure systems.

Table 2: Description of Indicators of Resilience

Indicators of Resilience	Description
Vulnerability	• Measured by how exposed and susceptible the infrastructure is before any impact of natural events (Ezell, 2007) • Use of vulnerability indicator allows one to evaluate if the pre-existing infrastructure is adequate to endure impacts of natural disasters
Anticipation	• Whether the infrastructure was built to withstand a natural event
Rapidity	• Defined as the capacity to meet priorities and achieve goals promptly (Bruneau et al., 2003) • Ability to quickly restore operations (Berkeley III, 2010)
Adaptive Capacity	• Adjust and respond to new situations (Widener et al., 2017) • Social factors of adaptive capacity include knowledge, ability to perceive and understand responses, and access to a greater diversity of knowledge (Ballester & Lacroix, 2016)
Redundancy	• Defined as the capability to meet operations although there are some disruptions within the system (Bruneau et al., 2003)
Resourcefulness	• Capability to maneuver materials and human resource when there's a disruption in the system (Bruneau et al., 2003)
Cross scale interaction	• Defined as the communication within the organization (Campanella & Gotham, 2011)
Learning culture	• Take considerations to future reconstructions

Interdependencies Between Infrastructure Systems

The component of infrastructure interdependencies in the proposed framework is based the study of Yazdani & Azizi (2016) (Table 3).

Table 3. Description of Types of Interdependencies

Types of Interdependencies	Description
Timing	• The chronological order between infrastructures (Yazdani & Azizi, 2016)
Information	• Information which is needed to relay to another sector in order to operate
Input-Output	• When a system is dependent on the output of another (Yazdani & Azizi, 2016)

CHAPTER IV

METHODOLOGY

This study follows a qualitative research approach. Qualitative data were collected from 45 in-depth interviews with 52 subject matter experts, who were involved in the response and recovery process of infrastructure systems and have rich knowledge of infrastructure conditions prior to the Gorkha earthquake. The subject matter experts include representatives from Nepal's local and national infrastructure agencies, international humanitarian agencies, and utility services in Nepal. Specifically, three infrastructure sectors were examined in these interviews: water supply, electricity, and roads.

The interviews were conducted during three visits to Nepal in September 2015, December 2015, and May 2016. The questions asked during the interviews are open-ended questions related to the pre- and post- conditions of infrastructure systems in Kathmandu Valley's, impacts of the earthquake on different infrastructure systems, response and recovery activities, challenges faced, and lessons learned. The questions were modified based on the time of the interviews. For example, the interviews conducted in September 2015 were more focused on the direct impacts of the earthquake and immediate response, while the interviews conducted in December 2015 and May 2016 had more questions related to recovery and reconstruction.

The following steps were taken in analysis of the data collected:

1. First, based on the proposed resilience assessment framework, a coding structure was developed for data analysis.
2. Recorded interviews were transcribed verbatim. Notes from the interviewers were used for generating complete text of interviews.

3. Using the coding structure, the transcribed interviews were examined for influencing factors that contributing to different resilience indicators. The coding was conducted using NVivo 11, a qualitative analysis software. Figure 1 showcase an example of the coding structure and nodes identified related to the resilience indicators in the water infrastructure sector in addition, different interdependencies between the three infrastructure sectors considered in this study were identified and coded.

   The coding activity was conducted by two researchers independently. The comparison between the coding results from the two researchers showed a high level of similarity (i.e., greater than 80% agreement in coding), Thus, the coding structure and process had an acceptable degree of validity (Miles & Huberman, 1994).

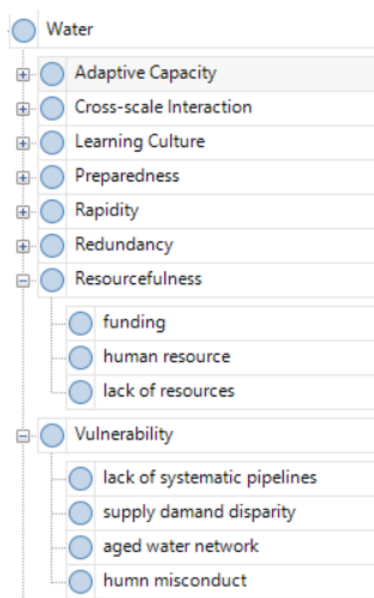

Figure 1: Node Structure in NVivo 11 for Water Supply Infrastructure

4. Fourth, after the interviews were coded, comparative analysis to identify and summarize common patterns and themes regarding infrastructure resilience and interdependencies.

CHAPTER V

RESEARCH FINDINGS

Water Supply Infrastructure

The Kathmandu Valley has a water supply system that is approximately 120 years old, maintained and operated by Kathmandu Upatyaka Khanepani Limited (KUKL) (Mostafavi et al., 2015). The system is composed of eight subsystems with approximately forty-five water reservoirs and seventy tube wells supplying water to the valley (Mostafavi et al., 2015). The distribution system consists of cast iron, ductile iron, galvanized iron, PVC and HDPE pipes but was in poor condition due to lack of maintenance (Mostafavi et al., 2015). KUKL faces challenges from the supply-demand disparity prior to the earthquake. The water system provides less than 100 million liters per day in the dry season and 150 million liters per day in the wet season but the demand is greater than 400 million liters per day (Mostafavi et al., 2015). The earthquake had caused disruption in the water supply however the demand decreased in the Kathmandu Valley because people migrating.

Vulnerability

The vulnerability of the water infrastructure system in Nepal is related to the condition of the infrastructure and supply-demand gap. Several interviewees talked about the aging problem of water infrastructure in Nepal. One interviewee mentioned that "*pipelines are very old, which makes them susceptible to leakages.*" Another leading factor for the infrastructure conditions is how the pipes were connected. According to the interviewees, many pipelines were loosely connected prior to the earthquake. Due to the impacts of the earthquake, the leakage problem worsened.

Anticipation

Kathmandu is an earthquake prone zone; its government recognizes that but lacks contingency plans according to several interviewees. However, one interviewee expressed that when designing the water distribution system, they had accounted for the forces of earthquakes. Due to this anticipation, *"the structures were not damaged completely and are just slightly cracked and damaged."*

Redundancy

Alternative water sources provided redundancy in Nepal. Prior to the earthquake, people relied on the water tanks, wells, bore hole, stone spout, and bottled water to address the supply-demand disparity according to several interviewees. After the earthquake, agencies were providing additional tank systems to camps and households as a result of water pipelines being unserviceable.

Adaptive Capacity

One interviewee stated, *"our water system was not a monolithic system."* Multiple approaches for supplying water in Nepal created the adaptive capacity in water supply infrastructure system, which makes the infrastructure less susceptible to full system failure. As a result of the earthquake, pipes were damaged and water could not be supplied from it. In order to adapt to the situation, water was supplied from tanks with the help of Red Cross and Norwegian agency. Another factor contributing to adaptive capacity that an interviewee brought into attention is the availability and accessibility of resources. An interviewee mentioned that they had stocks of pipes for construction of new projects. After the earthquake, they were able to utilize these pipes for reconstruction of the damaged sections immediately.

Rapidity

The prompt responses of organizations and agencies were hindered by several factors, such as limited financial resources and qualified work force. During the interview, an interviewee stated that they requested funds from the government to restore and maintain the damaged water infrastructure but have yet to receive any. Repairing water infrastructure also requires personnel with certain expertise. According to one interviewee, they do not have capable personnel to undertake the job and they had to hire outside the organization, which took the recovery process longer. Assessment of household water pipelines was also delayed because of the unknown condition of damaged house structures.

Resourcefulness

The water sector was challenged by the lack of resources in funding and work force, pointed out by several interviewees. Although agencies were aware of the damage, they could not immediately do repairs because of the lack of human resources. Recovery process in water supply system was also hindered by lack of funding. After the earthquake, the funding priorities were given to shelter and food supply issues.

Cross-scale Interactions

After the earthquake, large number of people from different backgrounds went to Nepal to help. It was challenging to coordinate them effectively. *"More than 100 agencies came to support us in the WASH sector,"* an interviewee said. Partnership established before the earthquake helped the cross-scale interactions in the face of disaster. One interviewee mentioned that Oxfam (an international confederation of charitable organizations focused on the alleviation of global poverty) coordinated with the Valley Tanker Entrepreneur Association and KUKL to agree that the private tankers could help deliver water.

Learning Culture

An interviewee stated that their organization will be preparing a contingency plan because of how prone Nepal is to earthquakes, landslides, and floods. Some people in that organization had experience abroad and used it to their advantage in the earthquake situation. The interviewee also expressed *"in the past we try to utilize local materials to the maximum level but we need to bring materials from the outside in order to make the structure earthquake-resistant."* However, another interviewee mentioned that despite the lessons learned from the earthquake, there is no separate budget for disaster management, which makes *"emergency preparation only in theory but not in practice."*

Electricity Infrastructure

Nepal Electricity Authority (NEA) supplies electricity through the national grid, generating power from hydropower and thermal as well as buying power from Independent Power Producers (IPP) (Zhu et al., 2017). This sector also faced supply-demand disparities, where load-shedding was used to meet demands (Sharma& Awal, 2013). The earthquake caused 800 km of distribution lines and 365 transformers to go out of service, damaged around 115 MW of operating hydropower facilities, and damaged around 1,000 MW of hydropower projects that were under construction (National Planning Commission, 2015).

Vulnerability

Because of the limited spacing between streets, many of the electricity distribution lines in Nepal were *"hanging at the wall of the house."* This issue was more pressing when houses collapsed, burying the distributions lines and making them inadequate to operate. Because of the lack of supply of energy, there is heavy presence of private sectors in Nepal's electricity infrastructure system. However, an interviewee stated that projects of the private sectors sometimes aren’t built within the same safety margins as large public project, resulting the electricity infrastructure in private sectors severely damaged. After the earthquake, 80 to 90 Megawatt out of the 200 Megawatt capacity of the private hydropower sector was out of service.

Anticipation

Based on the frequent number of earthquakes in Nepal, the Gorkha Earthquake was not a surprise to many people in Nepal. An interviewee from the electricity infrastructure sector said that they have started a disaster risk management system report before the Gorkha Earthquake happened. In the report, they have *“analyzed the prevailing practices and policies, identified gaps, and provided recommendations to improve resilience”* of Nepal’s electricity infrastructure.

Redundancy

Redundancy in Nepal’s electricity infrastructure was developed due to the supply-demand disparity. An employee from a hospital in Bhaktapur mentioned that they had their own generators prior to the earthquake. During the earthquake, the main electricity system was disrupted so that they used their own generators to sustain the operation in the hospital. Although hospital operations were not halted, the cost of fuel to operate the generators was expensive.

Adaptive Capacity

An issue faced by Nepal Electricity Authority (NEA) was the unknown condition of the distribution lines. Houses were in rubble, burying distribution lines and if power was restored into the system, it could trigger gas cylinders to explode. To address this concern, NEA sent personnel to isolate severely damaged distribution lines from the system and was able to resume supply to the non-affected areas safely in this way.

Rapidity

Having materials and personnel readily available assisted the rapidity of the response in Nepal's electricity infrastructure system. According to one interviewee, following the earthquake, a damage assessment was conducted to find out the situation of damages of power stations to restore power in Kathmandu. Then, the damages were repaired in a prompt manner. Two transformers were replaced in 3 to 4 days. Power was recovered within 5 to 6 days.

Resourcefulness

During the earthquake, some utility poles supporting electricity lines fell. According to one interviewee, authorities *"responded immediately by allowing them to utilize poles from other new projects"*. Insulators were also readily available to replace damaged ones, which helped restore the system in a timely manner. Although there were no significant challenges in the response and recovery phase due to the lack of materials, the electricity infrastructure sector did not have enough technical staff.

Cross-scale Interactions

As mentioned earlier, there was not enough technical staff in Nepal. However, experts from India helped resume the supply and restore the operation of transformers. Fortunately, communication systems were still operating, which allowed the experts in India to *"have the context of most power stations"* in order to help restore the power grid.

Learning Culture

The earthquake had revealed how unprepared the electricity infrastructure system in Nepal was for the event. Thus, people started considering on how to improve preparations in the design and operation phase of electricity infrastructure. One interviewee suggests to build structures underground as they have seen that *"structures exposed on the surface are more prone* *to damages caused by the earthquake."* They also see the need for a response guideline for the post-disaster management of the power system.

Road Infrastructure

A report published by Asian Development Bank in 2012 stated that in Nepal 32% of the designated Strategic Road Network (SRN) are paved, within that 32% only 90% are in good or fair condition. Fortunately, Nepal did not face any bridge collapses as a result of the earthquake. However, rural areas had accessibility issues because of landslides. In this study, there were limited interviews conducted with experts in the road infrastructure sector compared to the water supply and electricity infrastructure.

Vulnerability

Vulnerability in Nepal's road infrastructure is linked to lack of maintenance, design of the roads, and aging road infrastructure. Prior to the earthquake, many roads were not well maintained. An interviewee said that *"if the roads were well maintained, it would be easier to transport relief materials."* The roads in Kathmandu are very narrow. Thus, landslides due to the earthquake resulted in road blockage.

Anticipation

One interviewee mentioned that they knew they were in an earthquake-prone zone but *"lacked enough preparation for equipment like excavator, crane, dozer and helicopters."* Due to the lack of preparation, equipment was not immediately available to clear roads.

Redundancy

There were not many alternative routes in the area, which made accessibility to rural areas difficult when the roads were damaged.

Adaptive Capacity

Roads in some areas of Nepal were wide enough (20 to 25 meters) so that debris from falling buildings did not cover the entire roads. People who had their homes destroyed used these roads as temporary shelter places. *"The central portion of the roads opened for emergencies,"* stated by an interviewee.

Rapidity

Damage assessment of bridges within 100 kilometers from the epicenter was quickly surveyed followed by maintenance work, as mentioned by an interviewee. Highways were opened within 24 hours and was not a dominant problem. Urban areas took 15 days to clear roads of building debris caused by the earthquake. However, in some rural areas it took 3 to 4 months to clear the roads due to the lack of enough capability.

Resourcefulness

According to the interviewees, they did not have sufficient machines or resources to cope with the earthquake and urged the Government of Nepal to set aside funds for road repair and reconstruction such as funding for buying new equipment to help with the recovery from damages.

Cross-scale Interactions

One interviewee mentioned that Chinese government was interested in *"investing to recover and upgrade the existing roads as well as constructing new roads in Nepal."* Nepal's army also helped with clearing roads.

Learning Culture

The lesson learned from the earthquake has showed the value of expanding roads, so that the roads would wide enough for transportation when facing emergencies.

Water and Road Infrastructure Interdependencies

Based on the interviewees' responses, two types of interdependencies between water and road sectors were identified: *input-output* and *information*. Input-output interdependency exists between water and road infrastructure systems since the delivery of water through water trucks greatly depends on road accessibility. In places where roads were inaccessible, response and recovery efforts in the water system were delayed. In addition, the assessment of damages in water infrastructure was also affected in places where roads were inaccessible. The interdependencies between water and road infrastructure sectors is also reflected as information interdependency. The availability of information related to the accessibility to roads greatly affects the decision-making and route selection for water delivery using water trucks.

Water and Electricity Infrastructure Interdependencies

Input-output and *timing* interdependencies were observed in Nepal's water and electricity infrastructure sectors. Nepal's water distribution system relies on electricity to pump water sources and to fill transportable water tanks. An interviewee stated that *"50 to 60 percent of water is from groundwater sources and needs to be pumped."* Another interviewee mentioned that one area had a power outage for two days resulting the area to not have access to water supply. In terms of timing, since the electricity sector faces a supply-demand disparity and load shedding is one strategy to address the disparity, parts of the water sector were unable to operate 24 hours a day. Thus, the timing of load shedding may affect when water can be distributed.

Electricity and Road Infrastructure Interdependencies

Input-output and *information* interdependencies were observed between the electricity and road sectors. Response and recovery efforts of the electricity sector highly depend on travels to affected areas through roads. The response and recovery of electricity sector relies on information of where the damages are, especially in distribution lines that are under building debris. The road accessibility is critical for damage assessment and restoration in the electricity sector. The damage assessment activities were interrupted where landslides and road blockage occurred.

CHAPTER VI

CONCLUSION

The study proposed an integrated framework for assessment of resilience in interconnected infrastructure systems. Using the proposed framework, a case study of the 2015 Gorkha Earthquake was conducted to investigate the characteristics of infrastructure resilience as well as interdependencies between the water, electricity, and road infrastructure systems in Nepal.

The assessment results show that the vulnerability of Nepal's infrastructure systems are related to the age of the infrastructure, supply-demand gap, and lack of maintenance. Kathmandu Valley had water tanks and privately owned generators prior to the earthquake due to the supply-demand disparity. These redundancies developed over time helped the water and electricity sectors to cope with the effects of the earthquake. Although the infrastructure sectors anticipated the earthquake, they were not properly prepared for the earthquake because of limited resources in technical staff, funding, or proper equipment. The impacts of infrastructure interdependencies were prominent in electricity and water sectors as the water supply and distribution system relied on pumps powered by electricity. Narrow roads with collapsed buildings made streets inaccessible, which affected disaster assessments and recovery efforts in electricity and water sectors.

The case study identified the characteristics of infrastructure systems in Nepal that contribute to different resilience indicators which provides important implications for engineers and decision-makers. In addition, the systematic qualitative data analysis method and the resilience assessment framework proposed in this study provide new opportunities for disaster resilience studies in the future.

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