Road vulnerability assessment in earthquakes

A case study of Lalitpur, Kathmandu - Nepal

by
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Abstract

Vulnerability and damage assessment and physical losses of physical transportation infrastructure during earthquake is not fully and systematically developed. This study aims to assess roads and bridges vulnerability in earthquakes in Lalitpur, Kathmandu city-Nepal. The first part of the study reviews existing methods that have been used in physical vulnerability assessment. Road and bridge inventories of their existing condition are carried on during a field survey. Based on this data, roads and bridges are classified in terms of their characteristics and geographical locations. Vulnerability of road categories is assessed based on surface material (a RADIUS method) and liquefaction level at road locations. Damage states of the road and the bridge in a selected earthquake scenario are also evaluated. Comparison between results of the two methods is also mentioned. Road plays a significant role in evacuation in post earthquake emergency. In the second part, the study also looks at the function of road in post earthquake scenarios. The road is not malfunctioned by physical damage itself, but also by the blockage caused by collapsed buildings along the road. A methodology is developed to estimate the possibility of road blockage level. Factors of building collapse density, characteristics of the building, and relative distance between the building and the road are taken into the estimation. The study proposes a method to measure and to incorporate those factors. The found blockage levels consists of longitudinal and lateral blockages. The methodology is tested with real data of several neighborhoods in Lalitpur.

Keywords: Earthquake, road, bridge, vulnerability, physical damage, road function.

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ABBREVIATION

AASHTO	The American Association of State Highways and Transportation Official
BU	Bridge Unit in the Department of Transportation, Nepal
DoR	Department of Road - Nepal
GIS	Geographic Information Systems
HIMS	Highway Information Management System
IDNDR	International Decade for Natural Disaster Reduction
JICA	Japan International Cooperation Agency
NBCI	National Building Code of India, 1970
NSET	National Society for Earthquake Technology
PGA	Peak Ground Acceleration
PGD	Peak Ground Deformation
SA or **Sa**	Spectral Acceleration

1. Introduction

1.1. General introduction

Risk in developing countries due to natural hazards can cause serious effects to society. We are living daily in an environment that is confronted with tragic consequences due to negligence of urban risk management, resulting in disasters that could have been prevented.

Many cities have suffered from earthquakes during their developing history. The historical record of damaging earthquakes in Japan extends over 1,300 years. (Risk Management Solutions, 2000). In the Philippines, there is an average of five earthquakes a day, ranging from imperceptible to disastrous (Brown et al., 1991).

There have been many studies on risk assessment caused by natural hazards in urban areas. Besides losses of lives, losses related to lifelines like electric networks, water and sewage system network, transportation infrastructures are also remarkable

This study focuses on vulnerability assessment of transportation infrastructure (TI), because of three reasons:

- TI plays a crucial role in ensuring normal traffic circulation
- Since TI is spatially characteristic, TI vulnerability does not depend on itself but also on other types of infrastructure that spatially relative to TI: the TI vulnerability is spatially interactive and difficult to predict.
- TI is valuable asset and investment in TI requires a huge amount of money from society. The vulnerability assessment helps to reduce the risk of TI damages

Transportation infrastructure system has important spatial characteristics, because it connects different locations. For that reason, to deal with any infrastructure aspects, Geographic Information Systems (GIS) is a useful tool, since GIS is tailored to operate on spatial data and geographic analysis.

1.2. The road infrastructure in an earthquake context in Kathmandu, Nepal

Nepal is a land-locked country. There is only a very simple railway routes in the Western part, connecting Nepal and India, set up from 66 years ago by the Britain. A new railway that link Nepal to Kolkata will open until by March, 2004 (The Hindu, 2003). Airline transportation is also available, but mainly serves for passenger traveling, only. Therefore, the on-land routes still have been playing a principal role to transport of goods.

The on-land road system in Kathmandu valley can be categorized into following main types:

Main Access roads to Kathmandu City: Kathmandu valley almost completely relies on supplies from outside that are transported over very few roads that connect the Valley with India and China. Moreover, slopes along these roads have high potential to cause ground failures and land slides triggered by an earthquake (JICA, 2001).

Once an earthquake happens, these blocked roads can lead to the fact that the Valley is nearly isolated from the outside world (see Figure 1.1).

Figure 1.1: Main roads access to Kathamandu valleley

Roads inside of the Valley: The roads within the Valley play an important role in the connection and transportation of goods and persons among different parts of the Valley. However, the road is narrow and un-standardized. In fact, that it is quite difficult to classify the road network based on road width, mainly because no standard is applied for the construction (JICA, 2001). Figure 1.2 shows types of road width, which come from design drawings and field survey. Furthermore, many of the road sections are heavily damaged due to an increase in heavy vehicle traffic volume (JICA, 2001).

Bridges: According to a site investigation demonstrated by JICA, most bridges around the ring roads in Kathmandu valley and several other locations were seriously affected by scouring (JICA, 2001). As The Kathmandu valley, approximately 1300m above see level, is surrounded by high mountains (around 2500m above sea level). During rainy seasons, water from the mountains rush into rivers inside the Valley (see Figure 1.3). The foundation of the Manahara bridge was scoured by severe water flow in a flood in July, 2002. The severe river flow exposes the foundations of the bridges. The situation gets worse when almost major bridges in Kathmandu are mainly supported by bearing piers, which are directly placed on the weak foundation. Consequently, the weakening of the foundation structure indirectly influences the earthquake vulnerability of these bridges. As the bridge is considered as a critical component in a road system. Once the major bridges collapse, the whole network will be led to a disruptive situation.

Road class	Applied Width
Ring road	10.0m
Urban Road Major	12.0m
Urban Road Minor	4.0m
Urban Road Gravel	2.5m

Figure 1.2:Applied road width

(*Source*: JICA, 2001, pp. 51)

Figure 1.3: The Manahara bridge in the flood in July, 2002

Traffic volume in Nepal has been increasing significantly in last decade (see Figure 1.4). The traffic volume in the Kathmandu also increases simultaneously. However, statistics in passenger and goods, that are transported by road way system, have not been available, yet. According to Central Bureau of statistics 2002, there are only statistics in passenger and goods that are carried by air and railways. It means that there are still not comprehensive studies on the transportation system or this kind of transport mode is unplanned and out of state's control.

Besides, Nepal is a high disaster-prone country. During its history, there were a lots of earthquakes occurred. The Kathmandu city also experienced major earthquakes. The last great earthquake in this city came in 1934, M=8.4, caused a tragic disaster to lives, buildings and infrastructure in the Kathmandu valley. Recently, the earthquake in 1988, M=7.3, that occurred 168 km far from Kathmandu (Amateur Seismic Center, 2004), also caused a lot of damage.

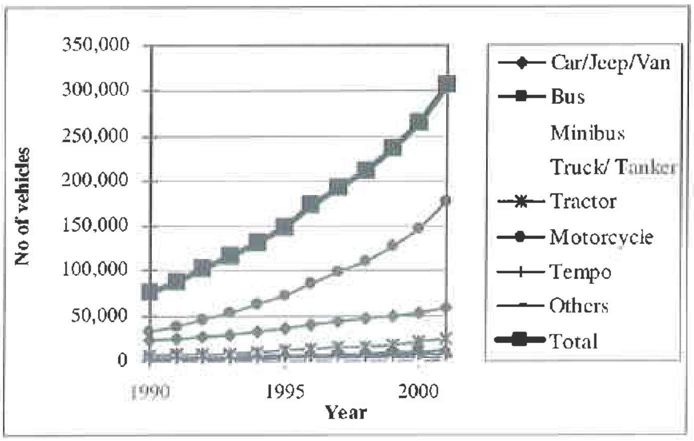


Figure 1.4: Vehicle cumulative registration

(*Source*: Department of transport management, Nepal-2002)

Unfortunately, there are not many documents, which recorded damages of the transportation system in Kathmandu in the past earthquakes. The Great earthquake in 1934 is the biggest one that was recorded, devastating Kathmandu, approximately destroyed 20 percent and damaged 40 percent of the Valley's building stocks (KVRRMP, 2004). Even the detailed information about the damage to the road system is not available, but based on estimation of building damages that was recorded (refer to Table 3.2), it can be imagined that the damage to the road system may be also very high, relatively compared to the existing road asset at that time.

The above overview shows that the on-land road system in Kathmandu is crucial to social-economic development of the Kathmandu city. Research on affect of an earthquake to the city when the whole city is isolated from the rest of the world is imperative, but it is a completely different study. This study only aims to assess road and bridge vulnerability caused by earthquakes.

To test the research methodology with real data, a southern part area of Kathmandu, a Lalitpur city, is used as a case study area.

1.3. Problem statement

As mentioned earlier, there are not many reported publications on the evaluation of vulnerability and risk assessment of road system, especially in developing countries. Some of the reasons are explained as follows:

- Most researches still have focused on the natural phenomena rather than on the study of its possible impact. (SLARIM, 2002)
- A road system is a highly valuable asset of a city and a road network plays a vital role in emergency operations. Thus, research about road vulnerability is crucial
- Most of the researches focus on risk assessment of buildings, whereas risk assessment of the others types of infrastructure is not well developed.

Furthermore, if the researches are conducted, they are mainly in developed countries. Meanwhile, in developing countries, although natural hazards occur frequently and seriously, their impacts still have not been well studied, yet. The city of Kathmandu, a capital of Nepal, is an example. There have not been many detailed studies in vulnerability assessment in a particular type of infrastructure like roads, bridges or water supply system etc... Therefore, this study aims to assess the vulnerability of the road and the bridge in an earthquake in the Lalitpur city.

1.4. Aim of the study

Vulnerability assessment in this study focuses on two important components of the transportation infrastructure system, namely roads and bridges. From now on, ***the road system terminology*** in this study stands for ***the road and the bridge***

The main objective of the research is to assess roads and bridges vulnerability in earthquakes.

1.5. Study objective

The followings are **three specified sub-objectives** of the research:

1. To determine factors that influence the vulnerability of the road system
2. To generate damage maps of the road system
3. To develop a methodology to estimate the debris blocking the roads

The above objectives come from identifying practical requirements of end users, including people living in an earthquake hit areas, local authorities, and urban planners. In both pre-earthquake preparedness stage and post-earthquake recovery stage, answers of all above sub-objectives are useful for local authorities. The urban planners will make use of answers of the first and second sub-objectives. People living in earthquake hit areas will gain most benefit from answers of the third sub-objective, since the level of road blockage significantly affects the effectiveness of evacuation activities in a post earthquake emergency.

1.6. Research questions

To achieve the research objectives, the study should be able to answer the following research questions:

For the first sub-objective:

1. Which features of the road systems can be taken into account into vulnerability assessment: type, location, or technical characteristics?
2. Which factors play important roles and are utilizable in determining the vulnerability of the road system? How to quantify these factors and visualize them in maps?
3. Which types of data/documents need to be used as input data? How to make optimum assessment with the limited amount of available data?

For the second sub-objective:

1. Which types of hazard maps can be used for generating risk maps: Modified Mercalli Intensity (MMI) maps, liquefaction maps, Peak Ground Acceleration (PGA) maps, or Peak Ground Deformation (PGD) maps?
2. How to generate the damage maps of the road and bridge based on road and bridge classification maps and hazard maps?

For the third sub-objective:

1. Which factors contribute to volume and distribution of debris of along the road in an earthquake? How to quantify these factors?
2. How to estimate the volume and the distribution of the debris? How to incorporate these data to road data to predict the blockage level of the road?

1.7. Study methodology

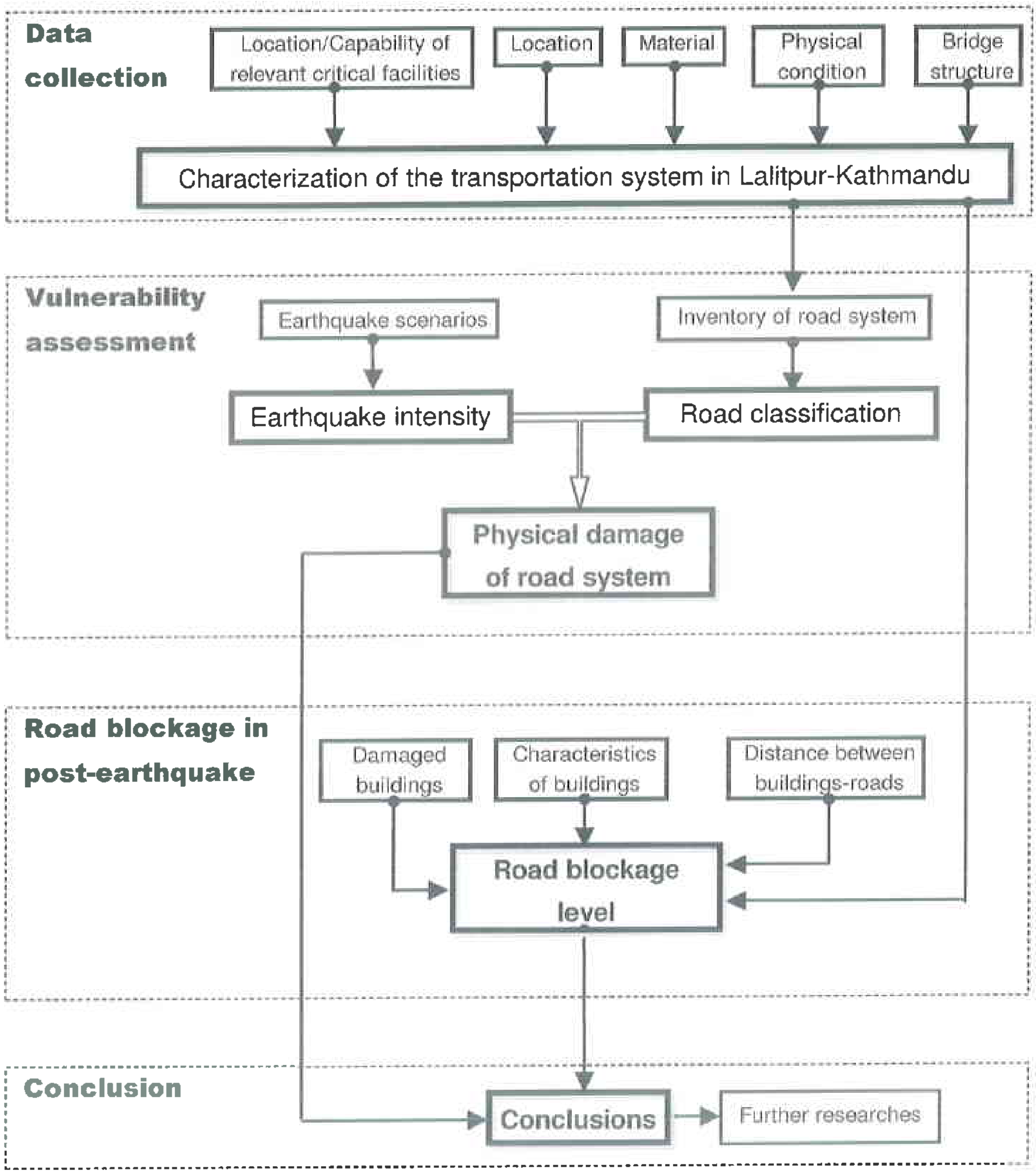


Figure 1.5: A flowchart of the research methodology

1.8. Expected outputs

The preliminary results should be answers for the research questions, namely:

- Factors that are used for the vulnerability assessment
- Damage states of the road and the bridge in an earthquake scenario
- Factors that contribute to the road blockage
- A methodology to estimate the road blockage level in an earthquake scenario

1.9. A structure of the report

Chapter 1: ***Introduction***
Chapter 2: ***Literature review***
Chapter 3: ***Lalitpur city, the case study area***
Chapter 4: ***Road vulnerability assessment***
Chapter 5: ***Post-earthquake function of road infrastructure***
Chapter 6: ***Conclusions and recommendations***

2. Literature review

This chapter includes three main parts:

- The first part reviews different types of TI
- The second part presents an overview of earthquake hazard and effects of the earthquake to roads and bridges
- The third part examines different methods used to assess the TI vulnerability

2.1. Transportation infrastructures

According to NIBS (1999) (pp.7-1), there are seven transportation systems: Highway, railway, light-rail, bus, port, ferry, and airport:

+ The highway system consists of roadways, bridges and tunnels.
+ The railway system consists of tracks/roadbeds, bridges, tunnels, urban stations, maintenance facilities, fuel facilities, and dispatch facilities.
+ The light-rail system, similar to railway system, includes railway tracks/roadbeds, bridges, tunnels, maintenance facilities, dispatch facilities and power substations.
+ The bus system consists of maintenance, fuel, and dispatch facilities.
+ The port system consists of waterfront structures (e.g., wharfs, piers and seawalls); cranes and cargo handling equipment; fuel facilities; and warehouses.
+ The ferry system consists of waterfront structures (e.g., wharf, piers and seawalls); fuel, maintenance, and dispatch facilities; and passenger terminals.
+ The airport systems consist of runways, control tower, fuel facilities, terminal buildings, maintenance facilities, hangar facilities, and parking structures.

The TI is basis structures that those systems are constructed on.

2.2. Earthquake hazard

2.2.1. Earthquake hazard and its induced hazards

According to the Oxford Advanced Learner's Dictionary (OALD, 2004), an earthquake is a sudden, violent shaking of the earth's surface.

The Longman dictionary (1995) (pp. 432) defines an earthquake as a sudden shaking of the earth's surface that often causes a lot of damage.

To identify the physical strength of an earthquake itself, there are two measurements: magnitude and intensity

Magnitude: Refers to the size of the earthquake and is a function of its energy release. Magnitude is an attribute of the earthquake itself, whereas ground motion intensity (see next paragraph), refers to the severity of shaking in the affected region (GeoRisk, 2004).

Intensity: Refers to severity of the ground shaking experienced at site. Given everything else is the same, a large magnitude and distant earthquake can cause the same level of ground shaking as a small yet closer earthquake. Ground motion intensity is site-specific, whereas the earthquake magnitude, is earthquake specific. It is a function not only of the earthquake magnitude and its distance to site, but on the site soil conditions and the orientation of the fault with respect to site, also known as directivity (GeoRisk, 2004).

To specifically identify the severity that an earthquake causes to elements at risk, there are several relevant terminologies are used: Liquefaction, Peak Ground Deformation (PGA), Peak Ground Deformation (PGD), spectral acceleration (SA), spectral velocity, and spectral displacement.

Liquefaction: Liquefaction is a soil behavior phenomenon in which a saturated soil looses a substantial amount of strength due to high excess pore-water pressure generated by and accumulated during strong earthquake ground shaking NIBS (1999) (pp. 4-27).

Another definition of the liquefaction: The phenomena in which saturated soils (usually loose sands) lose their bearing capacity and become fluid like "quick sand" during severe ground shaking. Structures built on liquefiable soils "sink" in and may even topple over (GeoRisk, 2004).

PGA: According to a United States Geological Survey (USGS, 2004), the peak acceleration is the maximum acceleration experienced by a particle during the course of the earthquake motion. Thus, PGA is the maximum acceleration of ground experienced by the particle during the course of the earthquake motion.

There is another PGA definition: PGA is a measure of the ground motion severity experienced at site due to an earthquake (GeoRisk, 2004).

PGD: The maximum displacement recorded on a displacement time history (GeoRisk, 2004).

SA: Is approximately what is experienced by a building, as modeled by a particle on a mass less vertical rod having the same natural period of vibration as the building (USGS, 2004). To identify SA, USGS (2004) describes as in an example: The mass on the rod behaves about like a simple harmonic oscillator (SHO). If one "drives" the mass-rod system at its base, using the seismic record, and assuming a certain damping to the mass-rod system, one will get a record of the particle motion which basically "feels" only the components of ground motion with periods near the natural period of this SHO. If we look at this particle seismic record we can identify the maximum displacement. If we take the derivative of the displacement record with respect to time we can get the velocity record. The maximum velocity can likewise be determined. Similarly for response acceleration also called response spectral acceleration, or simply spectral acceleration, SA (or Sa).

Spectral velocity: Refer to the above example, the spectral velocity is defined as derivation of the displacement record with respect to time.

Spectral displacement: Also from the above example, the spectral displacement of a infrastructure is illustrated as displacement of a modeled particle on a certain damping mass-less rod, which is driven on its base by the seismic record.

2.2.2. Effects of the earthquake and its induced hazards to TI

The intensity and amount of ground shaking caused by an earthquake depends on a distance to the earthquake, the magnitude, the depth of hypocenter, the rock types and structure soil between the

hypocenter and the site, and the local soil and topographical conditions. It is also noticed that in general the damage is always considered parallel with the type of hazard phenomenon.
Besides, an earthquake also causes induced hazards like tsunami, fire or landslide etc.., which sometimes are the reasons for many failures of infrastructure. The effects triggered by an earthquake sometimes causes more serious damages to elements at risk than the ground shaking of the quake itself.
There are various types of earthquake damage to different types of infrastructures. Because of the time constrains, only damages to roads and bridges are overviewed in this literature study. Furthermore, the study focuses on the vulnerability of the road and the bridge in an earthquake, so the review of damage to those kinds of infrastructure is the most essential.

2.2.2.1. Effects of an earthquake to roadway

An earthquake may harm road in various levels, ranging from minor cracks on the top surface to completely ruptured road structure

As in **Figure 2.1** in Tokachi-oki earthquake(M 8.1), Hokkaido, Japan in 2003. The road surface was damaged by slight deformation of sub-base layers. The deformation is about less than one inch. Along with crazing, long cracks also can be seen. Swallow pot holes also appeared, which caused by settlement of embarkation. These minor damages might not directly affect the function of the road, but indirectly degrade the road quality in a long term period. This damage requires slight maintaining activities.

Figure 2.1: Minor cracks on road surface

More seriously, an earthquake also severely defect the structure of road (see **Figure 2.2**).
Damage can be easily seen with big longitudinal cracks and rupture along the curb. The width of the crack may range from few inches to one foot. The reason is the sub-base layers and embarkation on the road side is not strong enough. This place is close to the aside natural ground, so the sub-bases layer slides to the right hand side when ground was vibrating during the quake. The concrete island nearby also was broken, caused by the settlement of sub-base layers below. The picture was taken in Hokkaido Toho-Oki earthquake (M 6.2), Japan in 1994

Figure 2.2: Severe defect on road surface

In the two above example of road damages, the road segments still play their function: vehicles are still able to travel on. However, there is also sometimes whole road section structure collapsed, so the road segment is completely malfunctioned, requiring to repair thoroughly or re-construct. **Figure 2.3** shows a completely damaged road segment in Hyogoken-Nanbu earthquake (Mw 6.8), (Kobe, Hanshin-Awaji) Japan in 1995. The structure bellow road surface was fully collapsed. The road surface is sharply divided into big plates. Some plates settled down of few feet.

Figure 2.3: Road structure collapses

The damage to road, that was mentioned above, are physical damages, more or less affects road function in different extents. There are also other types of effect that affect the road functionality, cause by induced hazard like landslide, tsunami or by debris felt onto the road surface.

Figure 2.4: Road blocked by landslide

Figure 2.5: Road blocked by house debris

In Figure 2.4, it can be seen that the road was blocked by landslide and trees falling down crossing the road section in Miyagiken-Hokubu earthquakes (M 6.2), Japan in 2003. The earthquake created stresses that make weak slopes fail. Even thought, the road surface is still in good condition. The road can be used again as long as the debris is removed. This type of damage usually is seen in mountainous or hilly areas.

There is another type of road blockage, happening in urban areas. Debris of other collapsed elements along the roads (house, electric post etc..) falls down onto the road. Similar to landslide, the road structure is not severely harmed, but only slight damage of road surface can be seen (at the low right corner of **Figure 2.5**). The road was un-passable for vehicles. The road is not only physically damaged, but also functionally damaged by other ruined types of infrastructure elements. The picture was taken in Chi-Chi (Ji-Ji) earthquake, Mw 7.5, Taiwan in 1999.

2.2.2.2. Effects of an earthquake to bridges

Damage to the bridge seems to give more attention to public than compared to the road. The collapsed bridge may also cause the loss of lives (travelling cars fall down or get accidents etc...when the bridges were collapsing). Once the bridge is damaged, it requires repairing activities intermediately, since the bridge usually play an important role in a road network (especially to over river bridges).

The types of damages to bridge are more various than compared to road: damage to pier, foundation, connection joints, surface etc...The damage level may also range from slight to extensive extent, or even full collapse.

Figure 2.6: Minor cracks on a pillar

Figure 2.6 shows minor cracks on the top of the column, where the column joints to the girder. These cracks do not seriously weaken the structure and make displacement of the abutment above. However, these defects are also needed to fix, preventing damage in the long-term use of the bridge. The crack may be a cause of rust for reinforce steel inside the column. The picture was taken in Erezinca earthquake (Ms 6.9) in Turkey in 1992

Bridge may be more seriously damaged. A quake can cause moderate movement of the abutment, extensive cracking, or moderate movement of the approaches. The damage more or less influences the strength of main structure, needs to be fixed instantly. Figure 2.7 shows moderate cracks at the main bearing pier of a bridge in the Tokachi-oki earthquake (M 8.1), Hokkaido, Japan in 2003. The cracks were fixed and the pier was retrofitted just the earthquake ends.

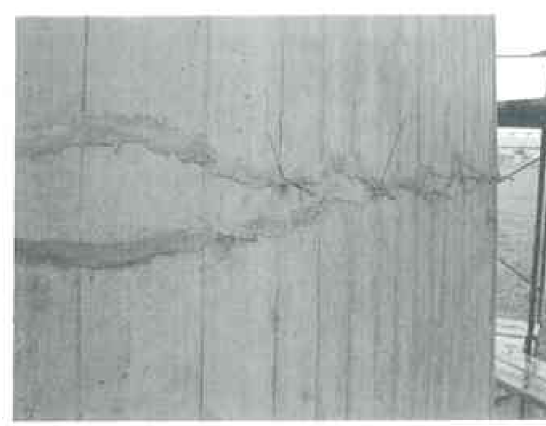


Figure 2.7: Cracks on main support

At the highest level of damage for a bridge, an earthquake may cause extensively damages or make the bridge completely collapsed. As shown in Figure 2.8, the bridge in the Kobe earthquake 1995 (M 6.8) had one span collapsed. The span felt out of bearing supports. That type of damage makes the bridge unusable and the bridge to be re-constructed or thoroughly repaired.

Figure 2.8: Bridge collapsed

2.3. Vulnerabilty assesstment

According to United Nation definitions (1991), vulnerability is a degree of loss to an element at risk resulting from the occurrence of a natural phenomenon and expressed on a scale from 0 to 1.

The physical infrastructure vulnerability describes the expected degree of direct damage to the physical infrastructure, given a specified level of hazard (Davidson, 1997) (pp. 40).

In general, the severity of structural damage is assessed as a damage ratio, i.e., the repair cost divided by the replacement cost, and structural vulnerability is portrayed using a vulnerability curve, or fragility curve (see Figure 2.9). A damage curve depicts the expected severity of damage associated with the level of hazard. The vulnerability of the individual structures can be assessed by applying the principles of criteria analysis (refer to Figure 2.10 for criteria for roads and bridges). The final vulnerability of a system (like a road system, a sewage system, etc.) could then be considered the aggregation of the vulnerability based on each criterion.

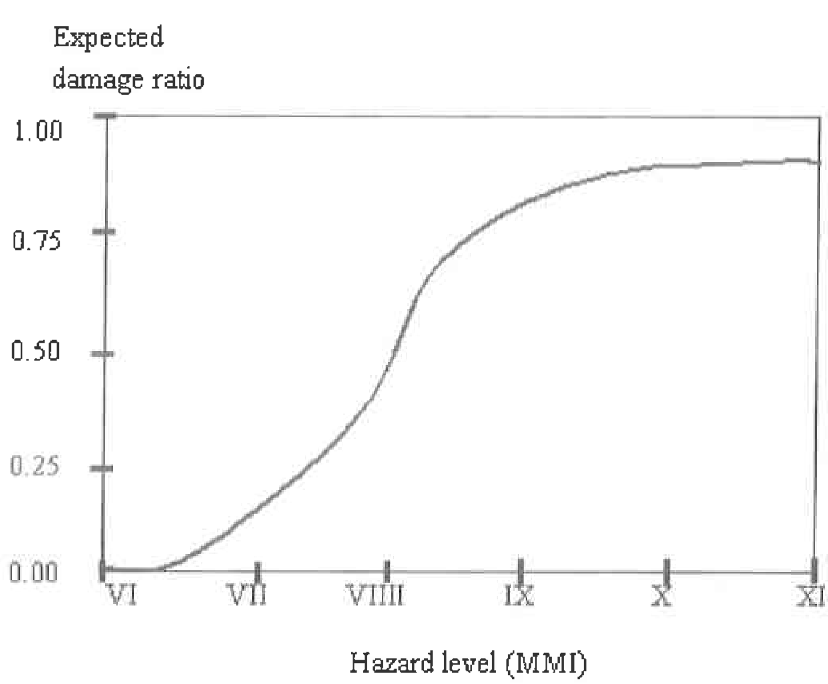


Figure 2.9: Schematic example of a damage curve (Based on NIBS, 1997)

2.4. General criteria for vulnerability assessment

There are several criteria used to determine the vulnerability of infrastructure components for roads and bridges:
The criteria for evaluating vulnerability are different for roads as compared to bridges. For instant, when considering the vulnerability of a bridge in a given earthquake scenario, we have to pay much concern about the structure and shape of the bridge. These criteria seem less important in road vulnerability assessment. Location of the roads is very important in their vulnerability assessment, since the roads usually cover large areas with various types of topography and geomorphology conditions. However, some infrastructure component includes typical characteristics of both bridge and roads like elevated roads or overpasses. In that case, their vulnerability assessment should be done based on all of the above criteria.

Road	Bridge
Location	Location
Structure	Structure
Design code	Design code
Physical condition	Shape (configuration)
Distance to structures (buildings, posts, electricity lines, overpasses) and the vulnerability of those elements. Embankment height Position (on ground level, or elevated, overpasses…	Structural continuity (joint type, span length, number of span) Embankment height
Age	Age
Material	Material

Figure 2.10: Criteria for vulnerability assessment of infrastructure

2.4.1. Structure

The vulnerability of an infrastructure component highly depends on its structure. The structure of the infrastructure component is the combination of element characteristics like shape, material, and structure connectivity (an example of a bridge, refer to 2.5.2.3). Nevertheless, when considering the strength of a structure, we have to take into account all those characteristics simultaneously. Some characteristics like design code, shape, and material, will be elaborated in next sections.

2.4.2. Design code

In general, the infrastructure that is designed according to anti-earthquake code will be stronger than that which is designed by conventional code in the same earthquake scenario. The anti-earthquake codes vary from countries to countries and is still under construction in many countries.

2.4.3.Shape or configuration

According to ATC-13 (1985), the effects of earthquake ground shaking depend on the specific response characteristics of the type of structural system used

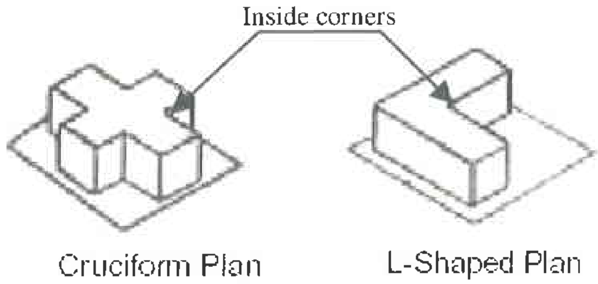


Figure 2.11: Examples of buildings with irregular configurations (ATC-13, 1985).

For example, in case of building, shape or configuration is important characteristic that affects building response. Earthquake shaking of a simple rectangular building results in a fairly uniform distribution of the forces throughout the building. In a more complex T or L shaped building, forces concentrate at the inside corners created by those shapes (see Figure 2.11).
Another important characteristic is the fundamental period of vibration of the infrastructure component (measured in seconds). The fundamental period of them depends in a complex way on the stiffness of the structural system, its mass, and its total height. Seismic waves with periods similar to that of the component will cause resonance, and amplify the intensity of earthquake forces the component must resist.

2.4.4.Material

Material is one of the main factors which determining the strength of the structure (especially in bridge structure). For instance, steel structure bridges perform better than un-reinforced masonry bridge. As the steel usually is highly capable of standing for repeated loads. The structure made by elastic material (e.g. metal wire, high tension cable) is also has lower vulnerability to earthquake load compared to which made by frangible material (e.g. concrete).
There have not been many studies about effect of a foundation of bridges to their vulnerability, although all earthquake loads always impact on foundation before shocking the above structure. It may be explained that foundation aspect itself is very complex and already consists of uncertainties.
The vulnerability that is assessed in terms of "strength of structure" is purely technical. However, strengthening a structure will increase the cost of construction, so higher their vulnerability should be evaluated in association with economic aspects. For that reason, a cost benefit analysis must be involved with the aim of reducing the vulnerability.

2.4.5.Age

In general, new infrastructure components sustain less damage than older ones if they are similar in design and material. Due to the fact that in the new one, material connectivity (in roads and bridge) or structure connectivity (based on good joints of bridges) can allow the roads or bridges to work with their maximum capacity as designed. For example, a new bridge has good joints connecting spans, then an earthquake force pushing on one pier can be transmitted to other piers through the joints. Than every piers suffer a less strong force. In the old one, if a connecting point does not work properly, the forces can not be well transmitted from one pier to others. Then, the whole bridge might be collapsed by the only one ruined pier, which was directly suffered from the earthquake force.

The age parameter can be qualitatively evaluated by a field survey. Age is used in association with other factors. For example, a field survey team assesses that a bridge was very old, than they can be sure that the bridge was not seismic designed (at the time that the bridge was constructed, the seismic design code had not been issued, yet). That may lead to evaluate that the bridge is earthquake vulnerable in terms of design code

There are several methods developed to assess the vulnerability. Some methods use a few of the above criteria, some use more other criteria. Details of these methods will be reviewed in 2.5.

2.5. Existing methodologies of vulnerability assessment

The methods range from very simple to very complex and data demanding. There examples of these extreme are given below:

- A method developed by JICA (2001)
- A methods developed by Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters (RADIUS) Program (RADIUS, 1996)
- A method of HAZUS developed by Federal Emergency Management Agency (FEMA) and the National Institute for Building Sciences (NIBS, 1999)

Vulnerability assessment for the road and the bridge are different and explained separately by each methods, respectively.

2.5.1. Road vulnerability

2.5.1.1. The method developed by JICA

The method was developed based on a study on Earthquake Disaster Mitigation (SEDM), which was conducted by Japan International Cooperation Agency (JICA) for Kathmandu. Road inventory maps were produced for whole Kathmandu valley and put into GIS database. The database also includes four earthquake scenarios with MMI maps, PGA maps, and liquefaction maps etc... accordingly. Roads are classified into different categories, which referred to The Nepal Road Statistics (JICA, 2002) (Vol. 3, pp. 50-51). The separate classification for ring roads was included considering its greater importance from an earthquake disaster viewpoint:

+ National highway
+ Feeder road, major
+ Feeder road, minor
+ District road bituminous
+ District road gravel/earthen
+ Ring road (additional class in this project: DoR classification in Urban Road)
+ Urban road major (Only Urban Road in DoR classification)
+ Urban road minor
+ Urban road gravel

Roads cross slopes more than 50m high (relative height from recent river bed) were taken as hazardous points (JICA, 2002) (Vol. 1, pp. 87). It is considered that a road segment likely to blocked/damage at slope failures. The example of hazardous map on classified roads are shown in the Appendix 1.

The method that proposed by JICA in the SEDM is a city oriented study. The vulnerability of roads are simple, based on road classification. The classification is based on function of roads, and the importance of the road in an earthquake scenario is also considered.
The vulnerability is evaluated simply based on probability of unstable slope failure, not on structure of the road itself. In physical sense, it is rather not logical. The asphalt roads might be physically damaged as same as to earthen roads if they suffer the same landslide/slope failures. However, if both types suffer the same Peak Ground Deformation, the asphalt road will certainly be less damaged than the earthen road. As strength of basement and surface of the asphalt road is higher than that of the earthen road.
Since the hazardous points are only ones have height greater than 50m (relative height e to a given landmark), if the method is applied in a gentle slope area (like Lalitpur metropolitan city), there is not any hazardous point at all (see Appendix 1- Figure 8.2). The method needs to be modified to make it applicable to individual city.

2.5.1.2. The method developed by RADIUS

The RADIUS project was launched by the IDNDR Secretariat to promote worldwide activities for reduction of seismic disasters in urban areas, particularly in developing countries. One of the main objectives of the project was to develop practical tools for urban risk management (Villacis and Cardona, 1999). The methodology of RADIUS for building losses can be divided into 10 steps (Westen, 2003) (pp. 1-10) as in Figure 2.12. The calculated unit is ward level.

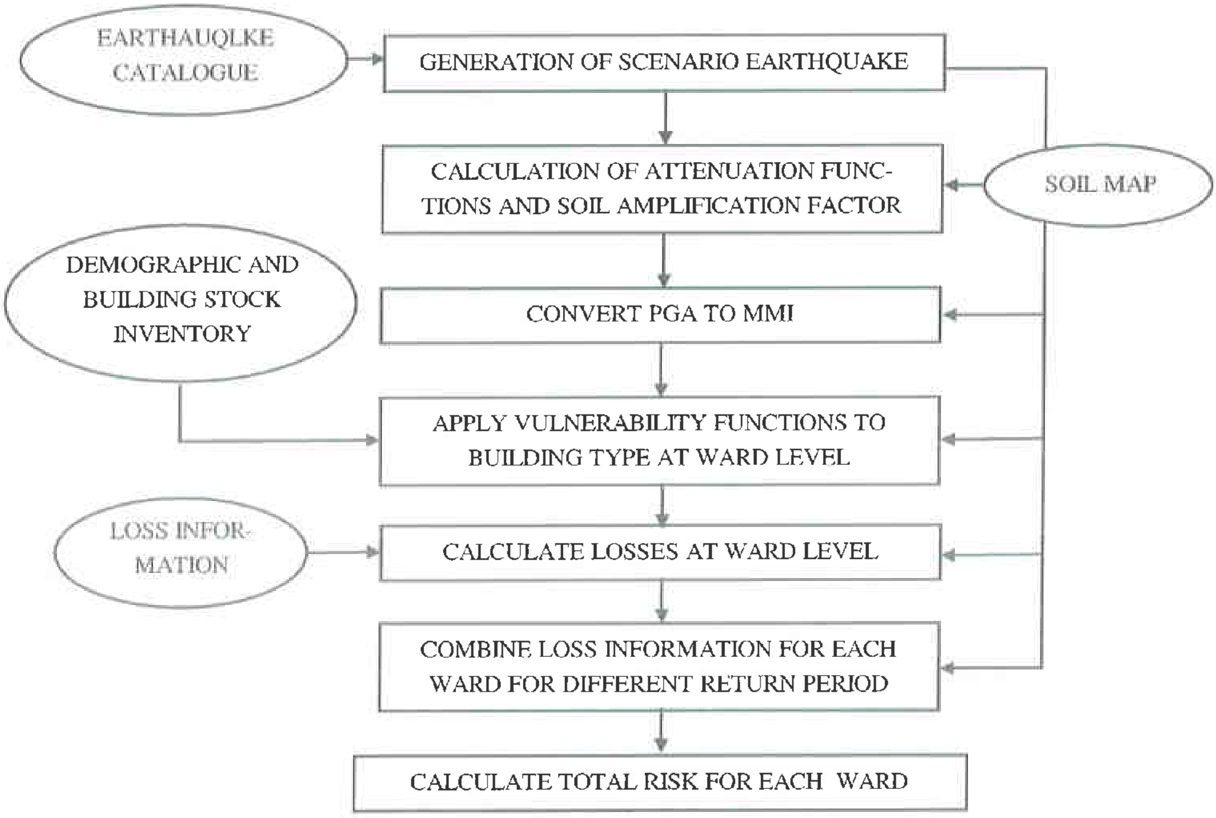


Figure 2.12: Schematic diagram of the RADIUS method (Westen et al., 2003) (pp. 1-10)

Step 1: Defining earthquake scenario. Location of epicenter, magnitude and depth
Step 2: Calculate the attenuation using the function of Joyner & Boore (1981)

Step 3: Calculate the amplification due to local soil conditions using the soil map.
Step 4: Convert the Peak Ground Acceleration to Modified Mercalli Intensity
Step 5: Apply Vulnerability Functions for Building types
Step 6: Apply Vulnerability Functions for Infrastructure types
Step 7: Apply Vulnerability Functions for casualties
If additional information on costs and the PGA value for different return periods is available, the analysis could be extended with the following steps:
Step 8: Apply cost information to the buildings and combine with vulnerability to calculate losses for different return periods.
Step 9: Combine loss information for different return periods and calculate the risk by adding up the losses from these periods.
Step 10: Combine information and make summary

The vulnerability function used in step 6 is generated from vulnerability assessment, including two steps (Villacis and Cardona, 1999):
-First, identify all the existing structural and infrastructural types of the city and then select representative ones.
-Second, existing vulnerability functions for the selected types are calibrated using data of past observed damage as well as the opinions and/or studies of local experts. For important and critical facilities, individual vulnerability studies are carried out.
The vulnerability functions used by RADIUS (e.g. for lifelines) is shown in Figure 2.13 (RADIUS, 1996). Roads are simply classified into two type: asphalt and non-asphalt road. Percentage of damaged road length per total road length corresponding to the MMI value is calculated from the damage curves. The method does not show where is the location of the damaged road.
This method is easy to use (using MS Excel 97). Recovery functions are also generated as final results. However, collecting data of all existing structural and infrastructural types of the city requires a period of time. Next, the result more or less is influenced by choosing a representative one. It will be come unfeasible if there has not been any observation of past earthquakes of there has not been any major earthquake happened to the city. Since the RADIUS method is a city oriented one, so the application of RADIUS is various from city to city. Those criteria were selected based on individual city. That may cause un-

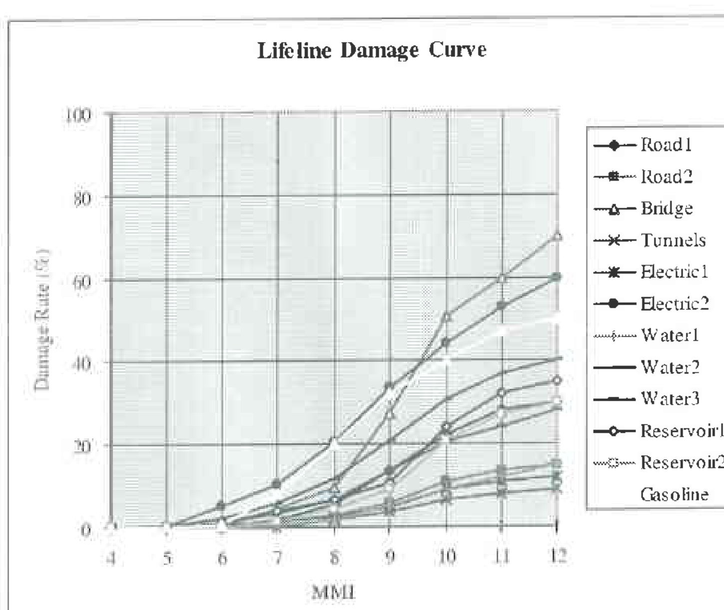


Figure 2.13: Damage curves for lifelines

unique selections in different city, producing different vulnerability functions for the same type of infrastructure component in different cities.
The hazard parameter used in vulnerability function is MMI. However, MMI is inherently subjective because it is based on descriptive measures of damage to furniture, chimneys, and buildings, whose performance may vary greatly from one part of the world to another for the same level of ground shaking.

2.5.1.3. The method developed by HAZUS

According the HAZUD method, roadways are classified as major roads and urban roads. Major roads include interstate and state highways and other roads with four lanes or more. Parkways are also classified as major roads. Urban roads include intercity roads and other roads with two lanes.
Damage functions or fragility curves (or vulnerability functions) for road are modeled as log-normally distributed functions that give the probability of reaching or exceeding different damage states for a given level of ground motion or ground failure (see Figure 2.14). Each fragility curve is characterized by a median value of ground motion or ground failure and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of Peak Ground Acceleration (PGA) and Spectral Acceleration (Sa), and ground failure is quantified in terms of Permanent Ground Displacement (PGD). For roadways, fragility curves are defined in terms of PGD (NIBS, 1999) (pp. 7-4).

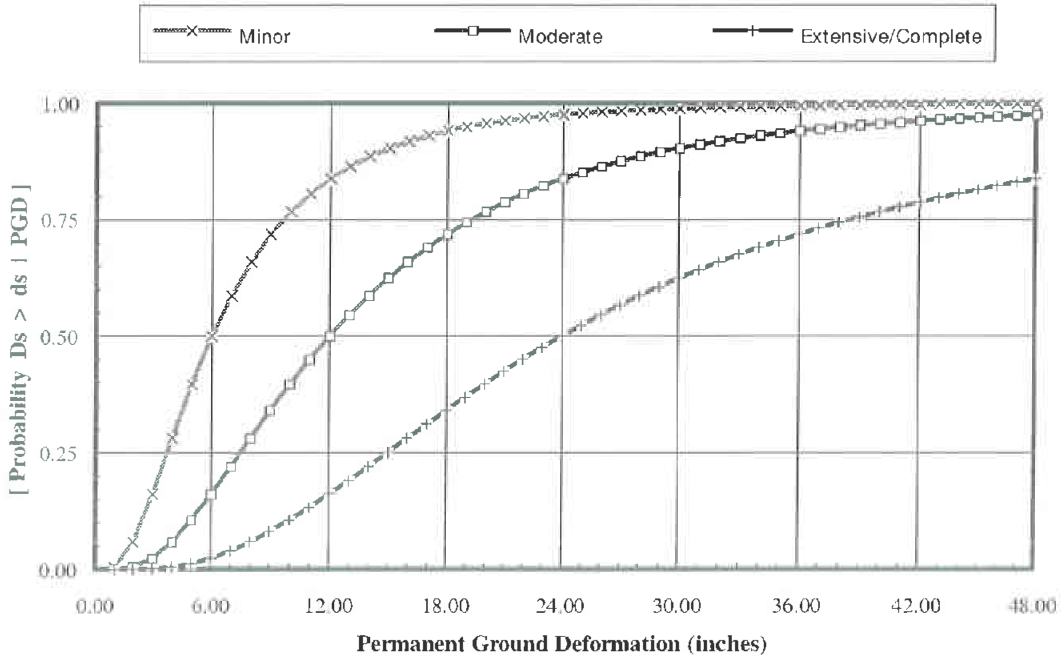


Figure 2.14: Fragility Curves at Various Damage States for Urban roads.

Where:

ds: Displacement at a given ground motion/failure

Ds: Displacement expected.

PGD: Peak Ground Deformation

The method does not take into account the road condition (material, width, existing condition etc). Furthermore, the classification of urban road in HAZUS is not able to applied directly to other cities (especially cities in developing countries). As the criteria, that used for road classification, are various from city to city.

The hazard parameter used is PGD, so this method requires technical data (compare to MMI parameter used in the RADIUS). However, the HAZUS method seems more logical and reliable, since observation from past earthquakes shows that roads are most probably damaged by ground failure.

2.5.2. Bridge vulnerability

2.5.2.1. The method developed by JICA

Similar to road vulnerability assessment (refer to 2.5.1.1), the method used is multi-dimensional qualification theory, based on an actual earthquake and highly practical. The bridges are also categorized into different types based on the following factors (JICA, 2002) (Vol. 3) (pp. 49):

+ Ground type (0.5-1.8)
+ Liquefaction (1.0-2.0)
+ Girder type (1.0-3.0)
+ Number of individual girder (1.0-1.75)
+ Bearing (0,6-1.15)
+ Minimum bridge set width (0.8-1.2)
+ Maximum height of abutment a and pier (1.0-1.7)
+ Earthquake intensity scale (1.0-3.5)
+ Foundation type (1.0-1.4)
+ Material of abutment and pier (1.0-1.4)

+ The number in parenthesizes are the score range for each factor according to the bridge condition. The score of each factor is decided by the field reconnaissance of the study team. The result of the analyses are expressed the product of ten score, one for each category. Judgment of the stability of bridges is generally defined as follows:
  + Score 26 and above: Collapsed
  + Score below 26: Stable

Noticeably, the method does not take scouring into account, though excessive scouring will reduce earthquake resistance because piers will have lower resistance to lateral forces.

There are two hazard parameters are included in the analysis: liquefaction and earthquake intensity scale.

Two other factors like damages in past earthquakes and age of bridges are not directly scored. Those factors can be involved in the analysis based on the field survey of the study team.

The result after applying the method is Boolean value: Collapsed or Stable. It sometimes does not cover all damage type to the bridge: minor, moderate or extensive damage.

2.5.2.2. The method developed by RADIUS

Similar to road vulnerability assessment (refer to 2.5.1.2), percentage of damaged bridges per total bridges are calculated based on the damage curves in Figure 2.13. The RADIUS method only shows the number of damaged bridges based on the earthquake intensity MMI, regardless of the bridge characteristics. Location of damaged bridges were not identified. Essential bridges (bridges connecting ring road, highways, etc…) require individual evaluation. The vulnerability assessment of these structures cannot be considered through the use of vulnerability functions, which are used to obtain a general, average description of damage (Villacis and Cardona, 1999).

2.5.2.3. The method developed by HAZUS

In the HAZUS approach, the bridges are categorized based on structure (design code, material, shape, etc,..). The HAZUS method is a purely technical method, based on valuating the respond of structures under an earthquake. This method requires a large amount of technical input data, which were not always available, especially in developing countries.

To identify the damage function, there are 28 primary bridge types for which all four damage states (minor, moderate, extensive, and collapsed) are identified and described. For other bridges, fragility curves of the 28 primary bridge types are adjusted to reflect a diminished or improved level of expected performance (NIBS, 1999) (pp. 7-11 to 7-21). A total of 224 bridge damage functions are obtained, 116 due to ground shaking and 116 due to ground failure.

Medians of these damage functions are given in Table 8.2 in Appendix 1. The dispersion is set to 0.4 for the ground shaking damage algorithm and 0.2 for the ground failure damage algorithm. Only incipient unseating and collapse (i.e., which correspond to extensive and complete damage states) are considered as the possible types of damage due to ground failure. That is, initial damage to bearings (i.e., which would correspond to slight and/or moderate damage states) from ground failure is not considered. The fragility curves for Conventionally designed major bridges and Seismically designed Major bridges shown in graphs in Figure 2.15 and Figure 2.16 (NIBS, 1999) (pp. 7-21):

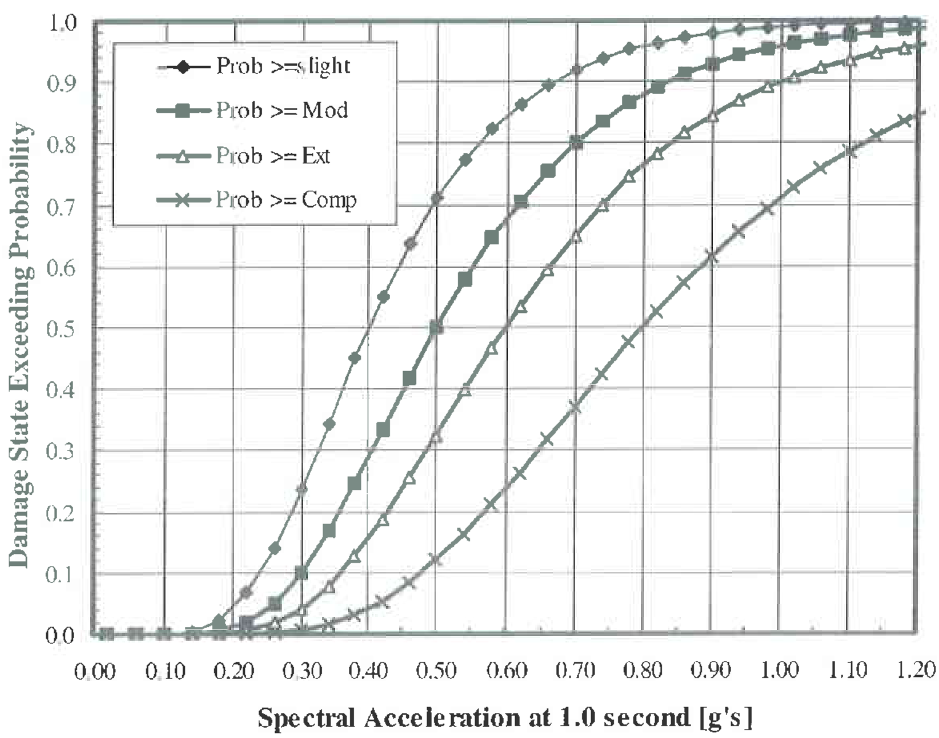


Figure 2.15: Fragility Curves for Conventionally Designed Major Bridges (HWB1).

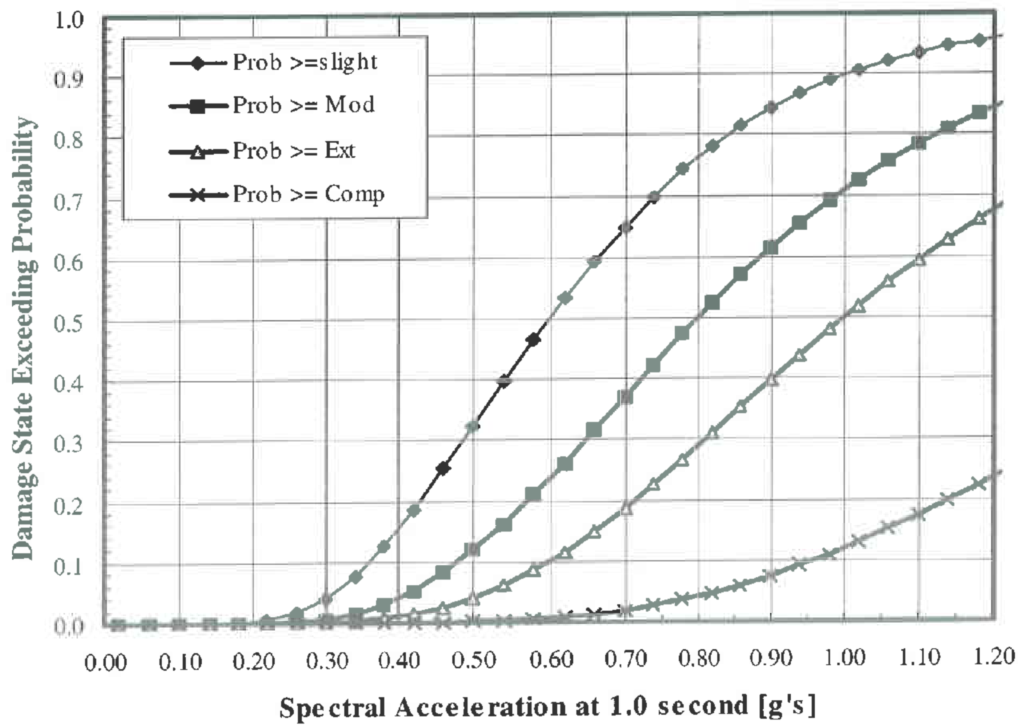


Figure 2.16: Fragility Curves for Seismically Designed Major Bridges (HWB2).

From the graphs above, we note some differences in the shape of the curves:

- There is little difference between slight curves for conventionally designed and seismically designed bridges. Thus, bridges designed according to anti-seismic code still suffer slight and moderate damage, although to a lesser degree than conventionally designed bridges.
- The difference is clearer between moderate/extensive damage curves in conventional design and seismic design. So, the seismic design code is effective in reducing the moderate and extensive damage of bridge
- The curve for complete damage in two figures is completely different. Thus, in case of a severe earthquake (significant number of bridges sustains complete damage), the seismic design code is very effective in minimizing the number of collapsed bridges.

The remarks made above indicate that the vulnerability of a bridge depends on the design code. The proper anti-seismic design can significantly decrease the number of extensive and complete damages to bridges in the event of an earthquake.

The damage algorithm for bridges can be broken into seven steps:

Step 1:

Get the bridge location (longitude and latitude), class (HWB1 through HWB28), number of spans (N), skew angle (α), span width (W), bridge length (L), and maximum span length (Lmax). Note that the skew angle is defined as the angle between the centerline of a pier and a line normal to the roadway center line.

Step 2:

Evaluate the soil-amplified shaking at the bridge site. That is, get the peak ground acceleration (PGA), spectral accelerations (Sa[0.3 sec] and Sa[1.0 sec]) and the permanent ground deformation (PGD).

Step 3:

Evaluate the following three modification factors:

K_{skew} = sqrt[sin(90-α]

K_{shape} = 2.5 x Sa(1.0 sec) / Sa(0.3 sec)

K_{3D} = 1 + A / (N – B)   A and B are read from Figure 2.17

Equation	A	B	K_{3D}
EQ1	0.25	1	1 + 0.25 / (N – 1)
EQ2	0.33	0	1 + 0.33 / (N)
EQ3	0.33	1	1 + 0.33 / (N – 1)
EQ4	0.09	1	1 + 0.09 / (N – 1)
EQ5	0.05	0	1 + 0.05 / (N)
EQ6	0.20	1	1 + 0.20 / (N – 1)
EQ7	0.10	0	1 + 0.10 / (N)

Figure 2.17: Coefficients for Evaluating K_{3D}

Step 4:

Modify the ground shaking medians for the "standard" fragility curves in Table 8.2 as follows:

New Median [for slight] = Old Median [for slight] x Factor slight

Where

$Factor_{slight}$ = 1 if I_{shape} =(I_{shape} is read from Table 8.3)

or $Factor_{slight}$ = minimum of (1, K_{shape}) if I_{shape} = 1

New median [moderate] = Old median [for moderate] * (K_{skew}) * (K_{3D})

New median [extensive] = Old median [for extensive] * (K_{skew}) * (K_{3D})

New median [complete] = Old median [for complete] * (K_{skew}) * (K_{3D})

Step 5:

Use the new medians along with the dispersion β = 0.4 to evaluate the ground shaking-related damage state probabilities. Sa(1.0 sec) is the parameter to use in this evaluation.

Step 6:

Evaluate the ground failure-related damage state probabilities. Note that the PGD medians listed in Table 8.2 will need to be adjusted as follows:

New PGD median [for slight] = 'Table7.7' PGD median [for slight] x f_1

New PGD median [moderate] = 'Table7.7' PGD median [for moderate] x f_1

New PGD median [extensive] = 'Table7.7' PGD median [for extensive] x f_1

New PGD median [complete] = 'Table7.7' median [for complete] x f_2

Where f_1 and f_2 are modification factors that are functions of the number of spans (N), width of the span (W), length of the bridge (L), and the skewness (α) and can be computed using the equations in Table 2.1. The skew angle is defined as the angle between the centerline of a pier and a line normal to the roadway centerline

Table 2.1: Modifiers for PGD Medians (NIBS, 1999)

CLASS	f_1	f_2
HWB1	1	1
HWB2	1	1
HWB3	1	1
HWB4	1	1
HWB5	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB6	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB7	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB8	1	sin (α)
HWB9	1	sin (α)
HWB10	1	sin (α)
HWB11	1	sin (α)
HWB12	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB13	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB14	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB15	1	sin (α)
HWB16	1	sin (α)
HWB17	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB18	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB19	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB20	1	sin (α)
HWB21	1	sin (α)
HWB22	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB23	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB24	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB25	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB26	1	sin (α)
HWB27	1	sin (α)
HWB28	1	1

Step 7:
Combine the damage state probabilities and evaluate functionality of bridge.

2.6. Conclusions

This chapter overviews different types of infrastructure, including the their main infrastructures and auxiliary facilities.
There are two measurements used to identify the physical strength of an earthquake: magnitude and intensity. The magnitude refers to the size of an earthquake and is a function of its energy release. The intensity refers to severity of the ground shaking experienced at site.

Transportation infrastructures are not only damaged by an earthquake itself, but also by earthquake induced hazards. The main reasons that cause damages to roads and bridge are the deformation and movement of the ground. To estimate damage levels of roads and bridges, several earthquake terminologies are used to present the characteristics of the deformation and movement of the ground like: PGD, PGA, SA, spectral velocity and spectral displacement.
Physical vulnerability of infrastructure is the expected as degree of direct damage to the physical infrastructure, given in a specified level of hazard. Generally, the physical vulnerability is portrayed by vulnerability curves, depicting the expected severity of damage associated with the level of hazard.
Several criteria that are used to develop the vulnerability curves for roads and bridges. These criteria depend on physical characteristics of the road and the bridge, like: design code, shape, material, age, embankment height ,etc. The use of these criteria depends on each developed method.
The JICA method was developed for Kathmandu city and is city oriented method. Roads are classified into nine categories. Only road segments that cross slopes more than 50mm higher are considered as hazardous points in earthquakes. Bridges are classified into different types based on ten factors. Factor are scored and then the scores are combined. Based on the final score, the found result is Boolean value: collapsed or stable. The damage states of bridges are not made out.
The RADIUS method develops fragility curves for two types of roads (asphalt and non-asphalt road) and all types of bridge for different MMI value. The result shows the percentage of damaged infrastructure (per total) corresponding to the MMI value. The location and damage states of the damaged infrastructure are not identified.
The HAZUS method is a data demanding method. Roads are classified into two types: major roads and urban roads. Fragility curves are defined for different probability of damage states in terms of PGD. The bridges are classified into 28 types. For each type of the bridge, fragility curves are defined for different probability of damage states in terms of Sa (0.3 sec), Sa(1.0) and PGD.

3. Lalitpur city, the case study area

3.1. Introduction

The Lalitpur Sub-Metropolitan City is situated in the Lalitpur District, Bagmati zone in the central part of Kathmandu valley (see Figure 3.1). Lalitpur is located on Latitude 850 17' 37" E to 850 20'45" E and Longitude 270 38' 25'' N to 270 41' 36'' N

It is bounded in the North and West by the Bagmati river, to the West by the Karmanasha river, to the South by Sunakoti and Dhaphakehl Village Development Committees (VDC) and to the South West by Nakkhu Khola (Amatya, 2002).

This chapter describes a profile of the Lalitpur city, including following aspects:

-Geological condition and past earthquakes in the area

-The road network

-Distribution of land use and population

-Hospitals

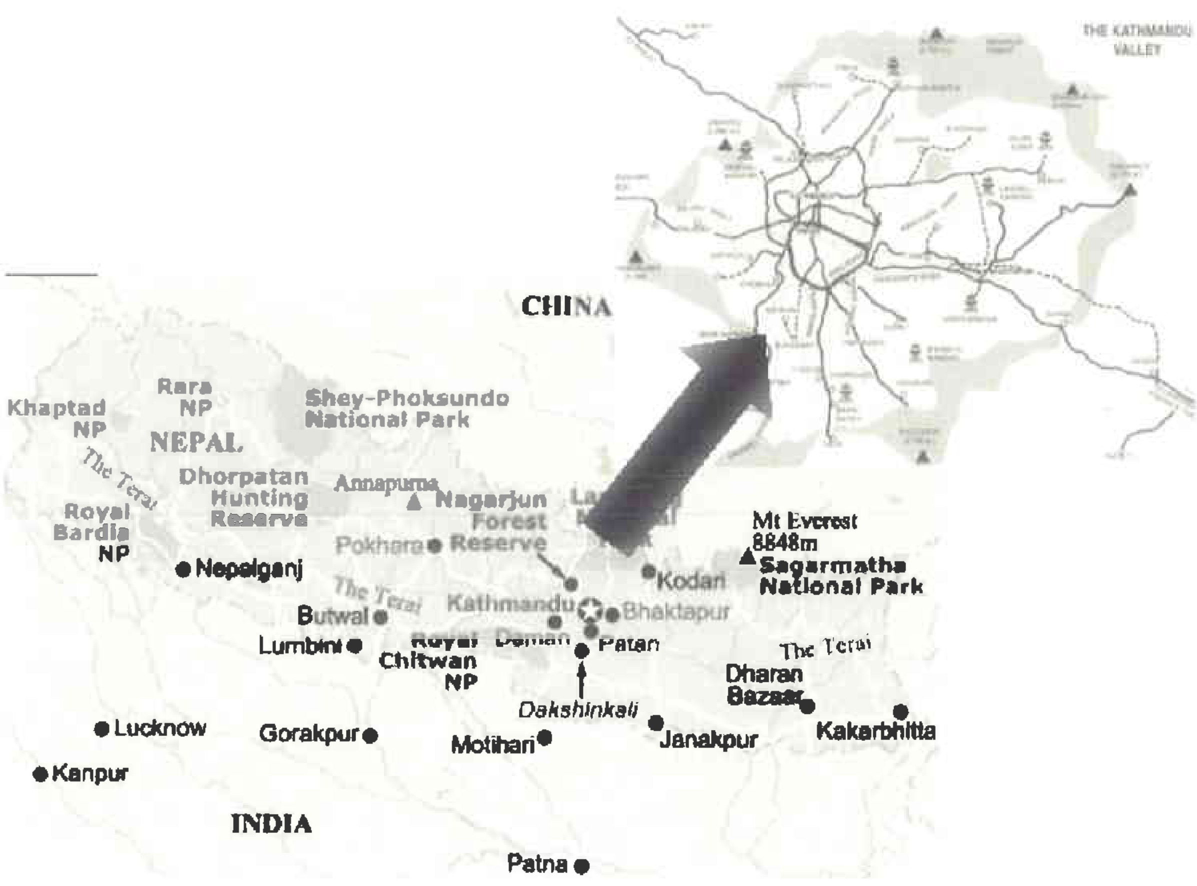


Figure 3.1: The location of Lalitpur in Kathmandu, Nepal

3.2. Earthquakes and geological condition and earthquakes in the Kathmandu valley

There were a lot of earthquakes happened in the past in Kathmandu valley. A following table summarizes some of those major earthquakes (see Table 3.1)

Table 3.1: List of earthquakes near Kathmandu (UNDP/UNCHS, 1994).

Year	Month	Day	Ms	Lalitude	Longtitude	Epicental distance (km)	Assumed PGA (gal)
1833	8	26	7.0	28.00	85.00	38.00	137
1833	10	4	7.0	27.00	85.00	84	75
1833	10	18	7.0	27.00	84.00	151	47
1869	7	7	7.0	28.00	85.00	45	121
1934	1	15	8.4	27.55	87.09	177	88
1936	5	27	7.0	28.5	83.50	199	38
1954	9	4	6.5	28.3	83.80	163	34
1988	8	20	6.5	26.75	86.62	167	36

The whole Kathmandu valley including Lalitpur city were severely damaged in the past historic earthquakes. In Table 3.2, an overview is given of the damage caused by the Great earthquake in 1934 (UNDP/UNCHS, 1994).

Table 3.2: Damage by the 1934 Bihar-Nepal earthquake

Region	Damaged houses				Casualties
	Completely destroyed	Much fractured	Slightly fractured	Total	
Kathmandu	725	3375	4146	8606	479
Outskirt of Kathmandu	2892	4046	4267	11221	245
Patan (Lalitpur)	1000	4170	3860	9030	547
Outskirt of Patan (Lalitpur)	3977	9442	1598	15017	1697
Bhaktapur	2359	2263	1425	6047	1172
Outskirt of Bhaktapur	1444	1986	2388	5818	156
Total	12397	25658	17684	55739	4296

(Note: Patan is another name of Lalitpur)

Although the damage to infrastructure in the 1934 earthquake was not recorded, from the table above we can more or less imagine the scale of damage to existing infrastructures at this time.

To understand why earthquakes happen rather frequently in Kathmandu valley, the geographical location and geological condition of the region should be considered. According to JICA (2002), Nepal lies in an active seismic zone that extends from Java, Myanmar, the Himalayans, and Iran, to Turkey. This zone has experienced many large earthquakes in the past. Earthquakes are mostly caused by regional faults at some distance from Kathmandu, although also local active faults in the Kathmandu valley may be causing small magnitude earthquakes. The Valley lies within the geological unit of the lesser

Himalayas which consists of Pre-Cambrian bedrock of some hundred million years ago. The bedrock is exposed on the periphery of the Valley and in some isolated hills, while thick unconsolidated sediments cover the central portion of the Valley as shown in Figure 3.2. The geological map shows that the core of Lalitpur lies in Kalimati formation, the formation with black clay deposit. The city is lying over a very thick sequence of clay deposit. The total percentage of clay contents in these boreholes is generally more than 50 percent, in some boreholes it is even more than 80 percent (Piya, 2004). Five of the boreholes that have been made in Lalitpur have touched the bedrock at depths ranging from 41m to 189 m., indicating that bedrock topography in this area is also very undulating. According to the liquefaction susceptibility map prepared by Piya (2004), most of the area of Lalitpur city including the core area lies in a moderate liquefaction susceptibility area, where as some areas that are lying in flood plains have a high susceptibility of liquefaction. These areas are normally in the fringe of the core city.

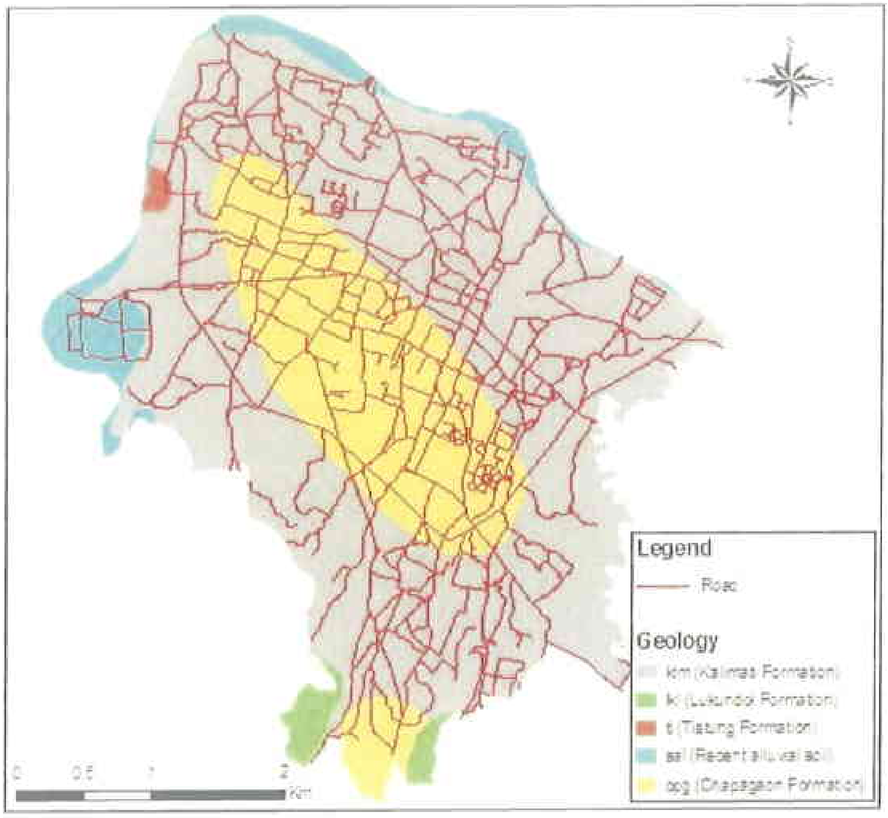


Figure 3.2: Geology map of the Lalitpur city

As the main objective of this study is the evaluation of vulnerability of the transportation network, in this section the two main components of the transportation network in Lalitpur will be evaluated: the oads and the bridges. Except for the on-land roads, Lalitpur doesn't have any other types of transportation systems, such as railroads, metro, etc.

3.2.1.Roads

The road network of the Kathmandu valley consists of different categories of standardized as well as non-standardized roads in the absence of well organized management. Uncontrolled growth in the numbers of vehicles in recent years and lack of improvement and management strategies have resulted in congestion, decrease in travel speed and capacity, as well as a decrease in road safety (JICA, 2002). The main roads inside the Valley consist of corridors, one from east to west and the other from north to south, along with the Ring road surrounding Kathmandu city and a part of Lalitpur city (see Figure 3.7). Several radial roads also exist, some radiating from the city core and others from the Ring road. Apart from these, there are urban roads, most of which are narrow and heavily built-up on both sides of the road (see Figure 3.3). The east-west and north-south corridors have four lanes each within the urban area and two lanes outside of the Ring road. The Ring road itself is of two lanes, whereas most of the radial roads are either two-lane or undivided two-lane roads. The urban roads are not constructed according to any standards and differ from narrow single-lane to two or more lanes.

Figure 3.3: A narrow road with both side built-up (Photo by author)

The physical features of the Lalitpur Sub-Metropolitan city represent a land extending from the South to the North with increasing elevation from North to South. It is divided into 22 wards with total area of 1546 hectares. The total length of roads within Lalitpur Sub-Metropolitan city including the Ring road is approximate 67 km, which consists of black topped (asphalt), gravel, earthen and brick paved roads (Amatya, 2002).

Charts in Figure 3.5 and Figure 3.4 display distribution of road length per surface material and road width. The data was collected for roads inside Lalitpur (bounded by the Bagmati river and the Ring road). The details of different types of road surface in Lalitpur are described in Chapter 4

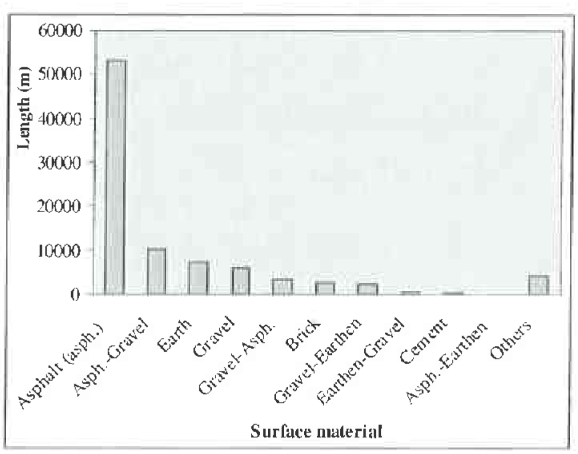


Figure 3.5: Length of road per surface material types collected in field survey

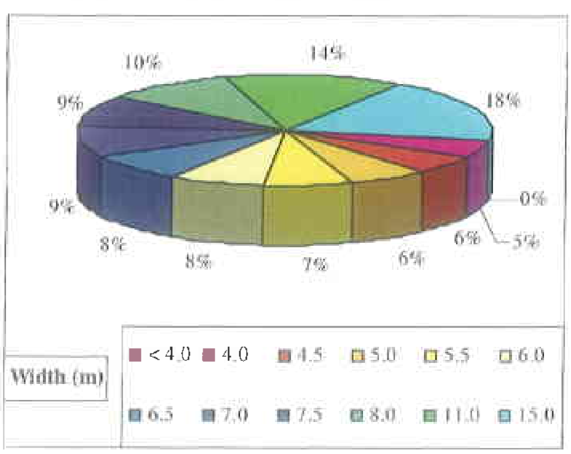


Figure 3.4: Percentage of road length per road width collected in field survey

3.2.2. Bridges

A major number of the bridges in the Kathmandu valley are old, having been constructed 30 to 50 years ago (JICA, 2002).

According to the Department of Road-Nepal (DoR), there are 54 bridges, including 33 in Kathmandu District, ten in Lalitpur District and eleven in Bhaktapur District. Most of the bridges were built with various sources of foreign assistance, mainly from the Government of China (17 bridges), Japan (11 bridges), the World Bank (4 bridges), India (2 bridges) and England (1 bridge) (JICA, 2002). A uniform bridge design standard does not exist and most bridges were based on the design standard of the assisting foreign countries.

Figure 3.6: The Manahara bridge

Most of the bridges around the Ring road and other major links are badly affected by excessive scouring around the foundations of the piers due to lowering of the riverbed.

According to the DoR, out of ten bridges in Lalitpur and Lalitpur fringe areas, some were designed by China and India in 1960s with non-seismic design code. Inside Lalitpur urban areas (bordered by the Ring road and Bagmati river), there are only 5 bridges (the Bagmati-Thapathali bridge actually includes two individual bridges: Thapathali old and Thapathali new ones). Three of them are major bridges on urban major roads and the Ring road, connecting Lalitpur to Kathmandu city and other cities. The locations of those five bridges are shown in Figure 3.7

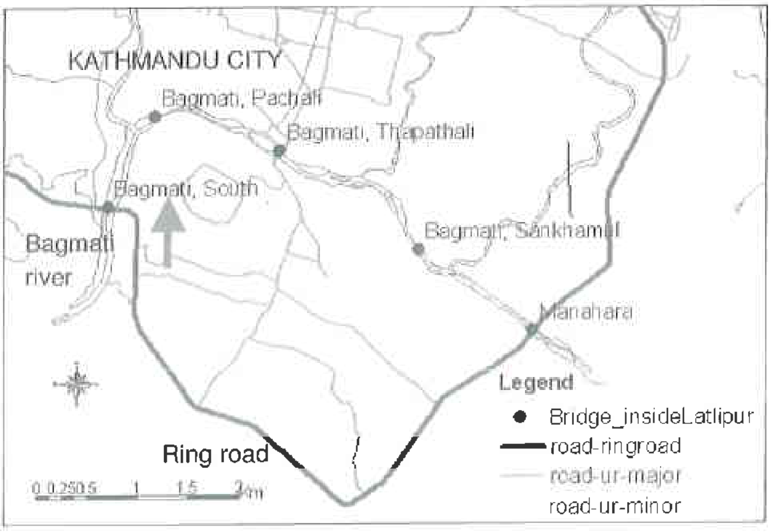


Figure 3.7: Bridges inside the Lalitpur urban area

However, except for the small bridges designed by Nepalese, and one bridge (Thapathali-new) that was constructed recently, technical data of the other old main bridges are not available at the DoR (e.g. Bagmati-South and Manahara). If they do have data, it is either insufficient or written in Chinese or Japanese, which makes management and maintenance of bridge quality, as well as vulnerability assessment rather difficult.

3.2.3.Traffic

The has not been any statistics in number of vehicles in Lalitpur. However, along with the dramatically increasing number of vehicle in the Kathmandu valley, the traffic density in Lalitpur is also highly increasing (see Figure 3.8).

Figure 3.8: Traffic: no where to run (Sharma, 2001)

The number of vehicles in Kathmandu Valley has grown exponentially. Kathmandu's roads carry ten times the number of vehicles they are supposed to (Sharma, 2001). There are more than 11,000 motorbikes and over 5,000 cars. The number of micro vans has crossed 1,500. Meanwhile, the total length of road in Kathmandu valley is only approximate 800 km (CBS, 2002).
Estimation of traffic density on side walking field survey in Lalitpur is shown in the map in.
The traffic density is high in high built up density area: the north west, city core area and the southern part of the city (see Figure 3.9). The high traffic density, along with the narrow roads in such areas may lead to the crisis of traffic flow in post-earthquake emergency. Note that the traffic density on many roads inside the city is even higher on the Ring road.

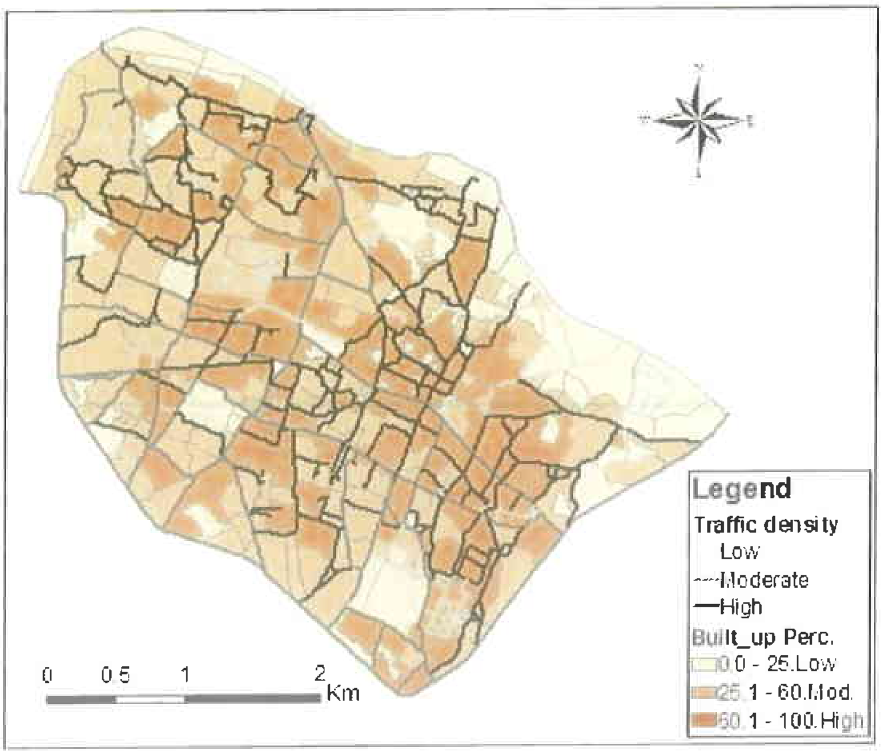


Figure 3.9: Traffic density interacting to built-up areas

3.3. Distribution of residential areas and population in Lalitpur

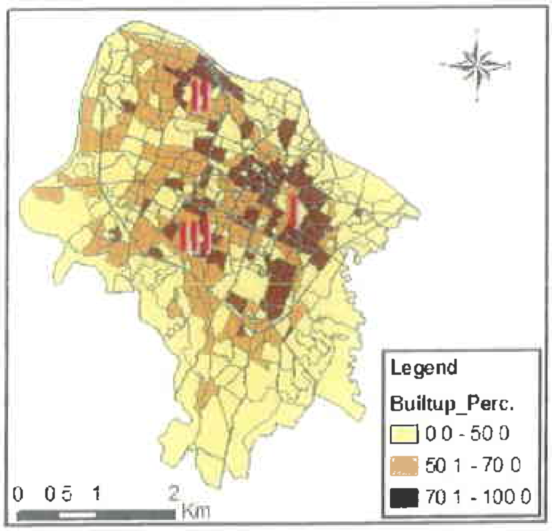


Figure 3.10: Distribution of built-up area

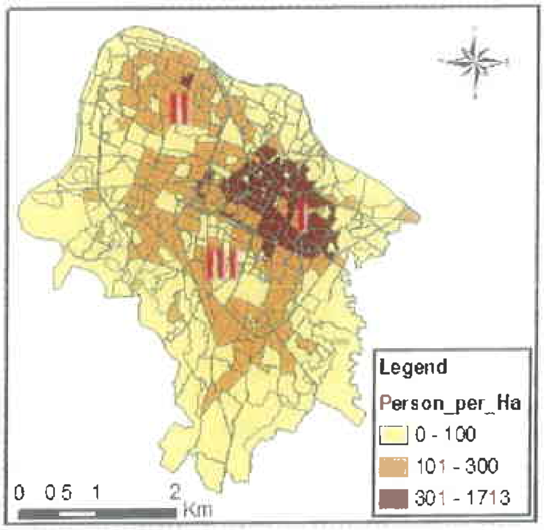


Figure 3.11: Population distribution

The distribution of residential areas in Lalitpur is not regular (see Figure 3.10). Furthermore, in residential areas, the building functionality is also varying considerably.

Figure 3.10 shows a distribution of built up areas in Lalitpur. Outside the Ring road and along the Bagmati river bank (on the right hand side of the map), the built up density is low. These areas are mainly dominated by agricultural and vacant land. Moving inward of the Ring road, the built-up density gets higher. However, there are still a lot of agricultural, institutional, or religious areas scattering in residential areas. The highest built up areas are city core area I, the area II and III. Buildings in the city core have multi-functional use: commercial and residential purposes. Ground floors are shops and so the buildings were built very closed to the road (see Figure 3.3). Upper floors were used for living.

Population density is also irregular (see Figure 3.11). Outside the Ring road, the population density is very low (less than 100 person per hectare). Meanwhile, in the core area, the population density is dramatically high, some neighborhood have the density up to 1713 persons per hectare. Majority of building in this areas are multi-storey ones, the average height of the building in this area is 2.4 floors (approximate 8m). Meanwhile, the average width of the roads in these areas is only 2.1m.

From the above overview, the roads in the core area are likely to be blocked by collapsed buildings in an earthquake for two reasons: narrow width and high density of high buildings along the road. These areas need to be seriously considered in the earthquake emergency.

3.4. Hospitals

Hospitals are considered as critical facilities in an emergency. There are two state hospitals in Lalitpur (see Figure 3.12). The biggest state hospital in Lalitpur, the Patan hospital, is conceived as a "district hospital", serving as a secondary level tertiary facility for the health posts of the Lalitpur district, while patients require tertiary level care would be refer to the Bir Hospital or a teaching hospital in Kathmandu. With 190 beds and an average occupancy rate of 103%, the Patan hospital is the fourth largest hospital in Nepal.

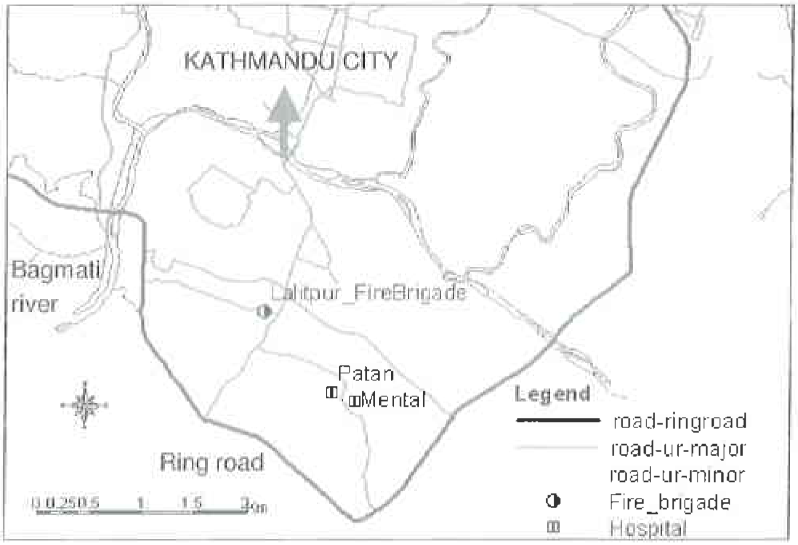


Figure 3.12: State hospitals in the Lalitpur urban area

The second state hospital is the Mental hospital. As the name indicates, this hospital serves a typical type of patient with mental diseases. This hospital should be treated as a key facility for evacuation activities in a post earthquake emergency.

3.5. Conclusions

From the above text, it can be concluded that:

Nepal is a high earthquake vulnerable country. The Kathmandu valley, including the case study city Lalitpur, suffered many earthquakes in the past. However, the damage of previous earthquakes is not well recorded.

Roads in Lalitpur are mostly narrow and have been degraded by heavy traffic and lack of strategic management.

Most of the bridges in Lalitpur are very old and conventionally (not seismically) designed. Besides, the lacking of their technical data makes maintenance and quality management activities difficult.

Population distribution in Lalitpur is not regular. Buildings in residential areas are multi-functional, especially in the core areas.

The number and capacity of the hospitals in Lalitpur is limited. However, they should be used as critical facilities in a post earthquake emergency.

4. Road vulnerability assessment

4.1. Introduction

In the context of Lalitpur, the physical road system consists of roads and bridges. Vulnerability of other types of transportation infrastructure components like tunnels and overpasses are not existing in Lalitpur and are therefore beyond the scope of this study. Based on ground survey data and secondary data collected during the field trip, the vulnerability of roads and bridges is assessed based on the method of RADIUS, and HAZUS (see the Chapter 2). Next, maps of damage states of the roads and bridges are generated.

An emphasis is given to a selected earthquake scenario of M 8, at a distance of 48 km from Lalitpur city, which induced intensities in Lalitpur ranging from MMI of IX to XI (Destegul, 2004). In this chapter only the physical vulnerability of roads and bridges is evaluated.

4.2. Road vulnerability

4.2.1. Physical condition of roads based on field observation

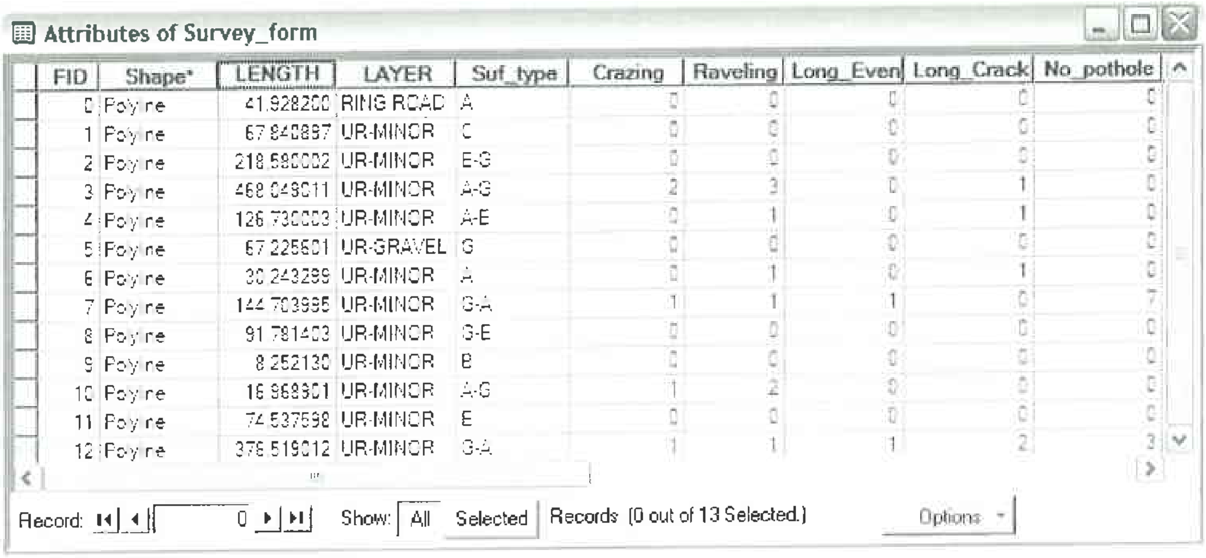
The physical condition of the roads in Lalitpur was examined during the fieldtrip in September, 2003. There are five types of road defects that were considered: crazing, raveling (see Figure 4.2 and Figure 4.3), long evenness, long crack and the number of pot holes per 100m . The data of surface material was also collected (see Figure 4.4).

Figure 4.2: Road surface crazing

(Field survey of roads -Lalitpur 17 Sep. 2003)

Figure 4.3: Road surface raveling

(Field survey of roads -Lalitpur 16 Sep. 2003)



Attributes of Survey_form

FID	Shape*	LENGTH	LAYER	Suf_type	Crazing	Raveling	Long_Even	Long_Crack	No_pothole
0	Polyline	41.928200	RING ROAD	A	0	0	0	0	0
1	Polyline	67.840897	UR-MINOR	C	0	0	0	0	0
2	Polyline	218.580002	UR-MINOR	E-G	0	0	0	0	0
3	Polyline	468.049011	UR-MINOR	A-G	2	3	0	1	0
4	Polyline	126.730003	UR-MINOR	A-E	0	1	0	1	0
5	Polyline	67.225601	UR-GRAVEL	G	0	0	0	0	0
6	Polyline	30.243299	UR-MINOR	A	0	1	0	1	0
7	Polyline	144.703995	UR-MINOR	G-A	1	1	1	0	7
8	Polyline	91.781403	UR-MINOR	G-E	0	0	0	0	0
9	Polyline	8.252130	UR-MINOR	B	0	0	0	0	0
10	Polyline	16.968901	UR-MINOR	A-G	1	2	0	0	0
11	Polyline	74.537598	UR-MINOR	E	0	0	0	0	0
12	Polyline	378.519012	UR-MINOR	G-A	1	1	1	2	3

Record: 0 Show: All Selected Records (0 out of 13 Selected.) Options

Figure 4.4: Physical condition of roads collected by the field survey

Where:

-In the Surf_type field, data of the road surface material was filled in

A: Asphalt

A-G : Asphalt and gravel: Originally, road is an asphalt topped surface. Due to degradation, the cohesive tar was removed, and gravel left only

G-A: Similar to A-G, but a proportion of single gravels is higher than the gravels that are connected by the tar

A-E: mixture of sections with topped asphalt and earth

B: Brick

C: Cement

E: Earthen

G: Gravel

G-E: mixture of sections with gravel and earthen

E-G: similar to G-E, but a proportion of earthen is higher than gravel

-Level of damage (crazing, raveling, longitudinal evenness and crack) ranges from 0 to 3:

0: No damage

1: Slight damage

2: Moderate damage

3: Severe damage

-The number of potholes is count for every 100 meter section

4.2.2.Physical conditions based on sample tests

Non-destructive tests incorporate deflection measurements and thus are the most common technique used to assist in evaluating the structural capacity and thus the physical characteristics of pavements. The non-destructive test does not alter the physical features of the material. Deflection measurements can be related empirically to future performance and total life expectancy (Amatya, 2002). The test shows the performance of a flexible pavement is closely related to elastic deflection under loads or its rebound deflection. Measurement of transient deflection of pavement under design wheel loads serves as an index of the pavement to carry traffic loads under prevailing conditions.

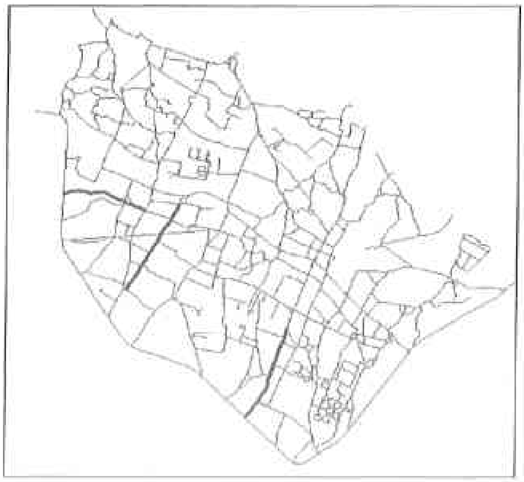


Figure 4.5: Road chainages were conducted non-destructive tests

(Based on Amatya, 2002)

The sample tests were mostly done in 2002 by the Department of Civil Engineering, of Tribhuvan University (Amatya, 2002). The tests were conducted for some linked sections of asphalt road. In the case of Lalitpur, the secondary data about sample test includes three road sections only with a total length of approximate 2200 m. Figure 4.5 shows the sections where the non-destructive tests were conducted.

Based on the test in every sections of 100 length, the strength of road surface at each section is evaluated. The values, then are classified and scored from 1 to 4: 1 means very high strength, 2 means high strength, 3 means moderate strength, and 4 means weak strength.

It is necessary to know the quality of other road sections in Lalitpur. That can be done by checking the correlation between the sample tests and field observations. If there is strong correlation between the strength of the road surface based on sample tests and field observation, an interpolation process can be applied to estimate the structural capacity of all road sections in the whole Lalitpur area.

Figure 4.6 and Figure 4.7 show the results of the correlation tests between field observations and sample tests (non-destructive test). A rho is a correlation coefficient, showing how variables are related. The rho value ranges from -1 to +1. If rho is positive, high scores on one variable are associated with high scores of another variables. If rho is zero, high scores on one variable are associated with neither high scores nor low scores of the other. If rho is negative, high scores on one variable are associated with low scores of another variables. The rho values of + 0.938 and +0.894 in Figure 4.6 show strong correlations between road surface weakness and crazing degree, road surface weakness and raveling degree: namely, the higher degree of either raveling or crazing, the lower strength of the road surface. Thus, the crazing and raveling degree might be used to predict the strength of the other asphalt road sections in whole Lalitpur.

Correlations

		CRAZING	NON_DES
CRAZING	Correlation Coeffici	1.000	.938**
	Sig. (2-tailed)	.	.000
	N	17	17
NON_DES	Correlation Coeffici	.938**	1.000
	Sig. (2-tailed)	.000	.
	N	17	17

**. Correlation is significant at the .01 level (2-tailed).

Figure 4.6:Correlation spearman rho between crazing degree and sample strength

Correlations

		RAVELING	NON_DES
RAVELING	Correlation Coeffici	1.000	.894**
	Sig. (2-tailed)	.	.000
	N	17	17
NON_DES	Correlation Coeffici	.894**	1.000
	Sig. (2-tailed)	.000	.
	N	17	17

**. Correlation is significant at the .01 level (2-tailed).

Figure 4.7: Correlation spearman rho between raveling degree and sample strength

Similarly, two table below (see Figure 4.8 and) shows that there is not strong correlation between long-crack degree and the long evenness test (rho= +0.745 and rho= +0.740, respectively) (see Figure 4.8 and). According to the results, these kinds of damage do not very much influence the capacity of road pavement. Consequently, these kinds of damage can not be used to predict the strength of the other asphalt road sections in the whole Lalitpur.

Correlations

		Long_Crack	NON_DES
Long_Crac	Correlation Coeffic	1.000	.745**
	Sig. (2-tailed)	.	.001
	N	17	17
NON_DES	Correlation Coeffic	.745**	1.000
	Sig. (2-tailed)	.001	.
	N	17	17

**. Correlation is significant at the .01 level (2-tailed).

Figure 4.8: Correlation spearman between long crack degree and sample strength

Correlations

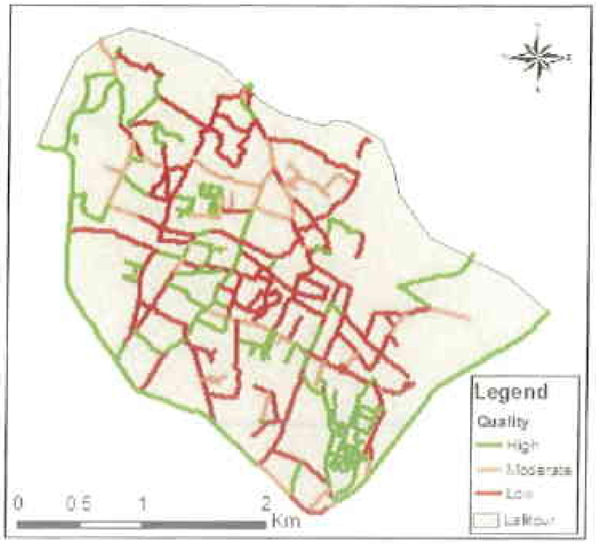
		Long_Even	NON_DES
Long_Even	Correlation Coefficie	1.000	.740**
	Sig. (2-tailed)	.	.001
	N	17	17
NON_DES	Correlation Coefficie	.740**	1.000
	Sig. (2-tailed)	.001	.
	N	17	17

**. Correlation is significant at the .01 level (2-tailed).

Figure 4.9: Correlation spearman between long evenness degree and sample strength

In short, the crazing and raveling levels may be used to predict the capacity of road pavement (asphalt and asphalt-gravel), based on the strong correlation between assessment of field survey and sample tests. The maps of road quality are shown in Figure 4.10 and Figure 4.11

The quality of asphalt roads based on the combination of the field survey and the non-destructive tests. The quality of non-asphalt roads based only on the field survey. Total length of each type of surface material and their quality is shown in Figure 4.13



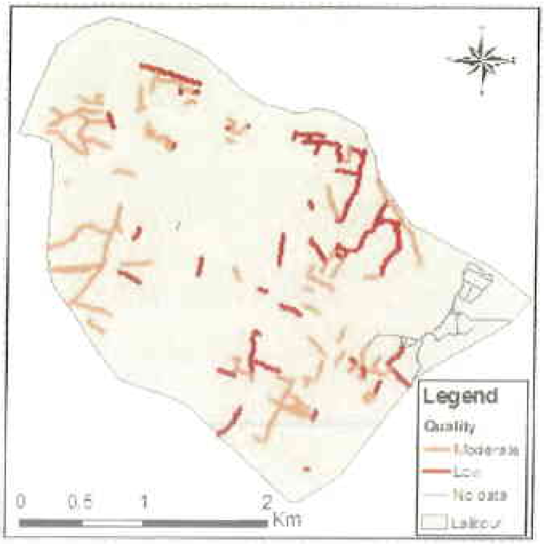
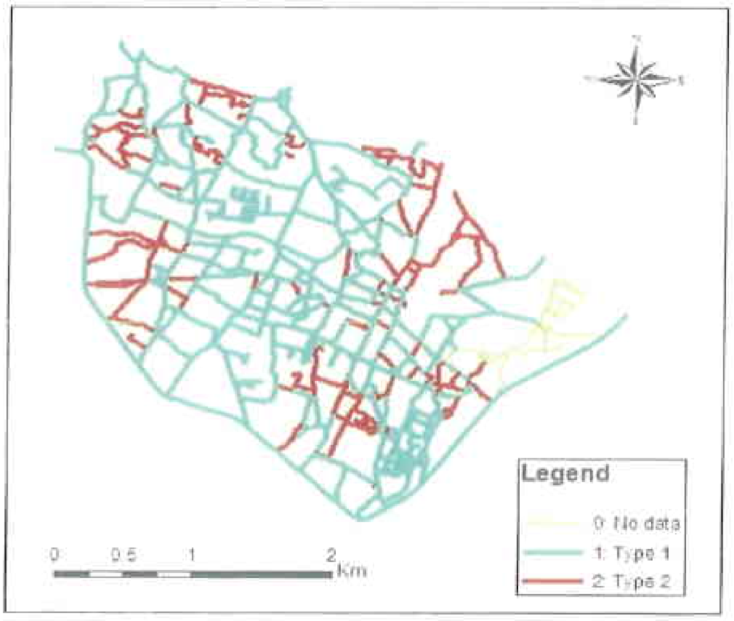


Figure 4.10: Quality of asphalt roads

Figure 4.11: Quality of non-asphalt roads

There have not been any studies on the relationship between physical conditions and damage states. Furthermore, there have not been any data of damage states of the road in historic earthquakes in Lalitpur, yet. For that reason, it is quite difficult to develop curves of earthquake intensity versus damage states for each type of road with a particular type of physical condition. For example, a damage curve for minor cement roads with low strength of road surface, or a damage curve for major asphalt roads with high strength of pavement. Hence, this study uses two methods to assess the road vulnerability: One uses the damage curves developed by the RADIUS, and the other is a liquefaction based method.

4.2.3. Vulnerability assessment based on the RADIUS method



Roads are classified into two categories: asphalt (type 1) and non-asphalt (type 2). Based on the existing physical conditions of roads in Lalitpur, these two classes were used as follow:

-Road 1: Asphalt and asphalt-gravel

-Road 2: Gravel, brick, earthen and the others (refer to 4.2.1)

A map of the two types of road is shown in Figure 4.12:

From road classification and the damage curves, damage state of roads is produced as follows:

Based on the simplified vulnerability curves of the RADIUS method , the road classifications and MMI map (Destegul, 2004), the procedure used in road damage assessment is displayed in Figure 4.14.

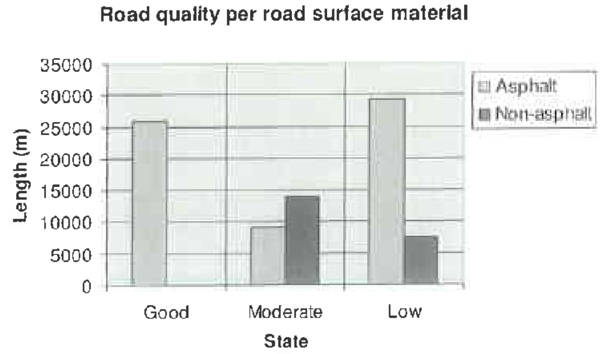


Figure 4.13: Length of road quality per surface material

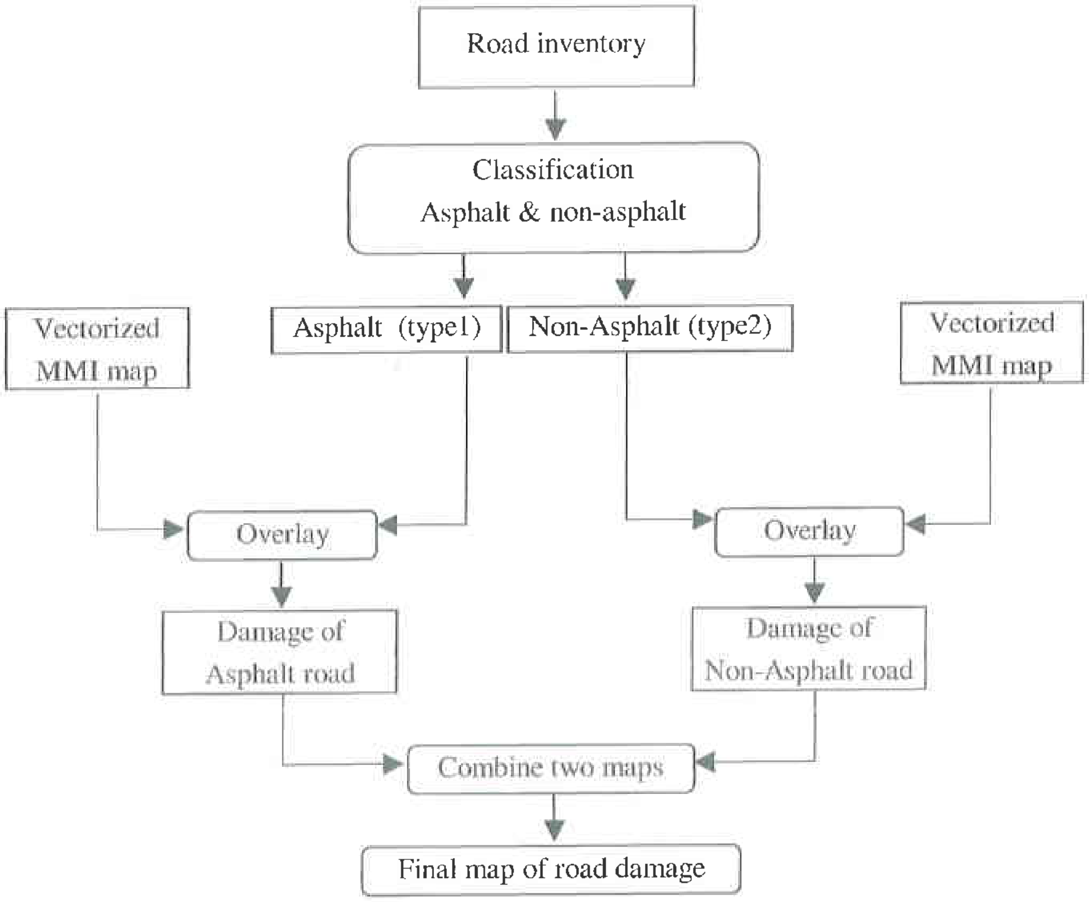


Figure 4.14: Application of the RADIUS method to road vulnerability assessment in Lalitpur

The raster map of MMI is generated for the selected earthquake scenario (Destegul, 2004). Then, the MMI map was vectorized and delineated into the polygon map (see Figure 4.15). The biggest one occupies a major part of Lalitpur has value MMI IX. The second biggest one (on the left hand side of the map) has value MMI X. The smallest polygon (at the lower left corner of the map) has value MMI IX.

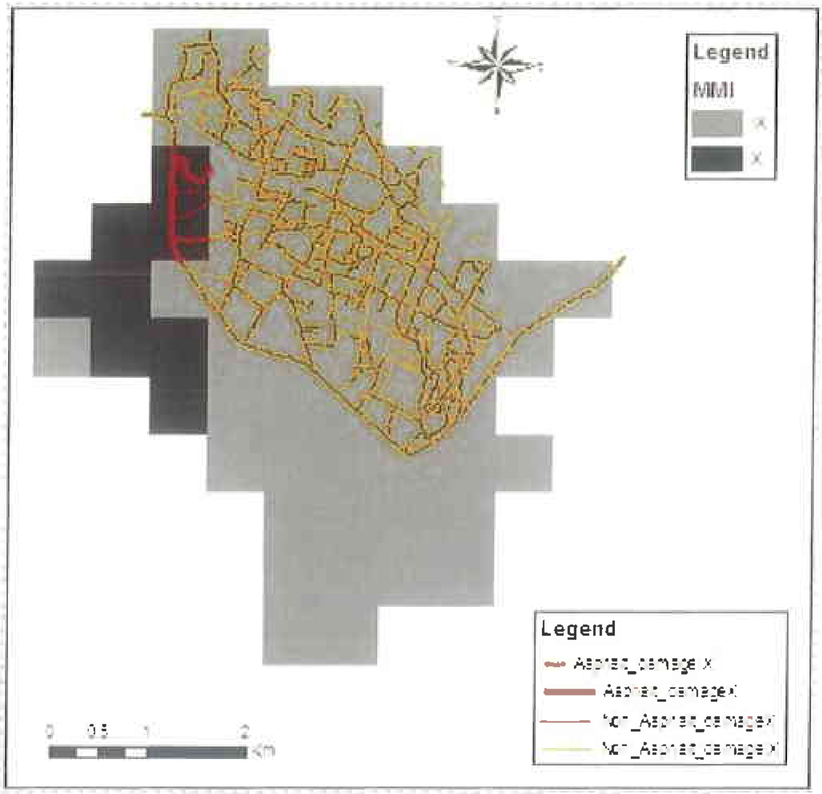


Figure 4.15: Road damage stages in the selected earthquake scenario

Note:

Road type 1 with center line (see the Asphalt_damageX in a map legend) are in the area of MMI X. According to the RADIUS, 22.12% of these road segments in this area is damaged. In the same area, 11.05% of non-asphalt road is damaged.

Majority of all roads in Lalitpur in an area of MMI IX. 13.55% of asphalt road in this area is damaged (see Asphalt_damageIX in the map legend). Meanwhile, 5.8% of non-asphalt road in the same area is damaged.

The table below show total length of damaged roads per type. There are totally 48556 m asphalt road (app. 13.8%) and 178757 m non-asphalt road (app. 6.3%) that are estimated damaged in a selected earthquake scenario.

Figure 4.16: Damage length per road type

Road type	Total length (m)	Damage length (m)	Total percentage damage
Asphalt	7791.15	48553.85	13.8%
Non-asphalt	1278.475	18756.525	6.3%

-Note that a part of the Ring road are damaged (in the area of MMI X). Although the RADIUS method does not mention how severe of the damage would happen, but if heavy damage occur at this section of the Ring road, traffic flow in Ring road may be interrupted.
-The RADIUS method only shows a ratio of damaged road length and total road length, but it does not mention where the damage may occur. One way that we might do is to use a random generator to indicate the damaged ones (Westen, 2003). Another way that we can use is to look at the quality of physical condition of road segments, then presume the damage will occur in the low quality roads.

4.2.4. Vulnerability assessment based on liquefaction

The HAZUD method assesses the probability of damage based on PGD and road classification (see Figure 2.14). Roads are classified in major roads and urban roads. Thus, the assessment bases on road types and the data of deformation of ground at the road location.
However, since there has not been any research in PGD in Lalitpur, so we can not apply directly the fragility curves of the HAZUS. However, the deformation level of ground can be estimated based liquefaction level. As a result, we can estimate the potential damage of the roads in qualitative sense based on liquefaction research in Lalitpur. A map in Figure 4.17 shows road potential damage based on liquefaction. The liquefaction map is from the research on liquefaction in Lalitpur (Piya, 2004).

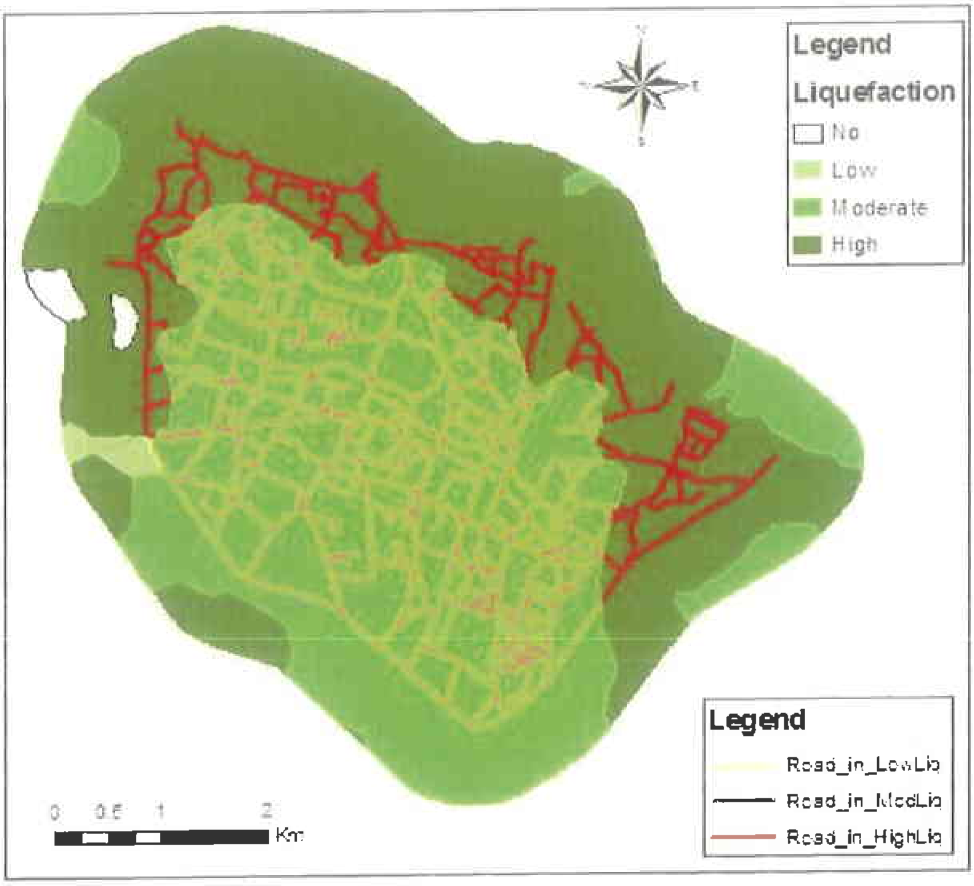


Figure 4.17: Road potential damage to liquefaction

Roads, which were presented in red, locate on high liquefaction area. As we can see in the map, the area along a Bagmati river bank have high liquefaction level (upper right side of the map). Consequently, roads in these location have high potential damage. There are two parts of the Ring road locating on high liquefaction areas: One, at upper left corner of the map, have high potential damage. That is similar to the part on MMI X area in the Figure 4.15. The other location at lower right corner of the map.

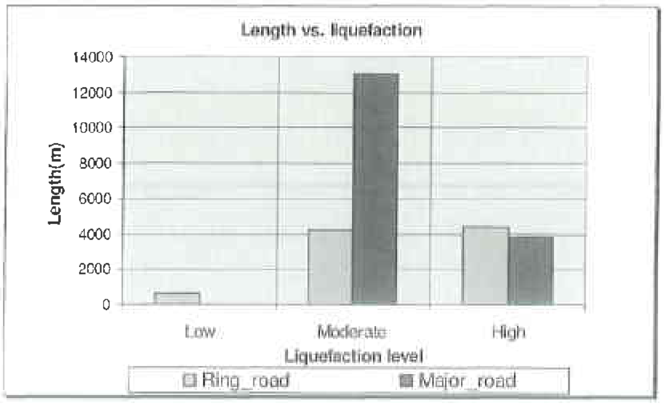


Figure 4.18: Ring road and major road in liquefaction area

Since the high liquefaction areas are nearby the river bank, the roads in this areas and the bridges on the Bagmati river also affected by the high liquefaction.
The chart in Figure 4.18 shows the length of the Ring road and the urban major road in different liquefaction areas. Most sections of the major urban road locates on the moderate liquefaction areas. Meanwhile, there are approximate 4000 m of either Ring road and urban major roads locates on the high liquefaction areas
The liquefaction based method does not take into account the type and characteristic of the road. The assessment only shows relative potential damage of the road in different locations. It also does not bring us the information about the severity of damage.

4.2.5.Comparison between results from assessment methods

-The RADIUS method is easy to use, since it uses the MMI value, the data can be achieved either from the PGA values or observation of non-professional people. Meanwhile, the assessment based on liquefaction requires technical data: geological data from boreholes.
-Both methods do not show damage states: The RADIUS method gives percentage of damaged road length per total road length. The liquefaction based method give results in terms of qualitative sense, showing only the relative damage severity of roads in different locations.
-According to the two methods, in general, majority of road inside Lalitpur have the same degree of damage. As Lalitpur city is small with homogenous geological condition, so the MMI values and liquefaction levels do not change significantly in the whole area.
-Some sections of the Ring road are expected to be damaged. This makes us be aware the risk to Ring road once an earthquake happen. The risk can be reduced by creating more open spaces along these high potential damage sections, in order to minimize possibility of traffic flow interruption.

4.3. Bridge vulnerability assessment

Data of existing bridges in Lalitpur was collected during the field work. Two methods will be used for bridge vulnerability assessment: the RADIUS and the HAZUD methods. Results from the two methods will be compared.

4.3.1. Bridge inventory

Data of six bridges in Lalitpur was collected including: design code, length, age, width, a number of spans, and material of main structure (see Figure 4.19). Location of these bridges can be seen from Figure 3.7.

Attributes of Bridge_insideLatlipur

BR_NO	NAME	ROAD	LENGTH	BRIDGE_WID	YEAR_	No_span	Mat_Mainst	Des_code
3	Bagmati, San	K T M Urban	115	3	1994	1	Stee	Yes
7	Bagmati, Sout	K T M Ring R	128	15	1960	8	RC	No
22	Bagmati, Pac	K T M Urban	134	6	1994	0	RC	Yes
35	Manahara	K T M Ring R	112	15	1960	7	RC	No
36	Thapatha ne	K T M Urban	184	14	1995	6	FRC-Stee	Yes
0	Thapatha old	K T M Urban	184	9	1967	6	Stee	No

Record: 0 Show: All Selected Records (0 out of 6 Selected.) Options

Figure 4.19: Data of bridges in Lalitpur

4.3.2. Vulnerability assessment based on the RADIUS method

A MMI map is created from a PGA map. The PGA map is generated from data of boreholes inside Lalitpur (Degestul, 2004). The PGA values for whole area inside Lalitpur is interpolated based on PGA values that were calculated from individual boreholes. Since there are not any data of boreholes at Bagmati river bed, then PGA and MMI maps do not cover the Bagmati river location.

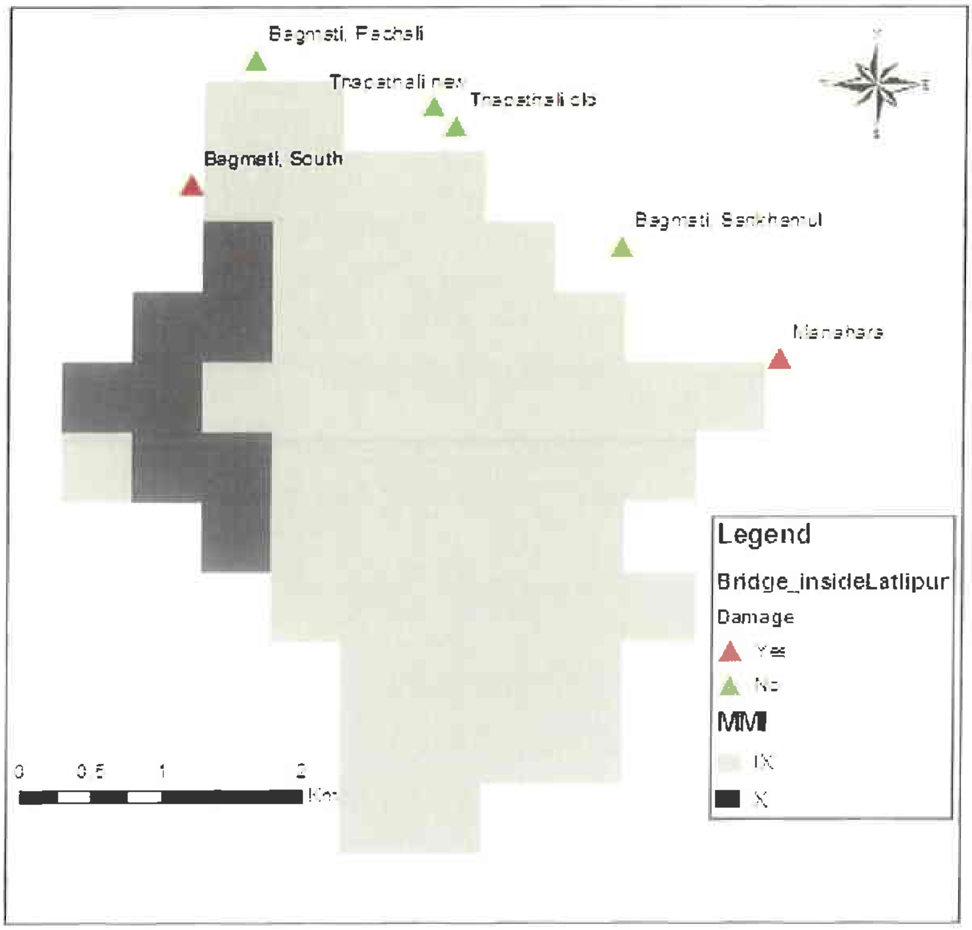


Figure 4.20: Damage of the bridge

However, since the raster map of MMI is delineated to a vector map, consisting of two main areas with MMI values of IX and X. The MMI IX value dominate a major part of Lalitpur. There are all six bridges are located in the area of MMI X, only the Bagmati South bridge is a bit near the area of MMI X. Based on the RADIUS damage curves, the number of damage bridges are approximate 28 % of total bridges (refer to Figure 8.2). Hence, the number of damage bridge are two. However, since we do not know exactly where are damage bridges, so we have to presume that bridges that are old, conventionally designed, reinforce concrete and closed to the high MMI value areas, should be damaged. Hence, the Bagmati South and Manahara bridges are presumed as damaged ones, because:

+ Both of them are conventionally designed. Meanwhile the Bagmati Pachali and Thapathali new were seismically designed
+ Both of them are the oldest ones. The others were constructed later
+ The Bagmati South location is near the area of MMI X
+ Both of them are concrete bridges. The concrete bridge, in general, is considered more susceptible to earthquake than steel one (refer to 2.4.4)
+ Observation in the field survey also shows that these bridges are old and not in good maintenance

The damage states of bridges are shown in Figure 4.20

4.3.3.Vulnerability assessment based on the HAZUS method

The assessment is done for individual bridges. The Manahara bridge vulnerability and damage probability was assessed in detail based on ***ground shaking*** and its technical characteristics. Similarly, damage probability of the other bridges was assessed. Data of these bridges are shown in Table 4.1

Table 4.1: Bridges are classified according to HAZUS

CLASS by HAZUS	Name	Year Built	# Spans	Length (m)	Length of Max. Span (meter)	Length less than 20 m	K_{3D}	I_{shape}	Design	K_{skew}	Description
HWB18	Manahara (Bagmati. South)	1960s	7 (8)	112 (128)	18 (14.7)	No	EQ1	0	Conventional	0	Multi-Col. Bent, Simple Support - Prestressed Concrete
HWB15	Thapathali old	1967	6	184	24.5	No	EQ1	0	Conventional	0	Continuous Steel
HWB16	Thapathali new	1995	6	184	24	No	EQ3	1	Seismic	0	Continuous Steel
HWB16	Bagmati Sankha	1994	6	115	6	No	EQ3	1	Seismic	0	Continuous Steel
HWB19	Bagmati Pachali	1994	6	134	7	No	EQ1	0	Seismic	0	Reinforce concrete

4.3.4.Manahara South bridge vulnerability

From the data of the nearest borehole to the Bagmati South bridge, the values of Sa (0.3s) and Sa(1.0s) were found as follows (Destegul, 2004):

Sa(0.3 sec) = 0.85g, Sa(1.0 sec) = 0.42g

The bridge is located in soft soil (type E) (see Table 8.4).

The median spectral acceleration ordinates for different damage states are determined as follows:

First, the ground motion data is amplified for soil conditions, according to

The amplification factor, that are selected, in dark in the table above.

Sa(0.3 sec) = 1.2 x 0.85g = 1.02g

Sa(1.0 sec) = 2.4 x 0.42g = 1.008g

K_{shape} = 2.5 x Sa(1.0 sec) / Sa(0.3 sec) = 2.5 *0.42/0.85=1.23

$K_{skew} = \sqrt{\sin(90^o - \alpha)} = \sqrt{\sin(90^o - 0^o)} = 1$

$K_{3D} = 1 + A / (N - B) = 1 + 0.25 / (7-1) = 1.04$

Modify the ground shaking medians for the "standard" fragility curves

I_{shape}=0, so $Factor_{slight}$ = 1.

Old medians are from Table 8.2

K_{3D} value is from the table in Figure 2.17

New Median [Slight] = Old median value for [for slight] x $Factor_{slight}$

= 0.26 * 1 =0.26

New median [Moderate] = Old median [for moderate] * (K_{skew}) * (K_{3D})

= 0.35 * 1 * 1.04 = 0.364

New median [Extensive] = Old median [for extensive] * (K_{skew}) * (K_{3D})
= 0.44 * 1 * 1.04 = 0.46
New median [Complete] = Old median [for complete] * (K_{skew}) * (K_{3D})
= 0.65 * 1 * 1.04 = 0.68

For more information, see HAZUS (NIBS, 1999) (Chapter 7: Direct Physical Damage to Lifelines - Transportation Systems)

Since the data of a fragility curves for all 28 type of major bridges from the HAZUS manual are not available (except types HBW1, conventionally designed bridge, and HBW2, seismically designed bridge), so it is assumed that fragility curves for HBW18 have shapes similar to the shapes of HBW1 's curves (see Figure 2.15) (both HBW17 and HBW1 are conventionally designed bridges). The curves go through points of new median values and corresponding probability of damage states (point A, B, C, D in Figure 4.21).

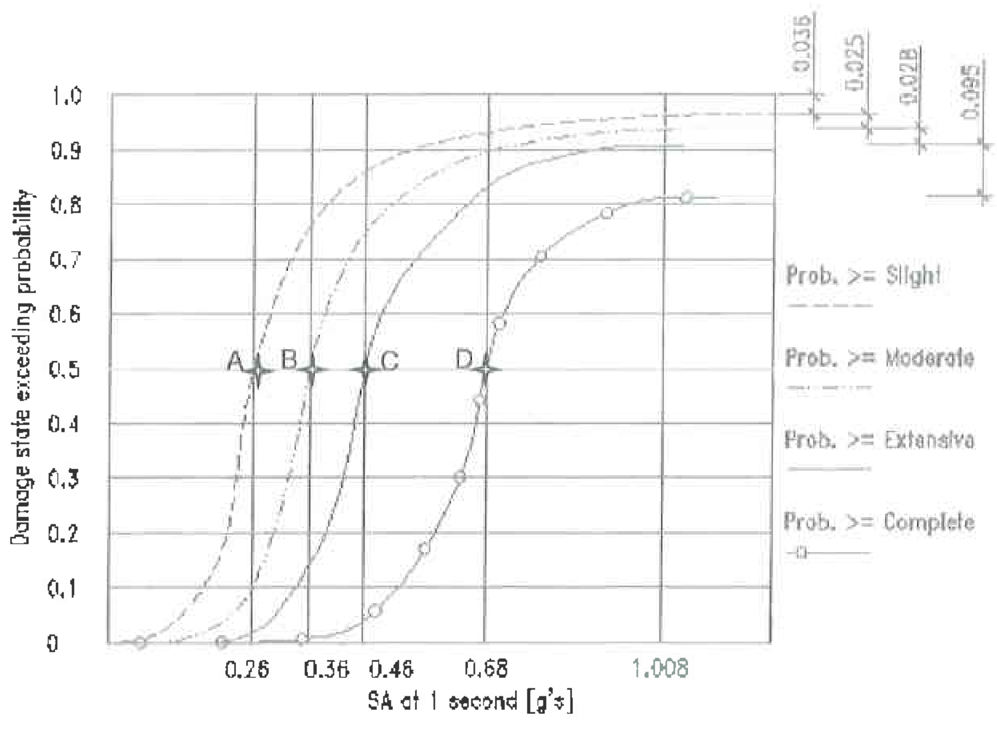


Figure 4.21: Manahara fragility curves

With these new medians, the shaking-related discrete damage state probabilities are (with the above medians and with betas β equal to 0.4) and Sa (1) : 1.008s (the amplification factor by soil was taken into account)

Probability [No damage] = 0.039
Probability [Slight damage] = 0.025
Probability [Moderate damage] = 0.028
Probability [Extensive damage] = 0.095
Probability [Complete damage] = 1 – 0.039 – 0.025 – 0.028 – 0.095 = 0.813

Similarly, for the other bridges, probabilities of damage states are shown in a table and a graph below:

Table 4.2: Probability of bridge damage states

Bridge name	Probability of damage states				
	No	Slight	Moderate	Extensive	Complete
Manahara	0.039	0.025	0.028	0.095	0.813
Bagmati South	0.035	0.025	0.026	0.095	0.819
Thapathali old	0.11	0.15	0.05	0.42	0.27
Thapathali new	0.23	0.19	0.25	0.21	0.12
Bagmati Sankhamul	0.15	0.12	0.06	0.40	0.27
Bagmati Pachali	0.15	0.12	0.1	0.25	0.38

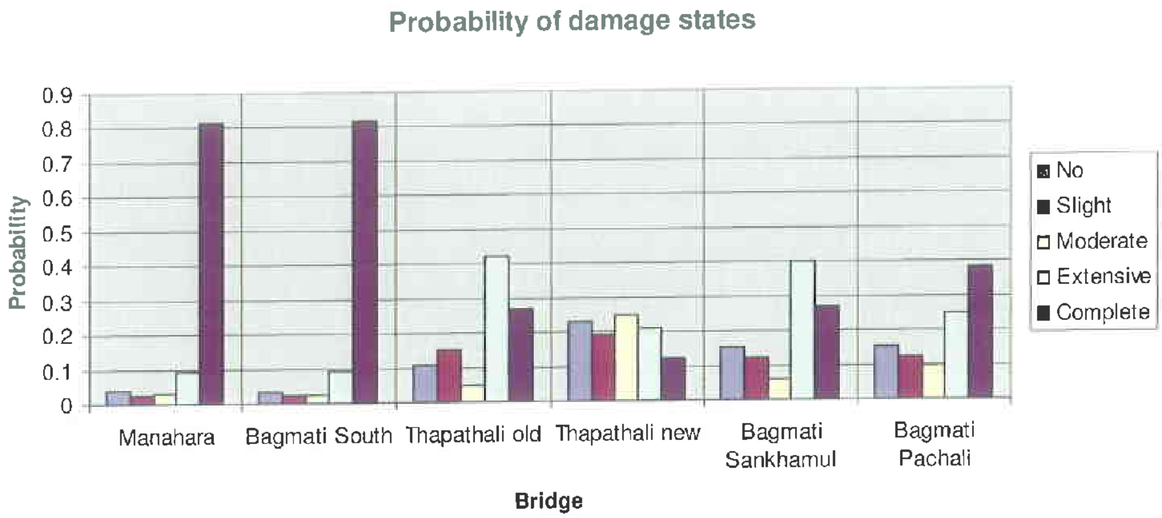


Figure 4.22: Probability of bridge damage states

+ The above graph shows that the two bridges: Manahara and Bagmati South bridges have very high probability of complete collapse.
+ A Thapathali_new bridge, the newest one was seismically designed by Japan has the lowest probability of complete collapse.
+ Thapathali old and Bagmati Sankhamul have similar probability in terms of complete and extensive damage. The Thapathali-old bridge is steel structure, which was designed by India in 1967. In fact, from observation in the field survey, it can be seen that this bridge is a very crucial one, connecting Lalitpur and Kathmandu city center. This bridge is well maintained and in good condition.

4.3.5.Comparison between results from assessment methods

+ It is interesting that the two bridges: Manahara and Bagmati South ones, according to the two method, are most vulnerable compared to the others. The RADIUS require less data to analyze. However, the results do not show exactly which bridges would be damaged in which levels, so it requires result interpretation, based on expertise of an examiner. In the meantime, the HAZUS method requires a lots of technical data. During the analyzing process, some missing data must be assumed. However, the result shows clearly the probability of the various damage states

+ To evaluate the vulnerability and damage states of the others bridge, it is required to use the HA-ZUD method. Since the RADIUS, along with expertise of the examiner, just simply says that these bridges are damaged or not. Meanwhile, the HAZUS lets the examiner know the probability of the damage states
+ Through the examples, it is certainly that the RADIUS is an easy-used method and requires less data. At the mean time, the HAZUS requires almost data of main characteristics of bridges. These data, sometimes is not available. For that reason, the output may change if missing-data is not assumed correctly, namely that the judgment of input data is very crucial when using this method.

4.4. Conclusions

-The roads in Lalitpur have a large variation in pavement types and pavement quality

-There is approximate 20% of total road will be damaged including both asphalt and non-asphalt roads. However, the locations of the damaged roads are not identified.

-A liquefaction map can be used for evaluation of road earthquake vulnerability in qualitative sense. Most of urban roads in Lalitpur are located on the moderate liquefaction areas.

-A part of the Ring road is likely to be damaged. This damaged section should be considered as a crucial location, which may cause traffic interruption in earthquake.

-Based on the RADIUS method, there are two bridges that are estimated to be collapsed. However, the RADIUS does not show which bridges would be damaged or not. Other characteristics of bridges like length, span, material of main structure, age etc.. were not taken into account. That makes the RADIUS seem to be suitable for primary assessment, only.

-The HAZUS method shows the results of probability of damage states of bridges. The Manahara and Bagmati south have the highest probability of complete damage. Meanwhile, the Thapathali new bridge has the lowest probability of complete damage.

-The HAZUS method, though is complex and high demanding one, gives damage states of bridges in quantitative sense. Moreover, almost all of the main characteristics of the bridge were taken into account, thus the result is rather reliable and is able to highly present the particular features of each individual bridge.

5. Post-earthquake function of road infrastructure

5.1. Introduction

In a post-earthquake scenario, one of the most important things that local authorities need to do is to evacuate dead and injured people. People are not killed or wounded by an earthquake itself, but they are victims of collapsed infrastructures like buildings or overpasses , or induced hazards like landslides, fire etc... Certainly, for a given number of wounded people, if an evacuation plan is well organized, the numbered of dead will be significantly reduced. Since a road network plays an important role in transportation in the evacuation plan, the assessment of the functioning of the road network in a post-earthquake crisis becomes crucial.

Inside a city, factors that significantly determine loss of lives are built-up density and population density. People are trapped and wounded by collapsed buildings, then may suffer from fire or electrical shock. Good evacuation activities should be done as follows: first, the injured need to be moved from collapsed buildings to vacant spaces or temporal evacuation sites nearby. Those spaces should be close to accessible ambulance roads. Second, after first aid activities, the injured people need to be evacuated directly to a hospital by ambulances.

Due to the fact that in Lalitpur, the traffic density is high (refer to Chapter 3), caused by a high number of traveling vehicles and the narrow roads. Thus, ambulances will face difficulty in going from a hospital to the damaged buildings to take the injured people, even in an everyday scenario. Additionally, in the post-earthquake situation, there are some extra impedances:

+ Roads are blocked by collapsed buildings. The debris of collapsed buildings occupies the road surface, reducing speed or preventing the vehicles from traveling, due to the fact that buildings are very close to the roads (see Figure 3.3). Furthermore, most buildings are not well constructed and mostly not according to standard codes, let alone anti-seismic codes). Those buildings have high probability of collapsing once an earthquake happens (Guragain, 2004)

+ Roads rupture: By ground motion and liquefaction phenomena, the pavement of important road segments might be broken, ranging from minor to severe damages (un-passable)

+ People gathering on the road. People are likely not to dare to stay in their houses after the earthquake shock. Their houses could collapse any time just after the main quake, caused by cracks that occurred during the main earthquake event and by aftershocks.

+ Bridge collapse. Bridges are key components in the road network. Once a bridge is damaged or collapsed, the whole network might be interrupted. However, bridges are usually isolated from buildings, so the function of the bridges mainly depends on their own physical damage. The physical damage of the bridges has already been described in the Chapter 4

+ Obstacles caused by collapsed facilities like lampposts, electric poles, or fences. Because they are usually located close to the roads, once they collapse they cause a high probability of covering the road sections, preventing the vehicles from passing.

+ Others.

From the above overview, it can be concluded that there are many factors affecting possible road blockage . However, taking all these factors into account was not feasible, because of the lack of data. For example, data about the number of people that gather in a particular earthquake in a particular road section is often unpredictable. Another example is the absence of data about the collapse possibility of lamp posts, and electric poles along a road section. For that reason, this chapter only focuses on the aspect of road blockage caused by collapsed buildings. The physical damage of the road has been already studied in Chapter 4.

There should be several alternatives routes for ambulances from hospitals to the evacuation site to take the injured or deaths. For that reason, planning suitable routes for ambulances is crucial to minimize the impedances along the route. Consequently, it minimizes traveling time and increases the effectiveness of evacuation activities.

To do identify the most suitable routes, it is necessary to:

+ Estimate impedances along the route
+ Predict temporal aid sites
+ Find the shortest path in a post-earthquake scenario

Speed of the ambulance is basis for the shortest path finding calculation. The speed of the ambulance in the post earthquake scenario is estimated based on three factors: Road blockage level by collapsed buildings, road rupture and normal speed in daily scenario (see Figure 5.1).

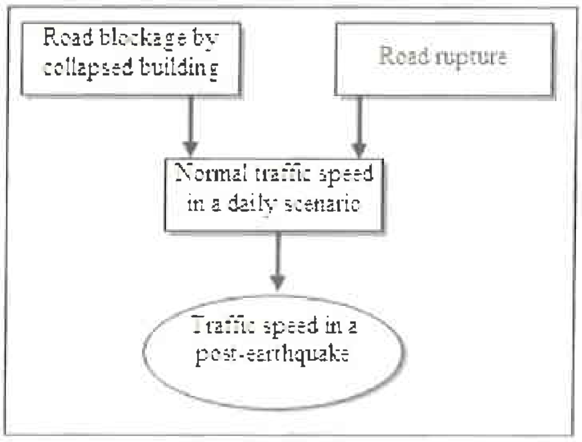


Figure 5.1: Traffic speed in a post-earthquake scenario

One of the most difficulties is to estimate the probability of the impedance along the route. Another challenge is how to predict which areas would be the destinations for the ambulances, namely the temporal aid sites for the dead and the injured. The third challenge is to incorporate three factors: road blockage level, road rupture and the normal speed in daily scenario into the final speed of the ambulance in the post earthquake scenario. This chapter proposes a methodology to deal with two challenges: Estimating the impedance caused by the collapsed buildings along the route and identifying the destination.

To test the methodology, the same earthquake scenario as in Chapter 4 is used.

5.2. Impedance estimations caused by collapsed buildings along the routes

A route consists of a series of continuous road segments. Thus, to estimate the impedances on the route, we have to estimate the impedances on each component of the road segments. The detailed explanation for impedance estimation is displayed in next sub-sections.

5.2.1. Factors influencing the possibility of debris from buildings blocking the roads

The possibility of debris from buildings blocking the road depends on the following factors:

+ The number of collapsed buildings. The higher this number, the higher the possibility of road blockage
+ Characteristics of buildings along the road (see Figure 5.11). For example, the presence of weak buildings (adobe, brick-mud buildings) or stronger buildings (reinforce concrete, steel buildings)., or the presence of buildings with soft storey or without cantilevers toward the road.

Figure 5.2: A collapsed mud-brick house
(Armenia, 1988)

Figure 5.3: A reinforce concrete collapsed building
(Tadjikistan, 1985)

+ The ratio between building height and distance from front-walls of the buildings to the road center line. The higher this ratio, the higher possibility of debris blocking the roads

The road network is divided into routes, where each route consists of a series of continuous arcs with the same width.

The routes consist of roads with width greater than or equal to 5m, since it is considered that only those roads are wide enough for the traveling of ambulances. The smaller roads also have the same story in terms of blockage estimation. However, since there are a lot of road sections (with width less than 5m), so the manual calculation is very much time consuming work. Moreover, those small roads are wide enough for passers-by only. Hence, calculation for such roads is beyond of this study.

Figure 5.4: A route

A detailed explanation of how to quantify and incorporate the above factors is given in 5.2.2

5.2.2. Calculation of the road blockage level

The amount of blockage by debris on the roads can be expressed in the following expression:

Road blockage level = Density of collapsed buildings + Building characteristics + Relative distance between roads and collapsed buildings

Note that the type of building is also taken into account. Even in the estimation of the number of the collapsed building, the type of building was considered. However, the debris shape or collapse form are various from different types of building. The detailed explanation will be shown in 5.2.2.3.
Since only debris from collapsed buildings that are in close proximity to the route and face directly to the same route may have chance to block the route, thus only homogenous unit consisting of those buildings are selected (seeFigure 5.5).

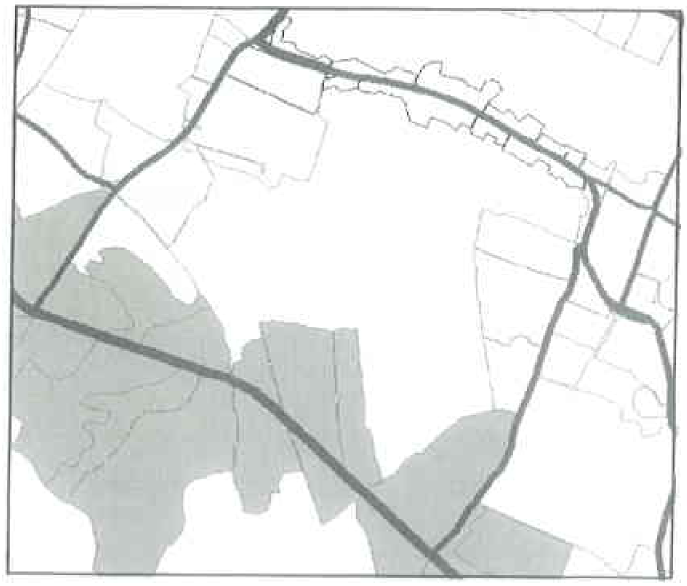


Figure 5.5: The selected homogenous units

The Figure 5.5 shows the selected homogenous units along the routes. Only units that have the edge adjacent to the routes that are selected.

5.2.2.1. Density of collapsed buildings

The density of collapsed buildings along the route is one of factors determining how much of a road segment will be blocked by debris or how much percentage of the road segment will be affected by the debris. This density can be estimated based on the numbers of collapsed buildings per homogenous unit, which is taken from the building vulnerability assessment research carried out by Guragain (2004).

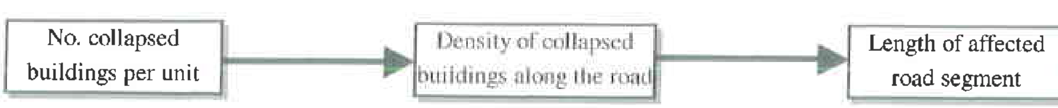


Figure 5.6: A relation between a collapsed building number and length of affected road segment

From the data of the number of buildings likely to collapse in a homogenous, and the total number of buildings in the same unit, we can calculate the plan area A_c occupied by the collapsed buildings

$$A_c = \frac{N_{cb}}{N_b} A_b$$

Where:

N_{cb}: The number of collapsed buildings per homogenous unit

N_b: Total number of buildings per homogenous unit (based on the foot print map)

A_b: The total area of all buildings in the homogenous unit (calculated from the foot print map)

In order to calculate the "collapse density by area"the ratio between the collapsed areas and the area of the entire homogenous unit is calculated (see a Figure 5.7)

$$P_A = \frac{A_c}{A_{unit}}$$

Where: A_{unit} is an area of the homogenous unit,. PA = ...

For a particular homogenous unit, we can calculate the "linear collapse density" from the "collapse density by area", as follow:

$$P_L = k\sqrt{P_A}$$

Where: P_L: linear collapse density of the density of collapsed building per a length unit

k: a factor taking into account the relative comparison between density of building along the road and the building density inside the homogenous unit.

k=0.9: Density along the road is less than inside

k=1.0: Density along the road is equal to inside

k=1.1: Density along the road is a bit higher than inside

k=1.2: Density along the road is very much higher than inside

The k value is chosen based on each particular homogenous unit. The distribution of buildings in a homogenous unit can be seen from the footprint map. Examples of homogenous units with different k values can be seen in –Appendix 1

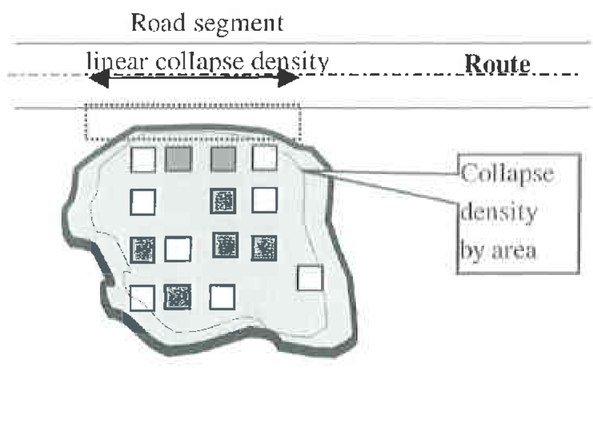


Figure 5.7: Linear collapse density

The assessment is based on the probability that a part of the road segment will be blocked by debris and it is measured as a percentage of the road segment, so this type of blockage is called ***longitudinal blockage***

5.2.2.2. The relative distance between the road and the buildings

The distance between the buildings and the road influences the possibility of the road blockage: the longer distance, the lower possibility of road blockage. This also refers to the distance between opposite buildings along two sides of the road: D_B (see Figure 5.8 and Figure 5.9). The D_B presents for passable width of the road in a post earthquake scenario, when vehicles might be allowed to travel even on sidewalks:

There are three ways to measure D_B:

-First, the distance is measured directly from the field.

-Second, the distance is measured from a high resolution image (like IKONOS image resolution 1m, or Quickbird image resolution 0.6m), or a footprint map.

-Third, the distance is estimated based on the road width (the data of road width is usually available in the database system of Transportation department). The distance is assumed to be proportional to road width at the same road section:

$$D_B = \gamma * W_R$$

The value of γ depends on the observation in several section samples in the field.

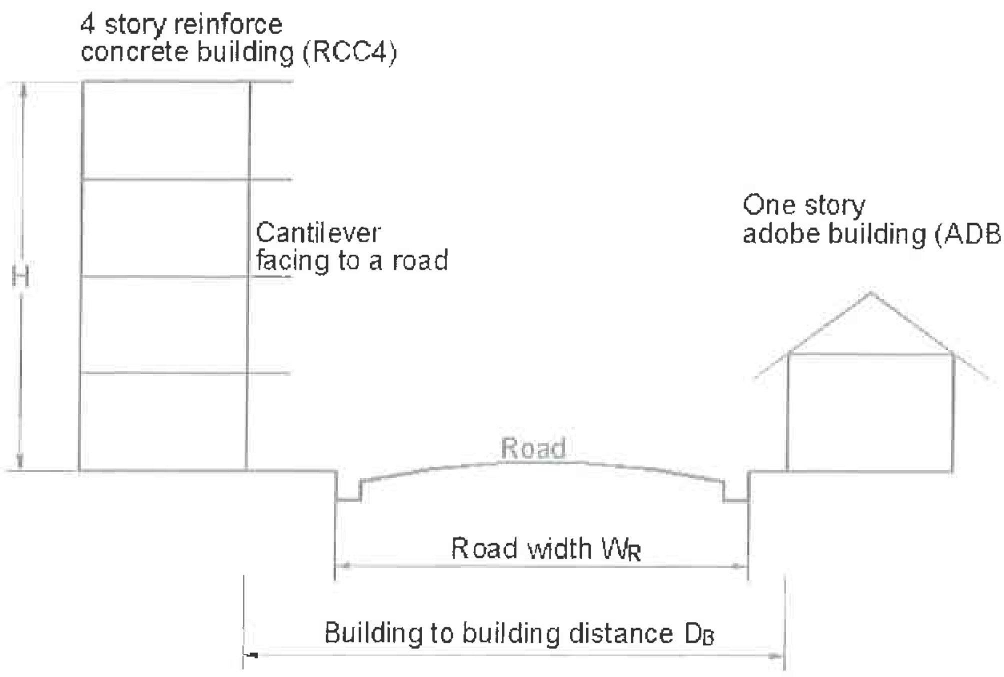


Figure 5.8: Distance between opposite buildings along two sides of a road

5.2.2.3. Building characteristics

- **Cantilever effect**

It is assumed that the percentage of buildings with cantilevers, which have been estimated for the homogenous units, is the same as the percentage of buildings with cantilevers at both sides of the roads. For example, if according to the field survey, there is 30% of the buildings in the homogenous unit with cantilevers, it is assumed that there are also 30% of buildings with cantilevers standing along the road.

If two similar buildings suffer the same earthquake force, the building with a cantilever is more likely to collapse than other buildings without cantilevers, since the cantilever and load on it cause an upturned moment M over an upturned point (see a Figure 5.10). Especially, there are many buildings along the roads in Lalitpur with cantilevers (see a Figure 3.9). Often the narrow roads are flanked on two sides by buildings with cantilevers. That is also a very typical type of construction in developing countries.

In the evaluation of the probability of road blockage by debris, therefore a factor C is introduced based on the percentage of cantilever buildings . If this factor is between 0 and 30 percent, C is taken as 1.1, and if it is higher, C will be 1.5.

In the field, the percentage of buildings with cantilevers was estimated in intervals of 5 %.

. No literature was found on the quantification of the effect of cantilevers on the probability of building collapse. Hence, the above-proposed C values are assumptions in a qualitative sense. It just means that cantilever increase the probability of building collapse. More detailed research on this factor should be carried out.

- **Type of collapse related to construction material**

In the evaluation of road blockage possibility another factor (M) related to the construction material type of the main structure of the building. "Masonry" buildings (brick-cement, brick-mud, adobe) are likely to disintegrate and collapse vertically, so the debris is likely not to go far way from the building plan. Meanwhile, "rigid" buildings (reinforce concrete, steel) are likely to lean and collapse towards one side (see Figure 5.3). The rigid buildings, even though they seem to be "stronger" than the soft masonry buildings, are likely to lean forward to the collapsing side, once they collapse, causing debris to go far away from the original building position (see a Figure 5.2 and Figure 5.3). Consequently, it leads to a larger width of the debris heap, and a the higher possibility of blocking the road. For this reason, the values for the material based factor M for RCC buildings was assigned as 1.3 and for other material types 1.1.

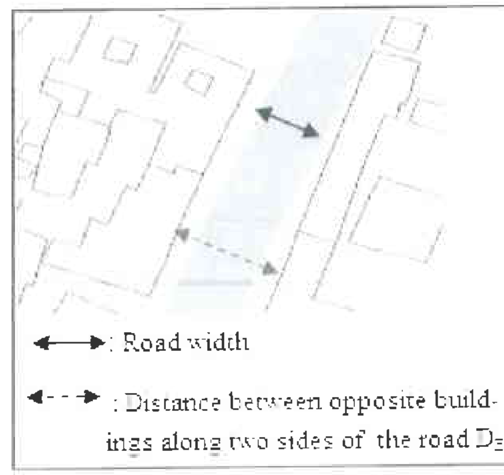


Figure 5.9: Road width compares to distance of opposite buildings
(extracted from the footprint map)

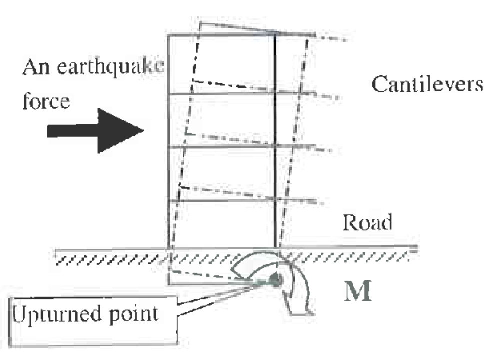


Figure 5.10: A cantilever building leans to collapse

- **Height of the buildings**

Another important is related to the height of the buildings along the road.
The average storey number of buildings along the roads is calculated as follows:

$$Height = 0.01 \times \sum Percentage\_of\_building.type_i \times No\_of\_storey$$

For example: a homogenous has: 50% of 1-storey adobe buildings (ADB1=50), 30% of 3-storey cement- brick buildings (BC3=30), and 20% of 4-storey reinforce concrete buildings(RCC4=20). The average height of buildings along the road in this case is:

H_E= 0.5x1+0.3x3+0.2x4=2.2 storey

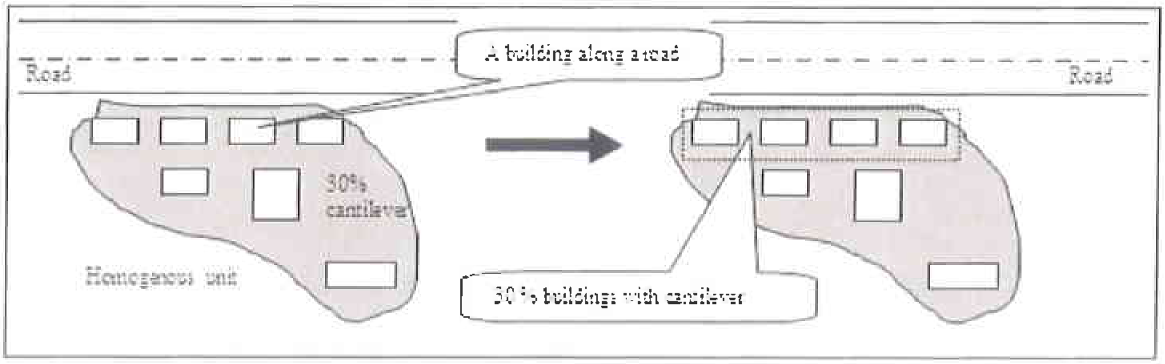


Figure 5.11: Buildings along the road

The average height of one storey in Lalitpur is estimated as 3 meters.

The width of the debris away from the building is estimated, based on pictures of debris shape and size from collapsed buildings in historical earthquakes, as compared to the height of the building and the type of buildings. It is estimated that the average debris width depends on the height of the buildings. The form of debris is estimated as in Figure 5.13.

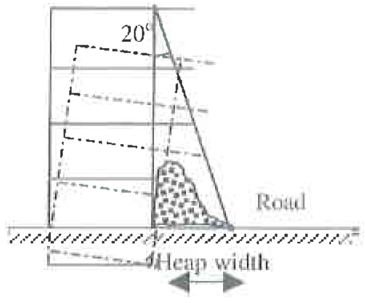


Figure 5.13: Estimation of debris form

The angle between the building front wall and the line, that connects the top of the front wall of the building and the furthest point of debris, is estimated as 20° (see Figure 5.13). The height of the building, in this case, is the average height. Thus, width of the debris heap is calculated as follows:

$$W_D = H_E * \tan 20^{\circ}$$

5.2.2.4. Final road blockage calculation

The blockage assessment tries to quantify the probability of debris occupying the road and is based on the building type and the relative distance between the road and the buildings. This is shown , perpendicular to the road center line, and this type of blockage is called ***lateral blockage***

A final debris heap width W_{FD} is a function of M, C, and W_D, and is calculated as follow:

$$W_{FD} = W_D * M * C$$

Below is a flowchart of the methodology to incorporate density of collapsed buildings, type of building, and relative distance between the road and the building into road blockage level (see Figure 5.14)

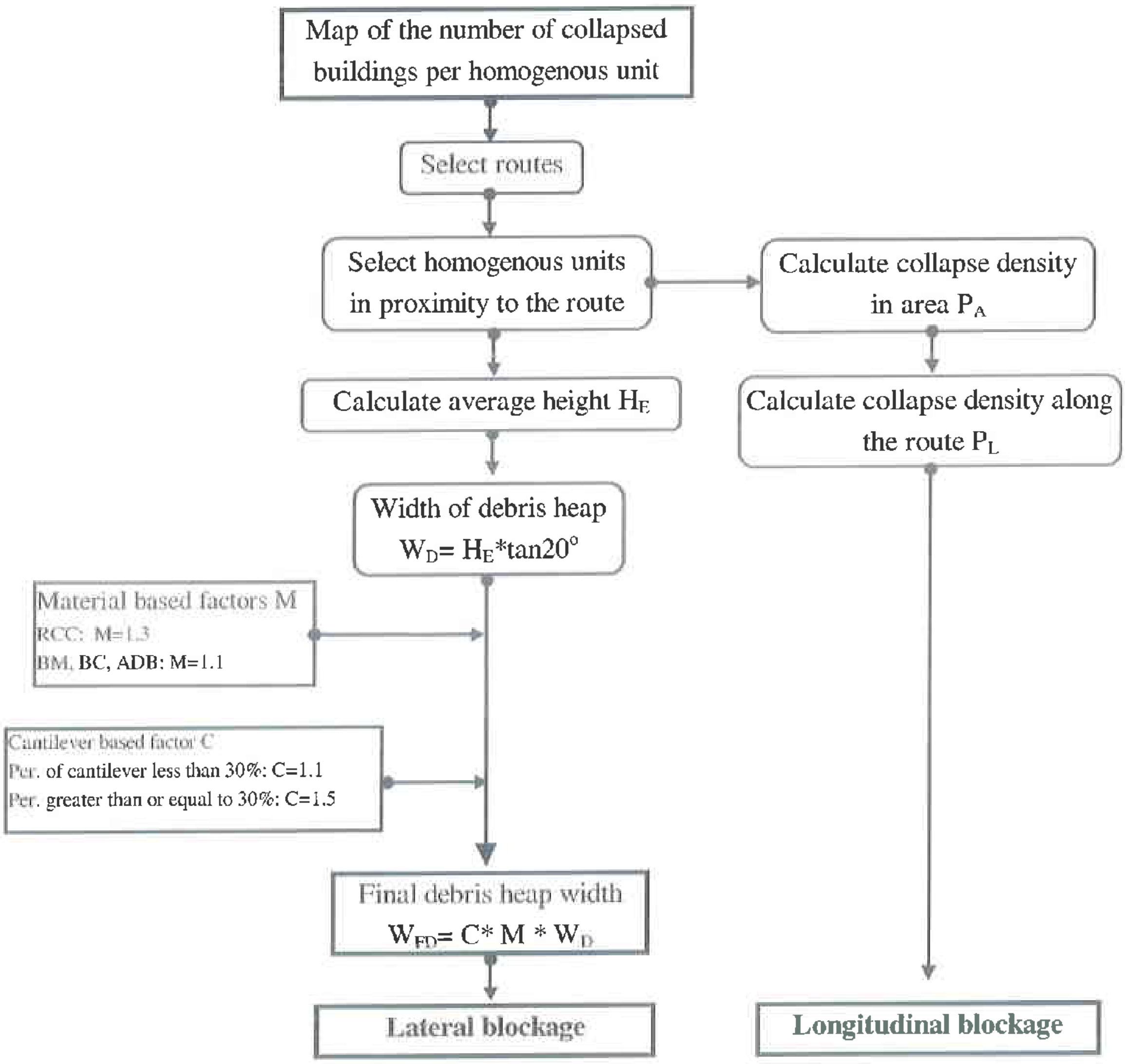


Figure 5.14: A methodology to estimate the route blockage level by debris

Note:

A ratio between the debris heap width, on one side of the road , and the useable width of the road D_B (see 5.3.3.2) is used to evaluate the lateral blockage by debris on the road surface at the corresponding road segment. The ratio D_{OCC} is calculated as follows:

$$D_{occ} = \frac{F_{WD}}{D_B}$$

The following classification was used for the severity of lateral blockage of roads by debris:

$D_{OCC} < 0.20$ — **Low** debris blockage level

$0.20 \le D_{OCC} < 0.50$ — **Moderate** debris blockage level

$D_{OCC} \ge 0.50$ — **High** debris blockage level

D_{OCC} was calculated for both sides of the road segment (see Table 5.1)

Table 5.1: Lateral blockage of a road by debris

Severity of lateral blockage		Lateral blockage on the Left side		
		Low	**Moderate**	**High**
Lateral blockage on the Right side	**Low**	Low	Low	Moderate
	Moderate	Low	Moderate	High
	High	Moderate	High	High

Based on the value of the linear collapse density P_L, we can classify the severity of longitudinal blockage of the road by debris as follows:

$P_L < 0.30$ — **Low** density of debris along the segment

$0.30 \le P_L < 0.50$ — **Moderate** density of debris along the segment

$P_L \ge 0.50$ — **High** density of debris along the segment

A classification of severity of the lateral blockage for both sides of the road segment is shown in Table 5.2:

Table 5.2: Longitudinal occupation of the debris

Severity of lateral blockage		Left side		
		Low	**Moderate**	**High**
Right side	**Low**	Low	Low	Moderate
	Moderate	Low	Moderate	High
	High	Moderate	High	High

5.2.2.5. An example of road blockage calculation

Below an example of calculating the road blockage is given for homogenous unit ID: 120501(see Figure 5.15). The homogenous unit is in close proximity and facing directly to a route R4.

The average height of building in the homogenous unit:

0.01*(30*5 + 40*4 + 10*3 + 0*2+ 0*1 + 0*4+ 0*3+0*2+0*1+20*4+0*3 + 0*2+ 0*1 + 0*1)= 1.41 (storey)

The height of one-storey is 3m. Width of the debris heap W_D

3*1.41*tan 20°= 1.539 (m)

Cantilever based factor C is 1.1, because CTNL =30%<31%

Material based factor M:

0.01*(1.3*(30+40+10+0+0) +1.1*(0+0+0+0+20+0+0+0+0)) =1.26

The final width of debris heap is W_{FD}=M*C*W_D

1.539*1.26*1.1= 2.133 (m)

Total number of buildings in the unit is 41

Total area of buildings inside the unit is: A_b=4986 m^2

The plan area of collapsed building is

$$A_c = \frac{N_{cb}}{N_b} A_b = \frac{26}{41} 4986 = 3161\text{m}^2$$

Collapse density by area

$$P_A = \frac{A_c}{A_{unit}} = \frac{3161}{14814.41} = 0.213$$

The linear collapse density with k=1.2, since we see in the map, the density of building along the road are much higher compare to the inside (see Figure 5.16):

$$P_L = k\sqrt{P_A} = 1.2\sqrt{0.213} = 0.554$$

Homo_unit ID	120501
No of collapsed buildings	26
Area (m^2)	14814.41
RCC5	30
RCC4	40
RCC3	10
RCC2	0
RCC1	0
BC4	0
BC3	0
BC2	0
BC1	0
BM4	20
BM3	0
BM2	0
BM1	0
ADB	0
Cantilever CANT	30

Figure 5.15: Data of homogenous unit 120501

The distance between two opposite buildings along the road. From the building footprint map and field survey, take γ = 1.3 for whole road segment adjacent to the homogenous unit

D_B=1.3*5=6.5(m)

A ratio of route width is occupied by debris of homogenous unit 12051 to one side of the route is

W_{FD} /D_B=100*(2.133/6.5)= 0.3281

It means that 73% of length of the segment (of the route R4) adjacent to the unit 120501 is affected by collapsed buildings (at lower side of the segment in Figure 5.16) with 32.8% of the segment width is occupied.

Classification of the lateral and longitudinal blockage by the debris, we have

Lateral blockage: **High**

Longitudinal blockage: **High**

Similarly, the calculation for the homogenous unit 120401 (at the upper side of the route 4), resulted in 67.5% of the length of the segment (of route 4) adjacent to the unit 120401 being affected by collapsed buildings, whereas 70.7% of the segment width is occupied by the homogenous unit 120401 (see a Figure 5.17).

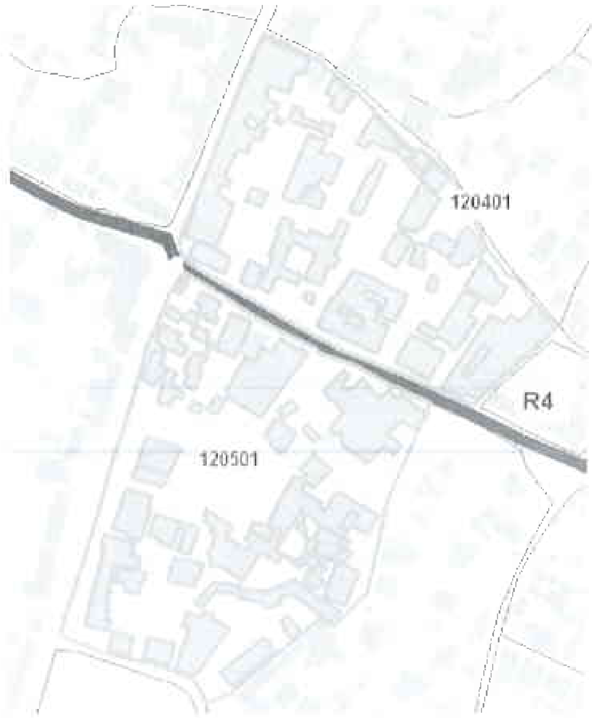


Figure 5.16: Location of the homogenous unit 120501

Similarly, we calculated the longitudinal and lateral blockages as well as the classification of blockage level for 8 homogenous along the route R4, where the road width is 5m, (see Figure 5.20). The blockage level is calculated separately for the left and the right hand sides of the road.

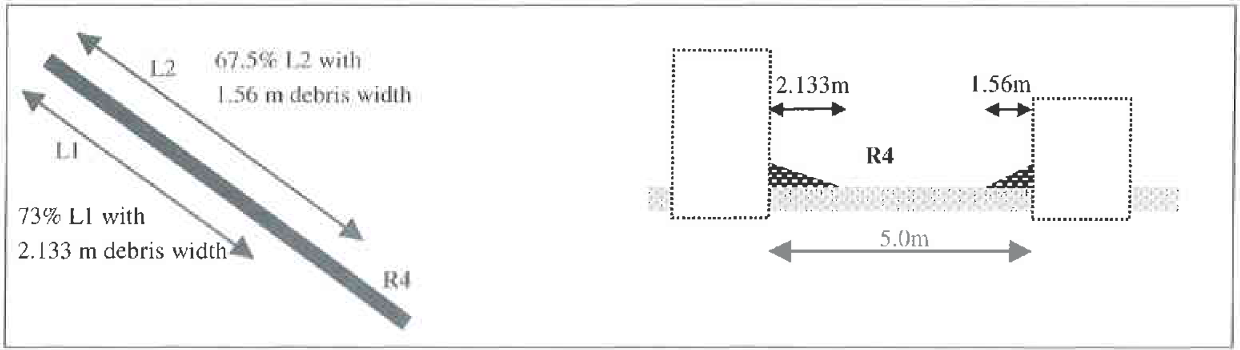


Figure 5.17: R4 is blocked by debris from the homogenous units 120501 and 120401

Going along the route R4, from the lower right corner to the upper left corner, a vehicle meets high level obstacles in terms of both the length and the width of the debris heap. It can be explained that in the homogenous unit 120402, there is a very high ratio of buildings with cantilevers (see Figure 5.18). Differently, the homogenous unit 120402 has long and narrow buildings along the road, and the research on vulnerability assessment shows that there were two out of three buildings in this unit that were expected collapse.

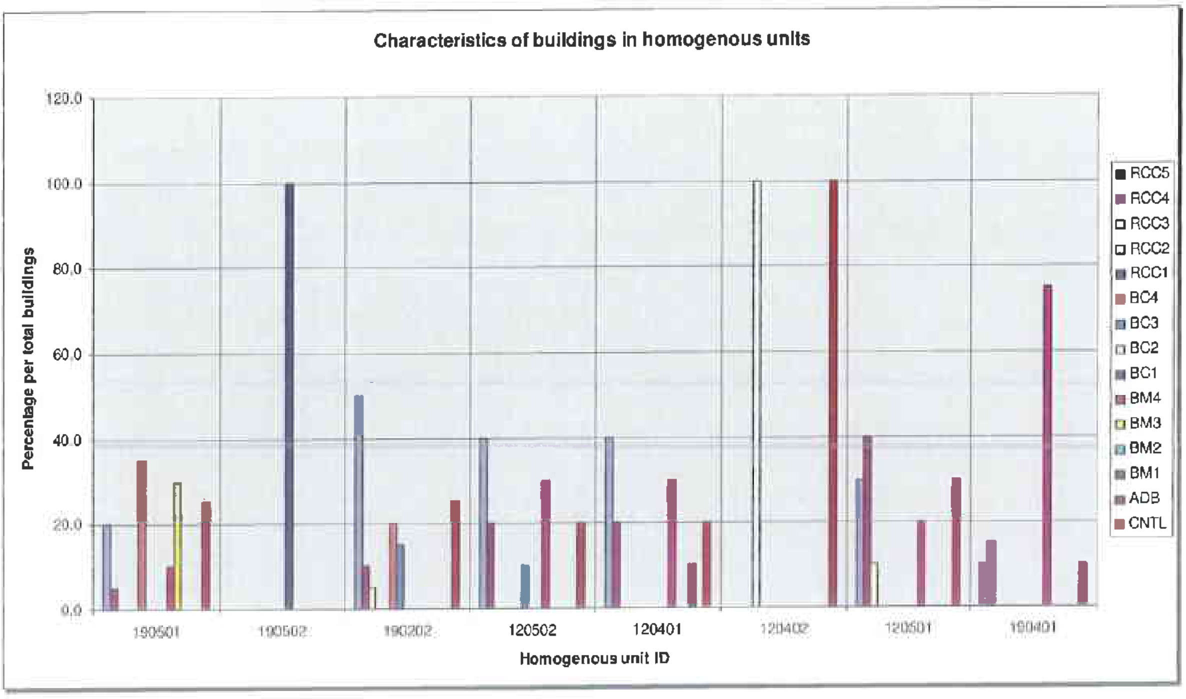


Figure 5.18: Characteristics of buildings in the investigated homogenous units

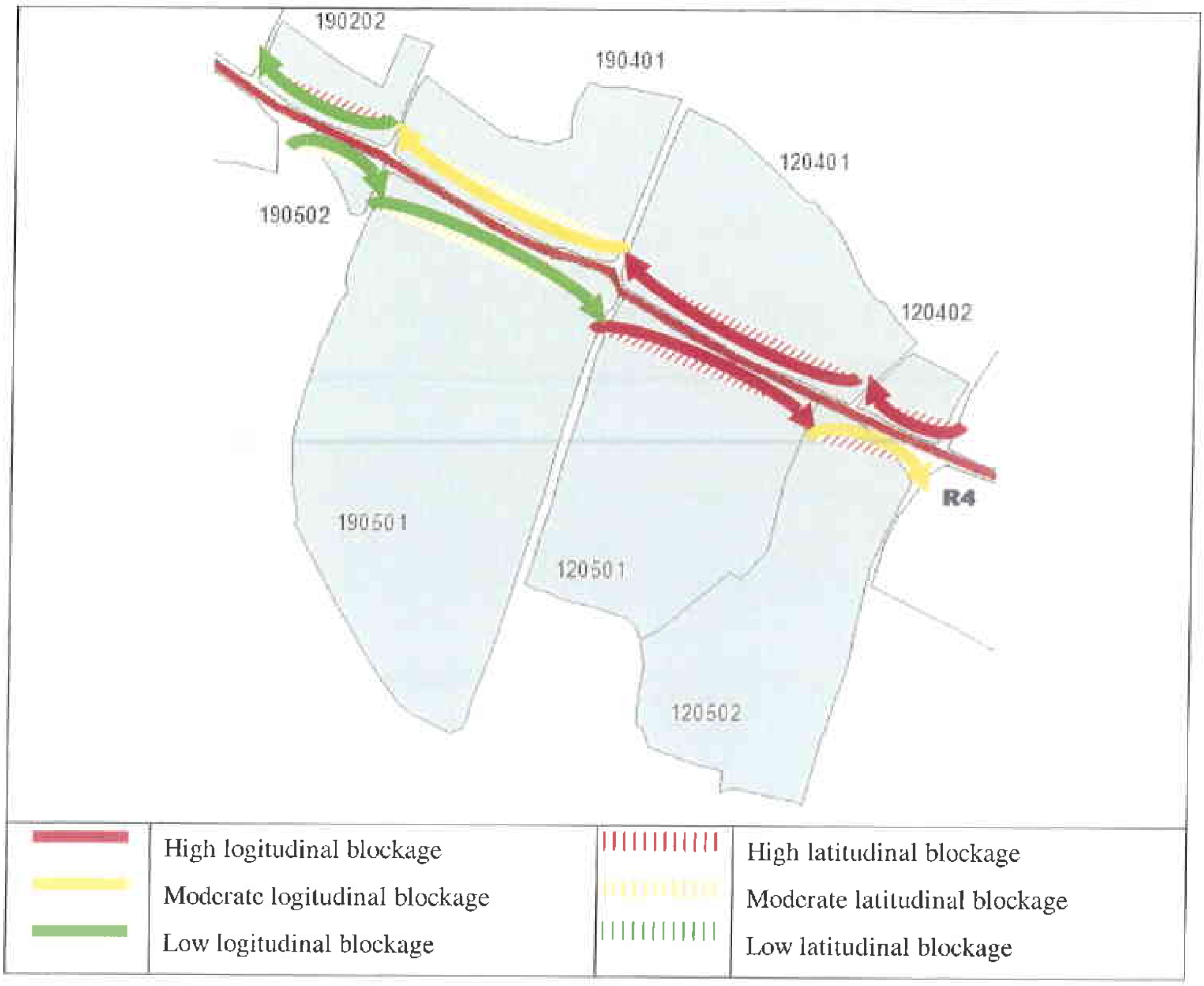


Figure 5.19: Longitudinal and lateral blockage level by the debris

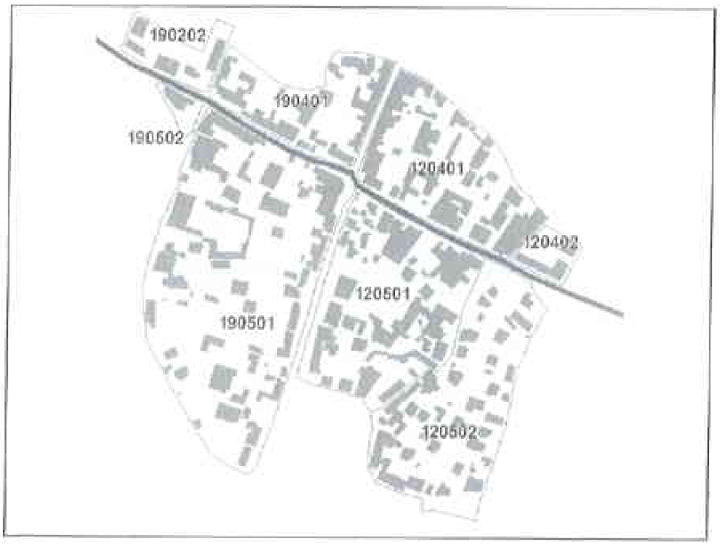


Figure 5.20: Building footprints in the homogenous unit

By contrast, the road segment that is adjacent to the homogenous unit 190502 and the homogenous unit 190501 has low levels of longitudinal and lateral blockage. There are only one-storey buildings of reinforce concrete in the unit 190502, and these buildings do not collapse according to the building vulnerability assessment. Meanwhile, the unit 190501 has soft buildings like cement-brick, mud brick with a small number of cantilever (25%). Furthermore, the density of buildings along the road segment is also low: there are only two blocks at the corner of the unit in proximity to the road, the remaining ones are only two small houses in the middle of the unit edge, where is adjacent to the road segment (see a Figure 5.20)

5.3. Combination of impedances caused by the building collpase and the road rupture along the routes

According to assessment of physical damage of roads in the Chapter 4, the damage level at the routes are calculated for both sides of the routes (a left and right hand side) and the value are the same for both sides of the same section (see Figure 4.17).

The physical damage level and blockage level of the road influence the maximum speed of or even prevent vehicle from travelling (refer to Figure 5.1). The speed usually becomes lower than in a daily scenario. However, these two types of the impedances need to be evaluated separately. It might be come more vague if these impedances were incorporated in order to predict the maximum speed of a particular vehicle like the ambulance, or other types of vehicles in general. According to a particular location, a combination of these impedances should be considered in order to predict traffic situation at this location.

5.4. Example of Identifing the temporal evacuation sites

The shortest path from a hospital to the temporal evacuation site in a daily scenario may be completely different to that in a post-earthquake scenario. Personnel who are in charge of evacuation need to figure out which routes for the ambulances (that is the shortest one in the normal daily scenario) may be blocked in the post-earthquake scenario. Thus, alternatives routes should be identified in advance in order to help the ambulances find the most feasible routes for traveling from the hospital to the temporal sites.

JICA (2002), in a research of mitigation of risk due to earthquakes in the Kathmandu Valley, proposed some locations for evacuation sites and relief storages (see Figure 5.21). The sites were located near the Bagmati river bank. However, these places seem more suitable for relief storage, since they are very close to the main road and the Bagmati bridge only. However, they are not very suitable for evacuation sites, since these places are rather far way from the Lalitpur core areas. Injured people stuck in the collapsed buildings in the core areas may not be able to be moved to these places.

Figure 5.21: Water-front greens proposed as temporal evacuation sites (Modified from JICA, 2002)

For this reason, suggesting a series of temporal evacuation sites both inside and outside the core areas of the Lalitpur is necessary. Places that were chosen are vacant or open places that are close to a high density of highly vulnerable residential buildings (Guragain, 2004). People injured in collapsed buildings when the earthquake happened need to be evacuated from their houses to nearby evacuation sites.

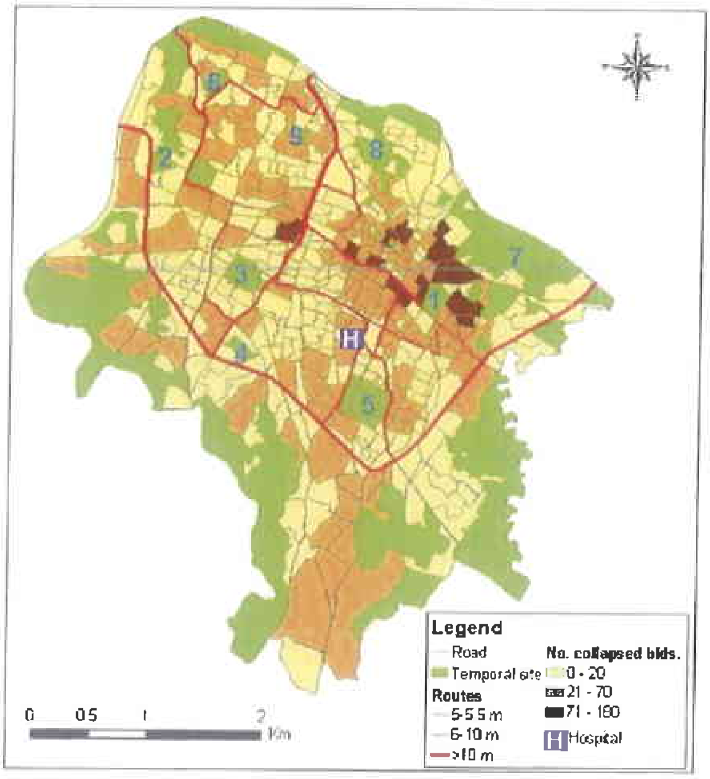


Figure 5.22: Temporal evacuation sites

The map in Figure 5.22 proposes some temporal evacuation sites (the sites are numbered). The sites are vacant spaces like parks, religious places etc.... The places are also near to the route that are wide enough for the travelling of the ambulance. These sites were selected manually after combining the loss estimation of buildings from Guragain (2004) with the road network and the urban land use map.

5.5. Conclusions

The building characteristics not only influence the possibility of collapse, but also influence the form of collapse. The distance from the building to the road also influence the possibility of road blockage. Further research in judgment of the factors like M, C, and k needs to be carried on. The factor values should be validated based on damage investigation of buildings in real earthquakes

The footprint map produces extensive and reliable information about a distribution of buildings as well as the distance between the building and the road.

The model was tested in eight homogenous units. Since the calculation is manual work, so if the model is tested in a whole city as small as Lalitpur city size, the calculation work is very time consuming and causes potential errors. A method to apply the model semi-automatically or automatically should be developed, in order to generate a blockage map of a whole road network.

Physical damage level and blockage level can be used as components for assessment of functional damage of the road. The incorporation of those levels along with traffic flow in daily situation in particular location should be further researched.

6. Conclusions and recommendations

6.1. Conclusions

In this study, the aim is to develop a methodology to assess road and bridge vulnerability in earthquakes

Two characteristics of roads were taken into account: type and location. These characteristics are basis for road classification. The road classification along with earthquake intensity and earthquake induced liquefaction are incorporated into vulnerability assessment. The damage states of road in a selected particular earthquake are also assessed and visualized in maps.

Location and technical data of bridges are used in vulnerability assessment. Two methods are used for assessment: one is low demanding data method and the other is high demanding data method. The potential damage and probability of different damage states are examined.

The MMI map, liquefaction map and the spectral acceleration values of the study area are used for damage assessment. These data are from concurrent researches in the SLARIM project, having been carried on at the same time with this study.

Factors, which are used in debris estimation from collapsed buildings, are material, height, percentage of the building with cantilevers, and a number of predicted collapsed buildings. These factors are quantified and combined based on observation of building collapse prototype in historic earthquakes and knowledge of the author in building structure. The number of collapsed building comes from the building vulnerability research.

The estimation the road blockage level bases on estimation of debris volume, debris distribution and relative distance between road and building along the road. The blockage is divided into two categories: lateral and longitudinal ones. This blockage estimation is proposed as a factor, affecting to the effectiveness of an ambulance traveling in evacuation activities.

Primary data and secondary data are collected to fulfill the research requirement. The primary data is collected in a field during the field trip. The secondary data is collected from different organizations and institutions. Collected data is also checked and rectified before being used.

6.2. Limitations

The nature of an earthquake is unpredictable in terms of location, magnitude and time. Hence, the prediction of the damage states consists of uncertainties. The uncertainties can be reduced by detailed studies of real damage of the road and the bridge in historic earthquakes. The data of the damage in the historic earthquakes is always valuable for damage estimation in future earthquakes.

In the road vulnerability assessment, the physical condition and structure of the road are not taken into account. Although the data of physical condition was collected during the fieldtrip, but there have not been a methodology to incorporate this data to road damage estimation in earthquakes. Similarly, the relationship between damage states and the structure of the road has not been developed, yet.

The PGD value is one of the factor presenting well probability of damage states of the road. However, this data for Lalitpur has not been available. For that reason, a good picture of the probability of damage states of the roads based on the PGD is not produced. This probability of damage states can be used as comparative results to that of other applied methods.
In assessing the probability of damage states of bridge, some missing data are assumed. These data more or less affect the accuracy of the output results.
The damage of the road system by past major earthquakes in Lalitpur was not recorded. For that reason, historic damage data is not taken into account in this study. If this data was incorporated in the research, the research result may be more reliable.
There are many factors were not taken into account in the road blockage estimation caused by collapsed buildings. First, factors affecting the probability of building collapse like: foundation, shape, proximity, geological condition, etc... Second, the relative distance between the building and the road is estimated constant for each individual homogenous unit. These unmentioned factors certainly influence the accuracy of the results.

6.3. Suggestion for further research

The data of physical condition and structure of the road can be incorporated in further studies in vulnerability assessment. The data, that was collected during the field, are quite updated data. However, if other studies are carried on in the future, the data needs to be updated again, securing the reliability and accuracy of the results.
In case of the bridge, the missing data need to be collected for detailed research, instead of data assumption. Bridges that are not exactly found amongst the given bridge classifications of the HAZUS need to be studied individually and separately.
The study have mentioned the probability of collapsed buildings and calculation is done for a homogenous unit. The result can be more accurate if further studies focus on individual houses, since different houses have different probability of collapse and different type of collapse. Nowadays, as the resolution of satellite images has been getting higher (0.6m or even less), the distinguishing of individual houses as well as their characteristics has become feasible.
The calculation of probability of road blockage in this study is done manually. It is time consuming work and causes potential errors. Further studying in how to calculate semi-automatically or automatically these probabilities should be carried on. It helps to estimate the road blockage level for whole network with a numerous number of road arcs.
Further studies in the incorporation of debris blockage level with traffic speed and road rehabilitation should be done. The traveling speed of vehicles in a post earthquake significantly influence the effectiveness of loss mitigation. Road rehabilitation can be optimized based good estimation of the blockage location and the blockage level.

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8. Appendix 1

A vulnerability function for building by the RADIUS
http://geohaz.org/radius/GuidelineCont.htm (1/28/2004)

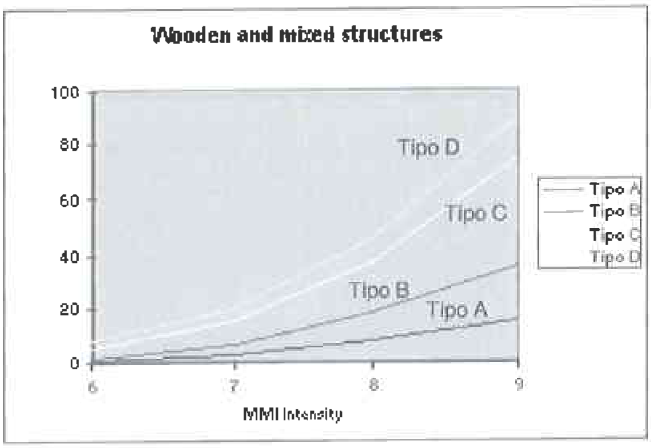

Figure 8.1: Example of vulnerability functions for the estimation of building damage. ("Tipo" = "Type")

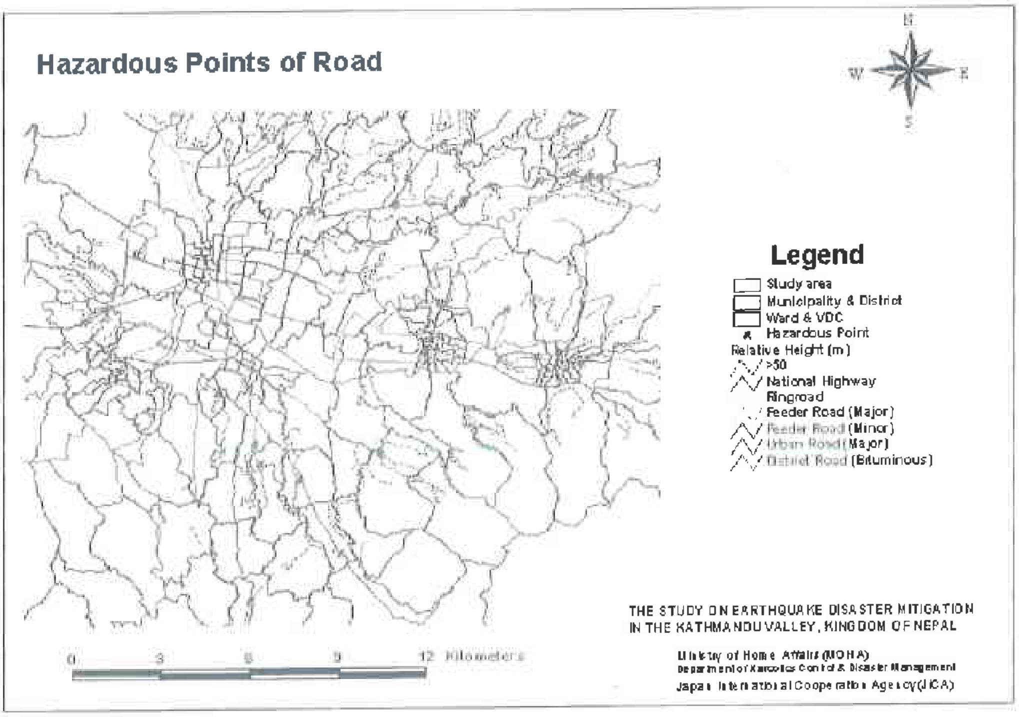

Figure 8.2: Hazardous points of roads (JICA, 2002) (Vol.3, pp. F23)

Table 8.1: The Abridge Modified Mercalli Intensity scale (Smith, 2001)

MMI	Description	Average PGA g = gravity (9.8 m s2)
I	Not felt except by a very few under especially favorable circumstances.	-
II	Felt only be a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.	-
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motorcars may rock slightly. Vibration like passing of truck. Duration estimated.	-
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motorcars rocked noticeably.	0.015g – 0.02g
V	Felt by nearly everyone, many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.	0.03g – 0.04g
VI	Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.	0.06g – 0.07g
VII	Everybody runs outdoors. Damage negligible in building of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motorcars.	0.10g – 0.15g
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motorcars disturbed.	0.25g – 0.30g
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.	0.50g – 0.55g
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.	above 0.60g
XI	Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bend greatly.	
XII	Damage total. Practically all works of construction are damaged greatly or destroyed. Waves seen on ground surface. Lines of sight and level are distorted. Objects are thrown upward into the air.	

Table 8.2: Damage Algorithms for Bridges (NIBS, 1999) (pp. 7-12)

	Sa [1.0 sec in g's] for Damage Functions due to Ground Shaking				PGD [inches] for Damage Functions due to Ground Failure			
CLASS	Slight	Moderate	Extensive	Complete	Slight	Moderate	Extensive	Complete
HWB1	0.4	0.5	0.6	0.8	7.9	7.9	7.9	15.7
HWB2	0.6	0.8	1	1.6	31.5	31.5	31.5	35.4
HWB3	0.8	0.9	1.1	1.6	3.9	3.9	3.9	17.7
HWB4	0.8	0.9	1.1	1.6	3.9	3.9	3.9	17.7
HWB5	0.26	0.35	0.44	0.65	3.9	3.9	3.9	13.8
HWB6	0.33	0.46	0.56	0.83	3.9	3.9	3.9	13.8
HWB7	0.45	0.76	1.05	1.53	3.9	3.9	3.9	13.8
HWB8	0.35	0.42	0.5	0.74	3.9	3.9	3.9	5.9
HWB9	0.54	0.88	1.22	1.45	23.6	23.6	23.6	35.4
HWB10	0.6	0.79	1.05	1.38	3.9	3.9	3.9	5.9
HWB11	0.91	0.91	1.05	1.38	23.6	23.6	23.6	35.4
HWB12	0.26	0.35	0.44	0.65	3.9	3.9	3.9	13.8
HWB13	0.33	0.46	0.56	0.83	3.9	3.9	3.9	13.8
HWB14	0.45	0.76	1.05	1.53	3.9	3.9	3.9	13.8
HWB15	0.76	0.76	0.76	1.04	3.9	3.9	3.9	9.8
HWB16	0.91	0.91	1.05	1.38	5.9	5.9	5.9	11.8
HWB17	0.26	0.35	0.44	0.65	3.9	3.9	3.9	13.8
HWB18	0.33	0.46	0.56	0.83	3.9	3.9	3.9	13.8
HWB19	0.45	0.76	1.05	1.53	3.9	3.9	3.9	13.8
HWB20	0.35	0.42	0.5	0.74	3.9	3.9	3.9	5.9
HWB21	0.54	0.88	1.22	1.45	23.6	23.6	23.6	35.4
HWB22	0.6	0.79	1.05	1.38	3.9	3.9	3.9	5.9
HWB23	0.91	0.91	1.05	1.38	23.6	23.6	23.6	35.4
HWB24	0.26	0.35	0.44	0.65	3.9	3.9	3.9	13.8
HWB25	0.33	0.46	0.56	0.83	3.9	3.9	3.9	13.8
HWB26	0.76	0.76	0.76	1.04	3.9	3.9	3.9	9.8
HWB27	0.76	0.76	0.76	1.04	3.9	3.9	3.9	9.8
HWB28	0.8	0.9	1.1	1.6	3.9	3.9	3.9	17.7

Table 8.3: HAZUS Bridge Classification Scheme

CLASS	NBI Class	State	Year Built	# Spans	Length of Max. Span (meter)	Length less than 20 m	K_{3D}	I_{shape}	Design	Description
HWB1	All	Non-CA	< 1990		> 150	N/A	EQ1	0	Conventional	Major Bridge - Length > 150m
HWB1	All	CA	< 1975		> 150	N/A	EQ1	0	Conventional	Major Bridge - Length > 150m
HWB2	All	Non-CA	>= 1990		> 150	N/A	EQ1	0	Seismic	Major Bridge - Length > 150m
HWB2	All	CA	>= 1975		> 150	N/A	EQ1	0	Seismic	Major Bridge - Length > 150m
HWB3	All	Non-CA	< 1990	1		N/A	EQ1	1	Conventional	Single Span
HWB3	All	CA	< 1975	1		N/A	EQ1	1	Conventional	Single Span
HWB4	All	Non-CA	>= 1990	1		N/A	EQ1	1	Seismic	Single Span
HWB4	All	CA	>= 1975	1		N/A	EQ1	1	Seismic	Single Span
HWB5	101-106	Non-CA	< 1990			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support - Concrete
HWB6	101-106	CA	< 1975			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support - Concrete
HWB7	101-106	Non-CA	>= 1990			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Concrete
HWB7	101-106	CA	>= 1975			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Concrete
HWB8	205-206	CA	< 1975			N/A	EQ2	0	Conventional	Single Col., Box Girder - Continuous Concrete
HWB9	205-206	CA	>= 1975			N/A	EQ3	0	Seismic	Single Col., Box Girder - Continuous Concrete
HWB10	201-206	Non-CA	< 1990			N/A	EQ2	1	Conventional	Continuous Concrete
HWB10	201-206	CA	< 1975			N/A	EQ2	1	Conventional	Continuous Concrete
HWB11	201-206	Non-CA	>= 1990			N/A	EQ3	1	Seismic	Continuous Concrete
HWB11	201-206	CA	>= 1975			N/A	EQ3	1	Seismic	Continuous Concrete
HWB12	301-306	Non-CA	< 1990			No	EQ4	0	Conventional	Multi-Col. Bent, Simple Support - Steel
HWB13	301-306	CA	< 1975			No	EQ4	0	Conventional	Multi-Col. Bent, Simple Support - Steel
HWB14	301-306	Non-CA	>= 1990			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Steel
HWB14	301-306	CA	>= 1975			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Steel
HWB15	402-410	Non-CA	< 1990			No	EQ5	1	Conventional	Continuous Steel
HWB15	402-410	CA	< 1975			No	EQ5	1	Conventional	Continuous Steel
HWB16	402-410	Non-CA	>= 1990			N/A	EQ3	1	Seismic	Continuous Steel
HWB16	402-410	CA	>= 1975			N/A	EQ3	1	Seismic	Continuous Steel
HWB17	501-506	Non-CA	< 1990			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support - Prestressed Concrete
HWB18	501-506	CA	< 1975			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support - Prestressed Concrete

CLASS	NBI Class	State	Year Built	# Spans	Length of Max. Span (meter)	Length less than 20 m	K_{3D}	I_{shape}	Design	Description
HWB19	501-506	Non-CA	>= 1990			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Prestressed Concrete
HWB19	501-506	CA	>= 1975			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Prestressed Concrete
HWB20	605-606	CA	< 1975			N/A	EQ2	0	Conventional	Single Col., Box Girder - Prestressed Continuous Concrete
HWB21	605-606	CA	>= 1975			N/A	EQ3	0	Seismic	Single Col., Box Girder - Prestressed Continuous Concrete
HWB22	601-607	Non-CA	< 1990			N/A	EQ2	1	Conventional	Continuous Concrete
HWB22	601-607	CA	< 1975			N/A	EQ2	1	Conventional	Continuous Concrete
HWB23	601-607	Non-CA	>= 1990			N/A	EQ3	1	Seismic	Continuous Concrete
HWB23	601-607	CA	>= 1975			N/A	EQ3	1	Seismic	Continuous Concrete
HWB24	301-306	Non-CA	< 1990			Yes	EQ6	0	Conventional	Multi-Col. Bent, Simple Support - Steel
HWB25	301-306	CA	< 1975			Yes	EQ6	0	Conventional	Multi-Col. Bent, Simple Support - Steel
HWB26	402-410	Non-CA	< 1990			Yes	EQ7	1	Conventional	Continuous Steel
HWB27	402-410	CA	< 1975			Yes	EQ7	1	Conventional	Continuous Steel
HWB28										All other bridges that are not classified

Table 8.4: Soil Amplification Factors (NIBSS, 1999) (pp. 4-24)

Site Class B Spectral Acceleration	Site Class				
	A	B	C	D	E
Short-Period, S_{AS} (g)	**Short-Period Amplification Factor, F_A**				
≤ 0.25	0.8	1.0	1.2	1.6	2.5
0.50	0.8	1.0	1.2	1.4	1.7
0.75	0.8	1.0	1.1	1.2	1.2
1.0	0.8	1.0	1.0	1.1	0.9
≥ 1.25	0.8	1.0	1.0	1.0	0.8*
1-Second Period, S_{A1} (g)	**1.0-Second Period Amplification Factor, F_V**				
≤ 0.1	0.8	1.0	1.7	2.4	3.5
0.2	0.8	1.0	1.6	2.0	3.2
0.3	0.8	1.0	1.5	1.8	2.8
0.4	0.8	1.0	1.4	1.6	2.4
≥ 0.5	0.8	1.0	1.3	1.5	2.0*

* Site Class E amplification factors are not provided in the *NEHRP Provisions when* $S_{AS} > 1.0$ *or* $S_{A1} > 0.4$. Values shown with an asterisk are based on judgment.

Figure 8.3: Examples of the k value representing difference of building density inside a homogenous unit and building density along the road.

9. Appendix 2

HOMOGENOUS UNIT AND BUILDING CLASSIFICATION (Guaragin, 2004)

The main idea of homogeneous area mapping was to divide the municipality area into smaller units, to delineate the area in the map and to take building information surveying it in the field. Here the concept of the word *homogeneous* is used to mark those areas, which have the same building material type and building occupancy. But in the field, except for some parts, there was no distinct area with buildings of the same material type and height, but normally there was a mixture of different types of buildings. Most of the buildings in this city have been constructed by the building owners themselves following different construction practices and using different building materials. It is also quite common to use the same building for different building uses giving a heterogeneous building character. Hence it was decided to divide the area according to building uses and take the information in percentage.

The following methodology was adopted while mapping the homogeneous units:

- The map made from the IKONOS-pan image of 2001 was taken as base map for the area delineation and field survey
- Ward boundaries, roads, streets, and rivers were taken as boundary lines of the homogeneous units
- Areas with no buildings (Vacant land) like ponds, rivers, agricultural fields, recreational areas and also distinct building occupancy areas like industrial area, military camp, zoo, institutional and educational areas were marked as separate units.
- The building occupancy was divided into the following class:
    - Institutional building (INST)
    - Educational (School and College) buildings (School: SCH, College: COLG)
    - Residential (RS0)
    - Residential with ground floor commercial (RS1)
    - Residential with ground floor and first floor commercial (RS2)
    - Total commercial buildings (COM)
    - Industrial building (IND)
- From the same unit building type was estimated into following material types also considering the height of the building. The number accounts for the number of storey.
    - Adobe building (ADB1, ADB2)
    - BM building (BM1,BM2, BM3, BM4)
    - BC building (BC1, BC2, BC3, BC4)
    - RCC building (RCC1, RCC2, RCC3, RCC4, CC5)
- The size of the homogeneous units was determined considering density and uses of buildings. In the dense core area, having mixed occupancy, the information was taken in smaller unit (up to 3 hectares) as compared to the outer fringe area (up to 5 hectares). For less dense newly

developed residential areas having more vacant space the size of the homogeneous units was often quite large unto 10 hectare. All the vacant land including agricultural field with few buildings were digitized separately.

- In each unit, built-up and non-built up area was taken in percentage of homogeneous unit area. Building material type and occupancy class was estimated in the percentage of built up area. Wider road and courtyard area was excluded in estimating the built up area but home garden , boundary wall , and narrow street was included.
- In each unit all the information of building types and uses was estimated in percentages (built up and non built-up area by percentage of homogeneous unit and building material type and occupancy class from the total built up area)
- Each unit was assigned a unique unit identifier, which consisted of a combination of the Ward no, block number and sub-block number (if any).

Each unit was evaluated in the field using a sidewalk study by observing the building material and construction type and building use. Information of each unit was filled in the survey form.