Earthquake Building Vulnerability and Damage Assessment with reference to Sikkim Earthquake, 2011

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Specialization: Natural Hazards and Disaster Risk Management

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dedicated to my brother

ABSTRACT

About 59% of India's land is prone to moderate to severe earthquakes (M > 5) which makes it one of highest seismic risk prone areas in the world. Destructive earthquakes (M > 6.5), which are highly unpredictable, don't occur frequently which makes people, local authorities ignore the importance of the earthquake resistant building design, disaster preparedness and post disaster management. Damage and vulnerability assessment of a city is very important and provides the probable amount of damage to the settlements due to potential earthquake hazard. The damage scenarios can act as the base for preparation of disaster management plans, taking mitigation measures and prepare population living in the high vulnerable areas.

HAZUS methodology, developed for US using GIS as platform, is used for assessing vulnerability and damage caused by the 18th September 2011earthquake at Gangtok (68 km from the epicentre) which is the capital city of state of Sikkim, a major hub for tourism and economy. The creation of databases with detailed information on buildings is the important task that has to be carried out before using the tool for generation of damage scenarios for reference earthquake. The scale and the details of the results are directly based on the amount of information used in the execution of methodology. For the vulnerability and damage assessment, the methodology requires parameters like, magnitude and type of earthquake, distance from epicentre to the study area, geology and local conditions of soil etc, and building characteristics. To achieve the defined objectives, research work was divided into three stages, Pre-field, Field work and Post filed work. Collection of literature regarding HAZUS methodology, collection of field data, GIS database organisation, damage assessment and validation with the actual damage data and field observation are some of the important activities carried out in different stages. The identification of building types and the damage to the building were done in the field by rapid visual screening procedure. Based on the methodology, expected damage to the identified building categories are given in the form of charts and figures for various ground shaking scenarios. Damages reported by the local authorities were used as the reference to validate the generated results and discuss the applicability of the method in Indian context. Based on the terrain conditions, the possible hazard zones and elements at risk, risk map was also generated.

The reasons for damage and the failure of structure were discussed and possible methods for retrofitting and improving future constructions have been recommended. The results showed that concrete types of buildings were highly vulnerable and there is a high probability of slight damage to such buildings. These scenarios were matched with the reported damage. So it is concluded that the HAZUS methodology can be used in Indian condition as HAZUS building types have some similarity with Indian building types. However, the drawback of using such method is that the capacity curves and vulnerability functions given in HAZUS have been derived for building types in the US, which may differ from the other parts of the world. Therefore, it is concluded that Indian building structural parameters, which are currently unavailable, should be developed and used for generating more realistic damage scenarios using such methodology.

Keywords: Earthquake, Building Vulnerability, HAZUS, Gangtok

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Teja Malladi

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1. INTRODUCTION

1.1. Earthquakes

Earthquakes are one of the most dangerous, destructive and unpredictable natural hazards, which can leave everything up to a few hundred kilometres in complete destruction in seconds. In more than 300 natural disasters in year 2011, over 30,000 people lost their lives (20,000 alone in Japan's Earthquake and Tsunami in March 2011) and 206 million people were affected and $366 Billion were the economic losses, which made it the costliest year in the history of the catastrophes (EM-DAT, 2011). The number of disasters and number of deaths were less compared to the year 2010, where the Haiti earthquake event in January 2010 alone claimed deaths of nearly 220,000. EM-DAT (2011) reports indicate that the earthquakes in the developed countries would result higher economic losses and more number of deaths in developing countries. In developing countries due to economic conditions people are forced to live in high vulnerable locations and people have invested so much money for construction, and post disaster moving to safer locations is not an option as they cannot abandon their present houses.

Therefore, a paradigm shift is required in earthquake risk mitigation and the first step in this direction is risk and vulnerability assessment using a recently occurred earthquake which will draw home the point to both decision makers as well as affected population.

1.1.1. Earthquake and India

India has enough experiences with earthquakes and the kind of damage that they can leave behind within seconds and it is not rare or unusual anymore. About 59% of India's land is prone to moderate to severe earthquakes which makes it one of highest seismic risk prone areas in the world (BMTPC, 2006). More than 25,000 people died in 8 major earthquakes during last 20 years and the last major earthquake in India was a decade earlier in Bhuj, Gujarat, which occurred on 26th January 2001 and claimed over 14,000 lives and caused severe damage to buildings and infrastructure resulting high economic losses(Arya, 2000; Ghosh, 2008; NDMA, 2011). Due to the collision of Indian plate with the Eurasian plate, the Himalayan region has emerged as one of the seismically active regions of world, resulting in many disastrous earthquakes in the past and recent times and North East India alone has emerged as one of the most seismically active regions in the country (NDMA, 2011).

Many active faults, such as Himalayan Frontal Thrust, Main Boundary Thrust (MBT) and Main Central Thrust (MCT) exist in the region. Bureau of Indian Standards (BIS) and Indian Meteorological Department (IMD) with records of seismicity in past 100 years, and other scientific data, divided the country into four major seismic zones and the possible Modified Mercalli Intensity (MMI) is given in Table 1-1, corresponding to the seismic zones shown in Figure 1-1.

Table 1-1 Seismic Zones and Associated Intensity

Seismic Zone	Possible Intensity	Area in %
II(Low)	VI and below	41
III(Moderate)	VII	31
IV(Severe)	VIII	17
V(Very Severe)	IX and above	11

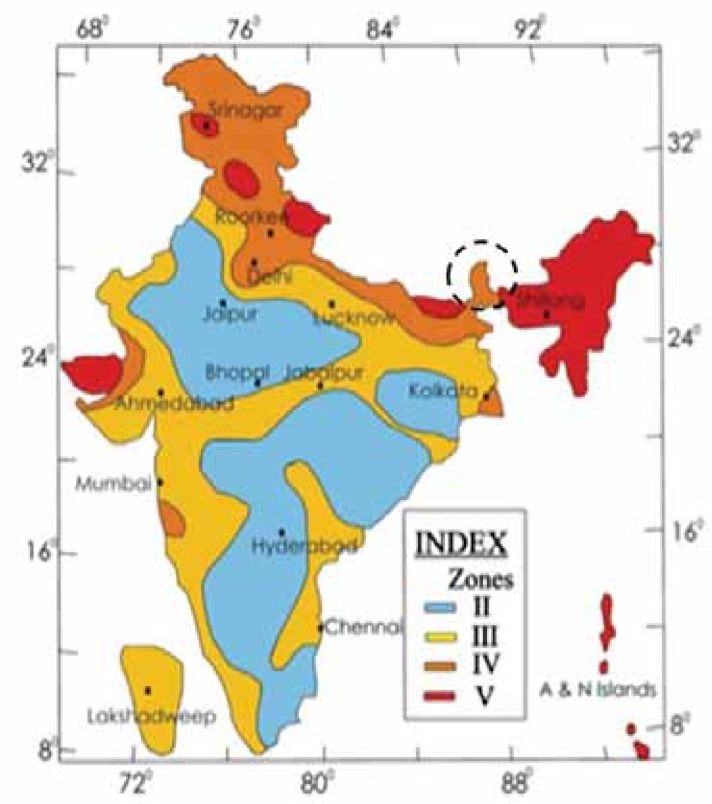


Figure 1-1 Seismic Zones of India(BMTPC, 2006)

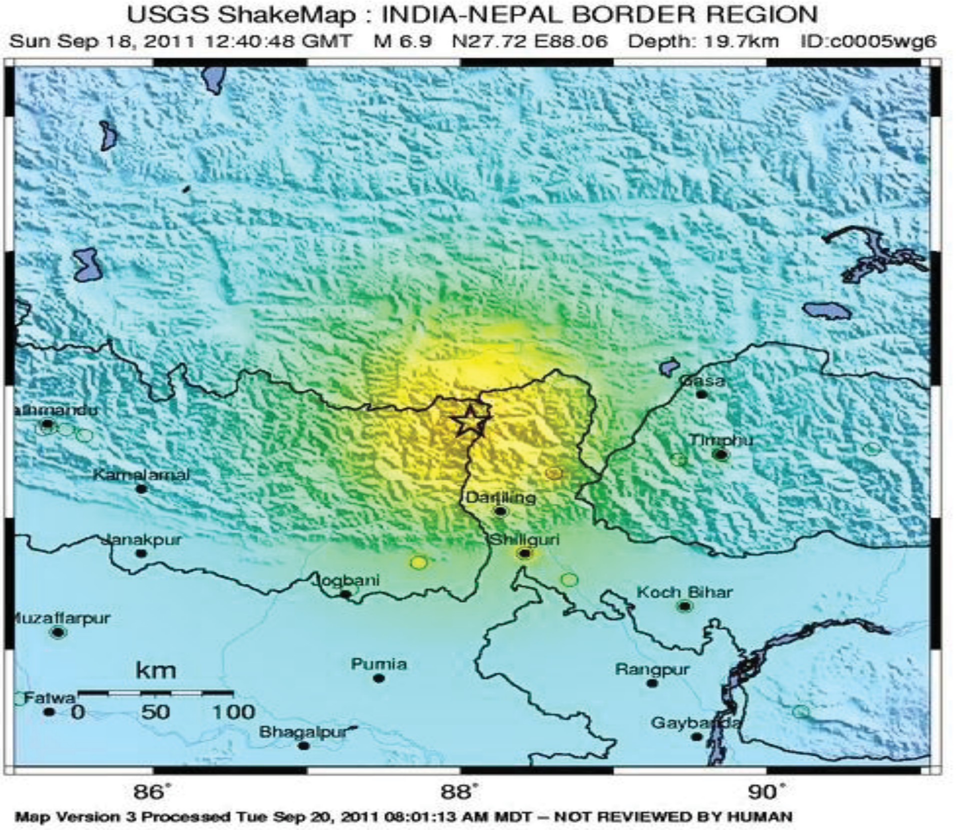
1.1.2. Sikkim Earthquake

An earthquake of 6.9 magnitude with its epicentre near the India-Nepal border (27.7 N, 88.2 E) shook the northeast and large parts of northern and eastern India on 18-09-2011 at 18 10 for 47 seconds (IMD 2011). Gangtok, capital city of Sikkim, which is around 58.74 km southwest from the epicentre, experienced earthquake intensity of VI in MMI scale. It caused extensive damage, wide spread panic and those who experienced the earthquake realised that the event was large enough and majority of their buildings were not strong enough to sustain another earthquake of same or higher magnitude.

According to preliminary report by USGS, at least 94 people killed, several injured and 5,000 displaced and several thousand buildings and many roads and bridges destroyed or damaged in the Sikkim-Bihar-West Bengal area; 6 people killed and 25 injured and at least 4,300 buildings destroyed or damaged in Bhojpur, Ilam, Panchthar and Sankhuwasabha, Nepal; 7 people killed and 136 injured in Tibet, China; 1 person killed and 16 injured and at least 6,000 buildings damaged in the Paro-Thimphu region, Bhutan; minor damage to several buildings in Dhaka, Bangladesh. Total economic loss in India estimated at 22.3 billion US dollars.

Table 1-2 IMD and USGS Earthquake Parameters [1] (IMD, 2011), [2] (USGS,2011)

	IMD[1]	USGS[2]
Date	18th September 2011	
Time	18:11 hrs(IST)	18:25hrs(IST)
Magnitude	6.8	6.9
Focal Depth(Km)	10	19
Epicentre	27.7 °N and 88.2 °E	27.72 °N and 88.06 °E



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 1-2 Sikkim earthquake: location of epicentre and intensities as felt across the region (USGS, 2011)

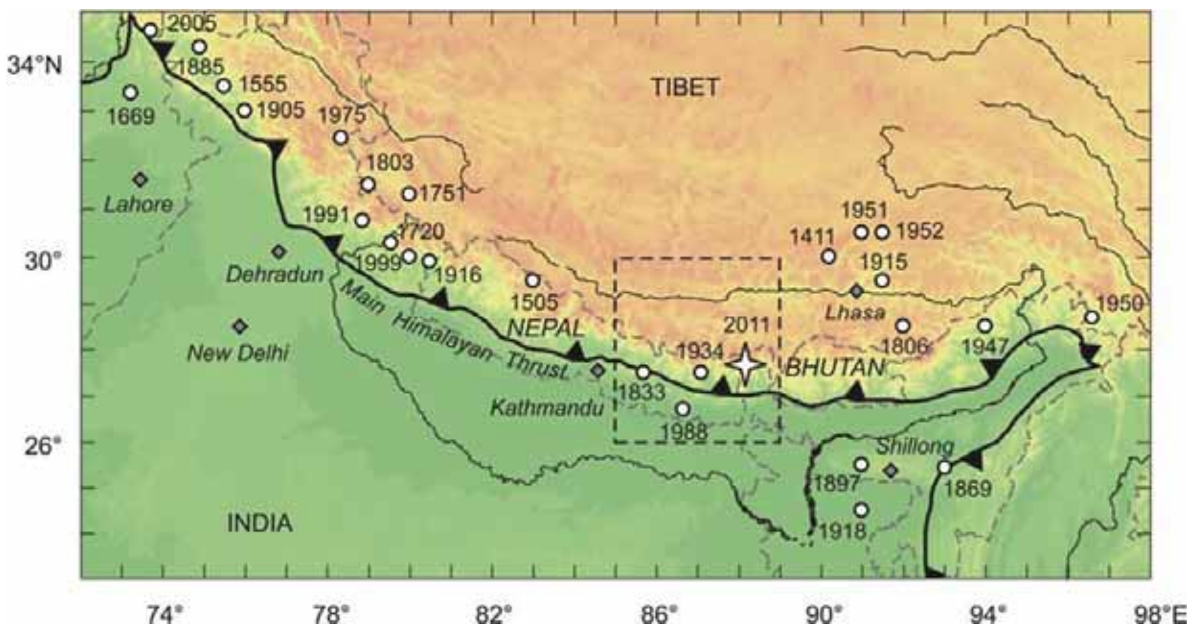


Figure 1-3 Main Boundary Thrust (MBT) and major earthquakes of the region (Rajendran et al., 2011)

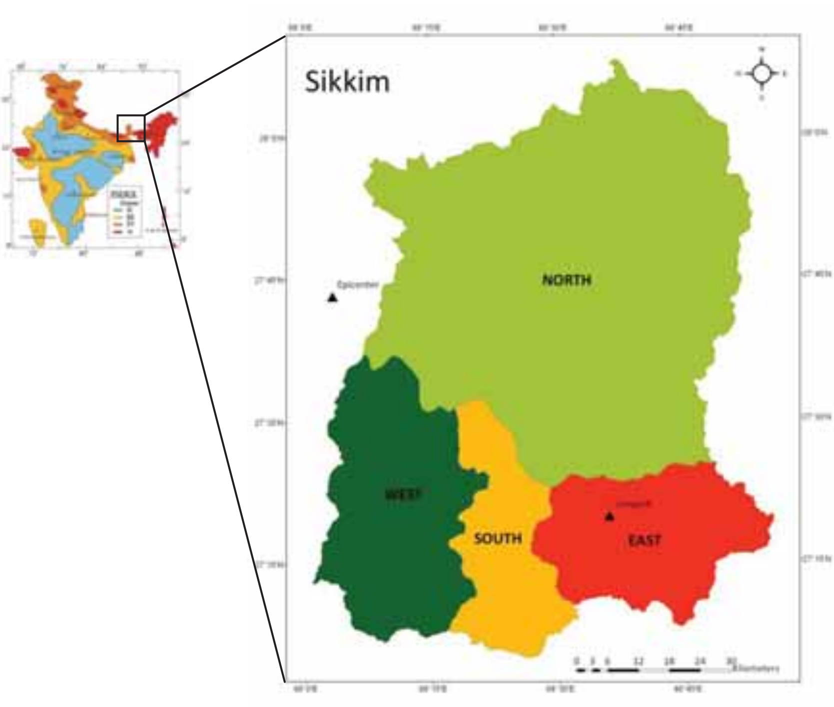


Figure 1-4 Sikkim Map showing Districts and Location of Epicentre and Gangtok (Rural Development Department, Sikkim)

Sikkim earthquake caused severe damage to built environment across the state of Sikkim and partly in Darjeeling district of neighbouring state of West Bengal. It also triggered numerous landslides that caused damage to the buildings in several parts of the state. Subsequent to earthquake, heavy monsoonal rainfall further added to the earthquake induced landslides and caused severe damage to the lifeline of the state, road network and as a result the post earthquake relief operations were severely affected. Within one hour of the major shock, IMD (2011) reported two aftershocks of M 5.3 and M 4.6 which created panic and also affected relief operations particularly extraction of injured from heavily damaged buildings.

Prior to 2011, people of the state Sikkim had experienced earthquake of higher magnitudes on February 14, 2006, which was of M 5.3 before that it was in 1988 of M 6.6 and in 1833 of M 7.7 (Rajendran et al., 2011). This area lies in Zone 4 (second highest category) of seismic zone atlas of India and according to USGS, this region has experienced relatively moderate seismicity in the past, with 18 earthquakes of M 5 or greater over the past 35 years within 100 km of the epicentre of the September 18 event.

The Sikkim earthquake occurred near the boundary between the India and Eurasia plates, at a depth of approximately 20 km beneath the Earth's surface. In this region, the India plate converges with Eurasia at a rate of approximately 46 mm/yr towards the north-northeast. The broad convergence between these two plates has resulted in the uplift of the Himalayas. The preliminary focal mechanism of the earthquake suggests strike slip faulting, and thus an intra-plate source within the upper Eurasian plate or the underlying India plate, rather than occurring on the thrust interface plate boundary between the two (USGS, 2011).

Table 1-3 Reported Aftershocks Date, Time and Magnitude (IMD, 2011)

Date	Time of Aftershocks (IST)	Magnitude
18.09.2011	18:42	5.3
18.09.2011	19:24	4.6
18.09.2011	20:35	3.0
19.09.2011	00:57	3.4
19.09.2011	03:21	3.8

State Government of Sikkim reported that in East District 13 people died, and approximately 6000 houses were fully damaged, 9000 houses were partially damaged, 201 schools and 23 hospitals were fully damaged. USGS PAGER estimated that around 31,000 people from Gangtok area of East District of Sikkim were exposed to MMI of VI.

1.2. Earthquake and Buildings – Indian Context

As it is always said "Earthquakes don't kill people, buildings do". Buildings have two important components: structural and non-structural. Structural components are the building load bearing elements like foundations, columns, beams and walls etc. Non-structural components include architectural and design features like doors, windows, false ceiling etc and services include features like electrical and plumbing fixtures. Buildings fail in the event of earthquake when major damage occurs to structural systems. Kircher et al. (1997) development of building damage functions. Ideally, buildings should be designed with respect to earthquake such that they survive in moderate earthquakes with non-structural damages and resist collapse with structural damages in strong and major earthquakes and ensure that no life is lost because of the collapse of buildings.

Destructive (M>6.5) earthquakes occur with low frequency which makes people, local authorities ignore the importance of the earthquake resistant building design, disaster preparedness and post disaster management. Previous earthquakes in the country have proven that both old and new constructions are vulnerable and structures in improper settlements like slums are more dangerous because of their sub standard and sub-optimal provisions of earthquake resistant designs. People who migrate from rural to urban areas in search of work often tend to live in these vulnerable settlements due to the low costs, thereby increasing the vulnerability of fast growing urban population. According to the vulnerability atlas of India, about 80 million housing units in India are vulnerable to earthquakes, of which 11 million falls in Zone V and 50 million falls under Zone IV of the seismic zones of the country (Agrawal and Chourasia, 2007). Uttarkashi (1991), Chamoli (1999), Bhuj (2001), Kashmir (2005), and Sikkim (2011) are some of the recent earthquakes in the Indian Sub-continent, which have caused severe damage to the built environment resulting in human and economic losses. It has raised wide spread concerns for earthquake safety and consciousness in people and government authorities about increasing vulnerability to earthquake hazards.

1.2.1. Material and Method of Construction

In India, age old construction practice using traditional to modern building materials exists even today in rural and small towns where as in big metropolis, advance technology and materials are in use, but ironically most of these don't match with the current Indian seismic safety codes which is the main cause for high building vulnerability across the country (Rai, 2008). Even though there are codes and standards for construction with RCC but for the construction with other local building materials that are followed at many places, there are hardly any standards and moreover it is difficult to monitor all such construction.

Since most of these buildings doesn't follow any regulations and are built by the local masons, often these structures turn out to be vulnerable to earthquake hazards. Most of these construction practices by local masons are inherited from earlier generations, they tend to follow the same practices used in past. In India engineers and architects do not design most of the buildings and these buildings were not approved by the local authorities before construction. Due to the economic conditions, the buildings are built in stages based on the availability of the money and buildings are also poorly maintained after construction. Even though building is only planned for few floors in the initial stage, years later, more floors are added to the same building which makes the structure weak and more vulnerable.

In India, old heritage structures are also vulnerable to earthquake hazards therefore, need to be protected with proper remedial measures. Preventing these structures from damage is important not only from historical point of view but also it helps tourism.

Table 1-4 Number of Houses and Level of expected Damage (BMTPC, 2006)

Material		No. of Houses	%	Level of Risk under EQ Zone			
				V	IV	III	II
Mud, Un-burnt Brick, and Stone Wall	India	99,280,979	39.9	VH	H	M	L
	Sikkim	20,501	15.9		H		
Burnt Brick Wall	India	111,891,629	44.9	H	M	L	VL
	Sikkim	9,300	7.2		M		
Concrete and Wood Wall	India	9,737,330	3.9	M	L	VL	VL
	Sikkim	70,738	54.6		L		
Other Materials	India	28,185,931	11.4	M	VL	VL	VL
	Sikkim	28,664	22.2		VL		
VH - Very High, H- High, M-Moderate, L- Low, VL- Very Low							

1.3. Motivationand Problem Statement

The main motivation behind this research is to use GIS based techniques for assessing earthquake vulnerability and damage, which can be further used by the local authorities for the preparedness and other disaster management measures. Preparedness and prevention are key elements of disaster management and GIS based damage assessment can contribute significantly towards this. The vulnerability of buildings can only be reduced with proper study of earthquake damage to the buildings in the past and planning structures and infrastructure accordingly so that they meet the challenges of earthquake safety in future. A proper study of earthquake and vulnerability of buildings to develop damage curves as required by various damage assessment techniques has not been developed in the country due to various reasons(Arya, 2000; Haldar et al., 2010). Damage to buildings generally occurs due to lack of awareness of earthquake resistant practices and current practices like use of building materials and reinforcement in the structures do not match with the standards (Haldar and Singh, 2009). It is very important to investigate the behavior of buildings after an earthquake to identify any problems in earthquake resistant design and develop damage scenarios. These damage patterns and scenarios would be helpful for damage prediction using user defined scenarios for the future earthquakes and prepare proper disaster management plans. Studying types of construction, their performance and failure patterns helps in improving the design and detailing aspects(Jagadish et.al, 2003). According to Census of India, 2011, rate of urbanization in the last 10 years is about 31.8 %, which means more and more people are living in urban areas where most of the buildings are vulnerable, thereby exposing a larger population to earthquake hazards.

It is a matter of concern that with history of so many earthquakes in India, no proper risk assessment methodologies have been developed for Indian conditions (Haldar et al., 2010). HAZUS (Hazard US) developed by Federal Emergency Management Agency (FEMA) for the National Institute of Building Science (NIBS) estimates the potential losses from earthquakes on a regional basis (FEMA 2011). HAZUS is a capacity-spectrum based method, which uses structural properties for estimating the probability of building damage and loss in the event of an earthquake. The drawback of using such method directly elsewhere is that the capacity curves and vulnerability functions published in the HAZUS manual have been derived for building types in the US, which completely differ from the other parts of the world. However, HAZUS has been adopted all over the world for the loss assessment using local specific modifications. Examples include the loss assessment of New York city carried out by Tantala et al. (2008), the seismic risk assessment of Dehradun by Gulati (2006), building replacement cost estimation by Aswandono (2011) for Yogyakarta, Indonesia and several such studies proved that HAZUS methodology with user supplied inputs and earthquake data can be applied to different urban areas. But it is not very clear how much these studies were successful in generating reliable results which could be used for risk assessment and loss estimation for future planning and preparedness in the event of an earthquake. Luckily there have been no earthquakes in the recent past in these areas to validate the results generated. The Sikkim earthquake of 2011 is a good opportunity to test the level of applicability of HAZUS to the Indian context, as the damage results generated can be verified.

1.4. Main Research Objectives

To assess earthquake building vulnerability adapting HAZUS methodology for buildings constructed with local building materials and techniques and validate the generated results with reference to a earthquake event.

1.4.1. Sub Research Objectives and Related Research Questions

Sub - Research Objectives	Research Questions
• To identify input parameters of HAZUS methodology for adapting to Indian condition	• What are the different building types that exist in the Gangtok area and what are the criteria to classify them? • How far do the building types in HAZUS match with building types in Gangtok area? • What are the parameters that should be modified in the existing HAZUS methodology?
• To estimate building damage in user defined earthquake scenario using HAZUS methodology adopted for Indian condition and validate them.	• What information can be derived from high resolution satellite data and what should be collected during field investigation for the study ? • How the GIS database is to be organized to adopt and implement HAZUS methodology for the Gangtok area? • What is the general characteristics of damage to built environment and how well the predicted and actual building damaged in recent earthquake match ?

• To make an general assessment of damage to built environment and comment on various prevention and retrofitting methods for reducing building damage.	• What are the main causes of building damage and how well these can be assessed and generalized based on field observation. • What are the retrofitting methods that can be applicable to reduce damage to the identified building types in Gangtok area?

1.5. Research Limitations

One of the important inputs is building foot print map and location of all damages buildings. As the area covers vast stretches of area, it was not possible to map approximately 12000 buildings; therefore, the building foot print map prepared in 2004 by the authorities was used for the research. The complete building data is available for the central wards of the city and data is not available for few wards away from the centre of Gangtok. So for wards at the centre of city was mainly considered for analysis and validation. Since it is impossible to collect damage data in short time, the damage data provided by the municipal authority was used for validation.

1.6. Organisation of the Thesis

Chapter 1 provides the general introduction of the earthquake and its vulnerability towards buildings in Indian context, the motivation behind the research, objectives and research questions related to the objectives of the research. Limitations and the expected outcome of the research were also discussed.

Chapter 2 gives an idea of the theoretical background for the research regarding Indian building types, HAZUS methodology, attenuation functions etc. It is basically theory behind the methods and process used in research for generating results.

Chapter 3 discusses about the material and methods used for the study. The process and details of the data collected in the field and other data acquired, tools and methodology used in the research are explained. The processing and preparation of the satellite imagery was also explained.

Chapter 4 and 5 describes about the study area Gangtok in detail and the experience of field work in the study area for three weeks. Damage observed and other details regarding the building types, construction practices and the problems that were found as the cause of the building damage are discussed in detail.

Chapter 5 gives the retrofitting recommendations that can be adapted for the buildings in Gangtok.

Chapter 6 explains the results and various scenarios generated using the described methodology. It also deals with generation of risk map and the validation of generated results.

Chapter 7 explain the conclusions based on the results generated and the various retrofitting methods recommended for the study area for repairing the damaged buildings and preparing for the future earthquakes.

2. LITERATURE REVIEW

In India, a variety of constructions methods and local materials are used for building construction, most of which don't match with the current Indian seismic safety codes which is the main cause for high building vulnerability. Even though there are codes and standards for construction with RCC, for construction with other materials and methods, codes don't exist and it is difficult to monitor all such constructions happening in different parts of the country.

2.1. Indian Building Types

The majority of Indian construction depends on the availability of building material and construction methods practiced by locals who don't involve architects and engineers and it is mostly based on traditional methods practised for decades based on the material, topography and the economic condition of the building owner. Prasad et al. (2009) believes that socio economic condition of the people defines the type and construction quality of the building and divided building patterns into three types. Firstly the independent houses which were built for residential purposes and secondly the group housing like apartment complexes etc. for multipurpose use and industrial, office and commercial buildings. In present day scenario, the small industries and retail stores have started functioning from residential complexes, which makes majority of the urban buildings multipurpose and comparatively more in commercial uses.

Prasad et al. (2009) identified 34 building types that are generally found in India. The classification is based on the structural system of the buildings, which are mainly divided into three types namely adobe and random rubble masonry construction, masonry construction and finally framed construction. These were divided into subclasses based on different parameters like roof material, floors etc. and classification is given in Table 2-1. Height of the building is also considered as one of the major factor in classification as the strength and natural period of vibration depend on the height of the building.

Analytical functions were not available for Indian building types and development of empirical curves is also not possible because of lack of sufficient damage data in previous earthquakes (Prasad et al. 2009). After some comparison between Indian building design standards and US standards, Indian framed structures have some comparison with high, medium and low-code of the HAZUS building types. Prasad et al. (2009) compared the classified Indian building types to the HAZUS model building types and found out that the Indian adobe and masonry building types cannot be compared to any of the fragility curves that are given in default HAZUS building types.

Table 2-1 Indian Building Types and their respective HAZUS building types (Prasad et al. 2009)

S.No	Description of Indian model building types			Most likely HAZUS Building Type	
	Wall/Framing type	Roof/Floor Type *	Floors		
Adobe and Random Rubble Masonry					
1	Rammed mud/ sun-dried bricks/rubble stone in mud mortar	R1, R2	1-2	Not Defined	
2		R3	1-2		
3	Rubble stone in lime-surkhi mortar	R1, R2	1-2		
4		R3, R4	1-2		
5		R5	1-2		
6	Rubble stone in cement mortar	R1, R2	1-2		
7		R3, R4	1-2		
8		R5,R6	1-2		
Masonry consisting of Rectangular Units					
9	Burnt clay brick/ rectangular stone in mud mortar	R1, R2	1-2	Not Defined	
10		R3, R4	1-2		
11		R5	1-2		
12	Burnt clay brick/ rectangular stone in lime-surkhi mortar	R1, R2	1-2		
13		R3, R4	1-2		
14		R5,R6	1-2		
15	Burnt clay brick/ rectangular stone/ concrete blocks in cement mortar	R1, R2	1-2		
16		R3, R4	1-2		
17		R5,R6	1-2		
18			3+		
19	Burnt clay brick/ rectangular stone/ concrete blocks in cement mortar and provided with seismic bands and vertical reinforcement at corners and jambs	R5,R6	1-2	Not Defined	
20			3+		
Framed Structures					
21	RC frame/ shear wall with URM infill's – constructed without any consideration for earthquake forces	R-6	1-3	C3L	Precode
22			4-7	C3M	
23	RC frame/ shear wall with URM infill's - earthquake forces considered in design but detailing of reinforcement and execution not as per earthquake resistant guidelines (Low-Code/Moderate-Code)		1-3	C3L	Precode/Low code
24			4-7	C3M	
25			8+	C3H	
26	RC frame/ shear wall with URM infill's - designed, detailed and executed as per earthquake resistant guidelines (Low-Code/ Moderate-Code/High Code)		1-3	C3L	Precode/Low code/Moderate Code
27			4-7	C3M	
28			8+	C3H	

29	Steel moment frames with URM infill's (Low-Code/ Moderate-Code/ High Code)		1-3	S5L	Precode/Low code/Moderate Code
30			4-7	S5M	
31			8+	S5H	
32	Steel braced frames (Low-Code/ Moderate-Code/High Code)		1-3	S2L	Precode/Low code/Moderate Code
33			4-7	S2M	
34			8+	S2H	

* Roof/Floor types: R1 - Heavy sloping roofs-stones/burnt clay tiles/thatch on sloping rafters; R2 – Heavy Flat flexible heavy roof - wooden planks, stone/burnt clay tiles supported on wooden/steel joists with thick mud overlay; R3 - Light sloping roofs - corrugated asbestos cement or GI sheets on sloping rafters without cross bracing; R4 - Trussed roof with light weight sheeting (without cross bracing); R5 - Trussed/hipped roof with light weight sheeting (with cross bracing); R6 - Flat rigid reinforced concrete or reinforced masonry slab

2.1.1. C3 Building Type

The C3 type of HAZUS building type is defined in Appendix C of Technical Manual prepared by FEMA (2011) which defines the structure Concrete Frame Buildings with Unreinforced Masonry Infill Walls. These buildings are frame buildings with unreinforced masonry infill walls and the frame is of reinforced concrete. The frames can be located almost anywhere in the building. Usually the columns have their strong directions oriented so that some columns act primarily in one direction while the others act in the other direction. In these buildings, the shear strength of the columns, after cracking of the infill, may limit the semi-ductile behavior of the system. In earthquakes these building fail and lead to partial or full collapse because of brittle failure as these are only designed with ductile properties. The other two types closer to C3 are C1 and C2. C1 type of structure is defined as the buildings with frames of reinforced concrete and C2 buildings are similar to C1, but in these buildings shear walls are used as load bearing walls instead of the vertical reinforced concrete columns. These walls tend to fail because of the lateral forces acted on these walls in the earthquakes.

Buildings with some level of seismic design were considered but they do not match with the suitable level of building codes and therefore, were considered as low-code and buildings which don't have any seismic design considerations falls under pre-code category of HAZUS classification.

2.1.2. W1 building Type

Buildings made out of wood are other types of structures usually found in hilly regions and are not listed t in the classification. These are typically single-family or small, multiple-family dwellings of not more than 5,000 square feet of floor area. The essential structural feature of these buildings is repetitive framing by wood rafters or joists on wood stud walls. These are light structures and usually all structural systems are made up of small spans. Most of these buildings, especially the single-family residences, are not designed and constructed any seismic design considerations of building codes. Lateral loads are transferred by wooden posts and beams to shear walls. Shear walls are the partition between the frames are made out of several kind of material like bamboo, fiber, plastic etc. as a covering material but has no structural importance. They are usually strong enough to resist lateral forces of minor quakes but not strong enough and don't meet the building standards.

2.1.3. Seismic Design Level in Buildings

HAZUS default building types represent typical buildings of a given model building type that are designed with respect to High-Code, Moderate-Code, or Low- Code seismic standards, or not seismically designed (referred to as Pre-Code buildings). The High-Code, Moderate-Code, or Low- Code seismic standards are given based on the level of seismic design considerations. Low-code seismic design buildings are constructed with basic structural design considerations to resist forces due to earthquakes. The low-code damage functions can be used for modeling the damage due to earthquakes in these buildings, where pre-code damage functions are appropriate for modeling buildings that were not designed for any earthquake load, which can also be used for buildings without any building codes and rules.

2.2. Vulnerability and Factors affecting building vulnerability.

UNISDR (2009) defines vulnerability as the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard. In our case the vulnerability is the degree of damage to the built environment to a given strength of earthquake shaking (Dowrick, 2005). Vulnerability is expressed on a scale of 0 to 1, where 0 is no damage and 1 defines complete destruction.

The form and shape of the structure are the important parameters defining building vulnerability. The form includes the material of the building, type of construction, height, architectural and design elements, seismic design levels etc, where as the shape defines the regular or irregular forms in plan and elevation. Dowrick (2005) defines that poor structures and design cannot be expected to perform well in earthquakes.

2.2.1. Strength of structure and Seismic design requirement.

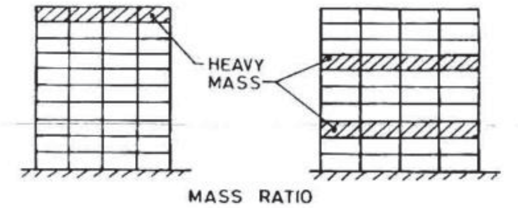
Based on the location of building, parameters which effect strength of the structure should be identified in advance. Parameters like local geology, soil conditions, and possible ground motion of earthquake also determine the performance of the buildings and design. These parameters will also determine what kind of damage that building can possibly resist in future events. Table 2-2 shows advantages and disadvantages of different types of structures.

Table 2-2 Advantages and Disadvantages of Flexible and Stiff Structures (Dowrick 2005)

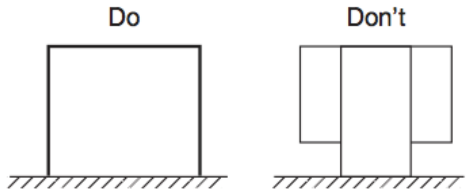
	Advantages	Disadvantages
Flexible structures	Specially suitable for short period sites, for buildings with long periods	Higher response on long-period sites
	Ductility arguably easier to achieve	Flexible framed reinforced concrete is difficult to reinforce
	Non-structure may invalidate analysis	More amenable to analysis
		Non-structure difficult to detail
Stiff structures	Suitable for long-period sites	Higher response on short-period sites
	Easier to reinforce stiff reinforced concrete (i.e. with shear wall)	Appropriate ductility not easy to knowingly achieve
	Non-structure easier to detail	Less amenable to analysis

2.2.1.1. Structural Elements of building.

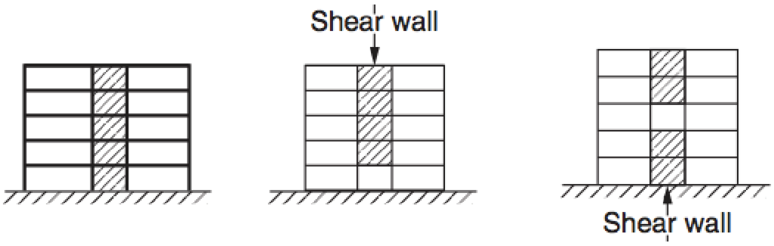
Proper design of structural elements improves the performance of the building in earthquakes. Foundations, shear walls, no soft storeys, regular loading, cantilevers, continuous beams, tie-beams, are some structural elements which improves the strength of the building. Connectivity of all the structural components of building from foundation to the roof is very important for its structural performance



a) Heavy mass in the upper floors or unequal distribution of mass is not advisable



b)Mass Should be equally distributed from top to bottom, cantilevers should be avoided



c) Soft storeys should be avoided, the open columns should be always connected with shear walls

Figure 2-1 Rules to be followed in construction practices (Dowrick 2005)

2.2.2. Function of building.

The building use often determines the building design, material to be use and the kind of construction to be undertaken. Function of the building defines the number of people likely to use the building and the kind of equipment or other items in the building to be stored which will define the economic value of the building. Space available and the space required for building use is what defines the number of floors that need to be constructed which also influences the material selection. Some buildings of important use like schools, hospitals, banks, and other government services which are important and availed by many people require high standards of safety, proper planning, and execution

2.2.3. Material and Method of construction

As discussed in Section 1.2.1, India has several materials and methods of constructions. The material of building is chosen based on various factors like availability of material, function of the building, economic condition of the owner, and expected life of building, temporary or permanent type of structure, and seismic design requirements of the building. Table 2-2 shows the kind of material that is ideal to use for different types of buildings based on their height. Structural properties like strength, weight of building, ductility etc are derived from the material used for construction.

Table 2-3 Suitable building material for different kind of Construction (Dowrick 2005)

	Type of Building		
	High Rise	Medium Rise	Low Rise
Advisable *Structural materials in approximate order of suitability	1. Steel 2. In-situ reinforced concrete	1. Steel 2. In-situ reinforced concrete 3. Good pre-cast concrete	1. Timber 2. In-situ reinforced concrete 3. Steel 4. Prestressed concrete 5. Good reinforced masonry 6. Good pre-cast concrete
Not Advisable			7. Primitive reinforced masonry

Even though when the structures are well designed for earthquake resistance and enough money is spent to obtain the best quality of material, if the workmanship of the building is poor, all the effort taken will be of no use. So the quality assurance during the period of construction and maintenance after construction are also very important for the life and safety of the building.

2.2.4. Height of the building

Height of the building is important as it is directly related to the weight of the structures and their response to ground motion. The natural frequency of building is low for tall buildings and high for short buildings. Since time period is inversely proportional to frequency, short buildings tend to collapse/experience damage when amplification is higher in high frequency domain and tall buildings experience damage when amplification is higher in low frequency domain.

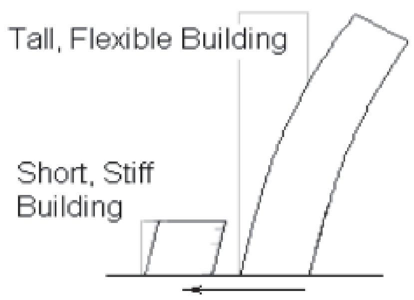


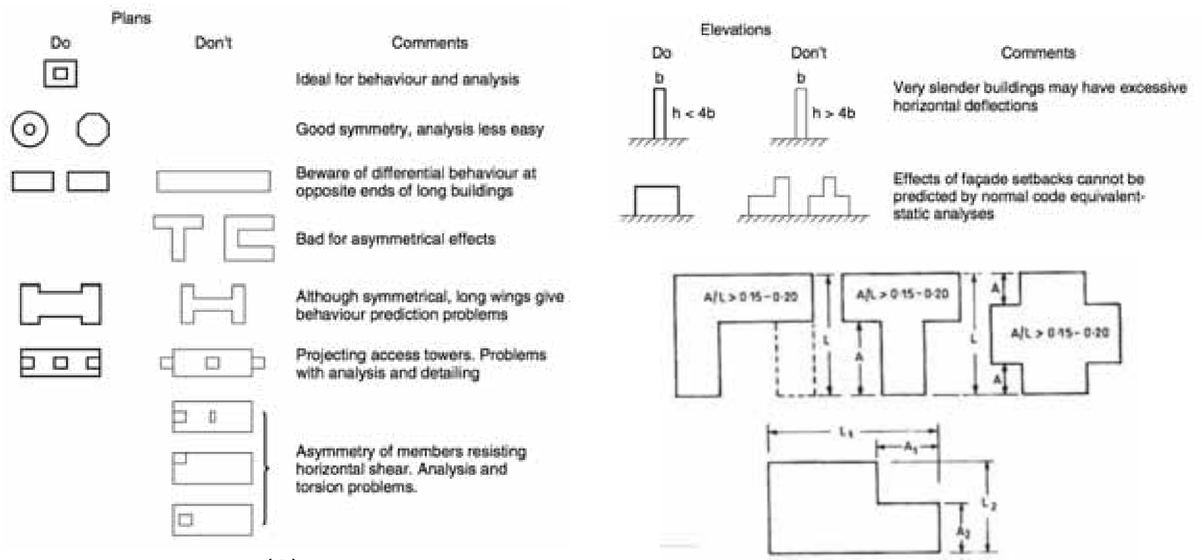
Figure 2-2 Stiffness of building (Dowrick 2005)

Table 2-4 Natural frequency of buildings (BIS, 2002)

Number of Storey's	Natural Frequency
1	10
2	5
3-5(Medium)	2
Tall Buildings	0.5-1.0
High-Rise	0.17

2.2.5. Shape of buildings.

Simple shapes and forms are recommended in earthquake prone zones. Dowrick (2005) explains the benefits with two reasons. First, it is easy to design and understand structurally the simple structures, second it is easier to build these structures and it is easier to repair or retrofit them post earthquake. Symmetry in the plan form defines the simplicity of plan and elevation of the building. Symmetry helps in simplifying the structural design, services and other parameters. Height-Width ratios in elevation, Length-Width ratios in plan are also very important. Tall buildings with less base and long buildings with less width are very prone to damages due to high ground motions. Sudden changes in these ratios in plan or elevation make structures asymmetrical and make them more vulnerable.



(A) (B)

Figure 2-3 Simple rules to be followed in shapes of Plans and Elevations A- (Dowrick 2005), B- (BIS, 2002)

In the case of long buildings in plan, buildings should be broken into parts of ideal length and should be given space for them to shake in earthquakes or else there will be chances of pounding effect that can cause more damage than expected.

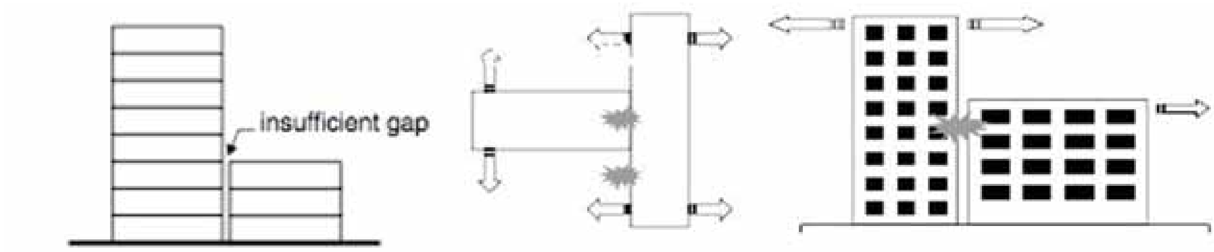


Figure 2-4 Figure showing insufficient gap and Pounding effects in Plan and Elevation (Dowrick 2005)

2.2.6. Building Codes

Building codes play a very important role in the vulnerability of the buildings. Building codes with proper land use planning can reduce the vulnerability of earthquakes in any area. But enforcement of the building codes in design and construction is very important. These acts as guidelines for all architects and engineers to make buildings and cities that are less vulnerable to earthquakes. Khose et al. (2010) believes that since the codes developed in India are not sufficient for modern day construction practices, there is a need to update the code.

Table 2-5 List of Indian Standard Codes

IS Code	Topic
IS:4326	Earthquake Resistant Construction
IS:13920	Ductile Detailing of Reinforced Concrete Structures
IS:13827	Earthen Dwellings
IS:13828	Low Strength Masonry Structures
IS:13935	Seismic Strengthening of Buildings
IS:1893(Part 2)	Elevated and Ground Supported Liquid Retaining Structures

2.3. HAZUS Methodology

Hazards US, commonly referred as HAZUS is a GIS based tool developed by National Institute of Building Sciences (NIBS) for Federal Emergency Management Agency (FEMA) for estimating risk due to disasters and estimate losses which can help authorities for making settlements prepared for the disasters and help in post disaster planning, recovery and reconstruction (FEMA, 2011). The tool uses GIS for developing databases, inventory of buildings, infrastructure, constantly updating databases, and carry out analysis for better presentation of results.

The creation of databases with extensive information on buildings is the important task that has to be carried out before using the tool for generation of results and scenarios in the event of any disaster. The scale and the details of the results are directly based on the amount of information used in the execution of methodology.

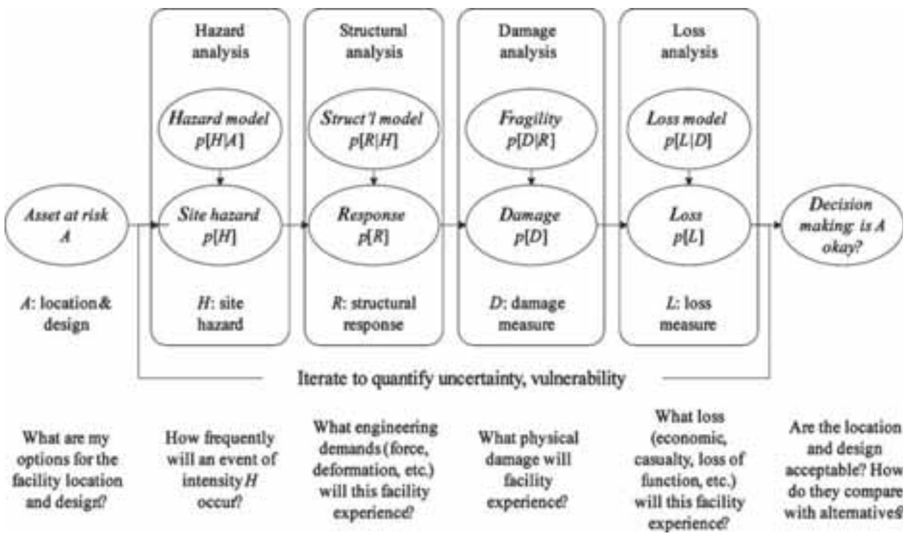


Figure 2-5 HAZUS Methodology (Porter 2009)

Kircher et al. (1997) described methods for estimating the probability of building damage from the functions developed by Whitman et al. (1997) for earthquake loss estimation. This methodology was originally developed for FEMA and is used in HAZUS. These functions as mentioned use the ground shaking parameters for assessing damage for various building types. Irrespective of the hazard, the methodology requires databases and inventories, which are then used for damage and impact assessment of a specific hazard. The following steps explain the methodology in a simplified form.

2.3.1. Deterministic Seismic Hazard Analysis

In this analysis, the ground motion parameters are specified from a defined event. The parameters like the magnitude of the earthquake, type of fault are defined from which the ground motion at the site is determined based on the distance from the source to the specific area.

2.3.1.1. Generation of Demand Spectrum

The ground shaking at a point due to the energy released from epicentre which is represented as demand spectrum. The demand spectrum is the plot between the Spectral Acceleration and Spectral Displacement. The spectral acceleration at a point at a given time period is derived from attenuation equations which uses several parameters like local soil conditions, rock types, distance from epicentre etc. Then derived spectral acceleration is plotted against the spectral displacement. Mandal et al. (2009) used attenuation function derived by Boore et al. (1997) as described in the Equation 2-1 for calculating peak spectral acceleration for Bhuj 2001 earthquake and suggested that this function suits for generating spectral acceleration for the Indian condition.

$$\mathrm{Ln}(\mathrm{S_A}) = \mathrm{b_1} + b_2(\mathrm{M}-6) + b_3(M-6)^2 + b_5\,\mathrm{Ln}(r) + b_v\,\mathrm{Ln}\left(\frac{V_s}{V_A}\right)$$

where $r = \sqrt{r_{jb}^2 + h^2}$

and

$$b_1 = \begin{cases} b_{1SS} & for\ strike - slip\ earthquakes \\ b_{1RV} & if or\ reverse\ slip\ earthquakes \\ b_{1ALL} & if\ mechanism\ is\ not\ specified \end{cases}$$

where

$\mathrm{S_A}$	is the spectral acceleration to be derived
$b_1, b_2, b_3, b_5, b_v,$	are constants provided with the equation
M	is the magnitude of earthquake
r_{jb}	is the horizontal distance from epicentre
V_s	the shear wave velocity of the soil class provided by NEHRP classification

Equation 2-1 Attenuation function.

Source: Boore et al. (1997)

The values of Shear Wave Velocity (V_s) of different soil classes are given in the Table 2-6

Table 2-6 NEHRP Site Classes

Site Class	Description	Shear Wave Velocity (V_s) in m/s
A	Hard Rock	V_s> 1500
B	Rock	760 < V_s <1500
C	Very dense soil and soft rock	360 < V_s <760
D	Stiff soil profile	180 < V_s <360
E	Soft soil profile	V_s <180

The spectral displacement S_D is calculated from the following equation.

$$S_D = 9.8 \times S_A \times T^2$$

where S_A is the Spectral Acceleration calculated from Equation 2.1
T is the time period in seconds

Equation 2-2 Spectral Displacement Equation

2.3.2. Development of Building Damage Functions

Kircher et al. (1997) describes Capacity and Fragility curves functions which are used by HAZUS methodology for estimating damage from ground shaking caused by earthquakes. Capacity curves define the non-linear behaviour of buildings which are described by the yield and ultimate strength and on the other hand the probability level of damage to the buildings at given ground shaking level is predicted by the Fragility curve.

2.3.2.1. Capacity Curve

Buildings respond to ground shaking in earthquakes. As buildings are tied to the ground with foundations, the free end i.e., roof shakes more than the ground. There is always some inbuilt strength to resist this shaking. But when it reaches it maximum level, it tends to reach its upper limit and finally collapses. Till a limit, inbuilt strength of the building resist the shake and allow the building remains stiff and stand straight, this is called yield capacity point. When building reaches its yield capacity it starts to shake to a limit and at a stage the building loses its complete strength and can no longer resist the force of shaking and structural systems completely fails. That point before losing all its strength to shake is called ultimate capacity point. The capacity curve is generally derived from these two points.

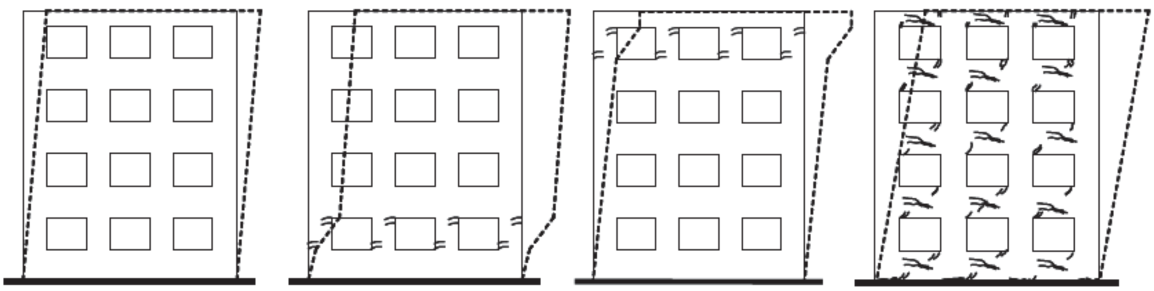


Figure 2-6 Deformation of building due to lateral forces (Calvi et al., 2006)

The building capacity curve is a plot of buildings' lateral load resistance as a function of characteristic lateral displacement (Kircher et al. 1997). The amount of lateral displacement at the roof of the building at a given level of ground shaking in the event of earthquakes is generally referred as "push-over" curve. The stage before building reaches its yield point, it is in solid state; from yield to ultimate point, it is in an elastic state; and post ultimate capacity, it will turn into plastic state. These curves define a building in structural terms and usually vary between different building types.

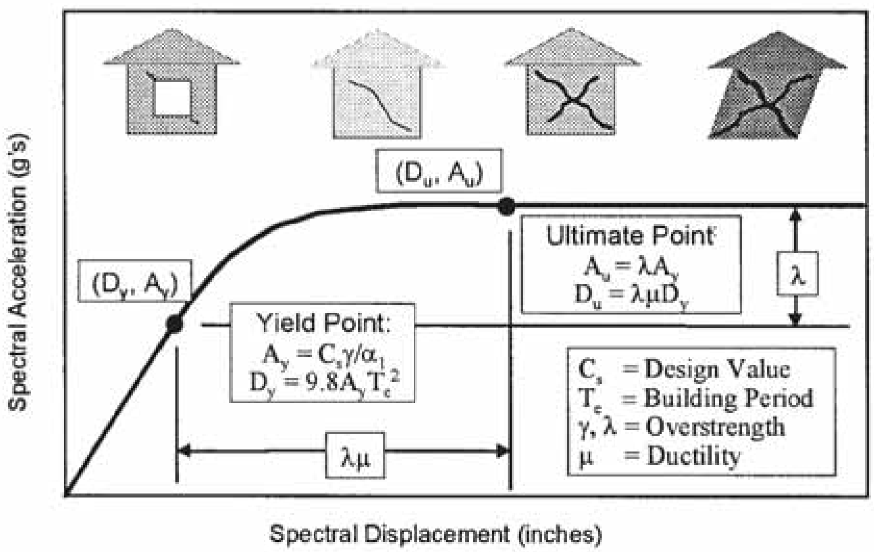


Figure 2-7 Capacity Curve showing Yield and Ultimate Capacity points (Kircher et al. 1997)

Yield capacity of buildings varies from building to building and is defined by the design strength of the building based on different seismic levels like high-code, moderate-code, low-code and pre-code. Factors such as soil condition, seismic zone, and height of the building and material of construction are considered in the seismic design levels which decide the time till which the building can resist the shaking.

The response of building is determined at the point where the demand spectrum intersects with building capacity curve (Kircher et al. 1997). Different buildings have different intersection points to different demand spectra. So for given ground shaking every building has a different level of damage.

The Figure 2-8 shows that stronger buildings usually have more time before they fail than the weaker buildings because they tend to take more time to reach their ultimate capacity compared to the weaker buildings.

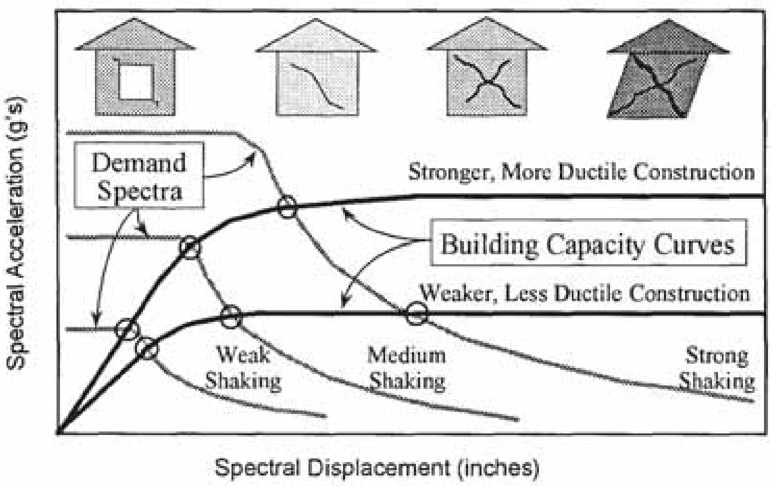


Figure 2-8 Capacity Spectra vs. Demand Spectra (Kircher et al. 1997)

The yield and ultimate capacity points of C3 model building type for low code and pre code seismic design levels are given below in Table 2-7.

Table 2-7 Code building Capacity Curves (FEMA 2011)

Building Type	Yield Capacity		Ultimate Capacity	
	D_y	A_y	D_u	A_u
	Low-Code –Seismic Design			
W1	0.24	0.200	4.32	0.600
C3L	0.12	0.100	1.35	0.225
C3M	0.26	0.083	1.95	0.188
C3H	0.74	0.063	4.13	0.143
	Pre- Code –Seismic Design			
W1	0.24	0.200	4.32	0.600
C3L	0.12	0.100	1.35	0.225
C3M	0.26	0.083	1.95	0.188
C3H	0.74	0.063	4.13	0.143

2.3.3. Discrete Damage Probabilities

Kircher et al. (1997) defines the fragility curves as the lognormal functions that describe the probability of reaching or exceeding the structural and non-structural damage for a given spectral displacement. These curves determine the probability of damage to the buildings from slight, moderate, extensive to complete damage. These damages are based on the seismic design level of the building.

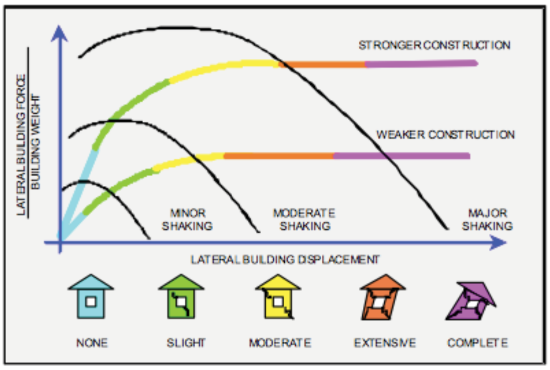


Figure 2-9 Capacity Spectrum Method showing the level of Damage (FEMA 2011)

Discrete damage probabilities are derived from cumulative damage probabilities which were calculated from the Equation 2-3 developed by Kircher et al. (1997).

$$P(d_S|S_d) = \Phi\left[\frac{1}{\beta_{ds}}\ln\left(\frac{S_d}{\bar{S}_{d,ds}}\right)\right]$$

where $P(d_S|S_d)$ is the probability of reaching the slight damage state for a given peak building response S_d

$\bar{S}_{d,ds}$	is the median value of spectral displacement at which the building reaches the threshold of damage state,
β_{ds}	is the standard deviation of the natural logarithm of spectral displacement for damage state d_s
Φ	is the standard normal cumulative distribution function

Equation 2-3 Equation for developing building damage functions

Probability of each damage state is calculated by substituting the value of peak building response and the damage state median of a specific damage state. The values of different damage states for a C3 building type are given in Table 2-9. The probable levels of expected damage vary from building type-to-type and level of different seismic design levels. Damage states of the concrete frame building with unreinforced masonry walls are described as given in the Table 2-8.

Table 2-8 Structural Fragility Curve Parameters (FEMA 2011)

Building Type	Slight		Moderate		Extensive		Complete	
	$\bar{S}_{d,ds}$	β_{ds}	$\bar{S}_{d,ds}$	β_{ds}	$\bar{S}_{d,ds}$	β_{ds}	$\bar{S}_{d,ds}$	β_{ds}
Low Code –Seismic Design								
W1	0.50	0.93	1.25	0.98	3.86	1.02	9.45	0.99
C3L	0.54	1.09	1.08	1.07	2.70	1.08	6.30	0.91
C3M	0.90	0.85	1.80	0.83	4.50	0.79	10.50	0.98
C3H	1.30	0.71	2.59	0.74	6.48	0.90	15.12	0.97
Pre- Code –Seismic Design								
W1	0.40	1.01	1.00	1.05	3.09	1.07	7.56	1.06
C3L	0.43	1.19	0.86	115	2.16	1.15	5.04	0.92
C3M	0.72	0.90	1.44	0.86	3.60	0.90	8.40	0.96
C3H	1.04	0.73	2.07	0.75	5.18	0.90	12.10	0.95

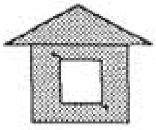
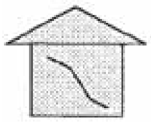
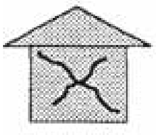
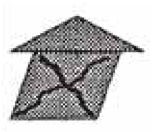
After calculating cumulative damage probabilities discrete damage probabilities are calculated from the following formula,

Table 2-9 Discrete Damage Probabilities(FEMA 2011)

Probability		
Complete Damage	$P[C]=$	$P(C\|S_d)$
Extensive Damage	$P[E]=$	$P(E\|S_d) - P(C\|S_d)$
Moderate Damage	$P[M]=$	$P(M\|S_d) - P(E\|S_d)$
Slight Damage	$P[S]=$	$P(S\|S_d) - P(M\|S_d)$
No Damage	$P[N]=$	$1 - P(E\|S_d)$

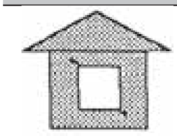
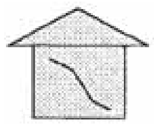
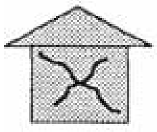
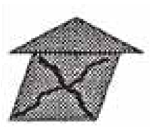
The C3 type of HAZUS building type is defined as the buildings with unreinforced masonry infill walls and the frame is of reinforced concrete. In these buildings, the shear strength of the columns, after cracking of the infill, may limit the semi-ductile behavior of the system. The infill wall is made of either brick or concrete blocks and these walls are not properly tied to the columns.

Table 2-10 Damage states of C3 building type (FEMA 2011)

Damage State		Description
	Slight	Diagonal (sometimes horizontal) hairline cracks on most infill walls; cracks at frame-infill interfaces.
	Moderate	Most infill wall surfaces exhibit larger diagonal or horizontal cracks; some walls exhibit crushing of brick around beam-column connections. Diagonal shear cracks may be observed in concrete beams or columns.
	Extensive	Most infill walls exhibit large cracks; some bricks may dislodge and fall; some infill walls may bulge out-of-plane; few walls may fall partially or fully; few concrete columns or beams may fail in shear resulting in partial collapse. Structure may exhibit permanent lateral deformation.
	Complete	Structure has collapsed or is in imminent danger of collapse due to a combination of total failure of the infill walls and non-ductile failure of the concrete beams and columns. Approximately 15%(low-rise), 13%(mid-rise) or 5%(high-rise) of the total area of structure

W1 buildings are made out of wood and other prominent types of structures usually found in hilly regions. These are light structures and usually all structural systems are made up of small spans. The partition between the frames are made out of several kind of material like bamboo, fiber, plastic etc. as a covering material but has no structural importance.

Table 2-11Damage states of W1 building type (FEMA 2011)

Damage State		Description
	Slight	Small plaster or gypsum-board cracks at corners of door and window openings and wall-ceiling intersections; small cracks in masonry chimneys and masonry veneer.
	Moderate	Large plaster or gypsum-board cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by small cracks in stucco and gypsum wall panels; large cracks in brick chimneys;
	Extensive	Large diagonal cracks across shear wall panels or large cracks at plywood joints; permanent lateral movement of floors and roof; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations; partial collapse of “room-over-garage” or other “soft-story” configurations;
	Complete	Structure may have large permanent lateral displacement, may Collapse, or be in imminent danger of collapse due to cripple wall failure or the failure of the lateral load resisting system; some structures may slip and fall off the foundations; large foundation cracks. Approximately 3% of the total area of W1 buildings with Complete damage is expected to be collapsed.

3. METHODOLOGY AND DATABASE ORGANISATION

3.1. Introduction

The present research emphasizes on assessing building vulnerability due to seismic hazard. The main objective is to assess the earthquake building vulnerability by adopting HAZUS methodology and validation of the results with the actual damage caused by the earthquake on 18th September 2011. The main part of the methodology is to develop or acquire the extensive databases that are required to develop the damage scenarios and produce risk map.

To achieve the defined objectives, research work is divided into three stages: Pre-field, Field Work and Post Filed Work. Collection of literature on HAZUS methodology, field data collection, GIS database organisation, damage assessment, validation and risk map generation are some of the important components of the study. The method of research work is given in the form of flow chart as shown in Figure 3-1. Complete methodology and the data used in the research are explained in the following sections.

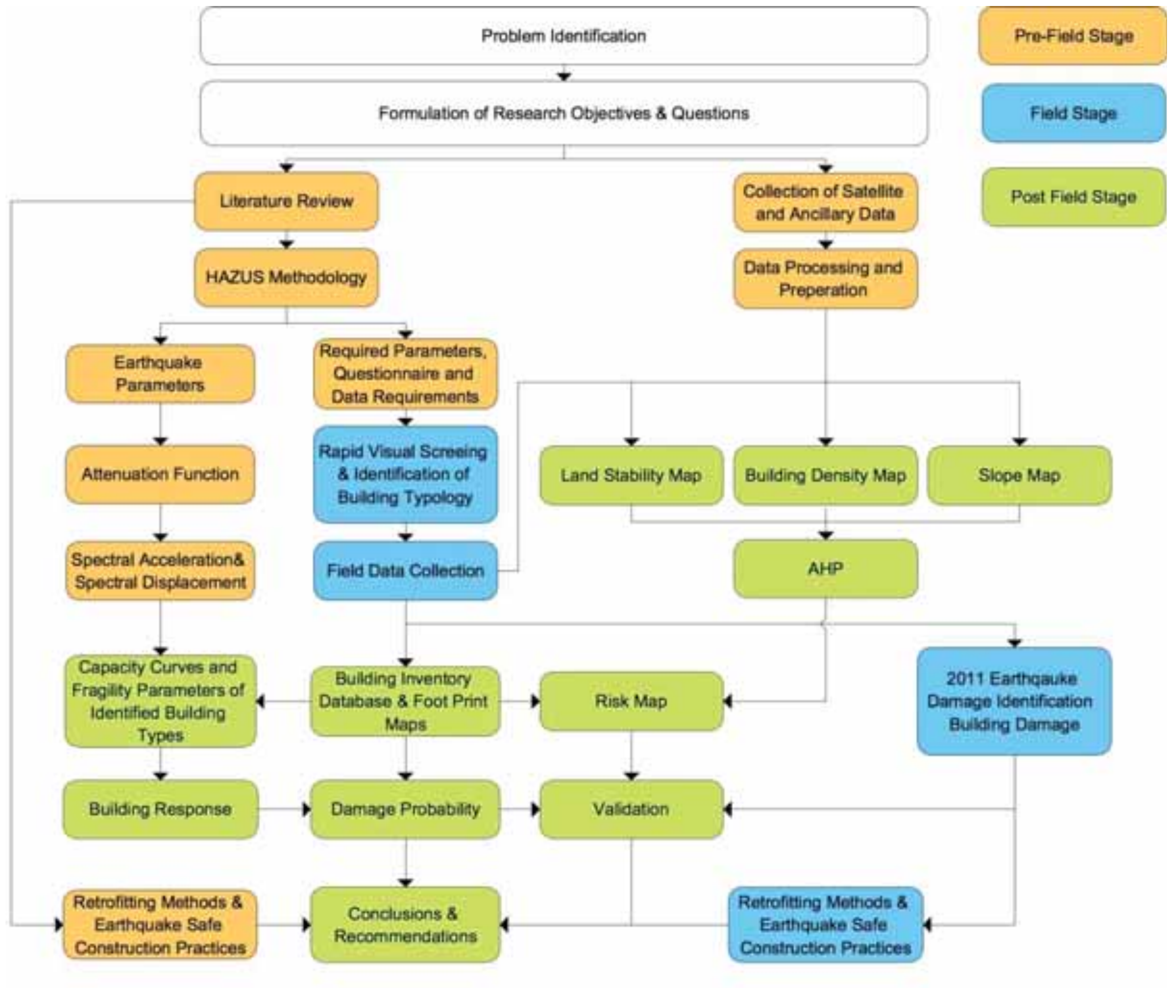


Figure 3-1 Methodology Flow-Chart

3.2. Pre- field stage

In the first stages of research, literature regarding HAZUS methodology was reviewed to understand the method to assess building vulnerability. Various journal papers, HAZUS user and technical manuals, reports and previous works that used HAZUS outside US were referred in the process (Boore et al. (1997);Tantala et al. (2008); Gulati (2006), Aswandono (2011)). By understanding how methodology worked, as described in literature review, the information and data required to generate the desired results were listed out and a checklist for the data collection and field plan were prepared. Literature based on building codes, Indian building types, theory on possible earthquake damage to buildings were studied for understanding the damage to the buildings in Gangtok region. FEMA's Rapid Visual Screening Procedure is referred for the screening of buildings in the field.

High-resolution satellite imagery was acquired from various sources. These images were then orthorectified and mosaic was prepared. Reports on previous studies were referred to get better idea before visiting the field. Earthquake parameters like source, type of faulting, magnitude etc were collected from various sources like IMD, GSI, and USGS. Attenuation function as described in Equation 2-1, developed by Boore et al. (1997), was used to generate spectral acceleration and spectral displacement required for generation of response spectra of an earthquake.

Table 3-1 List of the Satellite Imagery Used

List of high resolution imagery					
Platform	Sensor	Date of Acquisition	Path	Row	Resolution (m)
Cartosat -1	PAN	30th September 2011 21st March 2011 02nd February 2007	585	271	2.5
Cartosat -2	PAN	01st March 2011	001	002 and 001	0.8
			Centre Lat	Centre Long	
Geoeye	PAN	05th October 2011	27.292	88.597	0.40
Quickbird	MS	29th September 2011	27.334	88.590	2.4

Table 3-2 Data collected before Field Visit

Data	Source
Toposheet, 1:50,000 No: 78 A/11	Survey of India
Earthquake Scenario	IMD USGS Rajendran et al. (2011)
City Development Plan Strategic Urban Plan Gangtok City Mobility Plan	Urban Development and Housing Department, Government of Sikkim
Gangtok Housing Strategy	Department of Housing, School of Planning and Architecture, New Delhi
Population	Urban Development and Housing Department, Government of Sikkim
Soil and Geology	Mine, Minerals and Geology Department, Government of Sikkim Kumar Nath (2004); Sharma et al. (2011); Bhasin et al. (2002), Kumar Nath (2000) Kumar Nath (2009)

HAZUS Methodology Capacity curves and fragility curves	Technical Manual (FEMA 2011)
Rapid Visual Screening Procedure	Rapid Visual Screening of Buildings for Potential Seismic Hazard (FEMA, 2002)
Building Typology and building damage in previous earthquakes	Kaushik et al. (2006)
Questionnaire	Lang et al.(2009)

Table 3-3 Questionnaire prepared for Field Survey (Lang et al. 2009)

	Question	Observation	
1	Is the building irregular in plan	Yes	No
2	Are the columns regularly distributed	Yes	No
3	Are both building directions adequately braced	Yes	No
4	Does the ratio between the building's length and width is > 2.5	Yes	No
5	Does the building possess eccentric cores (staircases or elevators)	Yes	No
6	Does the building have a soft storey	Yes	No
7	Is the building irregular in elevation caused by setbacks of upper stories	Yes	No
8	Does the building have cantilevering upper stories	Yes	No
9	Does the building possess a heavy mass at the top or at roof level	Yes	No
10	Are pounding effects possible	Yes	No
11	Does the building have short columns	Yes	No
12	Are strong beams–weak columns available	Yes	No
13	Does the building possess shear walls	Yes	No
14	Did the building suffer any significant structural damage in the past	Yes	No
15	Does the building possess seismic retrofitting or strengthening measures	Yes	No

3.3. Field Work

Field work was an important component for this study. Information/data that was already available as listed was collected from various departments. The data collected from the field are given in Table 3-4 and explained in detail in next chapter. This helped in saving time in preparation of data bases and other digitisation work and allowed more time on observing building damage, interaction with local authorities and people.

The locations of damaged buildings in study area were collected from the local authorities/ people and important as well as sample points were visited. Location of the sample site was recorded by GPS and photographs of the building and damage were taken. Based on building inspection, site inspection, interaction with local population and literature, the possible causes of building damage was ascertained. Based on the data provided by the local authority, Municipal Wards were taken as the basic unit for vulnerability assessment. Rapid visual screening procedure was carried out for the study area to collect information on building types, structural information, building distribution at ward level, and kind of damage due to the earthquake at different locations. The building types, damage observed in buildings and other field observations were described in detail in the following chapter.

Table 3-4 List of Maps Collected during field work

Maps	Attributes	Source
Municipal and Ward Boundary		Urban Development and Housing Department
Building Foot Print Map	Number of floors Building Material Usage	
Road Map	National High Way State Highway, Bypass Internal Roads Footpath	
Contour Map (5m)		
Land Stability Map		Mines and Geology Department
River and Drainage Network		Water and Sanitation Department

3.4. Post Field Work

In the last phase of research, based on the collected field data/information and literature, acquired databases, maps, and images were organised using uniform georeference system in GIS. The collected field data was cross checked with processed high resolution imagery. Based on the different building types in the study area, and building typology information, different classes of buildings were determined with respect to HAZUS building classification as given section 2.1 of literature review. Based on the identified building types, the building parameters: yield and ultimate capacity values as provided in FEMA (2011) handbook were considered. Using the HAZUS method with building response and ground motion explained in section 2.3 of literature review, the damage probability of each building type at the ward level was generated. The results thus generated were compared with the damage details that were provided by local authorities and the level of applicability of HAZUS was evaluated. The complete step by step process for generating the discrete damage probabilities of building types is given in Annexure A. Based on the data collected, risk map were generated and was compared with the actual building damages in the 2011 earthquake. Based on the literature and field survey, different retrofitting methods that have been adapted in the study area were identified and discussed whether these methods were successful in decreasing the vulnerability and new methods were suggested which can be adopted for future construction.

Table 3-5 Generated Results and Input Provided

Input Data	Output Results
Building foot print map	Building Density Map
Contour Map	Digital Elevation Model
Digital Elevation	Slope and Aspect Maps
GPS points and Satellite Imagery	Surveyed Building Point Map
Slope, Land Stability and Building Density Map	Hazard Map
Ward Map and Population Data	Population Density Map
HAZUS methodology and Identified Building Types	Building Damage Probability

3.5. Database Preperation

3.5.1. Preparation of Satellite Imagery

High resolution satellite imagery, particularly Cartosat-1, Cartosat-2 and others as given in Table 3.1 were acquired to: 1) assess damage to built environment with respect to ground condition and 2) prepare building foot print maps in the study area. Before using these images for preparing foot print maps, these images have to be geometrically corrected. Cartosat-1 image stereo pairs were orthorectified using X and Y reference points from Google earth and the Z values are considered from the SRTM 90 m resolution data. Using Leica Photogrammetry suite in Erdas Imagine 9.3, the ortho rectification was done with a total RMS error of 0.74 m. Using orthorectified Cartosat-1 imagery as reference image other images were geometrically corrected. These images were analysed to assess damage to the buildings with respected to local geology and geomorphology with the support of field verification. For building foot print preparation, these images were clipped using the Gangtok municipal boundary shape file in ArcGIS.

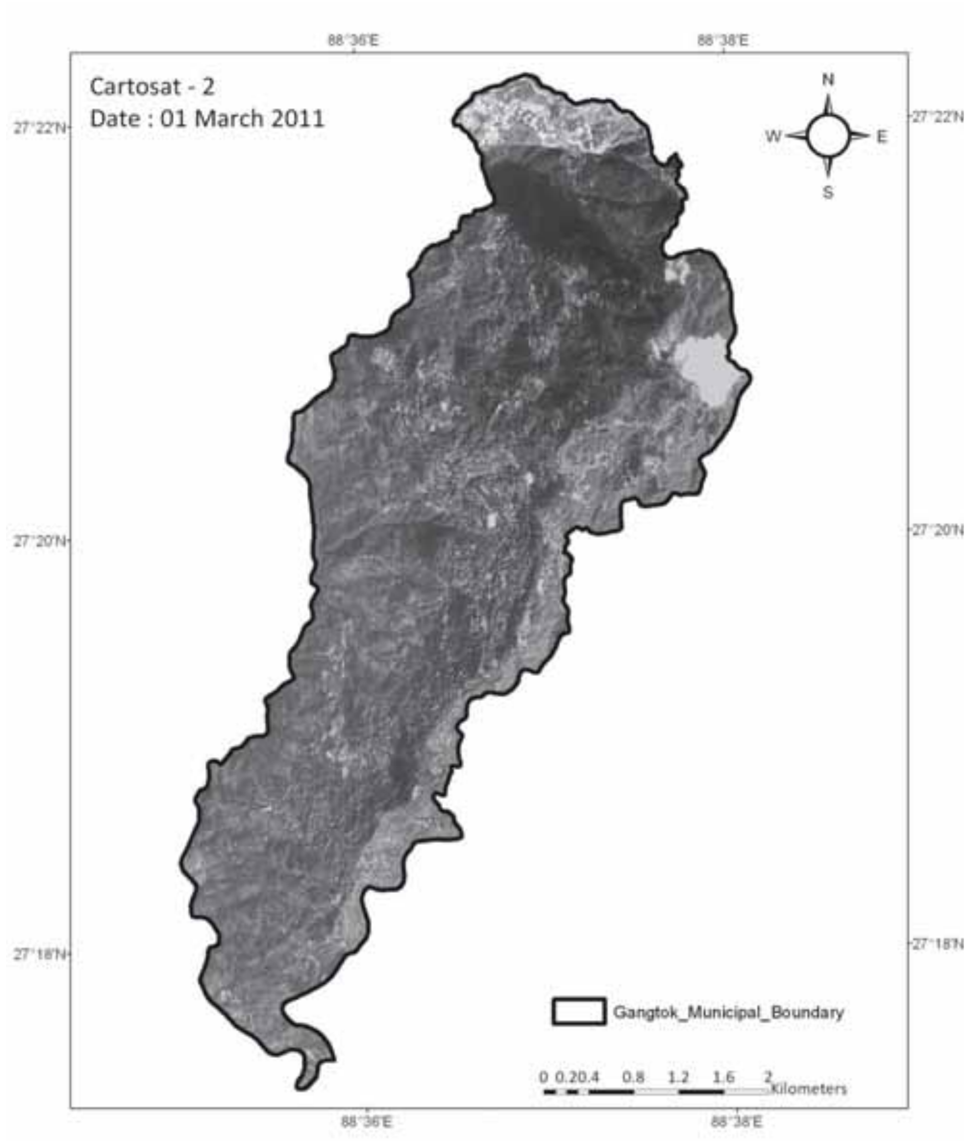


Figure 3-2 Cartosat-2 2011

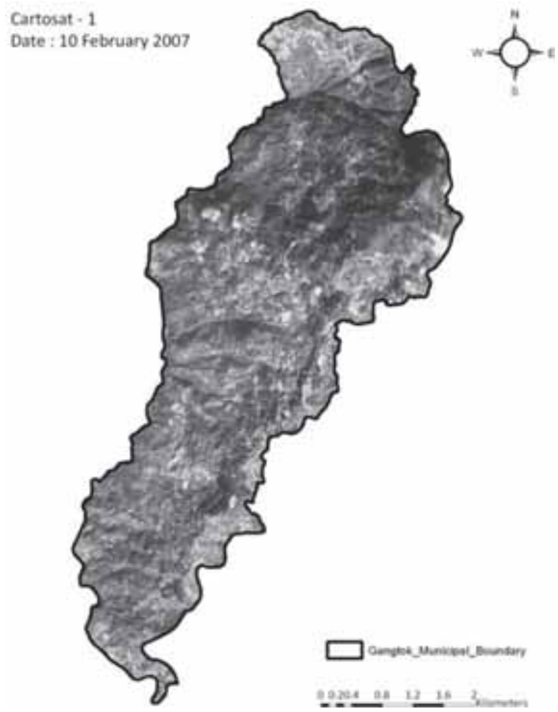
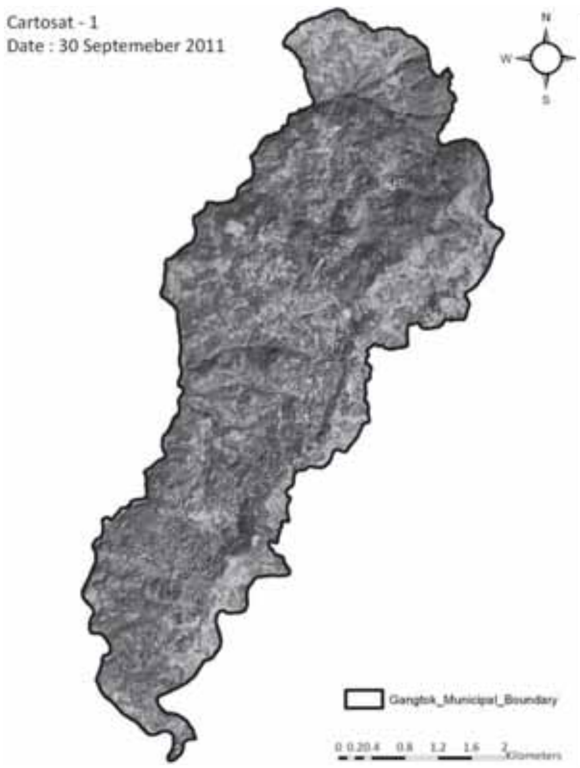


Figure 3-3 Cartosat-1 2007



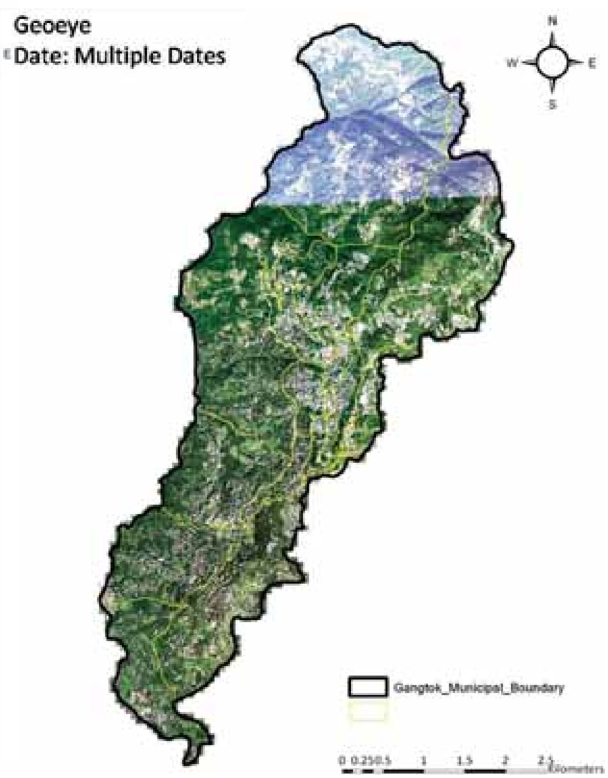


Figure 3-4 Cartosat-1 2011

Figure 3-5 Geoeye

3.5.2. Homogenous Area Mapping

The main idea of homogenous area mapping is to identify a small unit, in which all types of buildings can be represented in Gangtok area. Arithang ward, which is located in the centre of Gangtok and close to major commercial zone, is selected as the unit for homogenous area mapping. Then using the Google earth Geo-eye Image, the outline for the buildings were digitised. As the building foot print map of Gangtok region for the year 2004 was already available, that data was verified against the prepared foot-print map and good match was observed, therefore, it was decided to use the existing building foot print map. Since these foot print maps were prepared from aerial photographs, there was slight shift in the building outlines which was considered as negligible. However, in the outskirt of the city area, in some wards, additional buildings were observed on 2011 data compared to 2004 building foot-print map. In the city centre areas very little additional built up areas were observed therefore building foot print of 2004 was considered for all analysis.

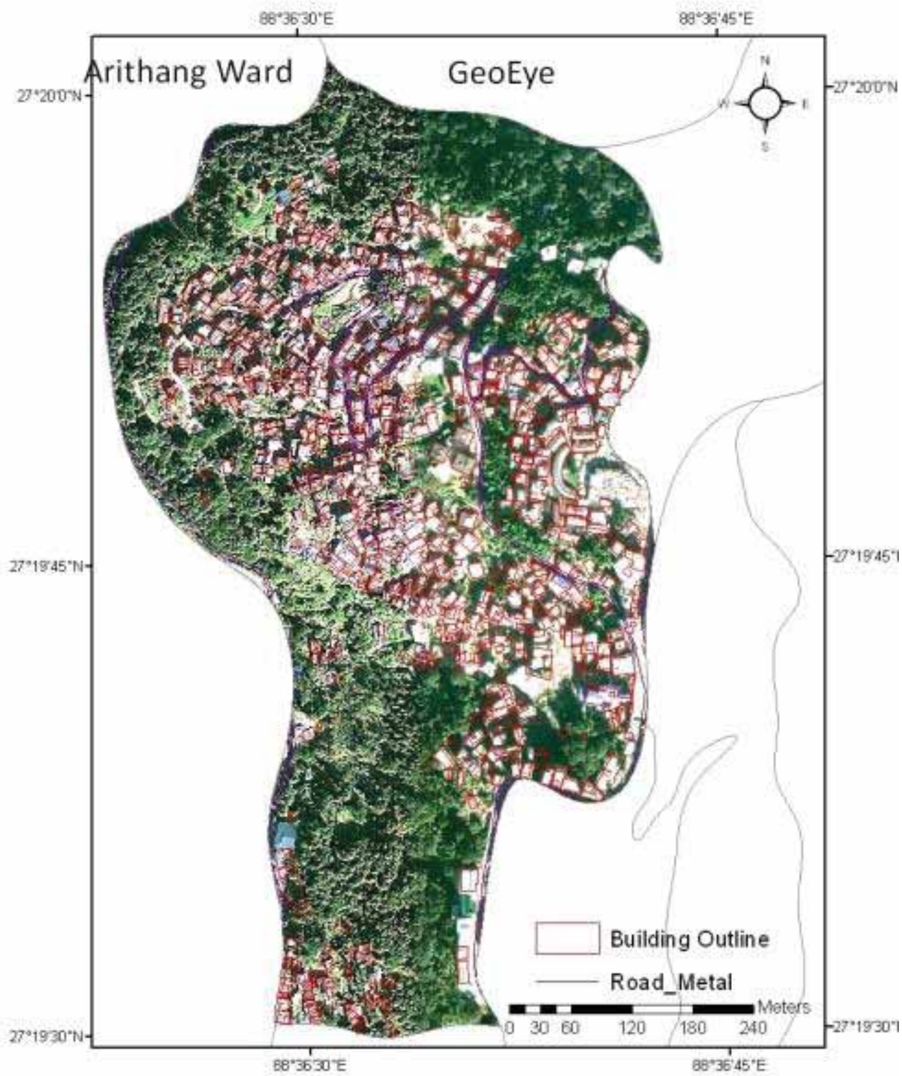


Figure 3-6 Digitisation of Buildings on Geoeye image

4. STUDY AREA

4.1. Introduction

State of Sikkim with lateral extent varying from East 88° 03' to 88° 57' longitude and North 27° 03' 47" to 28° 07' 34"with a total area of around 7096 km^2 lies in the north eastern part of India. It is entirely a mountainous state consisting of steep slopes, complex geology and number of important tectonic features such as MCT and MBT in close proximity. The entire state is located in the seismic zone IV and its capital, Gangtok city is located on the flat areas of an elongated NNE trending ridge. The city has further expanded to both the slopes of the ridge/hill. Population of the city is mixed with both local as well as migrated population from other parts of country. In recent times it has emerged as an important tourist destination attracting a lot of tourist, thus adding to the population at risk in the event of an earthquake. Elevation of the state varies from 244 m at south to 8534 m in North (Bhasin et al., 2002). The altitude of the state plays a major role in controlling the climate. It experiences usual Himalayan mountain climate of warm summers and cold winters. North part of Sikkim due to its high altitudes and mountains gets high snow fall in winters. Region receives average annual rainfall of around 3494 mm in about 164 days of the year (UDHD, 2011).

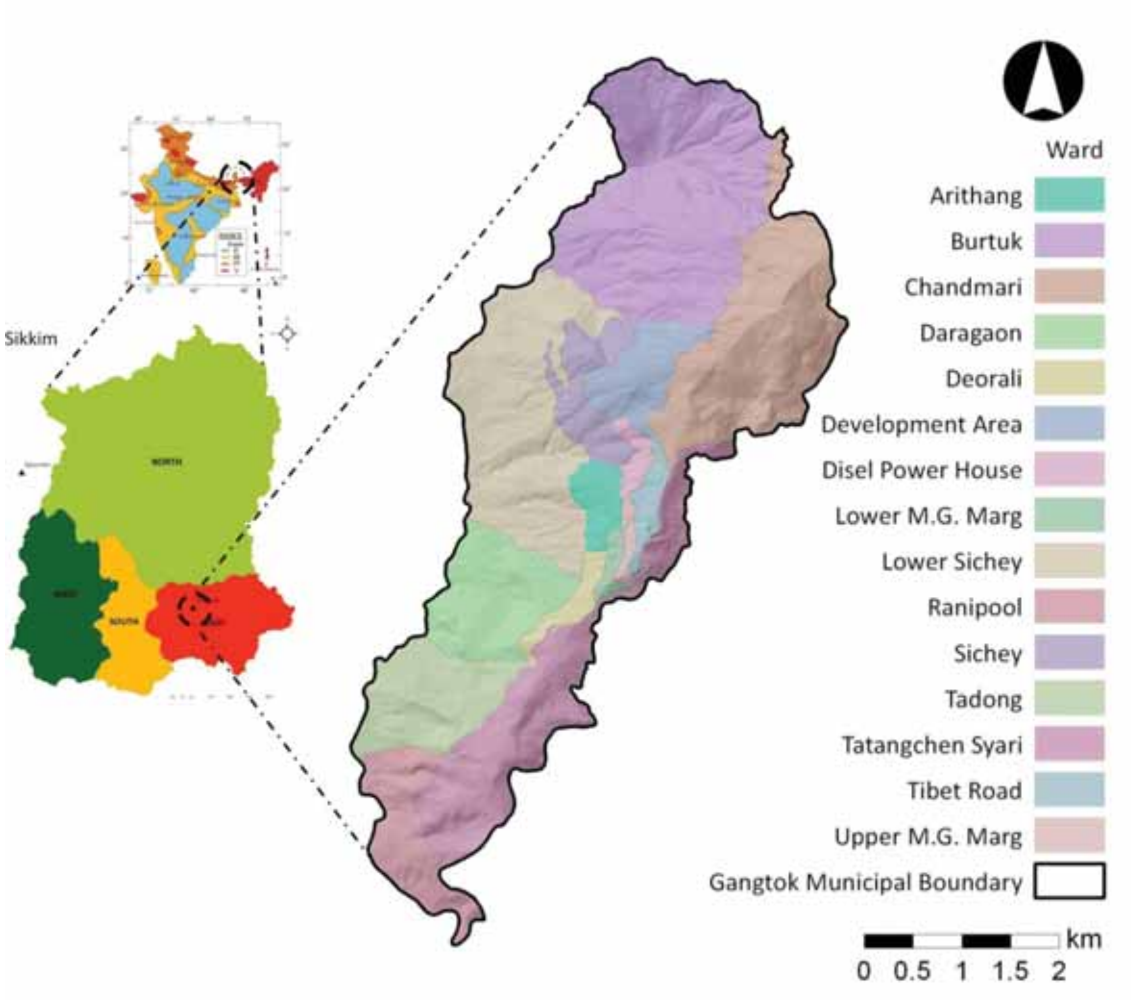


Figure 4-1 Gangtok Location and Municipal Ward Boundary

4.2. Geographical Location and Area

Gangtok, the state capital of Sikkim, is also the district head quarters of East district and is one of the main tourist destinations of the country. It is located on the steep slopes of Sikkim Himalaya with its extents lying between East 88° 35' to 88° 38' longitude and North 27° 16' to 27° 21' latitude with an average altitude of 1,667m above mean seal level. The area of Gangtok is around 19.62 km^2 (SPA, 2011)

4.3. Geology and Soil

The rock types of Gangtok region mainly consists of phylites, schists and gneissic rocks of Daling Group and Lingtese granitoid gneiss and due to high monsoonal rainfall and structurally disturbed nature of the area, rocks are highly weathered at many places. Because of the high weathering and erosion there are frequent landslides in the region. The soil is developed from schist and gneissic group of rocks and is characterized by coarse loamy type of soil with surface stoniness and susceptible to high erosion. The heavy rainfall also results in heavy soil erosion in the region (Bhasin et al., 2002; Kumar Nath, 2004; Sharma et al., 2011).

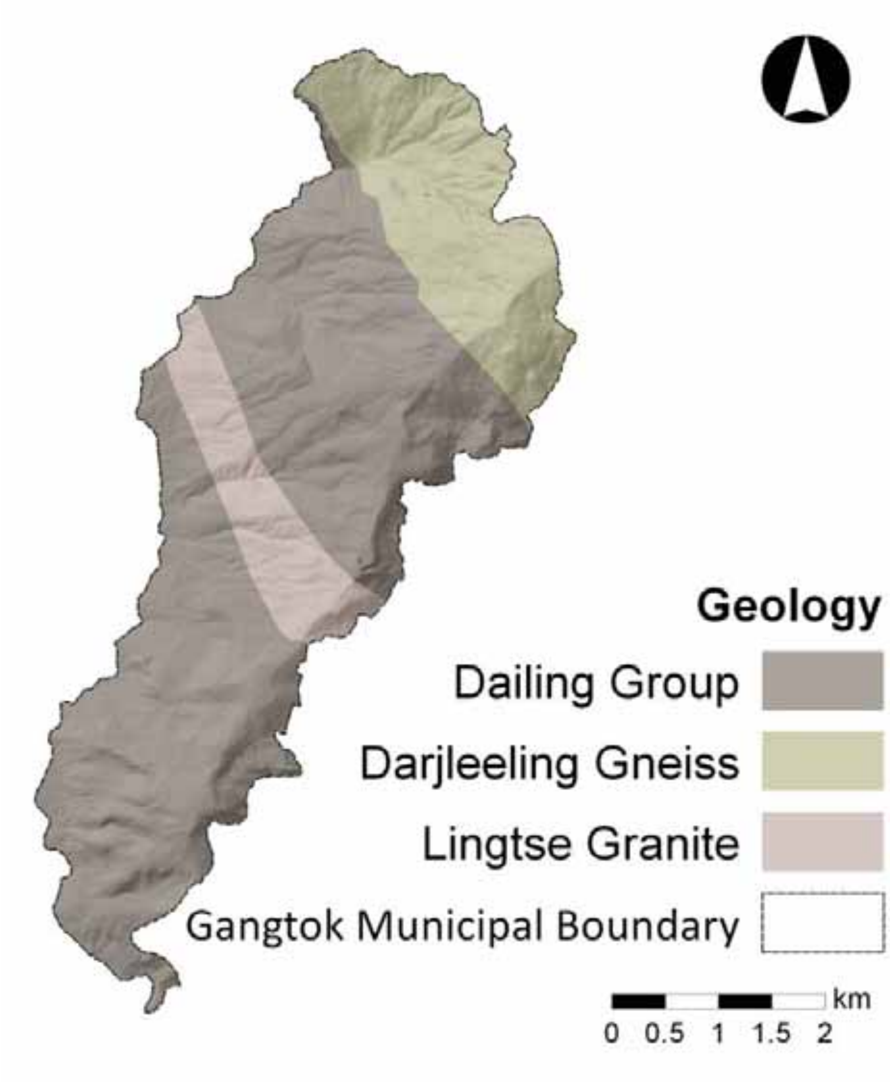


Figure 4-2 Geology Map of Gangtok MMG Dept. (2008)

4.4. Topograpghy

Gangtok city is located on flat top of a ridge oriented in NE-SW direction and sloping down in NW-SE direction. City has grown in a linear fashion along the ridge line. It has also started growing towards the NW direction as the slope on west side of the hill has a gentle slope than other side. Because of this kind of skewed development on one side of the hill slope, the city's building and settlement pattern and other infrastructure like water supply and sewerage systems are also located on one side of hill slope thus affecting the slope stability of the region.

Figure 4-3 Panoramic View of Gangtok and growth along its Ridge Line along N-S direction

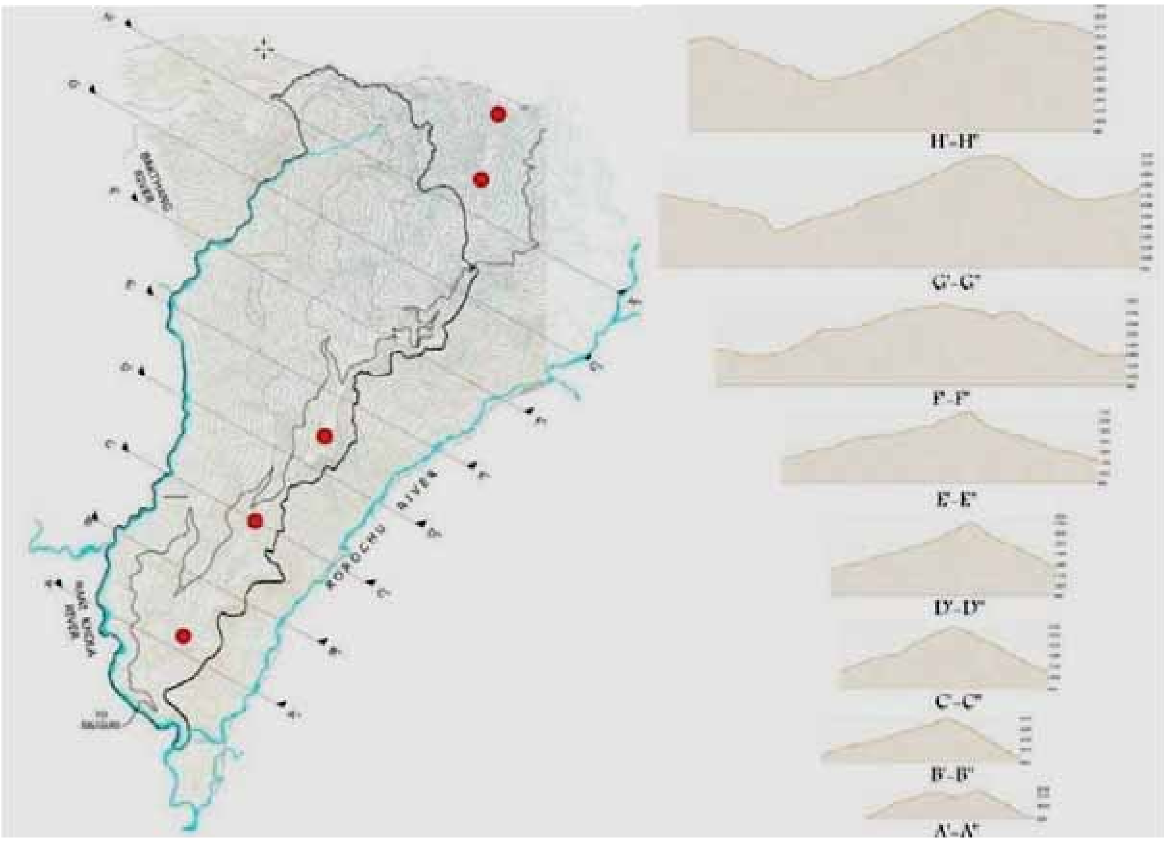


Figure 4-4 Sections through Gangtok Ridge showing its gentler western slope (SPA, 2011)

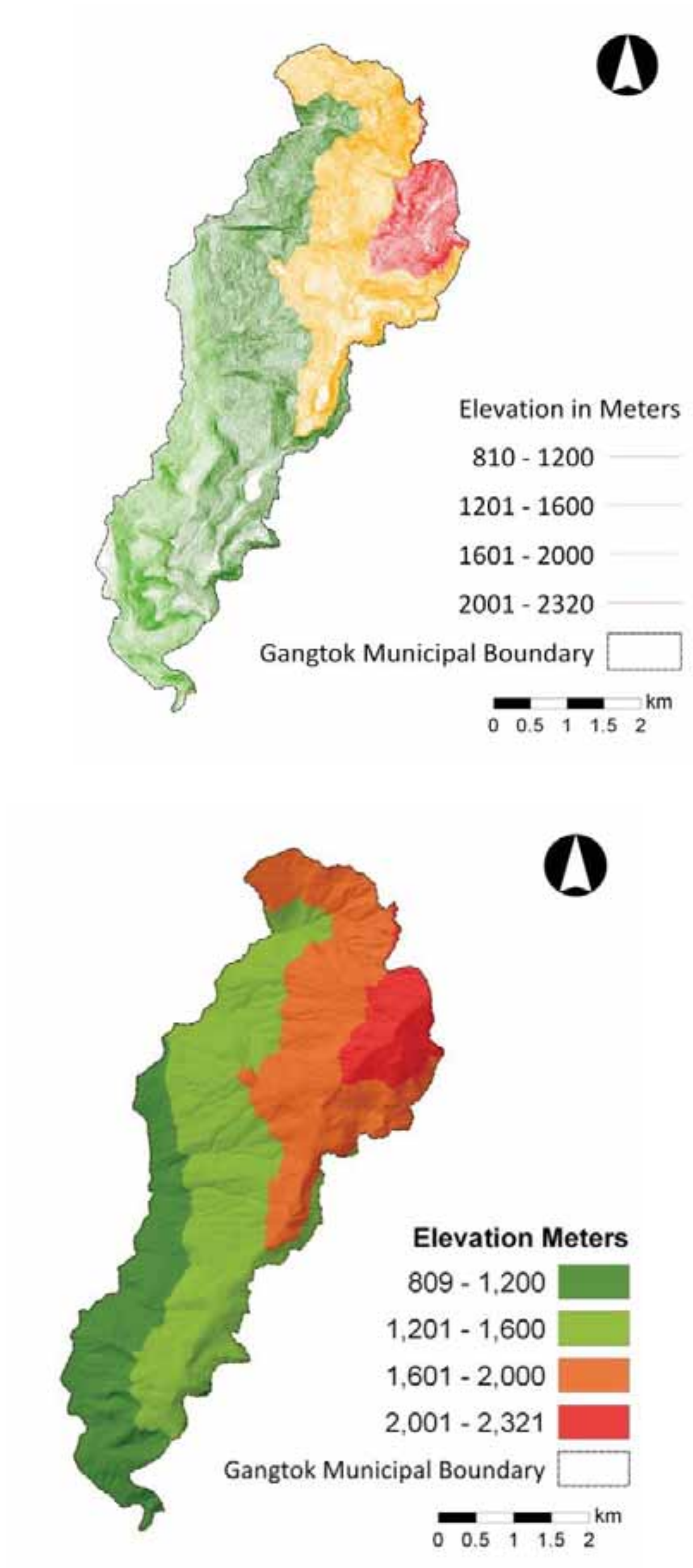
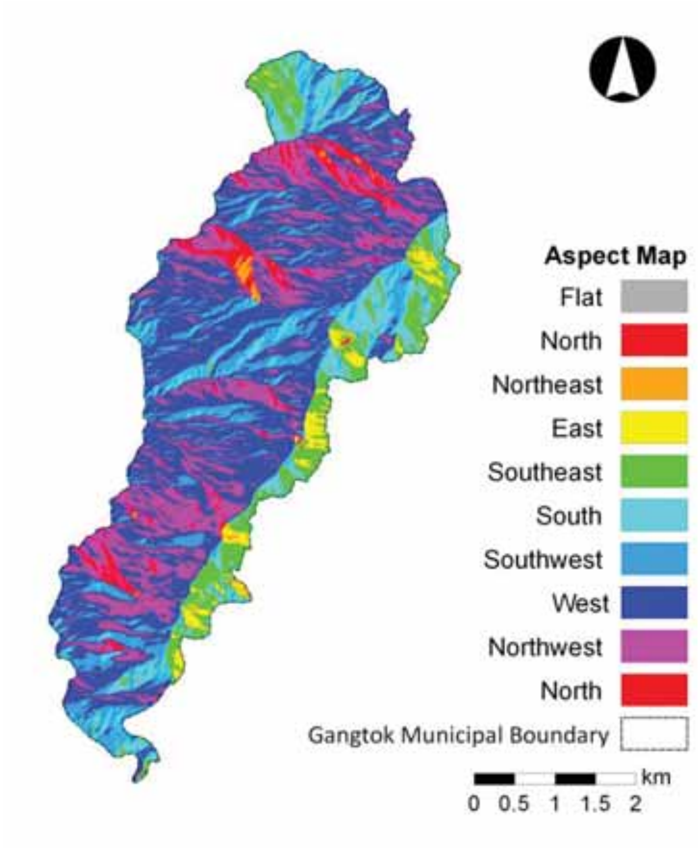


Figure 4-5 Contour Map and Digital Elevation Model showing its gentler western slope



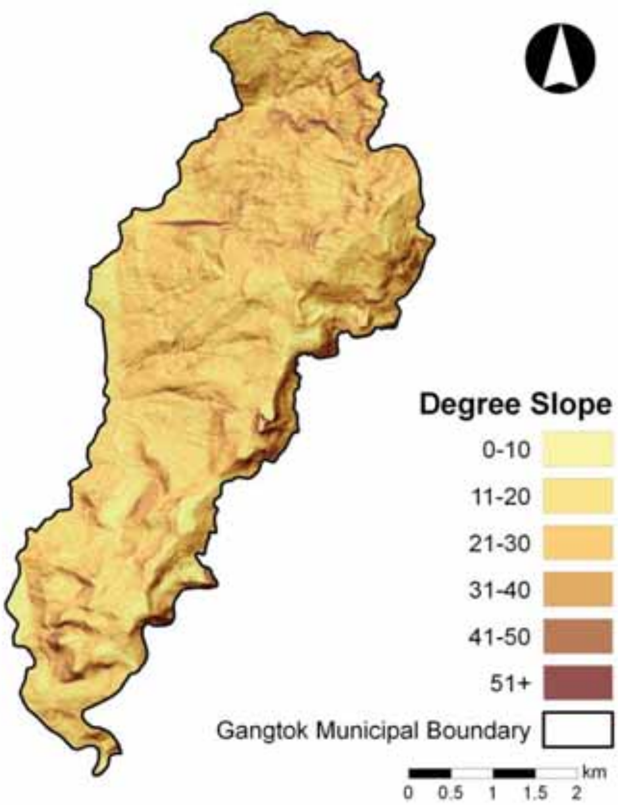


Figure 4-6 Aspect and Slope Map showing its gentler western slope

4.5. Land Stability

Since the Gangtok lies on the steep slopes, the stability of land plays a very important role in planning and construction. Based on parameters as listed in Table 4-1, Mines, Minerals and Geology Department of Government of Sikkim, divided the land into six categories based on their level of stability. They have recommended certain heights of buildings permissible in these areas.

Table 4-1 Factors - Land stability map MMG Dept. (2008)

Factors
Geology and Geotechnical Parameter
Slope with Aspect
Rainfall Pattern
Land use/Land cover
Hydrology and Ground water
Seismicity
Soil type and Rock Erodability
Vegetation

Table 4-2 Permissible No. of Floors MMG Dept. (2008)

Condition	Permissible Floors	% of Land
Very Stable	5 ½	20
Stable	4 ½	29
Relatively Stable	3½	24
Relatively Un-Stable	2 ½	18
Un-Stable	1 ½	5
Very Un-Stable	0	4

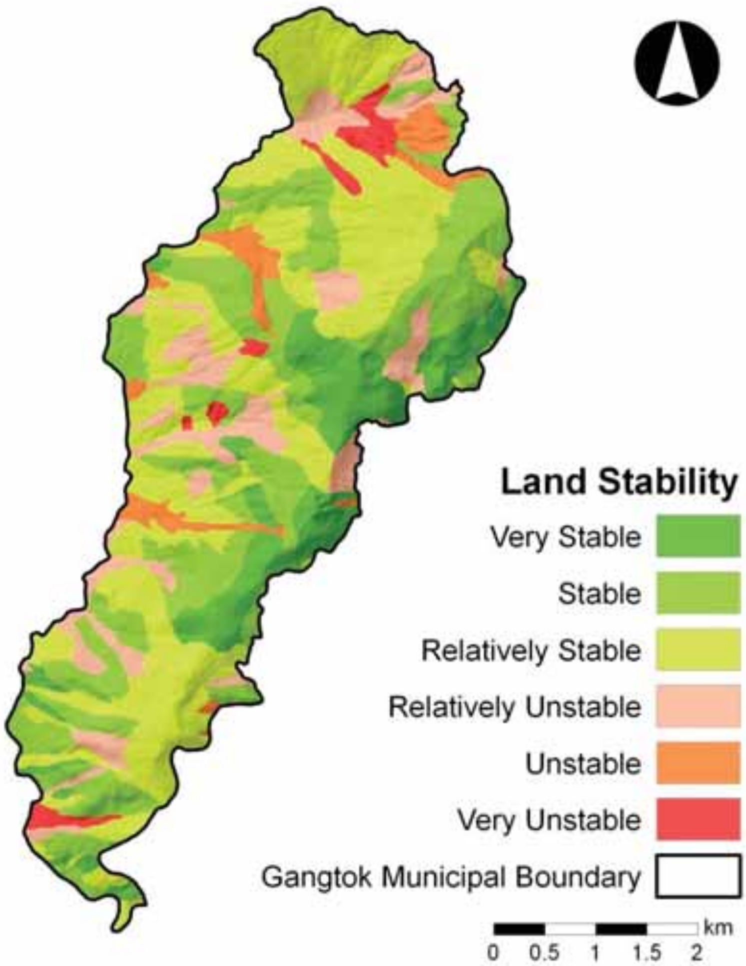


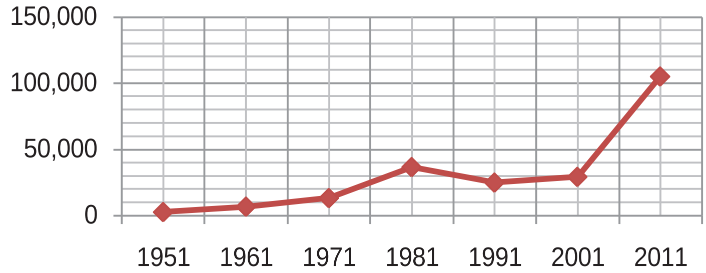
Figure 4-7 Land Stability Map
Source: MMG Dept. (2008)

4.6. Populationand Household

Gangtok, the state capital and district headquarter of East district, is the major urban area in the state of Sikkim. It attracts large number of tourists throughout the year because of its scenic beauty and proximity to snow clad mountains of Himalaya. Because of tourism and administrative activities, Gangtok has emerged as the main centre of economic activity and attracts people from all over the state for employment opportunities and better infrastructure. The growth of population is very high in the last decade. According to the Census of India, 2011, Gangtok municipal area population is 105,196 and the number of households is 27,464. Due to migration from other parts of Sikkim and increase in tourism activities, Gangtok population exploded in the last 10 years with an increase of 258.37 %, which is extremely high.

Table 4-3 Gangtok Population Data (UDHD, 2011)

Year	Population	Growth rate
1951	2,744	
1961	6,848	149.56
1971	13,308	94.33
1981	36,747	176.13
1991	25,024	-31.9
2001	29,354	17.3
2011	105,196	258.37



The negative growth as shown in 1991 is due to the reduction of the Gangtok municipality area. The area of Gangtok municipality was reduced into a smaller area and divided into 15 municipal wards. The detail list of population at ward level, with area and population density is given in Table 4-4 and Figure 4-8

Table 4-4 Gangtok Ward Population, Area and Density (UDHD, 2011)

S.No.	Ward Name	Area (Km^2)	Ward Total	Persons / Km^2
1	Deorali	0.282	7402	26248.23
2	Daragaon	1.1492	12407	10796.21
3	Tadong	1.3861	10049	7249.83
4	Ranipool	1.0872	4159	3825.42
5	Arithang	0.348	9333	26818.9
6	Burtuk	4.3621	8109	1858.96
7	Chandmari	2.9813	5975	2004.15
8	TathangchenSyari	2.3909	9117	3813.20
9	Lower Sichey	3.1619	5671	1793.54
10	Upper Sichey	0.7222	8640	11963.45
11	Development Area	0.7398	9244	12495.27
12	Upper M.G.Marg	0.1291	2800	21688.61
13	Lower M.G.Marg	0.13412	4110	30644.20
14	Tibet Road	0.2768	2914	10527.46
15	Diesel Power House	0.1752	5266	30057.08
	Total	19.626	105196	5360.033

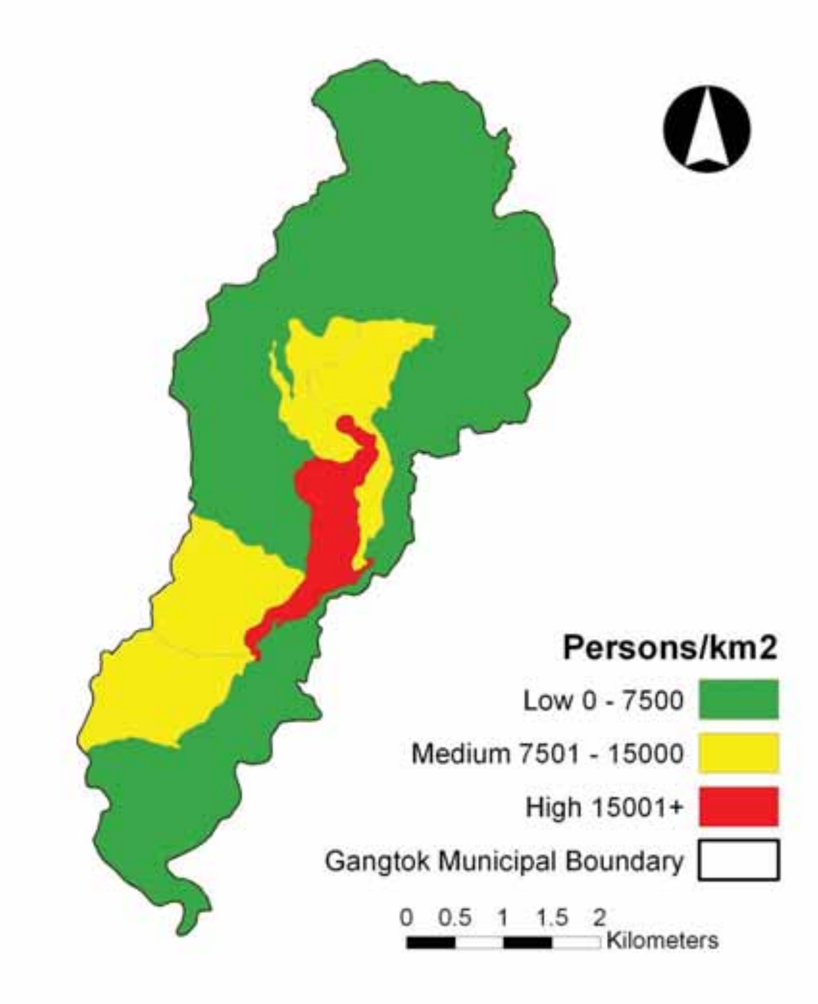


Figure 4-8 Ward level population density map

The density map shows the high population density at the centre of city close to the ridge line and it decreases as the distance from the ridge line increases. City Mobility Plan of Gangtok claims that around 2, 00,000 tourists visit Gangtok every year which increases burden on the city and population exposure to earthquake hazard also increases.

Due to steep population growth in Gangtok, there was a lot of demand for housing. In order to meet this demand, the buildings at the city centre became taller in already high density areas and also construction activity spread to the out skirts of the city with low rise buildings in the low density area. Due to changing requirements, buildings at the city centre which were designed for low to mid rise structure, were converted into high rise by adding number of floors to the existing structures.

Table 4-5 Number of Households and growth rate (UDHD, 2011)

.				Type of Structure			
Year	Population	Household	Growth%	Permanent	Growth%	Temporary	Growth%
1991	25,024	7103		5094		2009	
2001	29,354	9655	25.52	8244	31.5	1411	-5.98
2011	105196	27464	178.09	25554	173.1	1910	4.99

The 2011 data shows the unprecedented growth between 2001 and 2011, and increase in number of permanent structures in the city. The growth rate of concrete to wooden and other lighter material structures in the last decade shows the improvement in economic condition of people and the kind of buildings they prefer to live. As per UDHD (2011), there are 1650 houses that come under slums or informal construction, which is around 6% of building stocks in the city.

Table 4-6 Number of Households at ward level

S.No.	Ward Name	Households	%
1	Deorali	1749	6.36
2	Daragaon	1224	4.45
3	Tadong	2057	7.48
4	Ranipool	1638	5.96
5	Arithang	2220	8.08
6	Burtuk	1182	4.30
7	Chandmari	2447	8.90
8	TathangchenSyari	929	3.38
9	Lower Sichey	2100	7.64
10	Upper Sichey	898	3.26
11	Development Area	2060	7.50
12	Upper M.G.Marg	2989	10.88
13	Lower M.G.Marg	2596	9.45
14	Tibet Road	1133	4.12
15	Diesel Power House	2242	8.16
	Total	27464	100

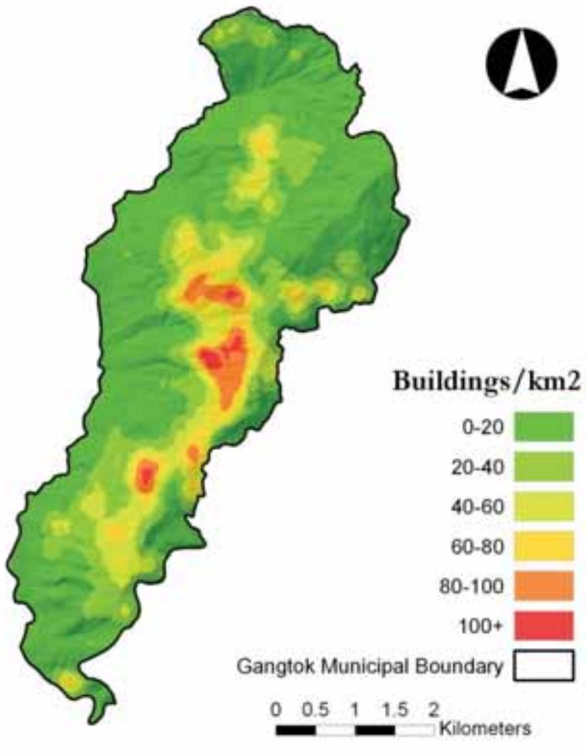


Figure 4-9 Building Density Map

4.7. Land-Use Distribution

Gangtok has mixed land-use pattern due to the unplanned development. As not much land is available for expansion, the growth of city is highly concentrated along its only lifeline, national highway running through mainly western slope of the region. Based on the need and availability, land is allocated to different uses. All government offices, commercial, retail activities and residential complexes are the major land/building uses found in the city. And as we move away from the national highway, the building use changes to mostly residential. The military areas are usually considered as the restricted areas which are located at the north and the south extents of the city, which are now blocking the growth of city along its length and forcing city to grow towards the slopes nearer to the river.

Table 4-7 Land- use classification and area (SPA,2011)

S.No.	Land use	Land Cover %	Area(Km^2)
1	Residential	23	4.416
2	Commercial	4	0.768
3	Industrial	2	0.384
4	Public and Semi-Public	8	1.536
5	Recreational	4	0.768
6	Transport	11	2.112
7	Cultivation	5	0.96
8	Undeveloped	28	5.376
9	Vacant	7	1.344
10	Restricted Area and Forest	8	1.536
	Total	100	19.6

4.8. The Sikkim Building Regulation Act 1991

As per the recommendations given by the Mines, Minerals and Geology Department of Government of Sikkim, and the sanction of plans and permissions for construction by the Urban Development and Housing Department, the maximum height of building permitted is 5 ½ storeys. The permissible covered area and set back are given below in the Table4-8.

Table 4-8 Permissible Built-up-Area and Set backs

Plot Area	Permissible Built-up area
> 2700sq.ft. and < 5400sq.ft.	70% of plot area
> 5400sq.ft. and < 10000sq.ft.	50% of plot area
> 10000sq.ft.	40% of plot area
Setback	
Plot Area	Required Setback
<2700 sqft	Minimum 27 feet away from the centre of the road
> 2700 sqft	10 feet from road and 3 feet on other sides

4.9. Description of Study Ward

For identifying the building types in the study region, Arithang ward was selected as basic unit, which is located in the suburb of Gangtok. The ward is located close to the main core of the Gangtok city. The area is characterized by different kind of buildings ranging from slums to major commercial buildings. Major commercial buildings are located along the national highway which passes along the ward boundary on the east side of the ward.

Arithang has around 2220 households which are around 8% of Gangtok total households. The population of Arithang ward is 9333 and it covers an area of 0.348 km^2 which makes it one of the densely populated areas in Gangtok. Figure 4- 10 shows the location of Arithang Ward in Gangtok and the location of the national highway.

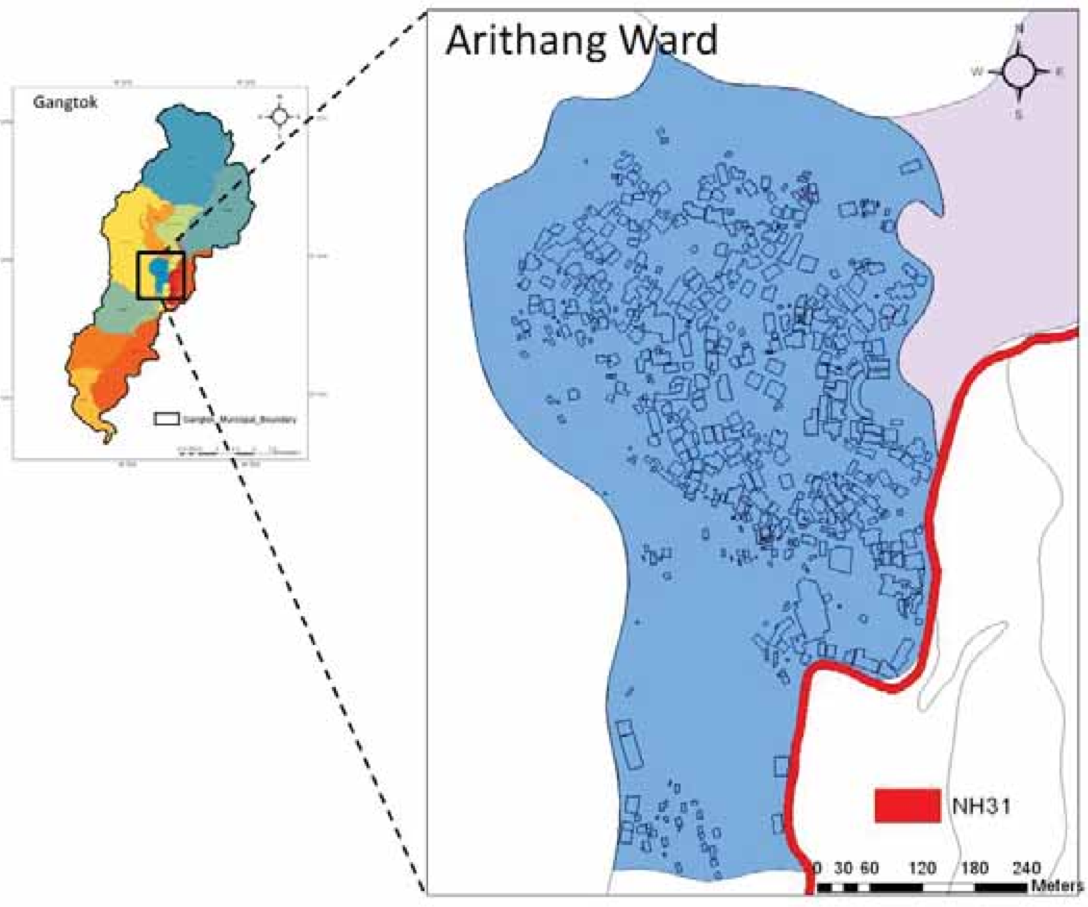


Figure 4-10 Location of Arithang Ward

4.9.1. Identified Building types

The major building typology identified in the Gangtok region are mid rise structure 5-7 storeys , but the buildings ranges from 1 and up to 12 storeys in few areas. The material used for construction is mainly concrete, and buildings are also constructed with wood, bamboo, asbestos etc. Details of identified building types are given below.

4.9.1.1. Traditional houses - Ekra houses

These are single- or two-storied huts built with a wood frame as main structural features along with columns and roof beams. Light metal sheets like asbestos are used as roofing material supported by the wooden frame. The in fills between wooden columns are cross-woven Ekra or bamboo spilt matting and these are plastered with mud or cement. In some cases these are replaced by half-brick thick burnt clay brick un-reinforced masonry walls. In few cases the metal asbestos sheets or plywood planks are also used instead of Ekra mats. These are usually ranging from 1-2 storeys as they are not strong enough for high rise construction. In most of these buildings, the wooden roofs are replaced by the asbestos sheets as they are much more resistant and durable in monsoon seasons.

(A) (B) (C)

Figure 4-11 Ekra – Traditional Building Types in Arithang Ward

Figure 4-11 shows the Ekra type of constructions in the Arithang ward. Figure 4-11 –A show the two storey Ekra construction with traditional wooden roof. The extension from the roof at two floor levels is to protect the building walls from rains. Figure 4-11 B shows the buildings with bamboo woven mats covered by the cement plaster. Figure 4-11-C shows the bamboo woven mats between the wooden columns with mud plaster and the asbestos sheet roofs. These are considered as HAZUS class W1.

4.9.1.2. Asbestos - temporary structures.

These are similar to the Ekra type construction but these are much more temporary and very light in weight. These are just bamboo posts and beams and connected by the asbestos sheets.

(A) (B) (C)

Figure 4-12 Asbestos Building Types in Arithang Ward

4.9.1.3. Un -reinforced Masonry Structures.

These structures are single-storeyed un-reinforced brick, stone or concrete block masonry without earthquake resistant features. The horizontal bands which tie these walls are rarely seen in these buildings. The infill material vary based on several building materials as random rubble masonry (RRM), cement concrete blocks un-burnt brick etc, and these are joined by the cement mortar. The roof is either flat concrete slab supported these un-reinforced masonry constructions or sloping asbestos roofs.



(A) (B) (C)

Figure 4-13 Un-reinforced Masonry Building Types in Arithang Ward

Figure 4-13 shows the un-reinforced masonry type structures in the Arithang Ward. Figure 4-13 A and C show the building with un reinforced masonry and asbestos sloping roof supported by these walls, Figure 4-13 B shows the flat slab roof resting on the un-reinforced masonry with wide openings for windows and doors which make these much weaker. These falls under HAZUS class C3L.

4.9.1.4. Low-rise Concrete frame structures

These structures are single or double storeyed, where the masonry walls are used as infill material between concrete columns. The first floor of the buildings is generally made of concrete and the roof is either concrete flat slab or sloping asbestos light roof material. The walls are built from floor to roof with openings as required. No horizontal tying between columns except at beam level and the openings are not supported by lintel and sill level beams. Sometimes the ground floor is made of concrete frame with un-reinforced masonry infill and first floor is built as traditional Ekra type. These are considered as HAZUS building type C3L.



(A) (B) (C)

Figure 4-14 Mid-rise Concrete Frame Building Types in Arithang Ward

Figure 4-14 –A shows the un-reinforced masonry walls constructed without any tie beams and not between the columns but at the end of slab/floor. Figure 4-14-B shows the building with concrete slab on first floor and the light asbestos roof on the second. Figure 4-14-C shows the mix type construction with concrete and masonry in ground and Ekra in first floor.

4.9.1.5. Mid -rise Concrete frame structures

These are the most predominant kind of constructions seen in Gangtok region. These range from 3 to 7 floors. The frame is built with concrete and walls are constructed without any structural features. These can be mainly seen in the areas of high population density. Most of these buildings have 230mm X 230mm columns with half brick thick walls. The roof is generally sloping asbestos roof and the slabs are concrete. Openings are not usually supported by structural members. Based on the availability of space the buildings are constructed in odd shapes and with setbacks or projection on upper floors. Most of the buildings are constructed without any gap between them. Due to the construction on slopes, these have irregular column heights and frames are not symmetrical either.

(A) (B) (C)

Figure 4-15 Mid-rise Concrete Frame Building Types in Arithang Ward

Figure 4-15 A, B, C shows the mid rise concrete frame structure constructed with projections in the top floor and no gap between structures. This lack of gap can lead to the pounding affect buildings in major earthquakes. These are considered as HAZUS building type C3M.

4.9.1.6. High -rise Concrete frame structures

Structures which are more than 7 floors are considered as high rise constructions. There are many buildings more than 7 floors in Gangtok, which are not allowed as per the rules. These also have similar size columns as low rise and mid rise, but they have to take the load of 8-12 floors, which make these very highly vulnerable. These are considered as HAZUS building type C3M.

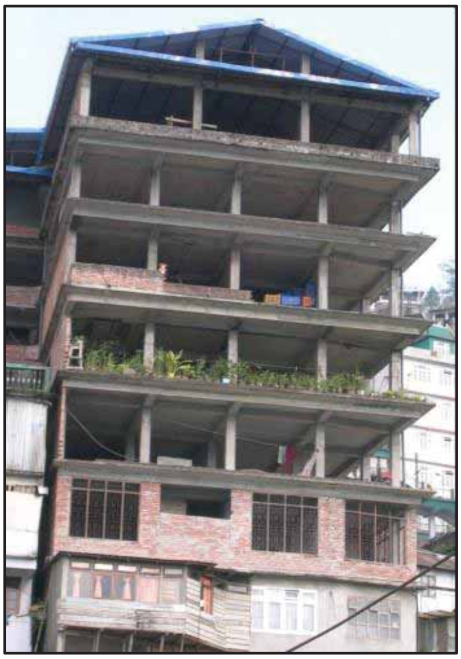


Figure 4-16 High-rise Concrete Frame Building Type in Arithang Ward

Figure 4-16 shows the 8 storey building without any seismic design considerations. Thin columns, walls without any tying, stand independent of columns and there are openings without any support, and is also irregular in shape. Figure 4-16 shows the building material used for construction. Majority of the construction uses concrete followed by wood and bamboo. Few buildings are even built with asbestos. It is clearly seen that all the buildings which are built with wood, bamboo or asbestos are smaller in size and have less number of floors compared to concrete buildings. Figure 4-17 shows the number of buildings in the study ward. Majority of buildings with higher number of floors are closer to the national highway.

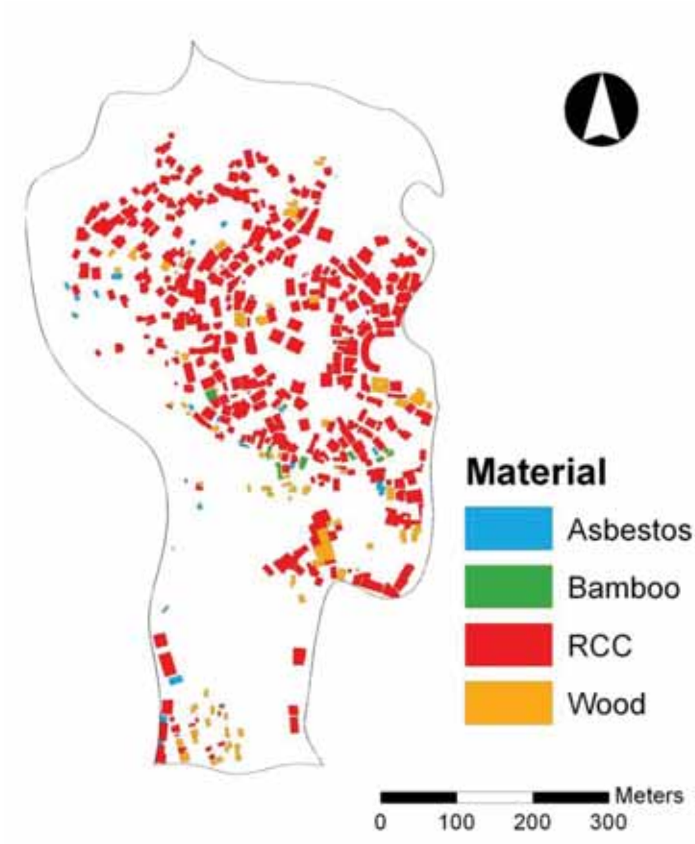


Figure 4-17 Building Material in Arithang Ward

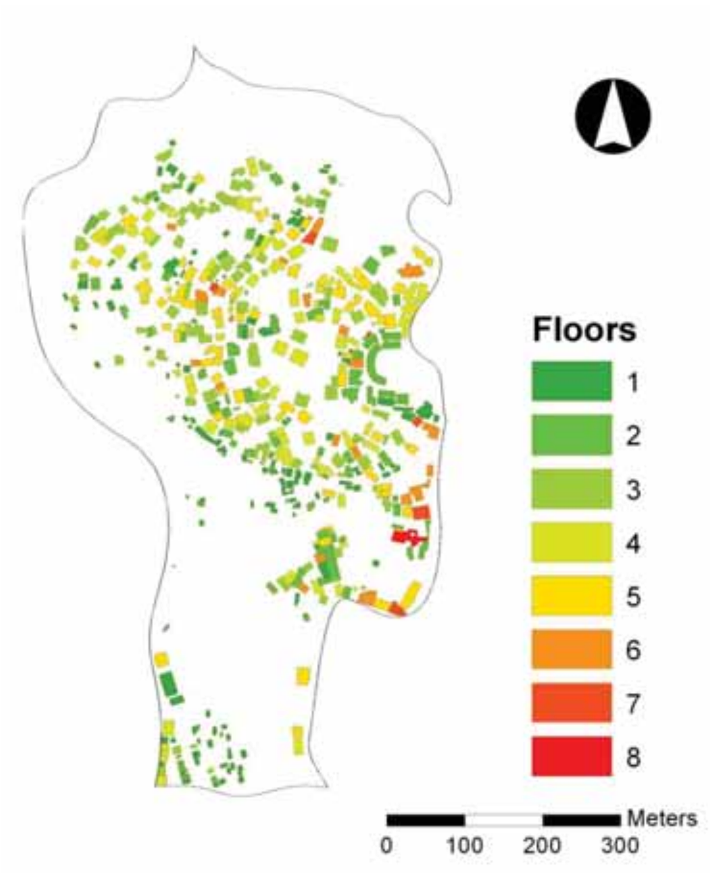


Figure 4-18 Number of Floors in Arithang Ward

Table 4-9 gives the details of number of buildings having number of floors. Majority of buildings are with 1-4 floors, followed by buildings with 5-6 floors and very few have 7 floors and 1 building of floors.

Table 4-9 Building Details

Number of Floors	Number of Buildings
1	184
2	113
3	114
4	125
5	86
6	30
7	7
8	1
9	0

The majority of buildings in the ward are privately owned and few buildings are owned by government and used for official purpose. Figure 4-16 shows the buildings which are owned by government and which are owned by private people. Most of the buildings privately owned are for residential usages and few commercial buildings. They are few hotels and guesthouses in the area as Gangtok is a major tourist destination and there is a lot of income generated by these hotels in peak seasons. Map indicates that these buildings are situated next to the national highway. Arithang ward is situated very close to the city centre and commercial areas, and vehicles have to pass through this region to reach there. There is no proper land use plan prepared before hand, the buildings are distributed randomly throughout the area and have different building usage.

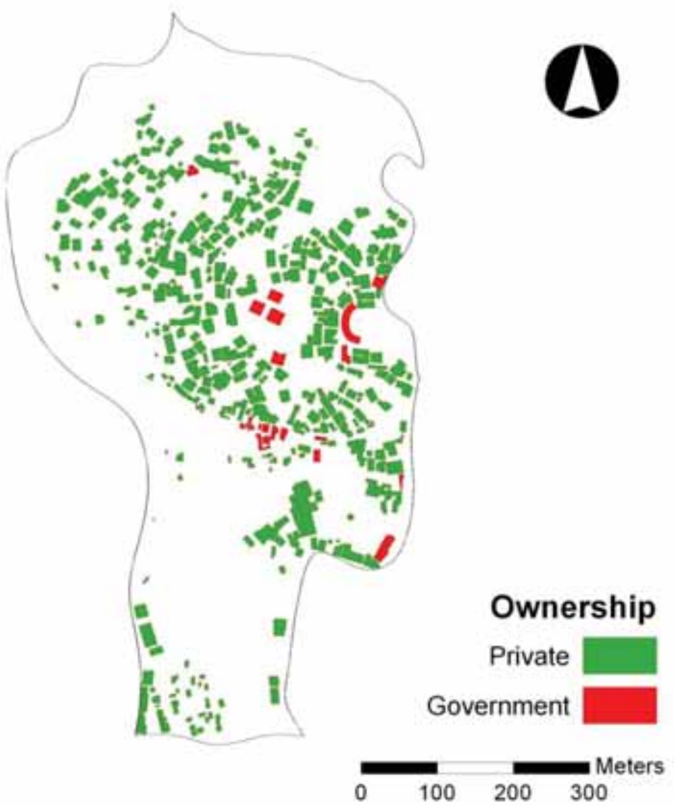


Figure 4-19 Building Ownership in Arithang Ward

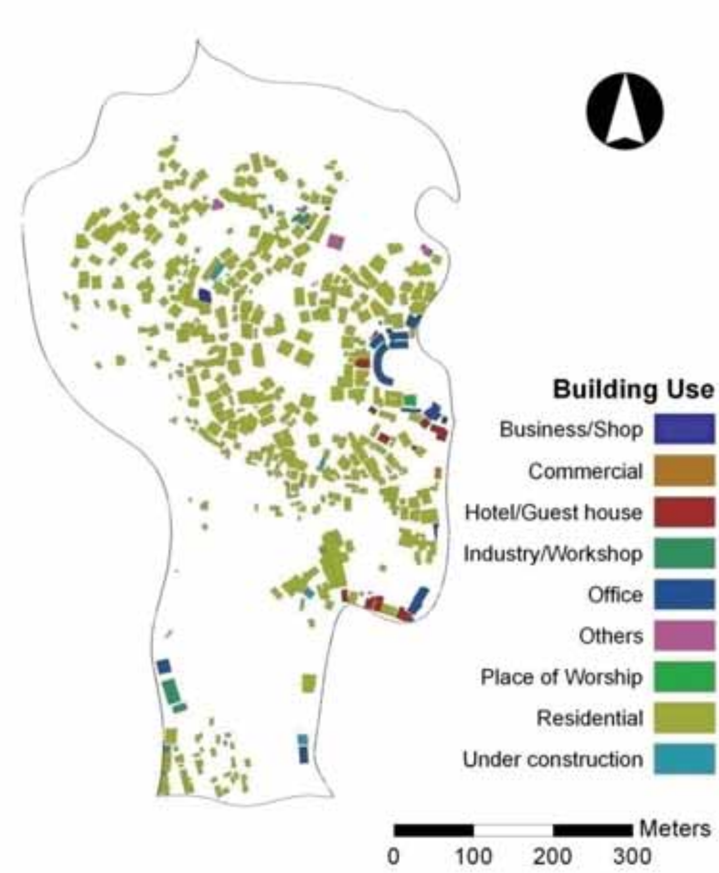


Figure 4-20 Building Use in Arithang Ward

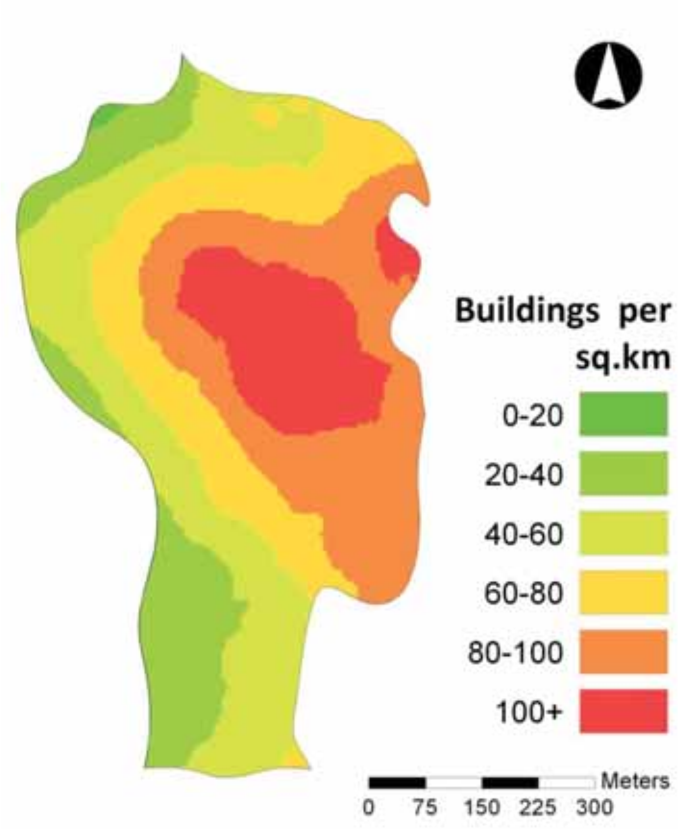


Figure 4-21 Building Density Map in Arithang Ward

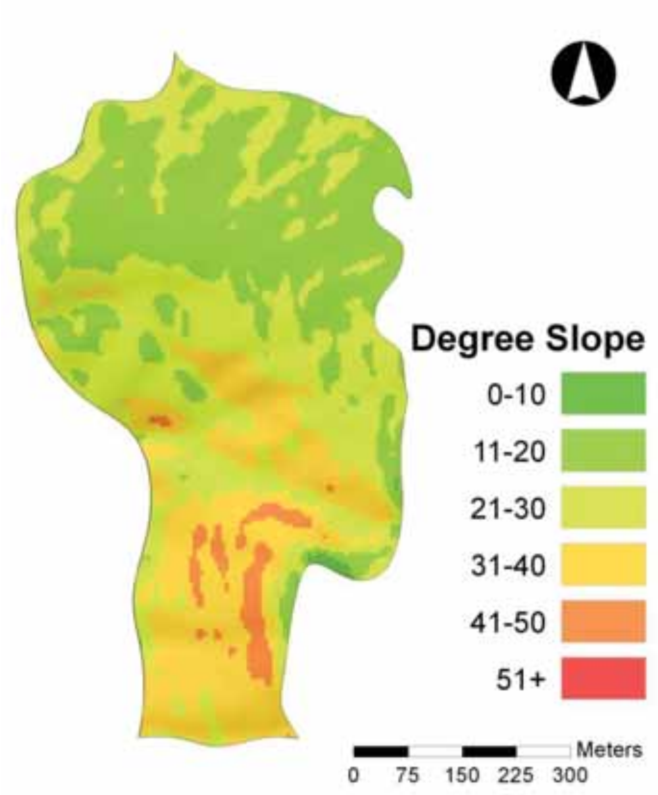


Figure 4-22 Degree Slope Map

Arithang ward is one of the high population density area in the Gangtok region. Figure 4-21 and Figure 4-22 shows the building density and slope map of the ward respectively. It is clearly seen that the steep slope regions in the south part of the ward are not highly populated compared to the central region which is comparatively flat.

4.10. Building Distribution

Sikkim's major lifeline, NH-31 passes through Gangtok City. National Highway passes from south to north of Gangtok along its ridge line. All other roads starts from the highway and runs to interiors of city away from the national highway. Most of the important structures are situated along the highway. Buildings have been built along the national highway and started moving towards valley to the western side away from the Highway


(

(A) (B)

Figure 4-23 Mid-rise Concrete Frame Building Types in Arithang Ward

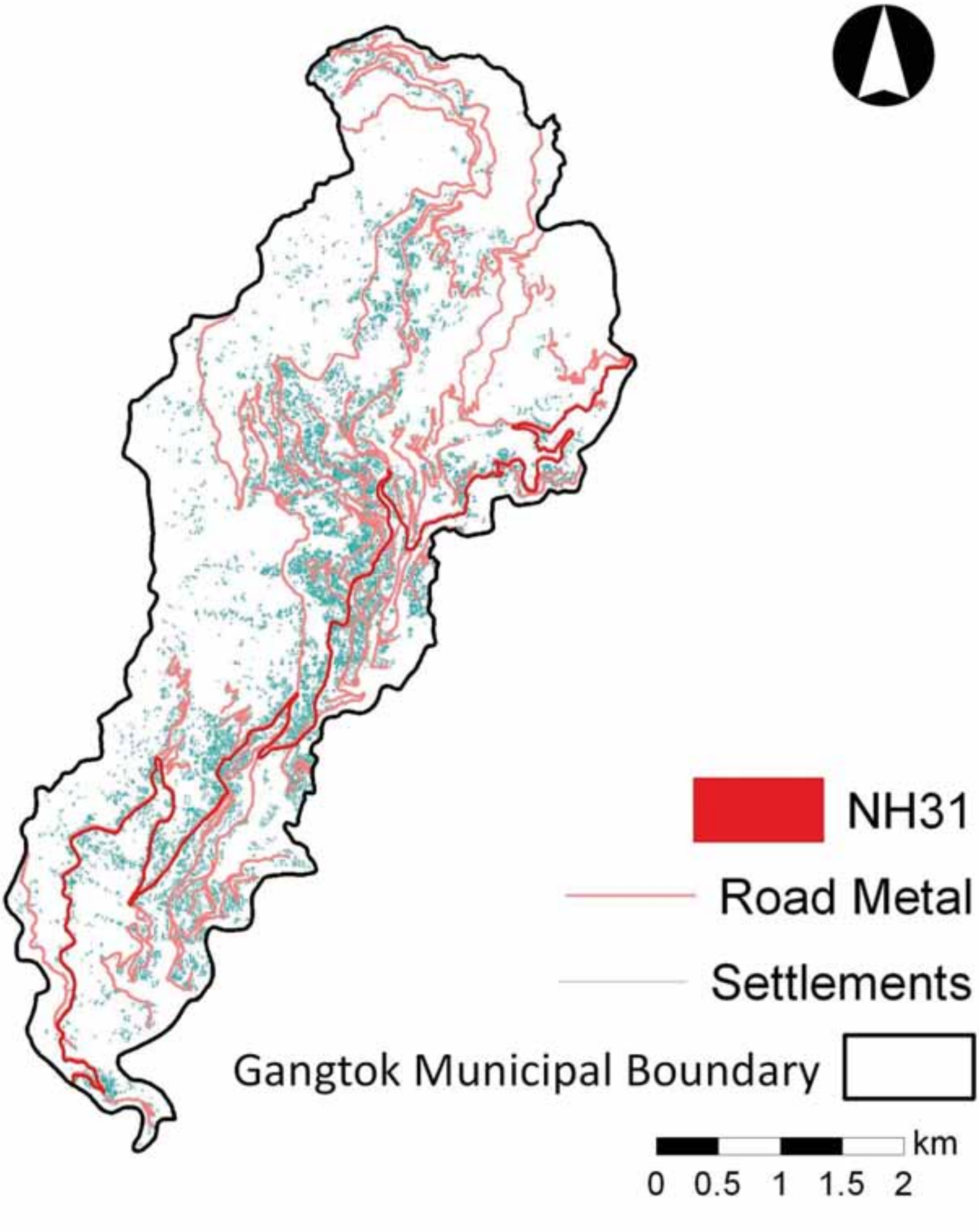


Figure 4-24 Building Distribution and Road Network

5. DAMAGE ASSESSMENT AND REMEDIAL MEASURES

5.1. Introduction

As discussed in Chapter-1, wide spread damage to built environment was reported from different parts of Sikkim. In order to assess the building damage due to both structural causes and foundation (terrain) related causes, field investigation was carried out in different parts of the north Sikkim district within a distance of 40 to 80 km from the epicentre. Different distance zones in different terrain conditions were covered in order to assess damage in different geological and terrain set up. This is referred as damage assessment at macro level for making general assessment on different structural, non-structural failures and failures due to differential ground acceleration. Building characterisation, modelling and damage prediction was carried out in detail at ward level for Gangtok city which was considered to be at at high risk. Field investigation was carried out for 21 days: 7 days were spent for damage assessment in Mangan, Chungthang, Lanchung and Lachen areas of North Sikkim and 14 days were for spent in Gangtok for collection of relevant data, field verification and validation.

5.2. Damage assessment at macro level

The 6.9 magnitude earthquake caused severe ground shaking and around 300 hundred new slides have been reported after the earthquake which caused severe damage to the roads and buildings (NRSC, 2011). Elevation of the state varies from 244 m at south to 8534 m in North (Bhasin et al., 2002). Due to steep slopes and high elevation of the state, the region is prone to landslides. National highway 31 which connects Gangtok to west Bengal and National 31 A which connects Gangtok and North Sikkim has been severely damaged because of the landslides. Compared to the east district, north district is more affected in the earthquake as north district is situated closer to the epicentre. The landslides affected the accessibility to these places because of the road blockage by heavy landslides and rock falls. Locations of major towns in North District and Gangtok are shown in the Figure 5-1. Even after a month of the earthquake, few places are still not accessible by road at the time of our visit and the damages in these areas were still not known. Mangan town is not that severely affected as compared to Chunthang. Location of Mangan and other areas visited in field shown in Figure 5-1.

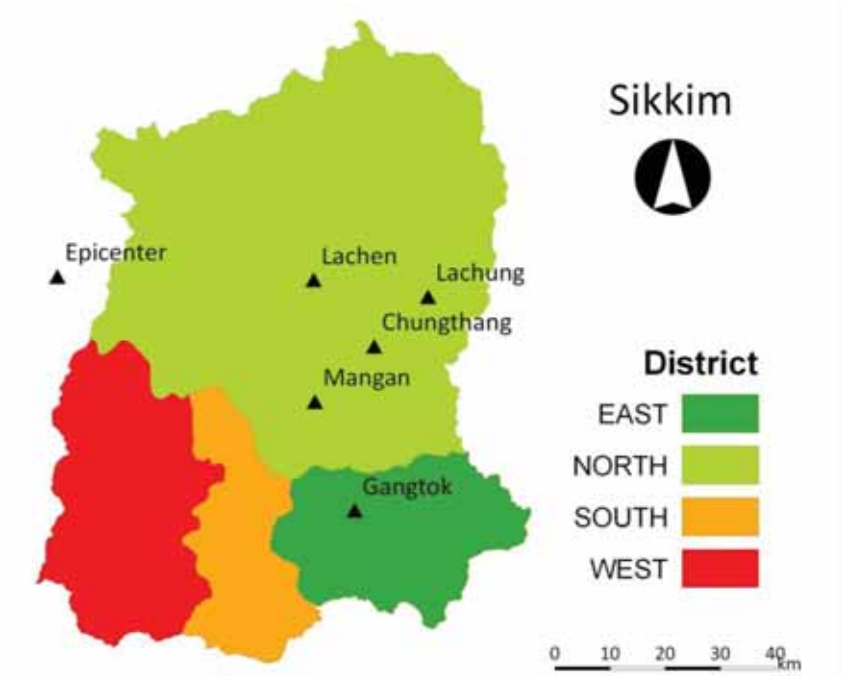


Figure 5-1 Sikkim Map showing areas visited during field and location of Epicentre

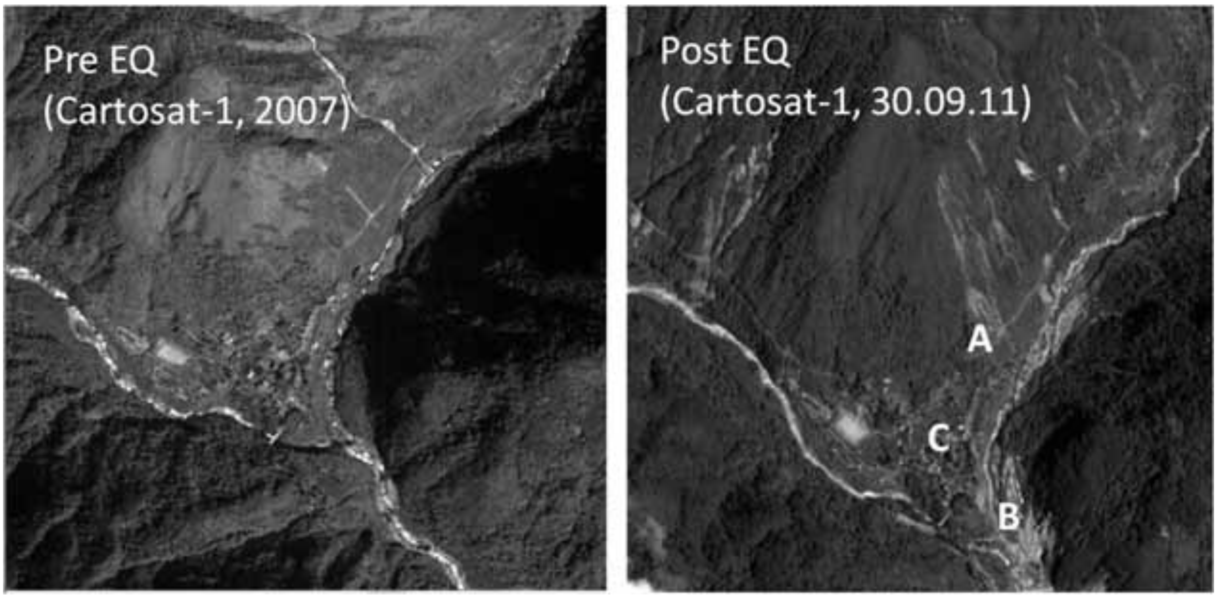


Figure 5-2 Sattelite Images showing chunthang and new landslides post earthquake

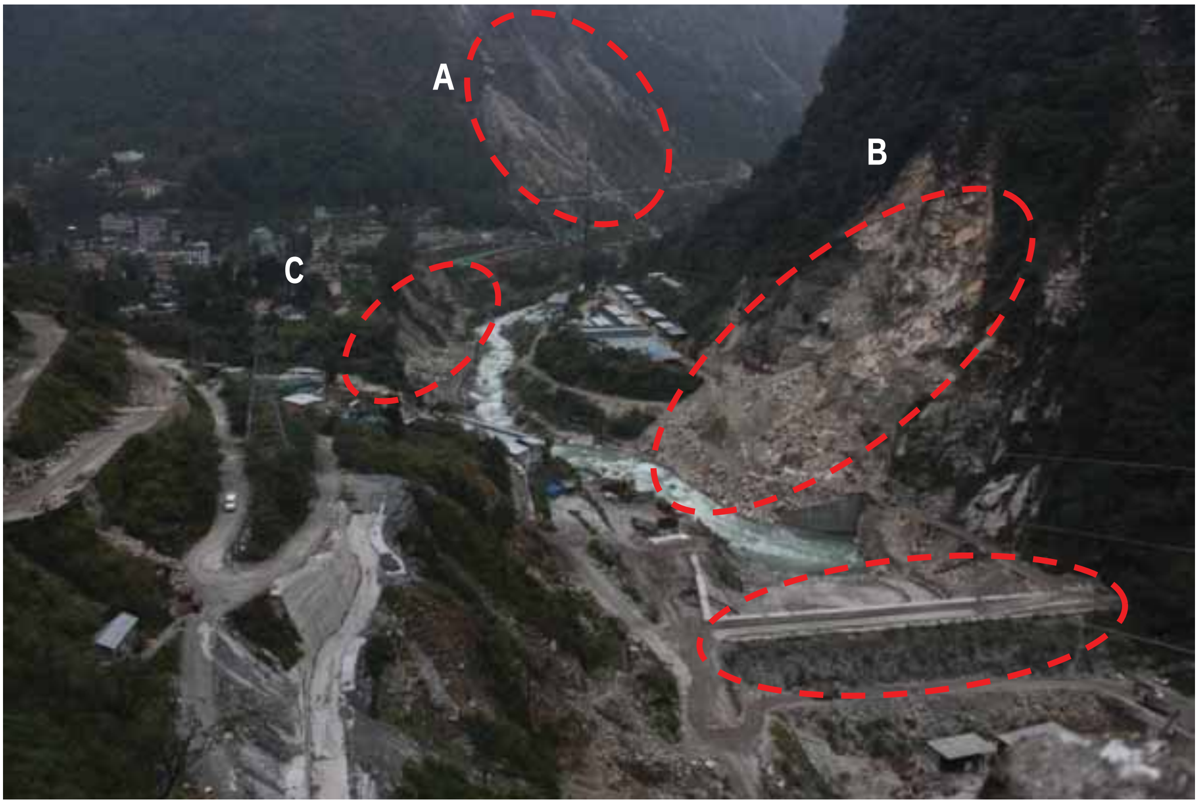


Figure 5-3 Figure Showing the chunthang area and new landsides

From all the areas visited, Chunthang area has experienced highest number of damaged in the earthquake. Located at the point where Lachen and Lachung rivers meet and turn into Teesta River, the major river in the state of Sikkim shown in Figure 5-2 and Figure 5-3. Because of the river, there are lot of colluvial material; the soil in area is very soft and sandy in nature. Many of the buildings experienced extreme to complete damage level.

(A)

(B)

Figure 5-4 Figure Showing the damaged building in Chunthang

Figure 5-4 shows school building damaged in Chunthang area. Several buildings are of the same damage states as shown in the figure. Figure 5-4 A and B shows the building in which couple of floors got pancaked as the columns were weak and not supported by shear walls and resulted in complete failure. Also part of the building was resting on a detrital rock (transported large boulder) which might have experienced severe shaking as it is located on soft soil.

Figure 5-5 River Terraces and Settlements

Figure 5-5 shows the colluvial deposits of the Teesta River. The buildings lying on this type of ground experience more damage than buildings on rock sites. These deposits are constantly cut by the flowing river, and make houses constructed on these deposits vulnerable.

(A) (B)

Figure 5-6 Figure Showing the chunthang area and new landsides

Figure 5-6 A and B shows the landslides and the scale of rock slides that happened earthquake that block roads.

Figure 5-7 Road damaged by landslides.

5.3. Damage Assessment at Micro Level

In the Sikkim earthquake of 6.9 M in 2011, buildings were severely shaken with an intensity of VI on MMI scale, particularly those on the edge of the cliff and steep slopes causing wide spread panic and distress. Majority of the buildings are of made up of concrete with column–pillar structure and masonry walls. As per the data from government sources, approximately 27,464 households occupy 25,554 permanent structures (Table 4-5). Around 17000 households were added in last 10 years, which shows the rate of growth in the city is very high and most of these buildings don't follow any seismic design considerations. As a result wide spread dame was reported from the Gangtok city alone and similar

Table 5-1 Damage Report Ward and Building wise (Municipal Corporation Gangtok)

Sl. No	Ward	Type of house				Type of house				
		Pucca						Kutcha		
		100%	Severe	Major	Minor	100%	Severe	Major	Minor	Total
1	Burtuk	-	2	22	148	-	5	4	154	335
2	Lower Sichey	-	8	53	123	-	1	12	83	280
3	Upper Sichey	6	9	35	71	2	3	40	53	219
4	Chandmari	-	2	158	4	-	41	113	42	360
5	Development area	2	1	7	26	-	2	-	22	60
6	Diesel power house	-	1	3	22	-	-	3	21	50
7	Arithang	-	4	24	82	-	-	5	20	135
8	Lower M.G Marg	-	-	2	35	-	1	2	-	40
9	Upper M.G Marg	-	-	1	-	-	-	19	-	20
10	Tibet road	-	-	4	37	-	-	1	1	43
11	Deorali	-	2	9	53	-	1	3	5	73
12	Daragaon	-	3	70	67	-	7	39	4	190
13	Tadong	3	7	79	299	-	5	77	50	520
14	Ranipool	-	-	130	-	-	-	159	5	294
15	Syari	-	11	28	151		3	10	11	214
	Total	11	50	625	1118	2	69	487	471	
	Grand total								2833	

In consultation with local authorities, severely damaged different types of buildings were selected for inspection/survey covering sample areas in Gangtok city across ridge to valley and length of the city. Out of all surveyed buildings, selected buildings of different types representing HAZUS classes were described in detail. Figure 5-8 shows the location of identified buildings where damage assessment was carried out such as Police head quarters, Sikkim secretariat, a residence in Development area and a hotel building.

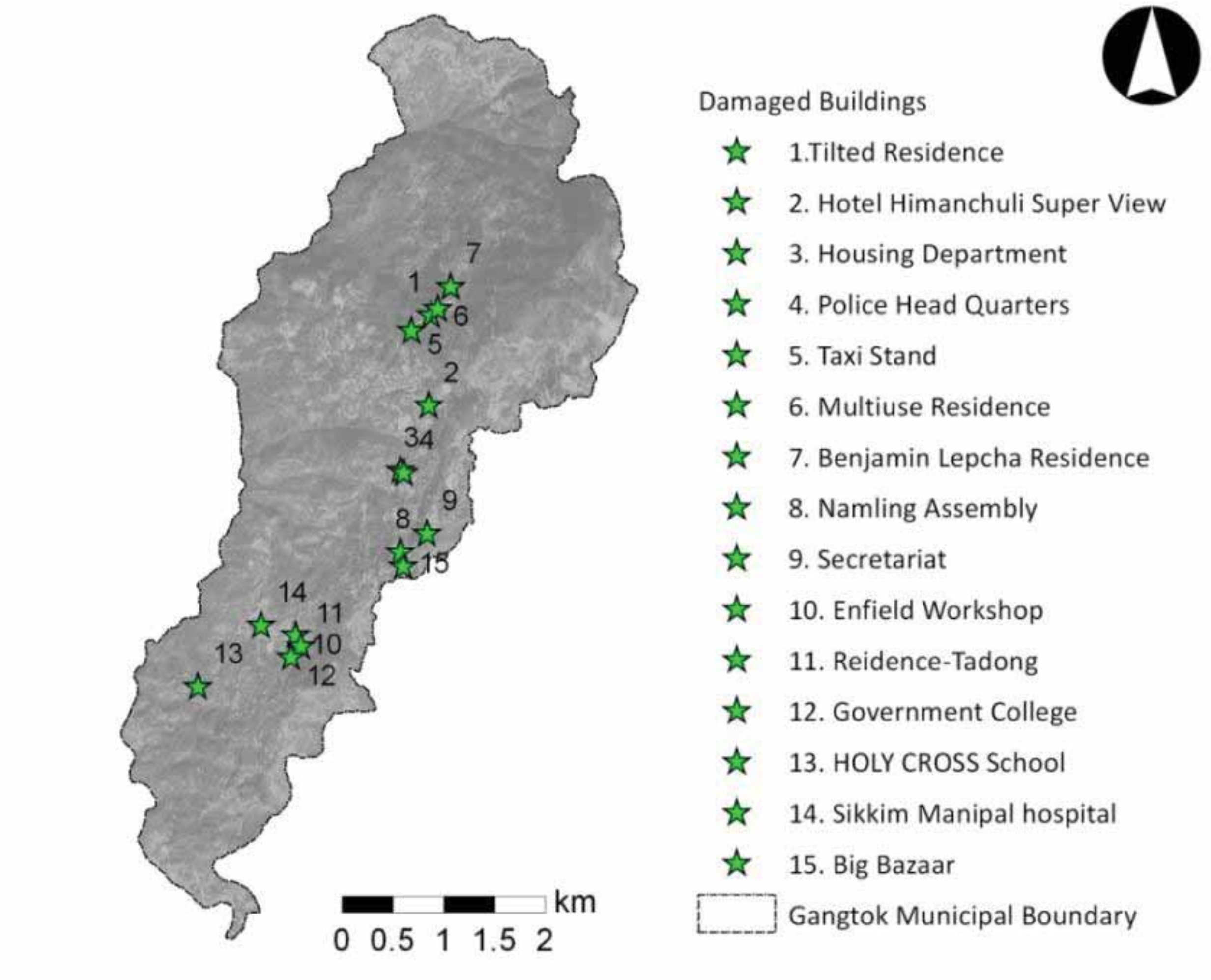
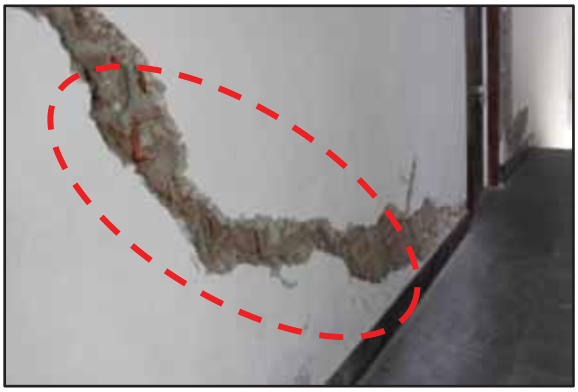


Figure 5-8 Identified buildings in Gangtok city

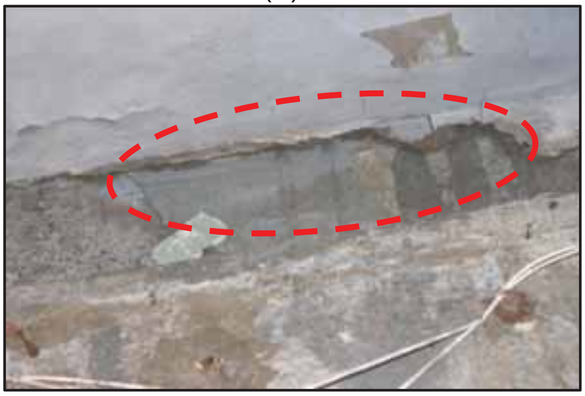
5.4. Damage in Buildings

Gangtok city situated mainly on the western slope of the hill has buildings constructed with different type of building material and styles. The buildings are predominantly mid-rise concrete frame structures as described in the study area, followed by low-rise concrete frame structures, masonry structures and traditional Ekra type buildings. It is observed that most of the buildings have suffered hairline crack in the infill walls. In poor quality constructions, the damages are seen from moderate to extreme where they have developed major cracks. The cracks are generally observed at the wall and column joints at the corners and at the corners of the openings. Few buildings have diagonal and horizontal cracks extending throughout the wall and in few cases walls have completely collapsed. The columns have failed in few structures where the shear walls are absent and this type column failure was observed in lower floors of the structures. It is also observed in the whole Gangtok area, that buildings on the down slope of the road have suffered more damage compared to the buildings constructed on the upslope of the road. The damage in the buildings on the down slope is mainly found in the lower floors, where buildings are attached to the road. Since the ground below the road and building are mostly filled up ground, that can experience lateral spreading thus developing cracks on the overlaying structure. Although very few total collapse and deaths have been reported, most of the buildings have suffered damages of different states as described in Chapter 2

(A)



(B)



(C)

(D)

Figure 5-9 Damages observed in Gangtok City

Figure 5-9 A and B shows the severe cracks in the walls and Figure 5-9-C shows the crack in the inside of building connected to the down slope. Figure 5-9-D shows the structure independent of slope and have not suffered any cracks.

5.5. Site -1

Name: Tashiling Secrateriat
Ownership : Government
Building Use: Office
Material : Concrete frame, Rubble Stone Masonry in Ground floor and Brick Masonry infill's in upper floors
Number of Floors : 5
HAZUS Class : C3M
Level of Damage : Moderate
Retrofitting Possible : Yes
Number of Deaths: 0
Building Age: 20 + years

(A)

(B)

(C)

Figure 5-10 Damages in Secretariat Building

	Question	Observation
1	Is the building irregular in plan	No
2	Are the columns regularly distributed	Yes
3	Are both building directions adequately braced	No
4	Does the ratio between the building's length and width is > 2.5	No
5	Does the building possess eccentric cores (staircases or elevators)	Yes
6	Does the building have a soft storey	No
7	Is the building irregular in elevation caused by setbacks of upper stories	No
8	Does the building have cantilevering upper stories	No
9	Does the building possess a heavy mass at the top or at roof level	No
10	Are pounding effects possible	Yes
11	Does the building have short columns	No
12	Are strong beams–weak columns available	Yes
13	Does the building possess shear walls	No
14	Did the building suffer any significant structural damage in the past	No
15	Does the building possess seismic retrofitting or strengthening measures	No

Damage Description

Sikkim Government Secretariat, the main centre for states government administration was closed down due to the damage it suffered in the earthquake. Major damage has occurred in the ground floor to the stone masonry walls and columns at the building junction of two buildings. Due to the irregularity in plan shown in the figure 5-10 A, the front long building and back horizontal structure moved in different direction which resulted in the major damage at the junction as shown in shown in the Figure 5-10 B and 5-10 C. Due to improper tying of reinforcement and due to pounding affect, the building failed. No major damage was seen in the upper floor other than few cracks in infill walls, but the ground floor walls have been completely destroyed. Building has sustained several earthquakes in the past and requires complete retrofitting or re-building.

5.6. Site -2

The grey colour building is referred as building B and the white colour building is referred as building C for explanation.

Name: Tilted Residence
Ownership : Private
Building Use: Residential
Material : Concrete and Masonry infill's
Number of Floors : Building B – 6
Building C- 3
HAZUS Class : C3M
Level of Damage : Complete
Retrofitting Possible : No
Number of Deaths: 4
Building Age: 15 + years

(A)

(B) (C)

Figure 5-11 Damaged buildings in Development area ward

	Question	Observation	
		B	C
1	Is the building irregular in plan	Yes	Yes
2	Are the columns regularly distributed	Yes	Yes
3	Are both building directions adequately braced	No	No
4	Does the ratio between the building's length and width is > 2.5	Yes	No
5	Does the building possess eccentric cores (staircases or elevators)	No	No
6	Does the building have a soft storey	No	No
7	Is the building irregular in elevation caused by setbacks of upper stories	No	No
8	Does the building have cantilevering upper stories	No	No
9	Does the building possess a heavy mass at the top or at roof level	No	No
10	Are pounding effects possible	Yes	Yes
11	Does the building have short columns	No	No

12	Are strong beams–weak columns available	Yes	Yes
13	Does the building possess shear walls	No	No
14	Did the building suffer any significant structural damage in the past	No	No
15	Does the building possess seismic retrofitting or strengthening measures	No	No

Damage Description

Two buildings located in the Balwakhani area of development ward suffered complete damage. These buildings are situated on the steep slopes. 1^{st} and 2^{nd} floors of building B have collapsed as shown in the Figure 5-11 B and the roof of the top floor has completely failed. Walls have not been constructed between the columns and were constructed at the end of slab. Due to shaking, the weight of whole building transferred to the free columns in the bottom floors, which failed and building completely collapsed. In building C, due to the weak columns in the ground floor, the back corner columns failed which made building to tilt and damage the building in the back as shown in the Figure 5-11 C. Both these buildings have suffered extensive damage and have become inhabitable.

5.7. Site - 3

Name: Sikkim Police Headquarters
Ownership : Government
Building Use: Office
Material : Concrete frame, Cement block Masonry infill's
Number of Floors : 5
HAZUS Class : C3M
Level of Damage : Moderate
Retrofitting Possible : Yes
Number of Deaths: 0
Building Age: 9 years

(A)

(B)

(C)

Figure 5-12 Damages in Police Head quarters Building

	Question	Observation
1	Is the building irregular in plan	No
2	Are the columns regularly distributed	Yes
3	Are both building directions adequately braced	No
4	Does the ratio between the building's length and width is > 2.5	No
5	Does the building possess eccentric cores (staircases or elevators)	Yes
6	Does the building have a soft storey	Yes
7	Is the building irregular in elevation caused by setbacks of upper stories	Yes
8	Does the building have cantilevering upper stories	Yes
9	Does the building possess a heavy mass at the top or at roof level	Yes
10	Are pounding effects possible	Yes
11	Does the building have short columns	No
12	Are strong beams–weak columns available	Yes
13	Does the building possess shear walls	No
14	Did the building suffer any significant structural damage in the past	No
15	Does the building possess seismic retrofitting or strengthening measures	No

Damage Description

Sikkim police headquarters building has suffered slight damage in the earthquake. Even though majority infill walls have suffered high damage and ready to fail, the building is still operational and no repairs or retrofitting measures have been taken up even after one month of the event. The building is irregular in plan and have soft storey for parking. As shown in Figure 5-12 A, the building is irregular in elevation, with cantilever in 4th floor and setback in 5th floor. Heavy weights like dishes, batteries and other equipment is placed on the top floor. Due to this, the part of ground floor under this part has suffered severe cracks in the walls. No damage is observed in the columns, due to lack to tying of columns and walls, at some places, the building walls were separated from the columns. All the walls can be repaired and retrofitted

5.8. Site -4

Name: Hotel Himanchuli Super View
Ownership : Private
Building Use: Hotel
Material : Concrete frame, Burnt brick Masonry infill's
Number of Floors : 7
HAZUS Class : C3M
Level of Damage : Severe
Retrofitting Possible : No
Number of Deaths: 0
Building Age: 15 + years

(A)

(B) (C)

Figure 5-13 Damages in Hotel Building

	Question	Observation
1	Is the building irregular in plan	No
2	Are the columns regularly distributed	Yes
3	Are both building directions adequately braced	No
4	Does the ratio between the building's length and width is > 2.5	Yes
5	Does the building possess eccentric cores (staircases or elevators)	No
6	Does the building have a soft storey	No
7	Is the building irregular in elevation caused by setbacks of upper stories	Yes
8	Does the building have cantilevering upper stories	No
9	Does the building possess a heavy mass at the top or at roof level	No
10	Are pounding effects possible	Yes
11	Does the building have short columns	No
12	Are strong beams–weak columns available	Yes
13	Does the building possess shear walls	No
14	Did the building suffer any significant structural damage in the past	No
15	Does the building possess seismic retrofitting or strengthening measures	No

Damage Description

First floor of the building which have no shear walls and open columns has failed in the earthquake due to the load of 5 floors on the top. The columns which don't have proper reinforcement and improper tying of rods in columns resulted in damage. The crushing of columns has occurred in all the columns of the floor. Other top floors which have infill walls between columns supported them but in the first floor they were absent. The size of each floor increased from ground to top floor, and top floors were constructed towards the slope taking the support of the rock in the slope. In the building it was also observed that the outer walls were constructed at the end of slab and columns were inside the floor. Figure 5-13 –A shows the failed stirrup which opened up freeing the reinforcement bars. Figure 5-13 B shows the crushed columns and failed tie rods and Figure 5-13 C shows the irregularity in the elevation and increase of floor size on the top.

5.9. Site - 5

Name : Government Degree College
Ownership : Government
Building Use: Educational
Material : Concrete frame, Brick Masonry infill's
Number of Floors : 2
HAZUS Class : C3L
Level of Damage : Moderate
Retrofitting Possible : Yes
Number of Deaths: 0
Building Age: 20 + years

(A)

(B)

(C)

Figure 5-14 Damages in Secretariat Building

	Question	Observation
1	Is the building irregular in plan	Yes
2	Are the columns regularly distributed	Yes
3	Are both building directions adequately braced	No
4	Does the ratio between the building's length and width is > 2.5	No
5	Does the building possess eccentric cores (staircases or elevators)	Yes
6	Does the building have a soft storey	No
7	Is the building irregular in elevation caused by setbacks of upper stories	No
8	Does the building have cantilevering upper stories	No
9	Does the building possess a heavy mass at the top or at roof level	No
10	Are pounding effects possible	No
11	Does the building have short columns	No
12	Are strong beams–weak columns available	No
13	Does the building possess shear walls	Yes
14	Did the building suffer any significant structural damage in the past	No
15	Does the building possess seismic retrofitting or strengthening measures	No

Damage Description

Government Degree college is one of few buildings which have been repaired immediately after earthquake. All the walls have suffered severe cracks. But these gaps have not been retrofitted. The gaps were opened and filled with cement to cover up the damage. The building is a part of the group of structures. All the corners at the opening have cracks and diagonal cracks have also been observed in few place of the building. Figure 5-8 B and C shows the building with repaired cracks.

5.10. Repair and Retrofitting

The main aim of this section of the report is to provide simple design and structural consideration that can be adopted by the local authorities and users which can increase the strength of the structure and decrease vulnerability. Damage from earthquakes can be controlled by adopting seismic design considerations at the time of construction. Since there's a lot of awareness after an earthquake, some techniques can be incorporated in the process of strengthening the building to make it ready for the future events. Due technical considerations are required while selecting building sites and material for construction. Expert advice need to be taken for restoration of a damaged building by retrofitting. Local authorities should be very particular in such cases because, the buildings which have lost inherent strength cannot withstand future earthquakes and can result in complete damage of the buildings.

Buildings move in all directions during earthquakes. It is not very cost effective to design the building for all the forces, but horizontal movement should be addressed, which is the major cause of building damage in earthquakes. Structural systems like shear walls, slabs, columns, beams etc should be properly braced or tied, so that all of these act as systems together. If one of these systems fails, they tend to result in severe damages, or sometimes these result in complete collapse of the buildings. Some of the common damages identified in all the buildings are summarized below.

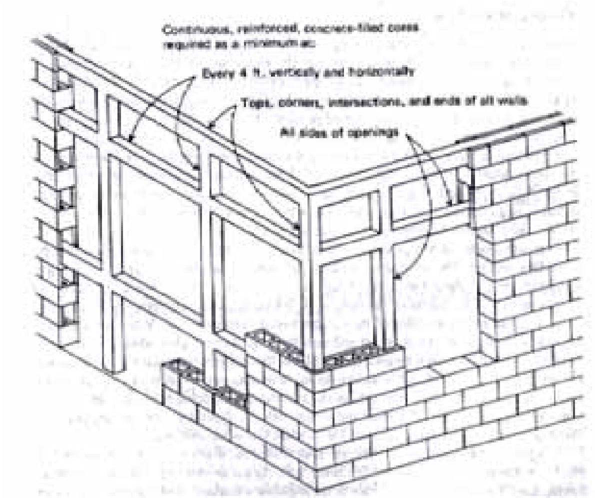
5.10.1. Damages in Masonry Walls

Most of buildings used burnt bricks as masonry infill in reinforced concrete framed structure. Few buildings like Police head quarters have used hollow concrete blocks as infill materials. All of these walls were observed to be untied with the concrete frame. As these are not connected, the columns and walls tend to shake at differently which results in cracks and failures. Figure 5-15 shows new constructions which do not have any tie beams or rods between walls and columns

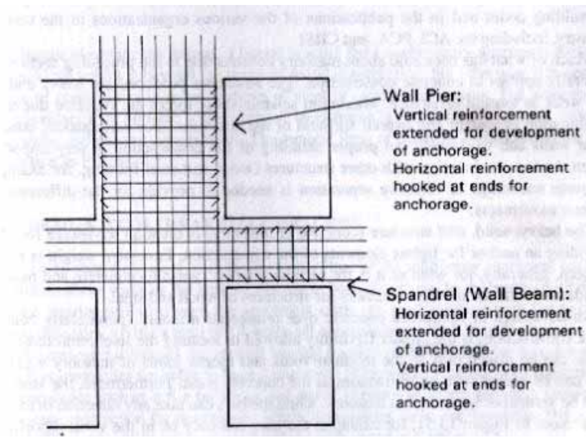
Figure 5-15 Unreinforced Masonry infill's

Figure 5-16 Damages in Unreinforced Masonry infill's

Figure 5-16 shows the kind of damages resulted in these kind of masonry walls where there are no tie beams. Figure 5-17 A and B shows the possible reinforcement measures that can be adopted for masonry walls. Figure 5-17 – A indicates that continuous horizontal reinforcement is needed at lintel and sill levels, and all sides of opening and vertical reinforcement at every 4 feet interval. Figure 5-17-B shows the possible retrofitting measures that can be used for repairing the cracks as shown in Figure 5-16 and these reinforcements should be connected properly to the structural members.



(A)



(B)

Figure 5-17 Details of Bracing for Masonry Walls (Ambrose and Vergun 1999)

5.10.2. Damages in Structural Systems

Columns and beams are the major contributors to the strength of the building. When these are not properly planned or designed, buildings have higher chance of failure. Different kinds of damages as seen in the columns are given in the Figure 5-18. Usually, the columns fails, when they are no rods of required sizes provided in reinforcements, the vertical reinforcement is not properly tied with the tie rods at equal intervals, there's no proper overlap between the vertical bars, not enough concrete thickness around the reinforcement and poor quality of concrete. These are the main reasons of column failure.

Figure 5-18 Reinforcement failures

All the columns, beams and slabs have to be properly connected with each other. Figure 5-13 shows the poor connections between columns and beams, and columns and slabs etc. Symmetrical arrangement of columns is also important for the structural stability.

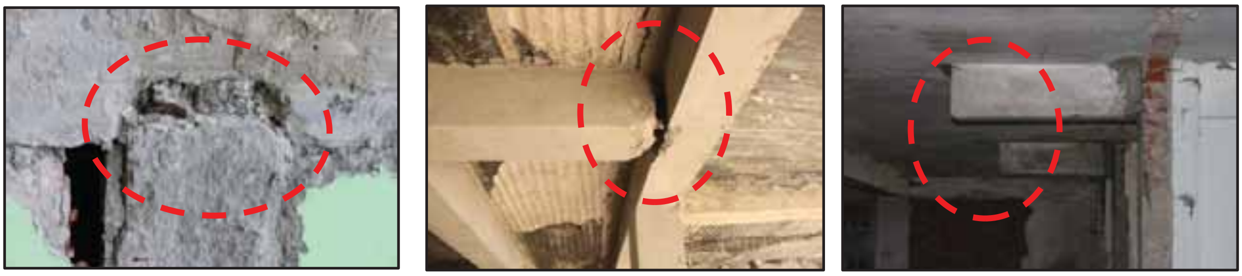


Figure 5-19 Connection between Structural Systems

The load of the buildings is transferred to the ground by columns. The load of slab is transferred by beams to the columns. In case of shaking in earthquakes, the horizontal shaking of columns between the floors is controlled by shear walls. These carry some weight from the slabs and beams and reduce load on the columns and control horizontal motion. They are higher chances of columns to fail in the absence of shear walls. These walls should be continuous between columns with minimum opening sizes. Figure 5-20 shows the absence of shear walls in buildings.

Figure 5-20 Absence of shear walls

In cases where shear walls cannot be provided and columns which suffered damage in earthquakes, use of braces is the recommended option. Vertical bracing is done by steel bars which connect columns and transfers load and also control the horizontal movement in columns. Few examples of vertical bracing are shown in Figure 5-21

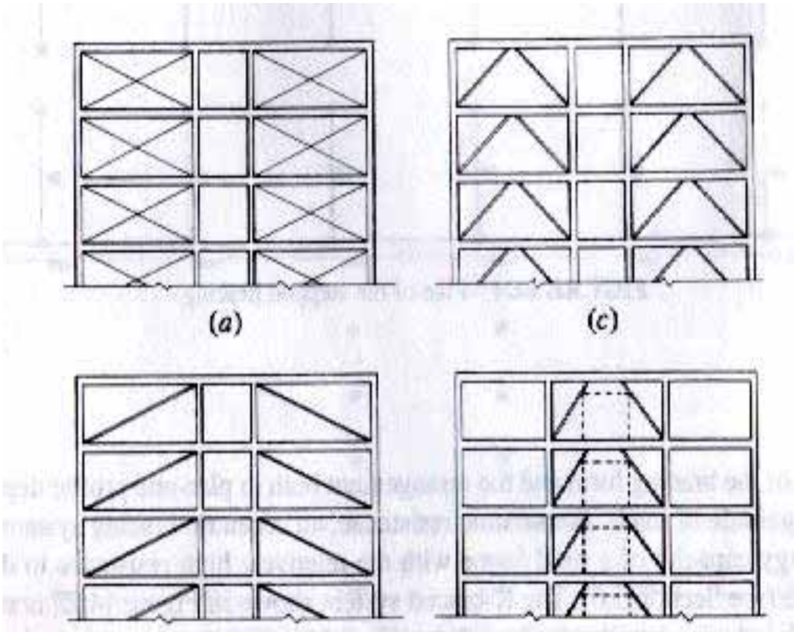
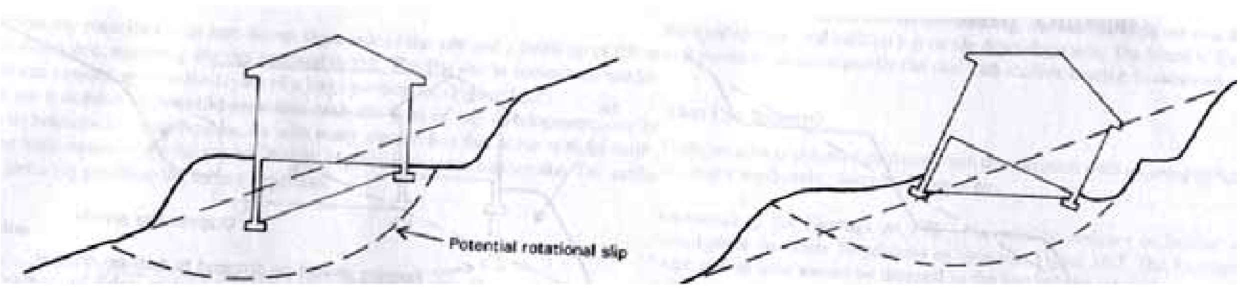


Figure 5-21 Vertical Bracing Systems Ambrose and Vergun (1999)

5.10.3. Construction on Sloping Sites.

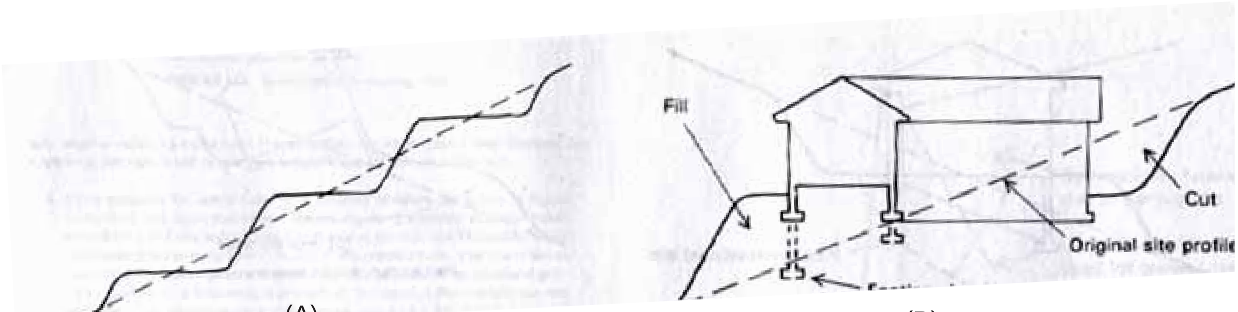
Enough precautions have to be taken before construction of buildings on sloping sites. Stabilization of slope is very important to decrease the potential problems to buildings. Figure 5-22 shows the failure of slope and the damage to the building. These unstable slopes are very dangerous and have high chances to fail anytime; Earthquake shaking is one of the reasons to trigger this failure. Figure 5-22- A shows the cut and fill of the slope to make the site flat, without any stabilization of down slope. Figure 5-22- B shows the rotational slip possible due to the failure of down slope.



(A) (B)

Figure 5-22 Failure of Slope (Ambrose and Vergun 1999)

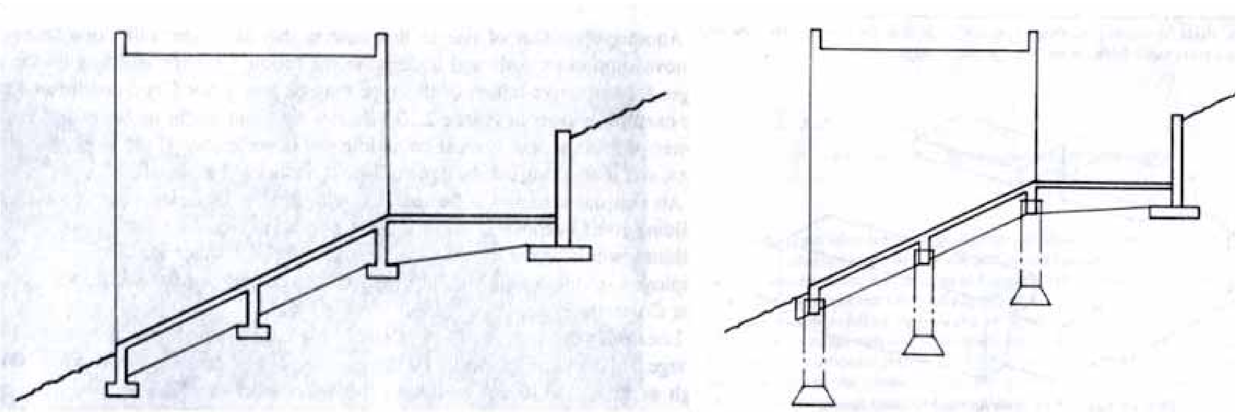
So before construction, slopes have to be cut and filled to make the site flat and stabilize the slope. There should be enough gap between the slope and the wall of the building, to let the building shake freely in earthquakes. Or else the joining areas of building and earth fail because both of these shake with different frequency and develop cracks at joints.



(A) (B)

Figure 5-23 Stabilisation of Slope. (Ambrose and Vergun 1999)

After stabilization of slope, the foundations have to be taken deep into the ground till it reaches the stiff soil or solid rock. Since the rocks have higher shear wave velocities they tend to accelerate less, where as the soft soil, that have lower shear wave velocities, experience amplification of ground motion, resulting in higher damage to the buildings. Figure 5-24 A shows the detail of foundations on surface slope and Figure 5-24 B shows the foundation taken deep to the stiff ground.



(A) (B)

Figure 5-24 Foundations (Ambrose and Vergun 1999)

6. ANALYSIS AND RESULTS

HAZUS building types W1, C3L, C3M, and C3H are identified building types in the study area. Two seismic design codes for selected building types Low-code and Pre-code as specified by FEMA (2011) are used for generating damage probabilities for different site classes. Equations given by Kircher et al. (1997) were used for generating cumulative and discrete damage probabilities by using capacity curves, damage probability parameters given in HAZUS technical manual (FEMA, 2011). The detail steps of calculating damage probabilities are given in Annexure –A of the report.

Based on the building material and number of floors, these buildings are assigned as per different HAZUS classes as shown in Figure 6-1. Based on the land stability map given by Mines, Minerals and Geology Department, number of floors are permitted for each stability class as described in the Table 4-2. Based on these values buildings which follow these bye-laws and which violet are identified and mapped as shown in the Figure 6-2..

Table 6-1 Number of buildings in each HAZUS class

HAZUS Class	Number of Buildings	Number of privately owned buildings
W1	159	135
C3L	139	128
C3M	360	347
C3H	1	1

Table 6-2 Number of buildings following Byelaws

Bye-laws followed	Number of Buildings
Yes	524
No	135

Figure 6-2, which clearly shows that almost quarter of these buildings violate the bye-laws for permissible number of floors, which make these buildings highly vulnerable and are highly prone to damage than buildings which follow municipal rules. Table 6-1 shows total number of buildings and total number of privately owned buildings in each HAZUS building type for Arithang ward and Table 6-2 gives the number buildings which follow the bye-law and which violate them

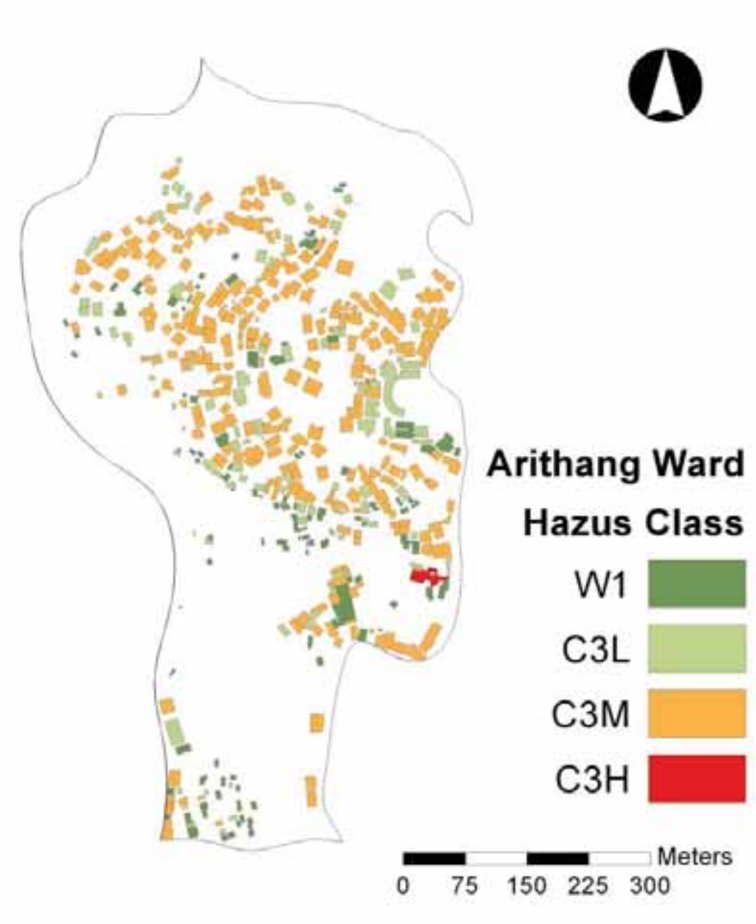


Figure 6-1 Building Material in Arithang Ward

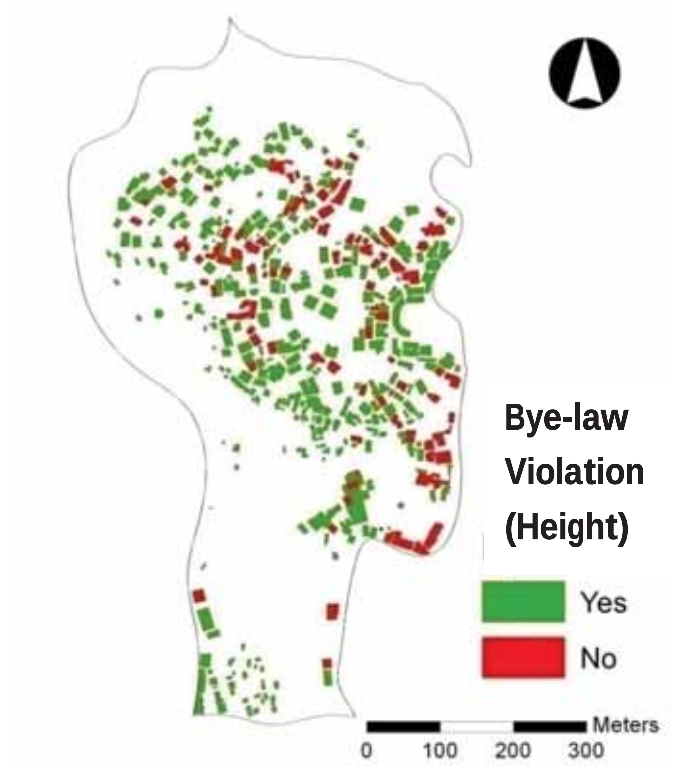


Figure 6-2 Bye-Laws Violation (Height) followed in Arithang Ward

6.1. Demand Spectrum

Earthquake of magnitude 6.9 with its epicentre located at 27.72 N and 88.06 E, with its focus at a depth of 19 km is used for generating demand spectrum using equation given by Boore et al. (1997), explained in Chapter 2 and Annexure-A. The distance from the study area Gangtok to epicentre is 68.74 km. Figure 6-3 shows the demand spectrum plotted for five different shear wave velocities. The average of shear wave velocities of site classes C, D and three values, minimum, average and maximum shear wave velocities of site class B are used for plotting the demand spectrum.

Table 6-3 PGA experienced at different Shear wave velocity

V_S	270 m/s	560 m/s	760 m/s	1125 m/s	1500 m/s
PGA	0.1847	0.1414	0.1284	0.1146	0.1057

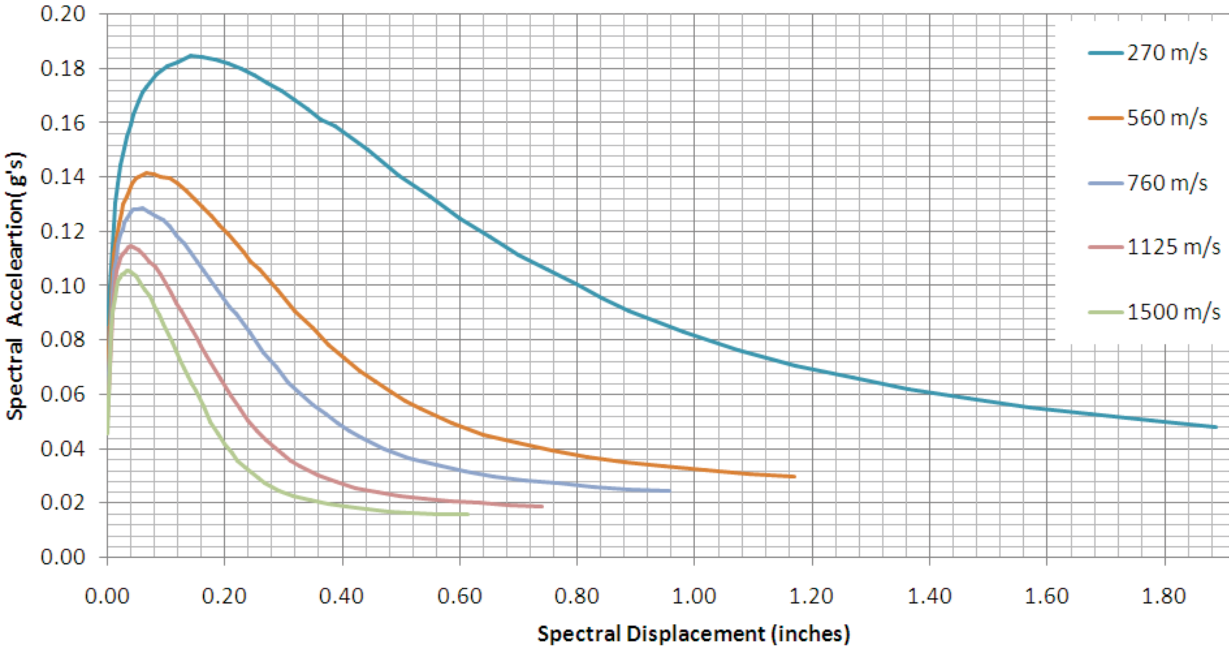


Figure 6-3 Demand Spectrum

Discussion

Figure 6-3 indicates that for a given time period, the values of spectral acceleration are higher for lower shear wave velocities resulting in higher spectral displacement at a specific location. Lower shear wave velocity takes longer time for wave to pass through the site compared to higher shear wave velocity. Site class C and D, which have low shear wave velocities, results in higher spectral acceleration and spectral displacement compared to site class B, which has comparatively higher shear wave velocities. In case of buildings, lower shear wave velocities cause higher spectral acceleration and this results in higher spectral displacement which causes higher level of building damage. Chunthang area of north Sikkim, which lies on the river borne material, is an example for the site class D which can experience high S_A in earthquakes.

In the Gangtok area, which lies mainly in the site class B, can experience shear wave velocities ranging from 760 m/s to 1500 m/s. Damage probabilities are generated for average shear wave velocity 1125 m/s and minimum value 760 m/s.

6.2. Capacity curves

Capacity curves are generated from the yield and ultimate capacity points of the building. These values change as per building types based on their seismic design level. Weight of the building and material of the building are important factors in development of these curves. These curves define the strength of the building to resist earthquakes. Figure 6-4 and Figure 6-5 shows the capacity curves for low-code seismic design and pre-code seismic design, respectively. W1 is wooden building type and C3L indicates low rise concrete frame structure with un-reinforced masonry infill walls, C3M indicates mid-rise concrete frame structure with un-reinforced masonry infill walls and C3H indicates high-rise concrete frame structure with un-reinforced masonry infill walls.

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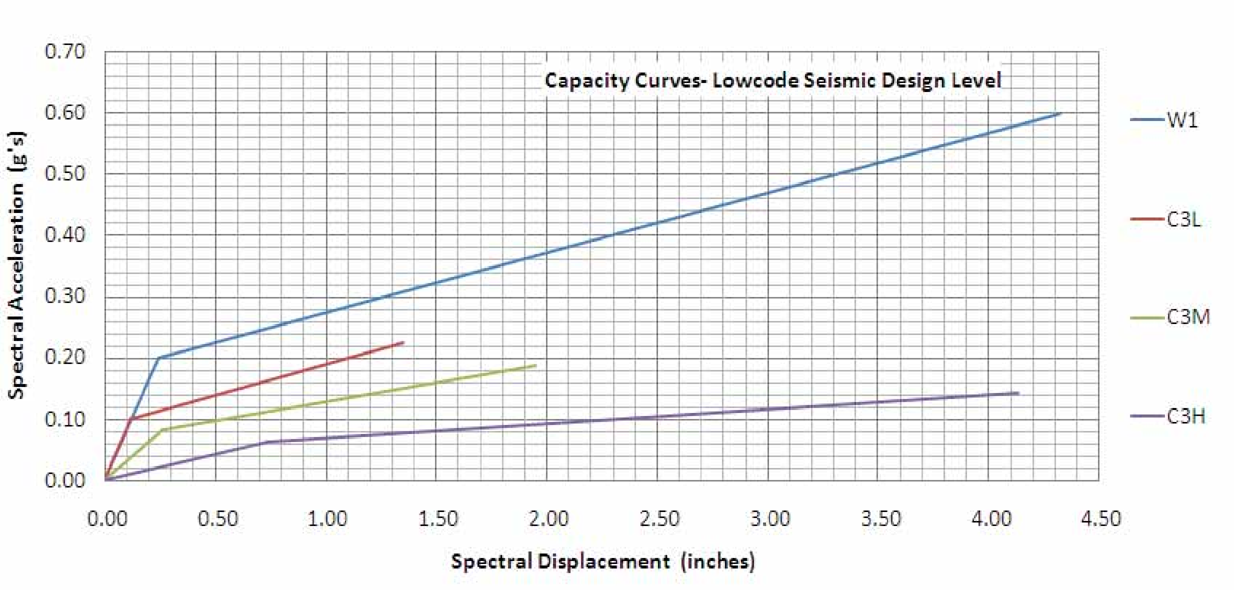


Figure 6-4 Capacity Curves for Low code Seismic Design

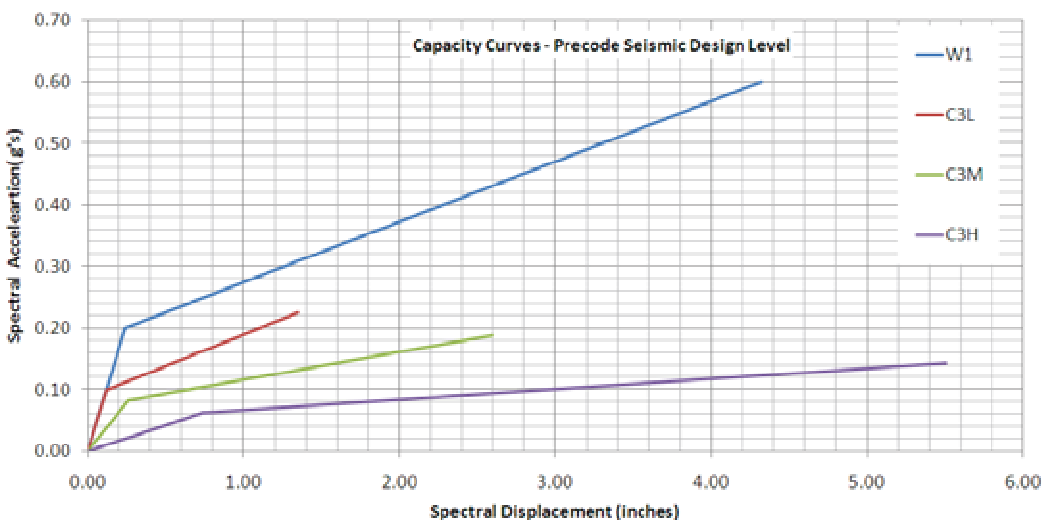


Figure 6-5 Capacity Curves for Pre code Seismic Design

Discussion

The yield and ultimate capacities of low code and pre code seismic design levels show minor difference which is due to few seismic considerations followed in the low code seismic design buildings. Due to the absence of these considerations in pre code seismic design buildings, they show higher spectral displacement values compared to low code design buildings, which results in higher level of damage due to earthquakes. C3H buildings which have more than 8 floors usually have lower natural frequency, therefore, can experience damage due to ground shaking at longer time periods. These buildings show high displacement values at low spectral acceleration. As the number of floors decreases, like in low rise C3L and mid-rise C3M, their natural frequency increases and they show lower spectral displacement values at comparatively higher acceleration. Wooden buildings, which are more flexible in nature, show small displacement at high spectral acceleration and therefore, these are considered as safer structures and experience lesser damaged compared to concrete buildings.

6.3. Peak Building Response

Peak Building response is the point at which demand spectrum meets capacity curves. It means that the building experience shaking till it reaches its peak building response and maximum damage occurs when it reaches its peak building response. So using this value the building damage probabilities are generated. Figure 6-6 shows the low code seismic design curves of the four identified building types overlaid on the demand spectrum to calculate peak building response.

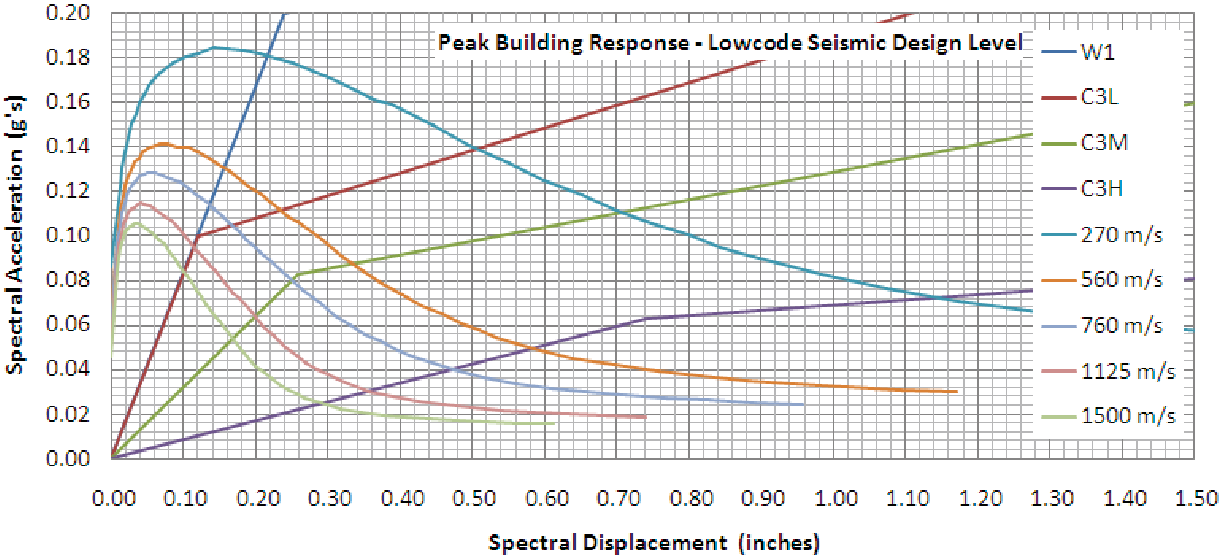


Figure 6-6 Demand and Capacity Curves for Low code Seismic Design

Figure 6-7 shows the pre code seismic design curves of the four identified building types overlaid on the demand spectrum to calculate peak building response.

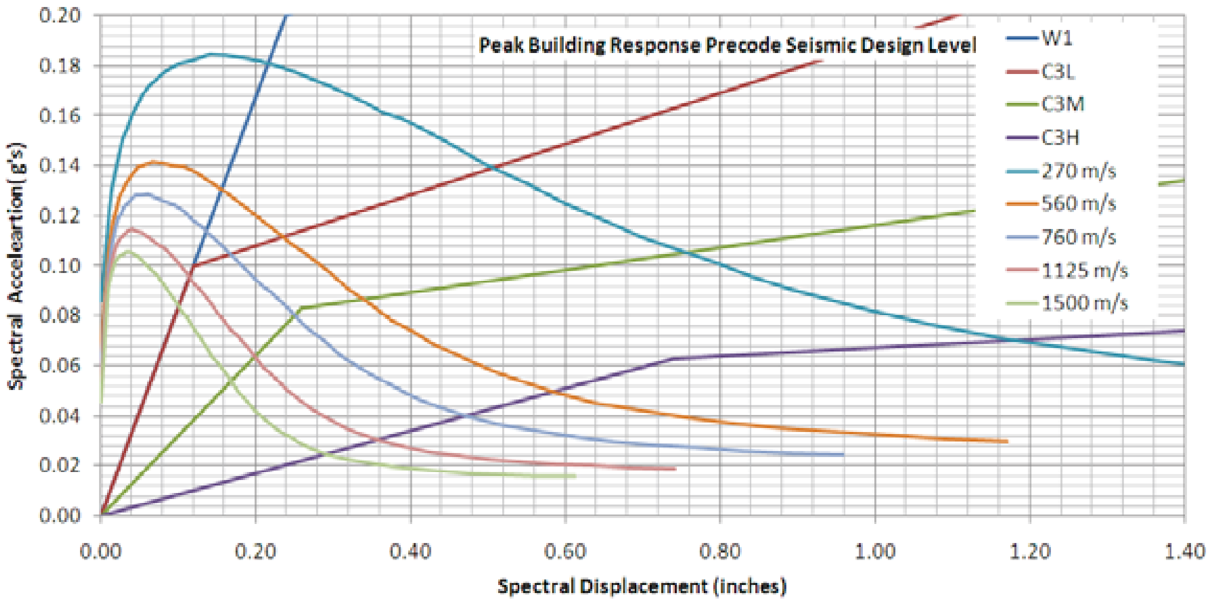


Figure 6-7 Demand and Capacity Curves for Pre-code Seismic Design

‘Table 6-4 Peak Building Response for Low Code Seismic Design

Peak Building Response – Low Code					
Building Type	270 m/s	560 m/s	760m/s	1125m/s	1500m/s
W1	0.22	0.16	0.14	0.12	0.10
C3L	0.51	0.24	0.17	0.12	0.10
C3M	0.71	0.33	0.25	0.20	0.17
C3H	1.14	0.59	0.47	0.36	0.29

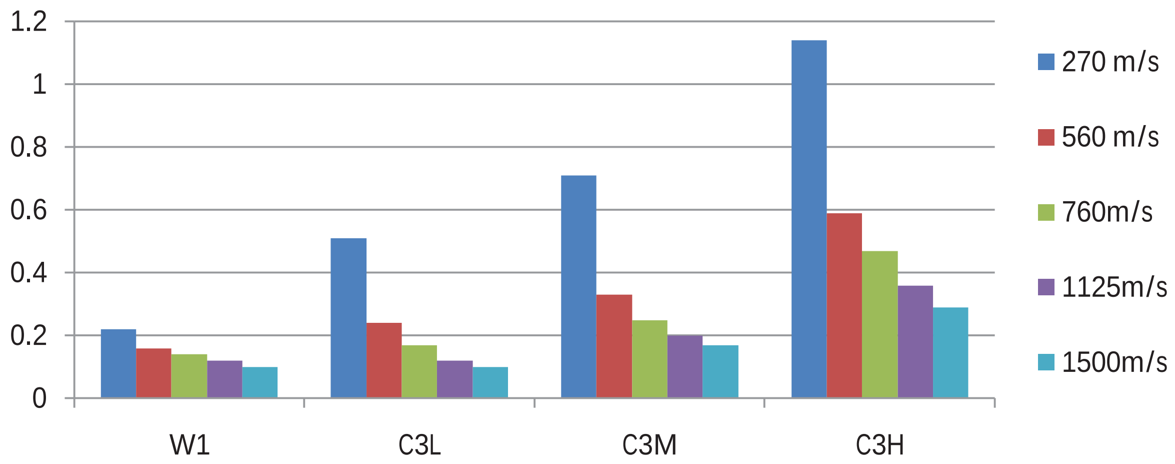


Figure 6-8 Peak Building Response Pre-Code Seismic Design

Peak Building Response – Pre Code					
Building Type	270 m/s	560 m/s	760m/s	1125m/s	1500m/s
W1	0.22	0.16	0.14	0.12	0.10
C3L	0.51	0.24	0.17	0.12	0.10
C3M	0.76	0.34	0.25	0.20	0.17
C3H	1.18	0.59	0.47	0.35	0.29

Table 6-5 Peak Building Response for Pre Code Seismic Design

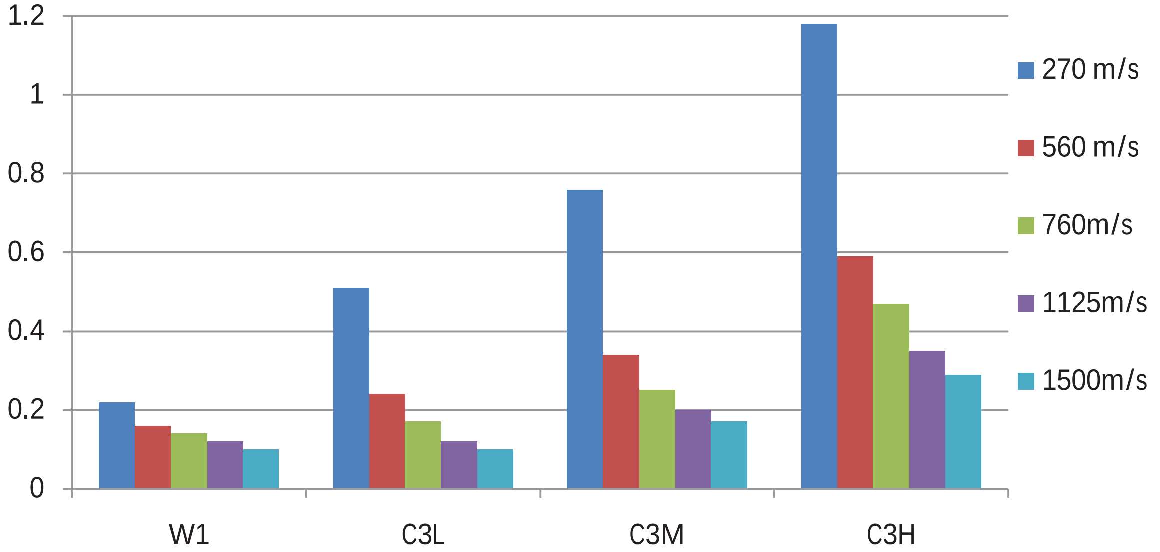


Figure 6-9 Peak Building Response Pre-Code Seismic Design

Discussion

Peak building response of low code and pre code are given in Table 6-4 and Table 6-5 respectively. The values indicate that there is no major difference in the building response between low code and pre code seismic design levels. In both the cases, for all the building types, peak building response is higher for the shear wave velocity of 270 m/s and decreases as it reaches to 1500m/s. In C3 type structures the difference between 270m/s and 560 m/s is very high compared to the difference between the other consecutive shear wave velocities from 560m/s to 1500m/s. C3H building type has the highest peak building response at 270 m/s. Wooden buildings (W1) have least peak building response compared to all the other building types and difference between peak building response values for all the shear wave velocities is very less in wooden building type.

6.3.1.1. Peak Building Response at shear wave velocities 760m/s and 1125 m/s

The peak building response values for all the building types at 1125 m/s shear wave velocity are given in Table 6-6 and Figure 6-10 and for 760 m/s shear wave velocity are given in Table 6-7 and Figure 6-11

Table 6-6 Peak Building Response at 1125 m/s

Peak Building Response – 1125m/s		
Building Type	Low-code	Pre-code
W1	0.12	0.12
C3L	0.12	0.12
C3M	0.20	0.20
C3H	0.36	0.35

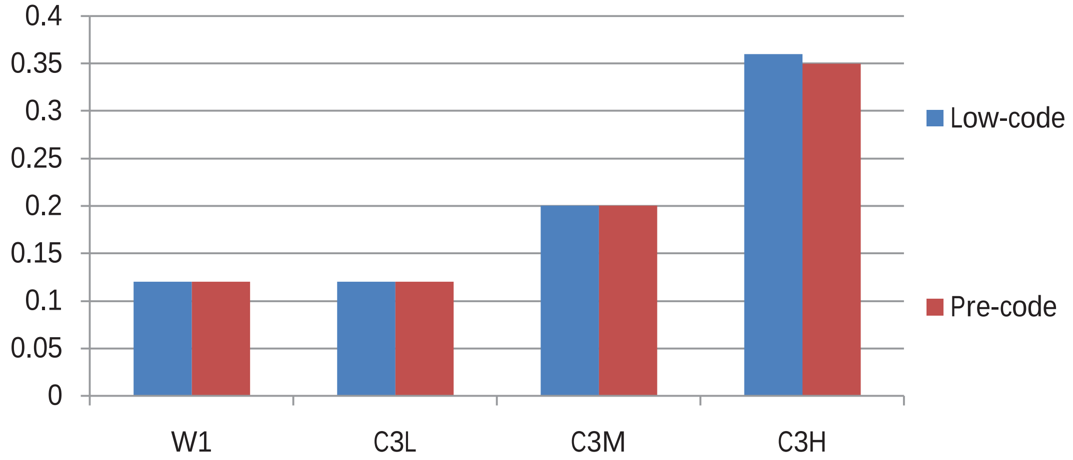


Figure 6-10 Peak Building Response at 1125 m/s

Table 6-7 Peak Building Response at 760 m/s

Peak Building Response – 760m/s		
Building Type	Low-code	Pre-code
W1	0.14	0.14
C3L	0.17	0.17
C3M	0.25	0.25
C3H	0.47	0.47

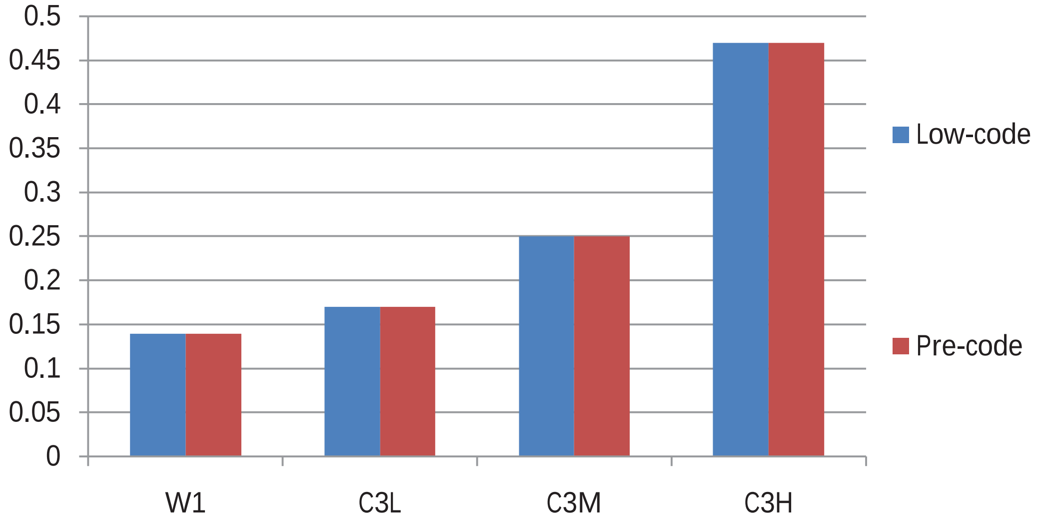


Figure 6-11 Peak Building Response at 1125 m/s

Discussion

The values indicates that the peak building response for two seismic design levels of the 4 building types are almost identical at the shear wave velocities of 1125m/s and 760m/s. C3H building type has higher building response value and W1 have the lowest building response value. But the level of damage depends upon the parameters given by HAZUS for calculating damage probabilities. Since most of the buildings in the study region don't follow any seismic design considerations, damage probabilities for Pre-code seismic design buildings were calculated.

6.4. Damage probabilities

Discrete damage probabilities are calculated from cumulative damage probabilities using formula given in Chapter 2 and Annexure-A. From discrete damage probabilities, percentage of damage for each building type were calculated. Damage percentage probabilities for four damage states: slight, moderate, extensive and complete damage for four building types W1, C3L, C3M, and C3H are generated for all shear wave velocities: 270m/s, 560 m/s, 760m/s 1125m/s and 1500 m/s. Figure 6-12 and Figure 6-13 show the damage probabilities of pre-code seismic design and low-code seismic design, respectively. The calculation for the cumulative and the discrete damage probabilities are given in detail for a building type W1 in Annexure – A. Similarly the values of all the cumulative, discrete and percentage damage probabilities are given in Annexure –A. Table 6-5 shows the cumulative damage probabilities of Pre Code Seismic design at shear wave velocity of 1125 m/s. Table 6-6 shows the discrete damage probabilities of Pre Code Seismic design at shear wave velocity of 1125 m/s. Table 6-7 shows the cumulative damage probabilities of Pre Code Seismic design at shear wave velocity of 760 m/s. Table 6-8 shows the discrete damage probabilities of Pre Code Seismic design at shear wave velocity of 760 m/s.

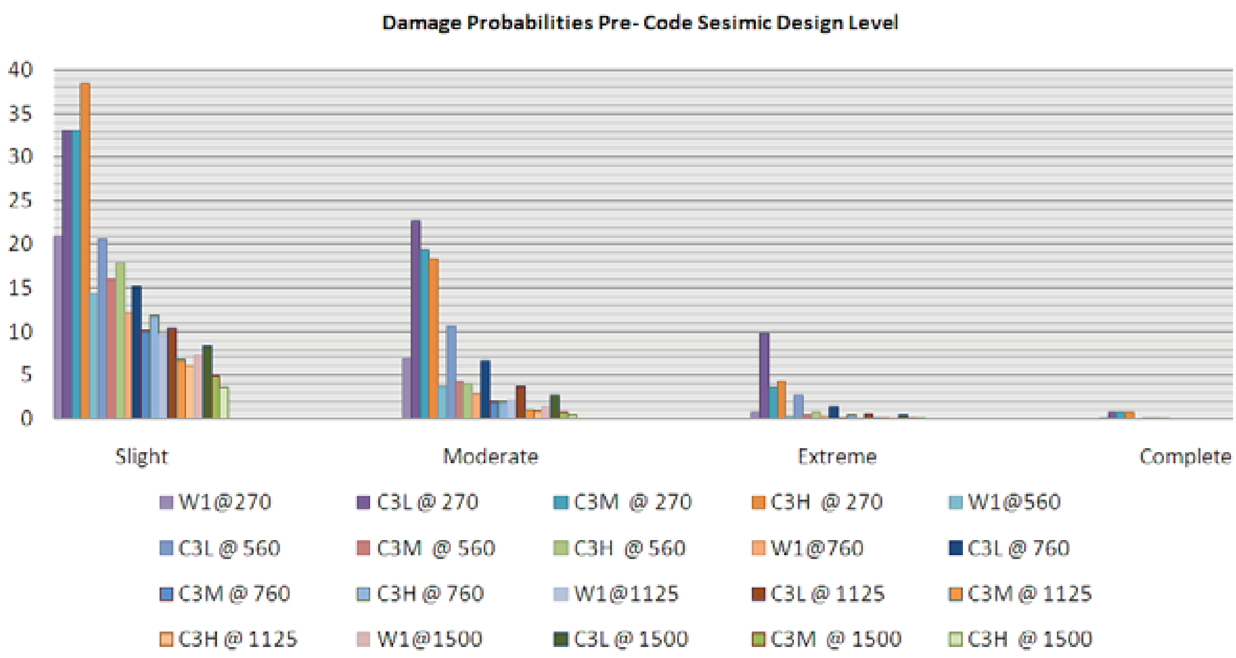


Figure 6-12 Damage Probabilities Pre-Code Seismic Design

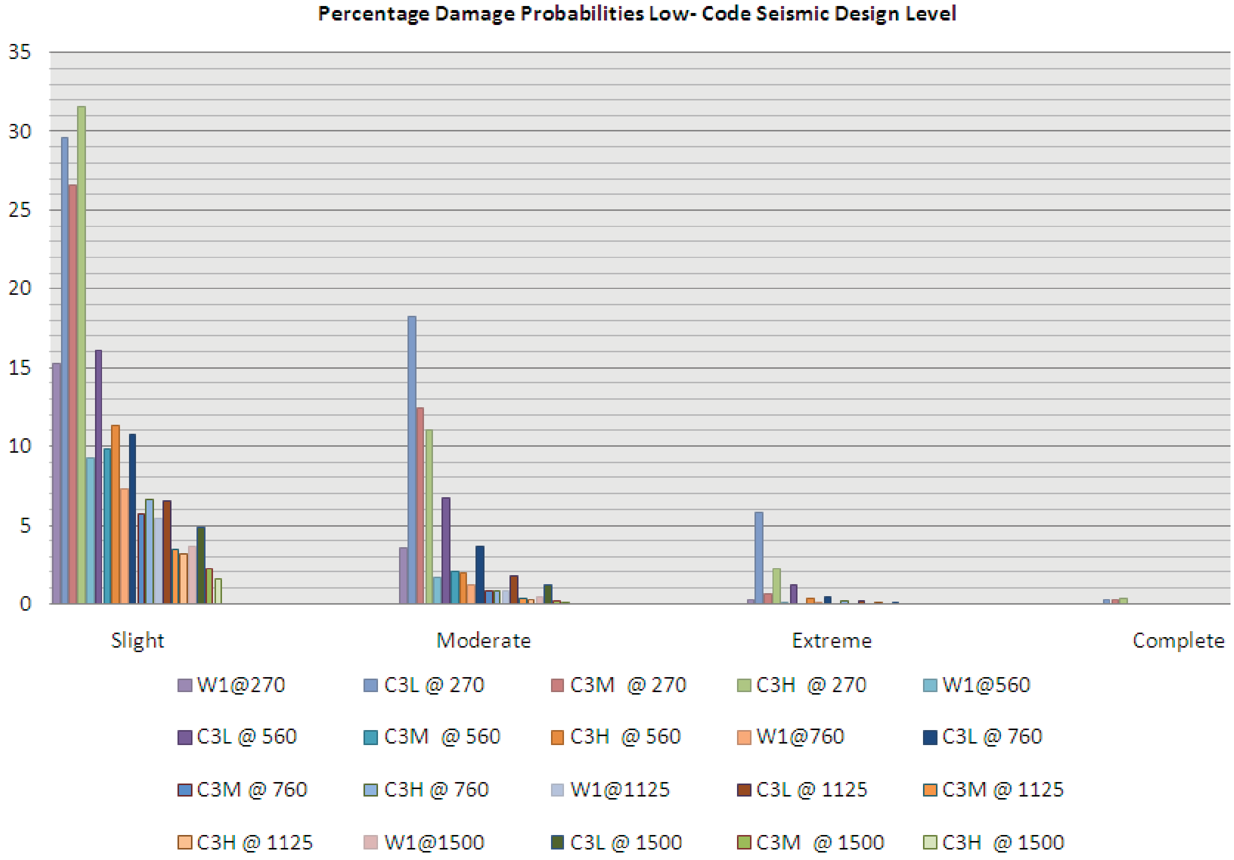


Figure 6-13 Damage Probabilities Low-Code Seismic Design

Discussion

Figure 6-12 and Figure 6-13 clearly shows that the pre code seismic design buildings have higher level of damage compared to the low code seismic design buildings. Even though the peak building response of both these seismic design levels are almost equal, the damage expected in these differ by almost 5% in all the building types except in the case of complete damage. The overall pattern of damage is similar for all the building types for these two building design levels for all the shear wave velocities. In both the seismic design levels, C3L indicated higher level of damage, followed C3M and then C3H, where as W1 indicated low level of damage for a given value of shear wave velocity. In all the four damage states from slight to complete, shear wave velocity of 270m/s corresponds to maximum damage and very less damage corresponds to 1500 m/s. At shear wave velocity of 270 m/s there is a major difference in damage between W1 and C3 type of buildings, but in higher shear wave velocities, C3L building type indicated more damage and W1, C3M and C3H have much less than the C3L building type. For the magnitude of 6.9 and at a distance of around 68.74 km, the expected level of complete damage is less than 1 %. For the same scenario, the graphs clearly indicate that the probability of higher level of damage for shear wave velocity 270 m/s, which is usually experienced in soft soil material and the expected damage decreases as the stiffness of the ground increases. This is clearly seen in the areas of Chungthang which belongs to site class D where similar building types have experienced more damage compared to the buildings in Gangtok which largely belongs to site class B.

Table 6-8 Cumulative Damage Probabilities – Pre Code at 1125 m/s

Building Type	Slight	Moderate	Extreme	Complete
W1	0.1166	0.0217	0.0012	0.0000
C3L	0.1417	0.0434	0.0060	0.0000
C3M	0.0773	0.0109	0.0007	0.0000
C3H	0.0679	0.0089	0.0014	0.0001

Table 6-9 Discrete Damage Probabilities – Pre Code at 1125 m/s

Building Type	Slight	Moderate	Extreme	Complete
W1	0.0960	0.0206	0.0012	0.0000
C3L	0.1043	0.0374	0.0060	0.0000
C3M	0.0671	0.0102	0.0006	0.0000
C3H	0.0603	0.0076	0.0013	0.0001

Table 6-10 Cumulative Damage Probabilities – Pre Code at 760 m/s

Building Type	Slight	Moderate	Extreme	Complete
W1	0.1493	0.0306	0.0019	0.0001
C3L	0.2177	0.0793	0.0135	0.0001
C3M	0.1199	0.0209	0.0015	0.0001
C3H	0.1383	0.0240	0.0038	0.0003

Table 6-11 Discrete Damage Probabilities – Pre Code at 760 m/s

Building Type	Slight	Moderate	Extreme	Complete
W1	0.1206	0.0287	0.0018	0.0001
C3L	0.1519	0.0659	0.0134	0.0001
C3M	0.1005	0.0195	0.0014	0.0001
C3H	0.1178	0.0205	0.0035	0.0003

Table 6-12 Percentage of Damage – Pre Code at 1125 m/s

Building Type	Slight	Moderate	Extreme	Complete
W1	9.6045	2.0575	0.1153	0.0046
C3L	10.4302	3.7442	0.5955	0.0024
C3M	6.7087	1.0243	0.0611	0.0049
C3H	6.0253	0.7618	0.1281	0.0096

The number of damaged buildings is calculated by multiplying the discrete damage probability with the total number of buildings in each class. For example, the number of buildings in each HAZUS class for Arithang ward is given Table 6-1 of this chapter.

Table 6-13 Number of predicted damaged pre-code seismic buildings in Arithang Ward at 1125 m/s

Building Type	Slight	Moderate	Extreme	Complete
W1	15	3	0	0
C3L	14	5	1	0
C3M	24	4	0	0
C3H	0	0	0	0

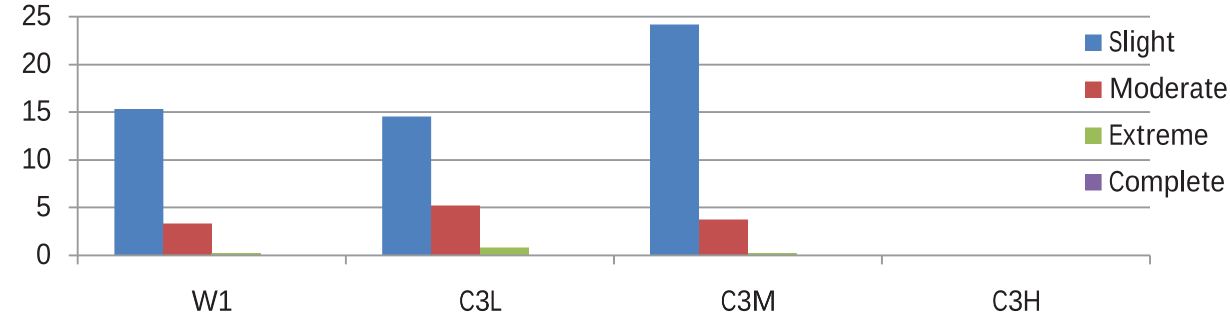


Figure 6-14 Graph showing Number of predicted damaged pre-code seismic buildings in Arithang Ward at 1125 m/s

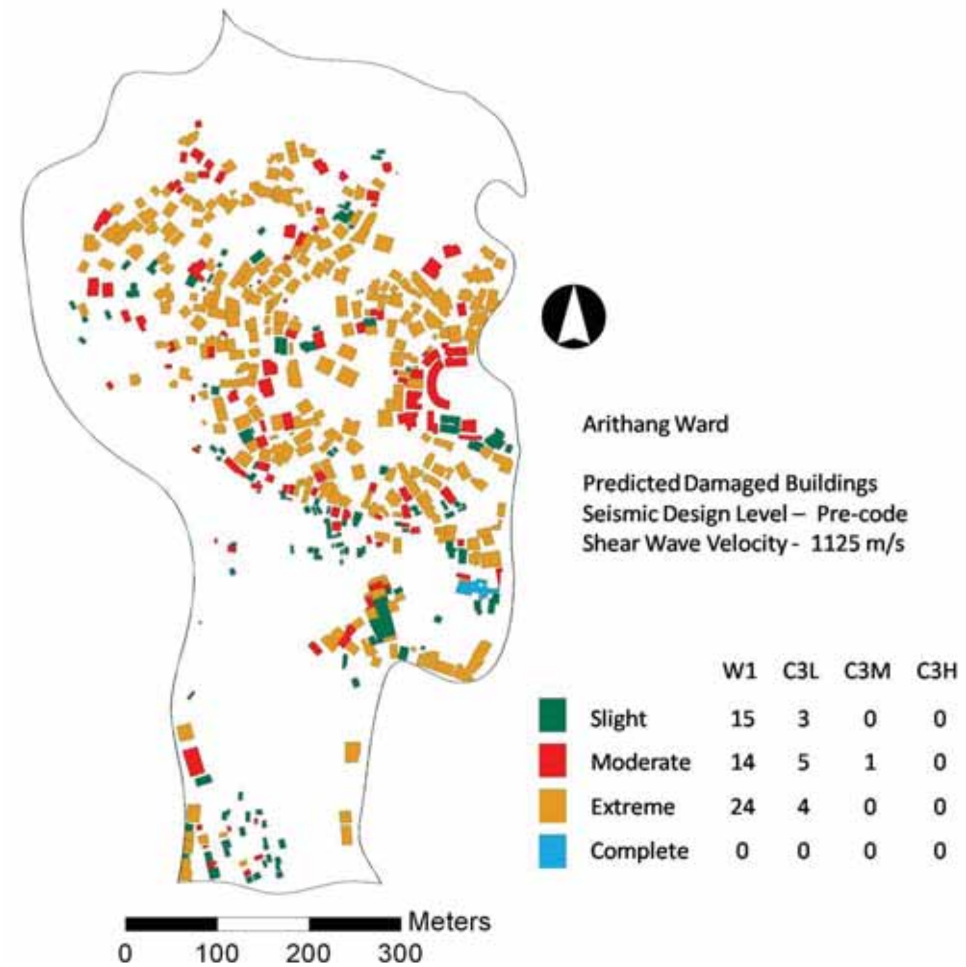


Figure 6-15 Number of predicted damaged pre-code seismic buildings in Arithang Ward at 1125 m/s

Table 6-14 Percentage of Damage – Pre Code at 760m/s

Building Type	Slight	Moderate	Extreme	Complete
W1	12.0564	2.8739	0.1831	0.0084
C3L	15.1852	6.5896	1.3421	0.0115
C3M	10.0451	1.9482	0.1395	0.0126
C3H	11.7781	2.0516	0.3519	0.0314

The number of damaged buildings is calculated by multiplying the discrete damage probability with the number of buildings in each class. The number of buildings in each HAZUS class is given Table 6-1 of this chapter.

Table 6-15 Number of predicted damaged pre-code seismic buildings in Arithang Ward at 760m/s

Building Type	Slight	Moderate	Extreme	Complete
W1	19	5	0	0
C3L	21	9	2	0
C3M	36	7	1	0
C3H	0	0	0	0

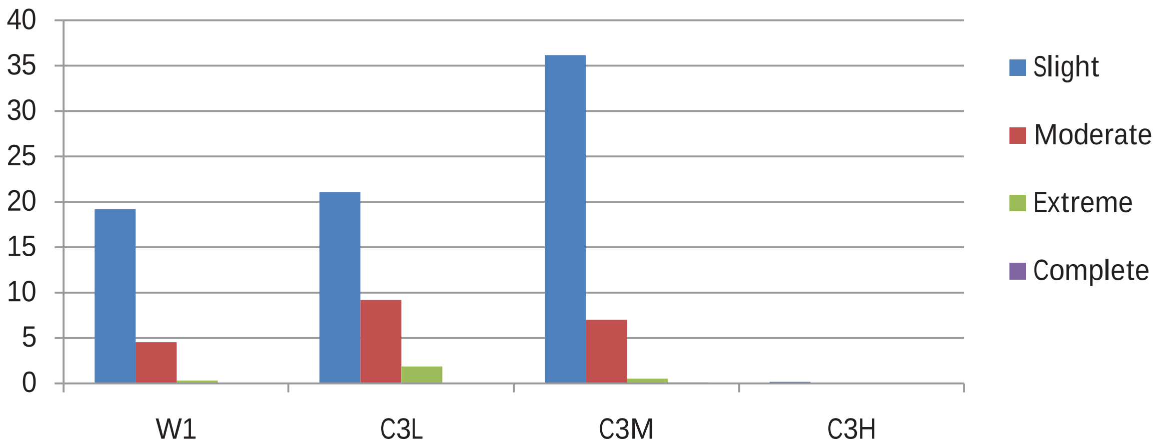


Figure 6-16 Graph showing Number of predicted damaged pre-code seismic buildings in Arithang Ward at 760 m/s

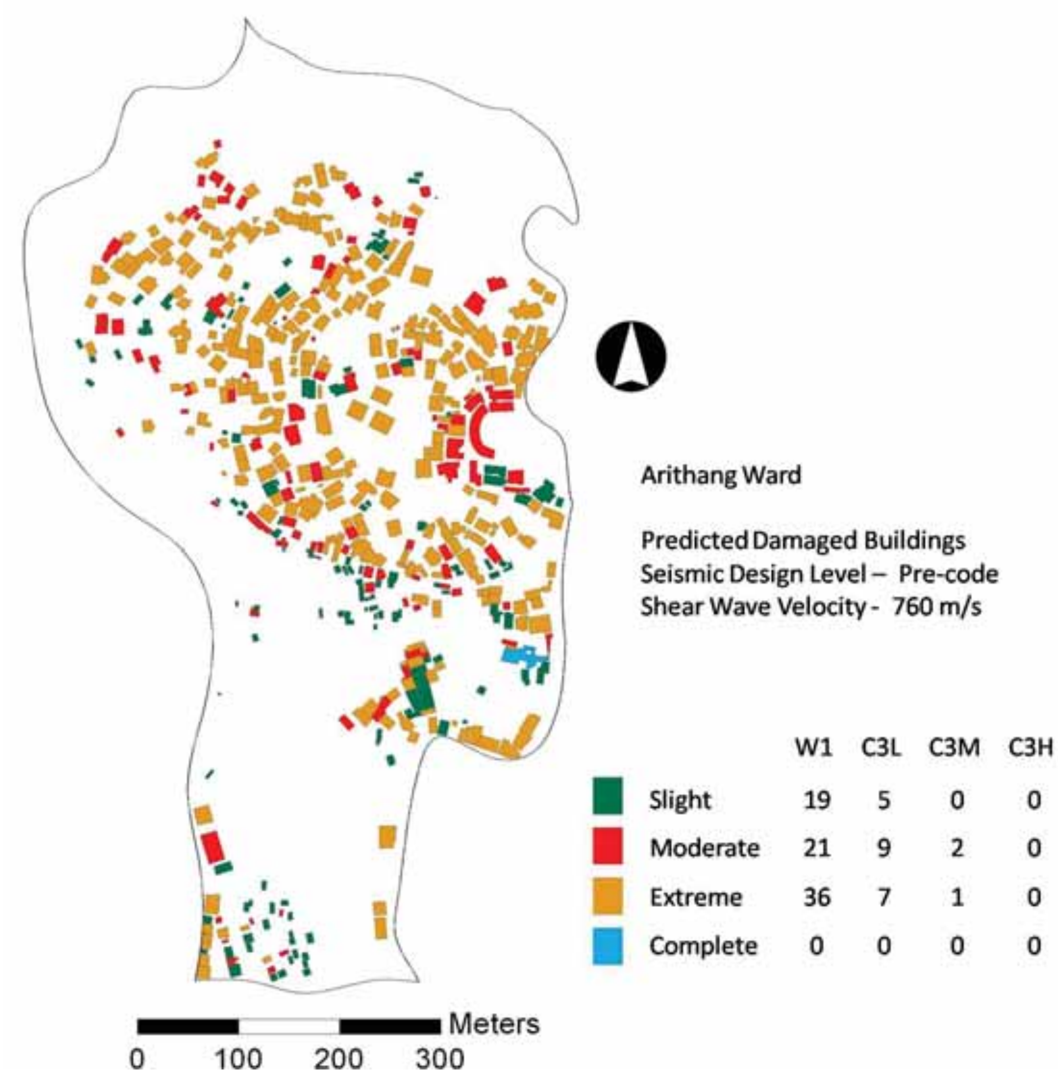


Figure 6-17 Number of predicted damaged pre-code seismic buildings in Arithang Ward at 760 m/s

Discussion

Table 6-8, Table 6-9, Table 6-12 and Table 6-13 describes the Cumulative, Discrete, Percentage damage probabilities and Number of damaged buildings of 4 building types at pre code design level at 1125 m/s, respectively. Table 6-10, Table 6-11, Table 6-14 and Table 6-15 describes the Cumulative, Discrete, Percentage damage probabilities and Number of damaged buildings of 4 building types at pre code design level at 760 m/s, respectively. Figure 6-15 and Figure 6-17 show the number of damaged buildings of four damage states for four identified building types for pre code seismic design level at 1125 m/s and 760 m/s, respectively.

Results indicate at shear wave velocities 1125 m/s and 760m/s, C3L building type has highest probability of experiencing slight damage(10%) compared to other building types, followed by W1 (9%), C3H and C3M (6%). At 1125 m/s, C3L building type has highest probability of experiencing moderate damage (4%) compared to other building types (1-2 %), which have equal probabilities of experiencing moderate level damage. At 760m/s, C3L building type has highest probability of experiencing moderate damage (7%) compared to other building types (2-3 %), which have equal probabilities of experiencing moderate level damage. At 1125 m/s C3L indicated less than 1% probability of extensive level damage. At 760 m/s C3L indicated low probability (1%) of extensive level damage and it is than 1% in W1, C3M and C3H. In all the building types there is very low probability of experiencing complete damage at both 1125 and 760m/s.

In Arithang ward out of 659 buildings (W1-159, C3L-139, C3M-360, C3H-1) results indicated at shear wave velocity 1125 m/s, C3M building type has highest number of buildings (24) experiencing slight damage compared to other building types, followed by C3L(14), W1(15) and none in C3H. At 760 m/s, C3M building type has highest number of buildings (36) experiencing slight damage compared to other building types, followed by C3L (27), W1 (19) and none in C3H. At 1125 m/s, C3L building type has highest number of buildings experiencing moderate damage (5) compared to other building types, followed by C3M(4), W1(3) and none in C3H. At 760 m/s, C3L building type has highest number of buildings experiencing moderate damage (9) compared to other building types, followed by C3M(7), W1(5) and none in C3H. At 1125 m/s C3L indicated one building of extensive level damage and none in other building types. At 760 m/s, C3L indicated two buildings of extensive level damage followed by one C3M type and none in other building types. In all the building types the number of buildings experiencing complete damage is none at both 1125 and 760m/s.

6.5. Validation

Table 5-1 shows the number of damaged buildings in Gangtok reported by the Municipal Corporation of Gangtok at each ward level. These are the observed damages in the first phase of damage assessment by the local authorities within a month after earthquake. Based on this damage assessment, compensation was to be paid to building owners for the building damage by the local government. So for this purpose, government building damages are not included in the Table 5-1. So for comparing the predicted number of damage to the actual damage reported, government buildings are not considered. In Arithang ward out of 659 buildings, 611 buildings are privately owned and 48 are government owned buildings. Table 6-16 gives the number of privately owned buildings in each HAZUS class and Table 6-17 gives number of buildings as per their construction material. Numbers of predicted damaged buildings in Arithang ward are given in Table 6-18 and Table 6-19 respectively. Actual numbers of damaged buildings in Arithang ward are given in Table 6-20.

Table 6-16 Number of private owned buildings in each HAZUS class in Arithang ward.

HAZUS Class	Number of Buildings
W1	135
C3L	128
C3M	347
C3H	1

Table 6-17 Number of buildings according to construction material

Material	Number of Buildings
Wooden	135
Concrete	476

Table 6-18 Number of predicted privately owned damaged pre-code seismic buildings in Arithang Ward at 1125 m/s

	Damages Reported			
Building Type	Slight	Moderate	Extreme	Complete
Wooden(Kutcha)	13	3	0	0
Concrete(Pucca)	37	8	1	0

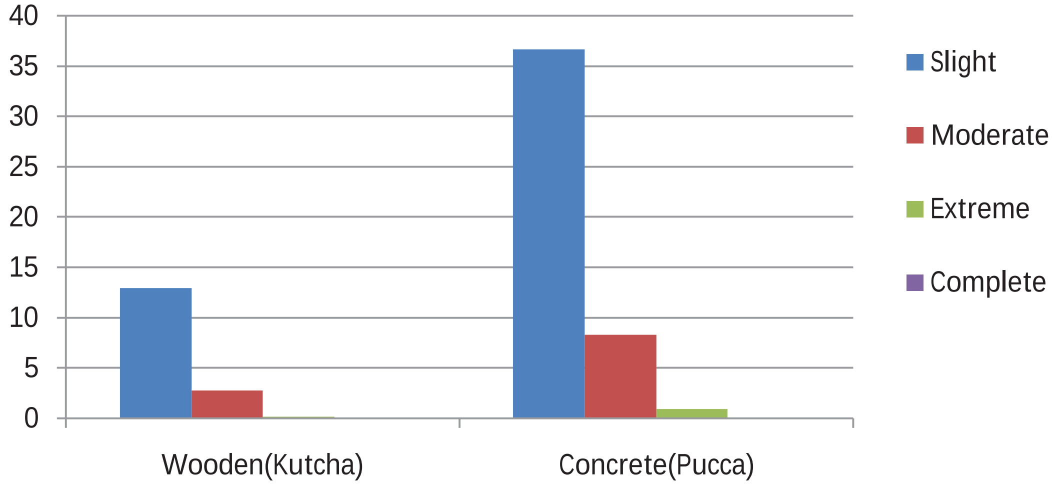


Figure 6-18 Predicted privately owned damaged pre-code seismic buildings in Arithang Ward at 1125 m/s

Table 6-19 Number of predicted privately owned damaged pre-code seismic buildings in Arithang Ward at 760 m/s

	Damages Reported			
Building Type	Slight	Moderate	Extreme	Complete
Wooden(Kutcha)	16	4	0	0
Concrete(Pucca)	54	15	2	0

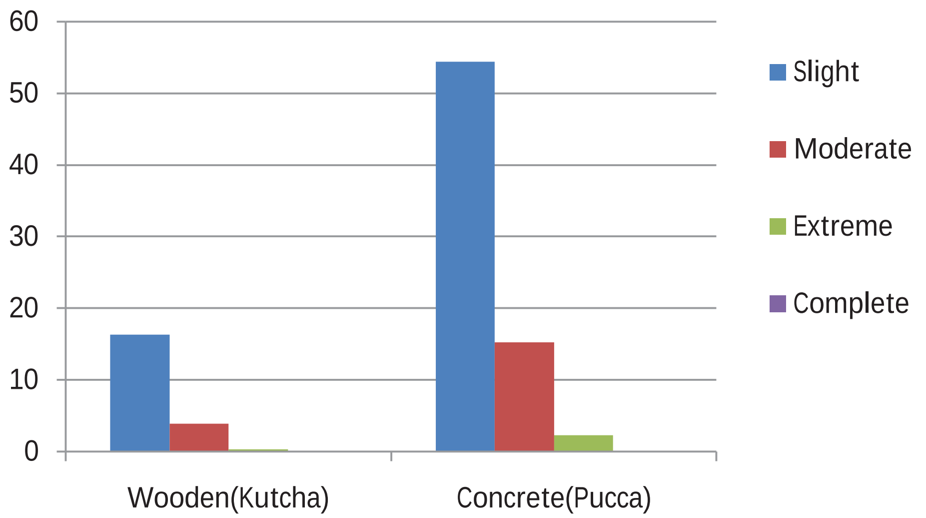


Figure 6-19 Predicted privately owned damaged pre-code seismic buildings in Arithang Ward at 760 m/s

Table 6-20 Number of actual reported damaged buildings of private ownership in Arithang Ward (Municipal Corporation of Gangtok)

	Damages Reported			
Building Type	Slight	Moderate	Extreme	Complete
Wooden(Kutcha)	20	5	0	0
Concrete(Pucca)	82	24	4	0

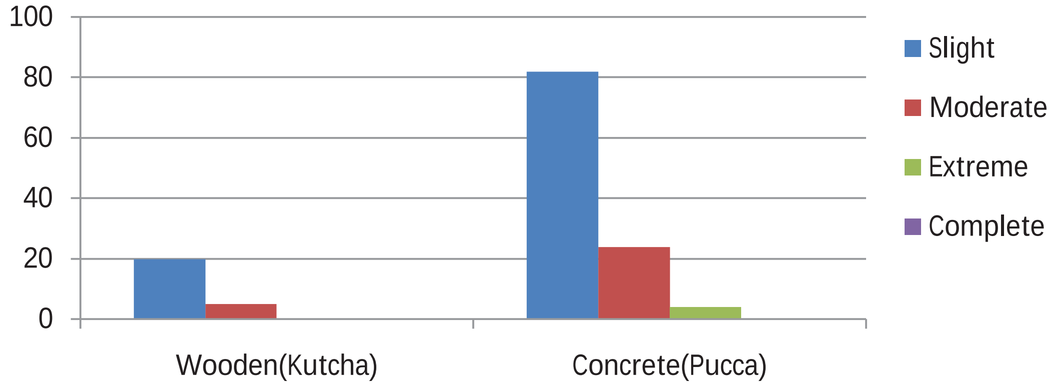


Figure 6-20 Actual damage reported in Gangtok Area

Discussion

The actual numbers of damaged buildings indicate that the highest numbers of buildings damaged are concrete buildings (82) and most of the damage is reported as the slight damage followed by moderate damage (24) extreme damage(4) and no complete damage is reported. Number of slight damaged buildings are more in wooden buildings (20) followed by moderate damage (5) and extreme and complete damage is zero. At 1125 m/s, predicted numbers of slight damaged buildings are concrete buildings (37) damage followed by moderate damage (8) extreme damage (1) and no complete damage. At 1125 m/s predicted number of slight damaged buildings are more in wooden buildings (13) followed by moderate damage(3) and extreme and complete damages are zero. At 760 m/s, predicted numbers of slight damaged buildings are concrete buildings (54) damage followed by moderate damage (15) extreme damage (2) and no complete damage. At 760m/s predicted number of slight damaged buildings are more in wooden buildings (16) followed by moderate damage(4) and extreme and complete damages are zero

At 760 m/s the predicted numbers of slightly damaged concrete buildings (54) are close to the actual reported slightly damaged concrete buildings (82) by the local authorities than the slightly damaged concrete buildings (37) at 1125m/s. Similarly at 760 m/s the predicted numbers of moderately damaged concrete buildings (15) are close to half the actual reported moderately damaged concrete buildings (24) by the local authorities than the moderately damaged concrete buildings (8) at 1125m/s which is one third of actual damage. Similarly at 760 m/s the predicted numbers of extremely damaged concrete buildings (2) is half the actual reported slightly damaged concrete buildings (4) by the local authorities than the slightly damaged concrete buildings (1) at 1125m/s. And in both the cases at 760 m/s and 1125m/s the complete damage is zero and there are no completely damaged buildings reported in Arithang ward.

At 760 m/s the predicted numbers of slightly damaged wooden buildings (13) match 65% to the actual reported slightly damaged wooden buildings (20) by the local authorities than the slightly damaged wooden buildings (8) at 1125m/s which is 40% match to the actual damage. At 760 m/s and 1125 m/s there are predicted no moderately damaged wooden buildings predicted but 5 buildings reported to have moderate damage. And in both the cases at 760 m/s and 1125m/s the extreme and complete damage in wooden buildings is zero and there are no completely damaged wooden buildings reported in Arithang ward. Since the building damage prediction at 760 m/s matches closely with the actual damage in Arithang ward, 760 m/s shear wave velocity is considered for prediction of building damage at Gangtok city level.

As on 2010, based on the building outline map provided by the Town Planning Division of Urban Development and Housing Department, the number of buildings counted in the Gangtok region are 11188 buildings, which include all the building types, ownership etc. Based on the damage data provided by the municipal corporation of Gangtok is given in Table 5-1. Total number of damages reported in the first phase of evaluation is 2833, in which 1804 are concrete structures and 1029 are wooden and other light material structures. The divided damage break up numbers in each damage state is given in Table 6-21.

Table 6-21 Predicted Percentage of Damage – Pre Code at 760 m/s

Damages Reported					
Building Type	Slight	Moderate	Extreme	Complete	Total
Wooden(Kutcha)	471	487	69	2	1029
Concrete(Pucca)	1118	625	50	11	1804

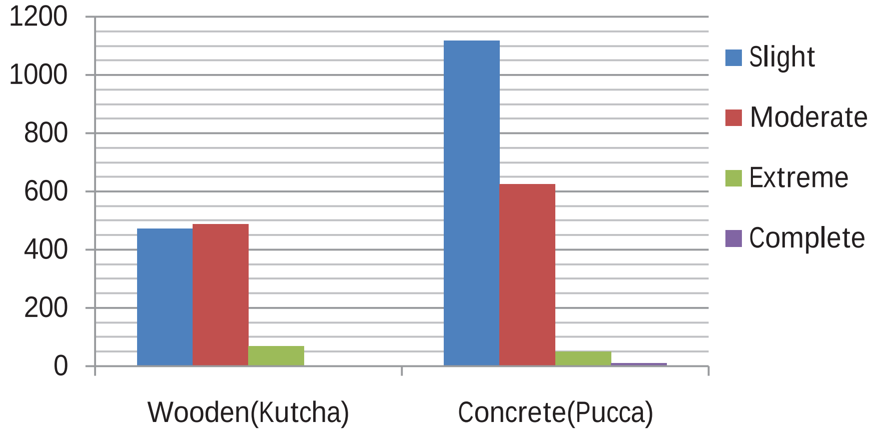


Figure 6-21 Predicted Percentage of Damage – Pre Code at 760 m/s

So for total number of 11,188 buildings in Gangtok the numbers of modelled damaged buildings and actual reported buildings are given in Table 6-23. As the breakup of each building type is not available average values of four damages states were considered for calculating the total number of damaged buildings for each damage state and compared with the actual reported damage in each damage state. Table 6-22 shows the predicted damage percentage probability of pre-code seismic design level and calculated average percentage probability of each damage state.

Table 6-22 Predicted Percentage of Damage – Pre Code at 760 m/s

Building Type	Slight	Moderate	Extreme	Complete
W1	12.0564	2.8739	0.1831	0.0084
C3L	15.1852	6.5896	1.3421	0.0115
C3M	10.0451	1.9482	0.1395	0.0126
C3H	11.7781	2.0516	0.3519	0.0314
Average	12.2662	3.365825	0.50415	0.015975

Table 6-23 Number of actual reported damaged buildings and predicted building damage at 760 m/s.

Building Type	Slight	%	Moderate	%	Extreme	%	Complete	%	Total	%
Actual	1589		1112		119		13		2833	
Predicted	1372	86	377	34	56	48	2	15	1807	64

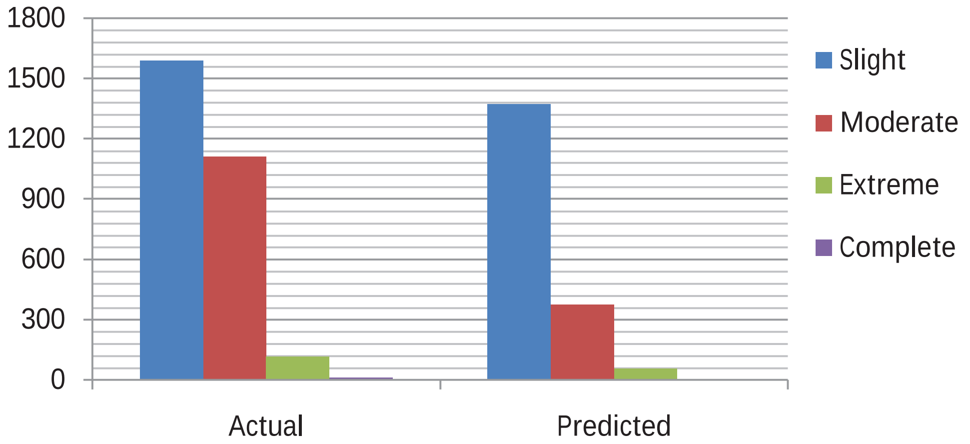


Figure 6-22 Damage reported in Gangtok Area

Discussion

Table 6-23 indicates that at 760 m/s predicted number of slight damaged buildings (1372) is 86% of the actual damage buildings (1589) at pre-code seismic design level. At 760 m/s predicted number of moderate damaged buildings (377) is 86% of the actual damaged buildings (1112) at pre-code seismic design level. At 760 m/s predicted number of extremely damaged buildings (56) is 48% of the actual damaged buildings (119) at pre-code seismic design level. At 760 m/s predicted number of complete damaged buildings (2) is 15% of the actual damaged buildings (13) at pre-code seismic design level. Overall at 760 m/s total predicted number of damaged buildings (1807) is 64% of the actual damaged buildings (2833) at pre-code seismic design level.

6.6. Damage in Chungthang Area

During the field work it was observed that Chunthang area in the north district of Sikkim has experienced high building damage in comparison to all the places in Sikkim. Chunthang is situated at around 58.66 km from epicentre and the town was constructed on the river sediments which corresponds to the site class D which has an average shear wave velocity of 270 m/s. As described in the earlier sections peak building responses of all 4 identified building types are calculated by overlaying the capacity curves of four identified building types at pre-code seismic design levels for the demand spectrum of shear wave velocity 270m/s. From the generated peak building response, cumulative discrete and percentage damage probabilities are calculated. Figure 6-23 shows the pre code seismic design curves of the four identified building types overlaid on the demand spectrum of 270 m/s at Chunthang area to calculate peak building response and Table 6-24 shows the Peak building response for Pre Code Seismic Design at 270 m/s for Chunthang Area

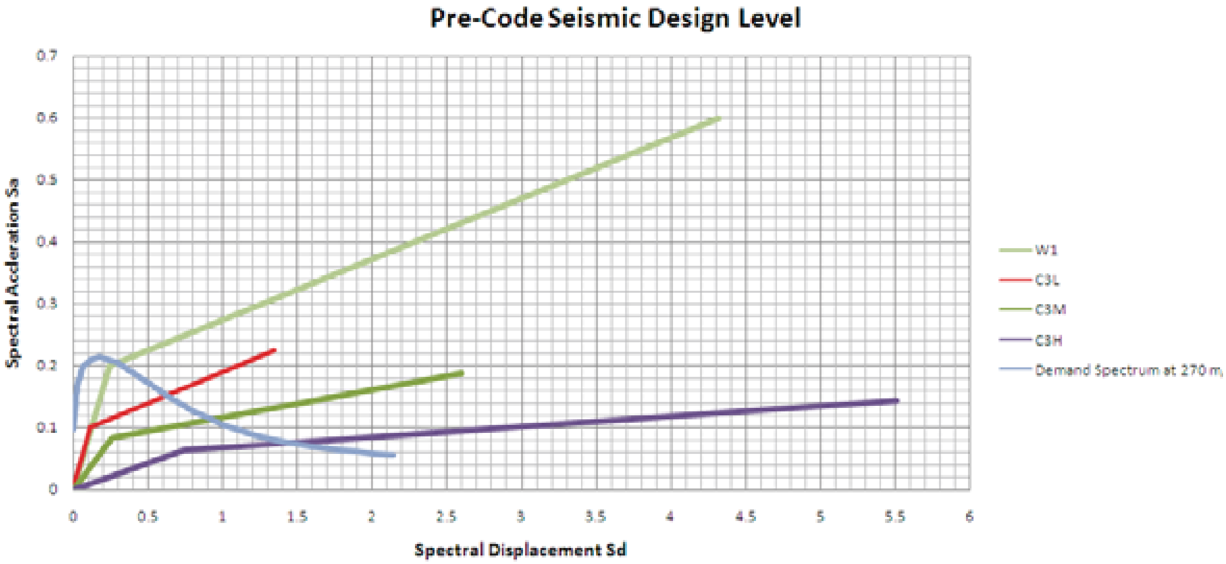


Figure 6-23 Demand and Capacity Curves for Pre-code Seismic Design

Table 6-24 Peak Building Response for Pre Code Seismic Design at 270 m/s for Chunthang Area

Building Type	Peak Building Response
W1	0.25
C3L	0.63
C3M	0.93
C3H	1.45

Table 6-25 Cumulative Damage Probabilities – Pre Code at 270 m/s for Chunthang Area

Building Type	Slight	Moderate	Extreme	Complete
W1	0.3619	0.1126	0.0124	0.0009
C3L	0.6155	0.3825	0.1357	0.0108
C3M	0.6209	0.3143	0.0694	0.0115
C3H	0.6755	0.3175	0.0785	0.0127

Table 6-26 Discrete Damage Probabilities – Pre Code at 270 m/s for Chunthang Area

Building Type	Slight	Moderate	Extreme	Complete
W1	0.2607	0.1012	0.0114	0.0009
C3L	0.3578	0.2576	0.1249	0.0108
C3M	0.3644	0.2565	0.0578	0.0115
C3H	0.4238	0.2517	0.0658	0.0127

Table 6-27 Percentage Damage Probabilities – Pre Code at 270 m/s for Chunthang Area

Building Type	Slight	Moderate	Extreme	Complete
W1	26.077	10.121	1.147	0.093
C3L	35.788	25.767	12.492	1.085
C3M	36.445	25.650	5.780	1.159
C3H	42.383	25.170	6.581	1.276

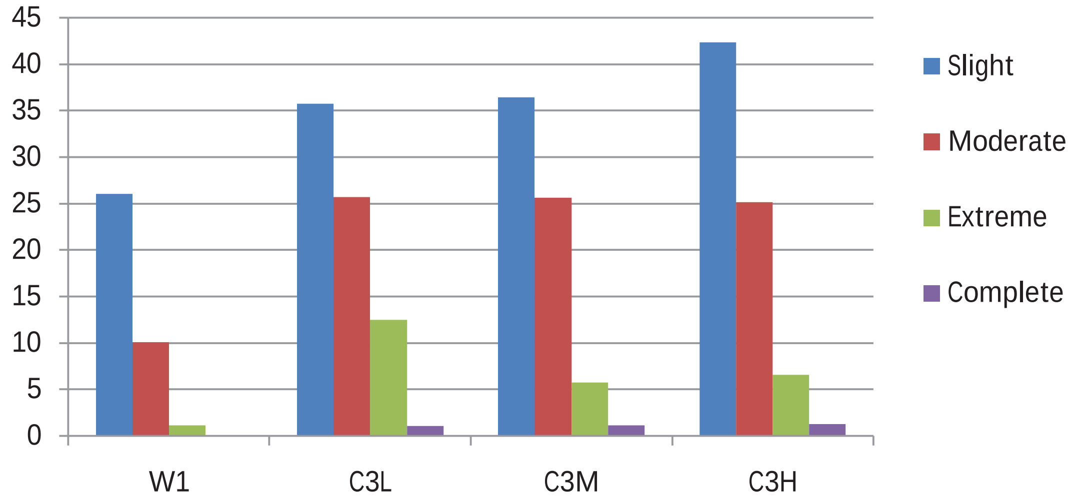


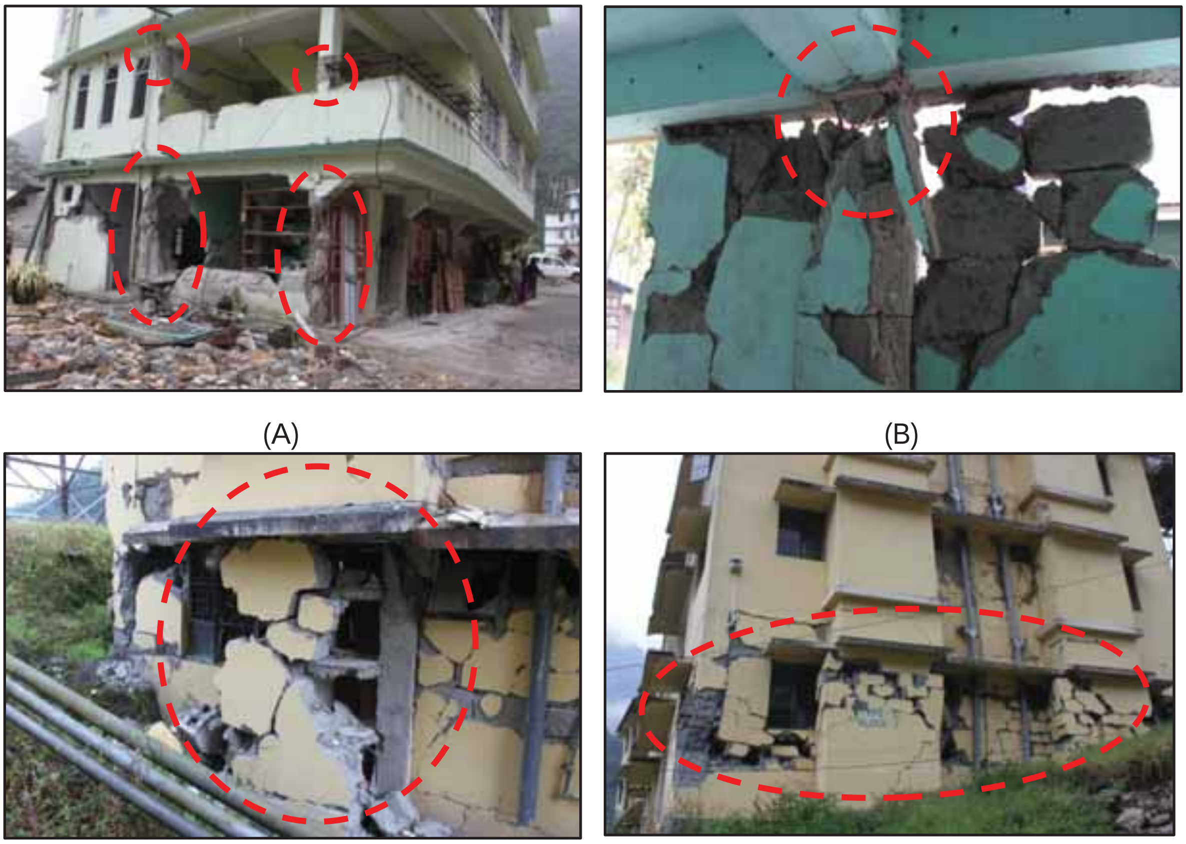
Figure 6-24 Damage probabilities for Pre-code Seismic Design

Discussion

Table 6-22, Table 6-23, Table 6-24 describes the Cumulative, Discrete, and Percentage damage probabilities of 4 building types at pre code design level at 270 m/s in Chunthang area, respectively.. Figure 6-21 shows the percentage of damage probability of four states for four identified building types for pre code seismic design level at 270 m/s in Chunthang area. Results indicate at shear wave velocity 270 m/s, in Chunthang area, C3H building type has highest probability of experiencing slight damage compared to other building types, followed by C3M, C3L and W1. The damage probability of C3H is close to 45%. C3M and C3L have almost similar probability of around 35%. At 270 m/s in Chunthang area C3L, C3M and C3 H building types has almost equal probability of experiencing moderate damage (25%) compared to W1 (10 %). At 270 m/s in Chunthang area, C3L indicated very high probability (13%) of extensive level damage and it is around 6.5 to 7 % in C3M and C3H building types, and it is comparatively very less in W1(2%). At 270 m/s in Chunthang area C3L, C3M and C3H indicated equal probability (2%) of complete level damage and there is no expected complete damage in W1. So in all the cases except slight damage state, wooden building show low probable damage in all damage states compared to concrete building types.

Field Observation

As indicated by the percentage damage probability calculated, slight damage is seen everywhere followed by moderate and extensive damages. Because of poor construction, columns are seen separated from the beams, and most of the infill walls have developed extreme to severe cracks and in some cases complete collapse.



(A) (B)

(C) (D)

Figure 6-25 Damaged buildings in Chunthang Area

Discussion

Figure 6-25 A to D shows the failure of columns and complete damage to the walls at ground floor level compared to moderate and slight damage at upper levels. Figure 6-25 C, D shows the crushed and detached columns where concrete has completed failed and reinforcement was broken. Even though the difference between epicentre in Gangtok and Chunthang is approximately 10km, Chunthang suffered extreme damage because of the soft soils beneath the buildings which shake with high frequency than the rocky areas.

6.7. Risk Zonation

In the previous section, various analyses showed percentage of different kind of buildings that are expected to be damaged in the reference earthquake. Now it is important to know the probable location of such buildings with a first order assumption that all building types considered are of similar quality and age, which is an over simplification. However, it is worthwhile to assume this in order to assess the role of local ground condition in possible amplification of ground motion or adverse impact on building because of its location. This is more important in the present case as Gangtok is a landslide prone area and buildings located on steep and unstable slopes are more likely to develop damage compared to similar buildings on flat and stable areas.

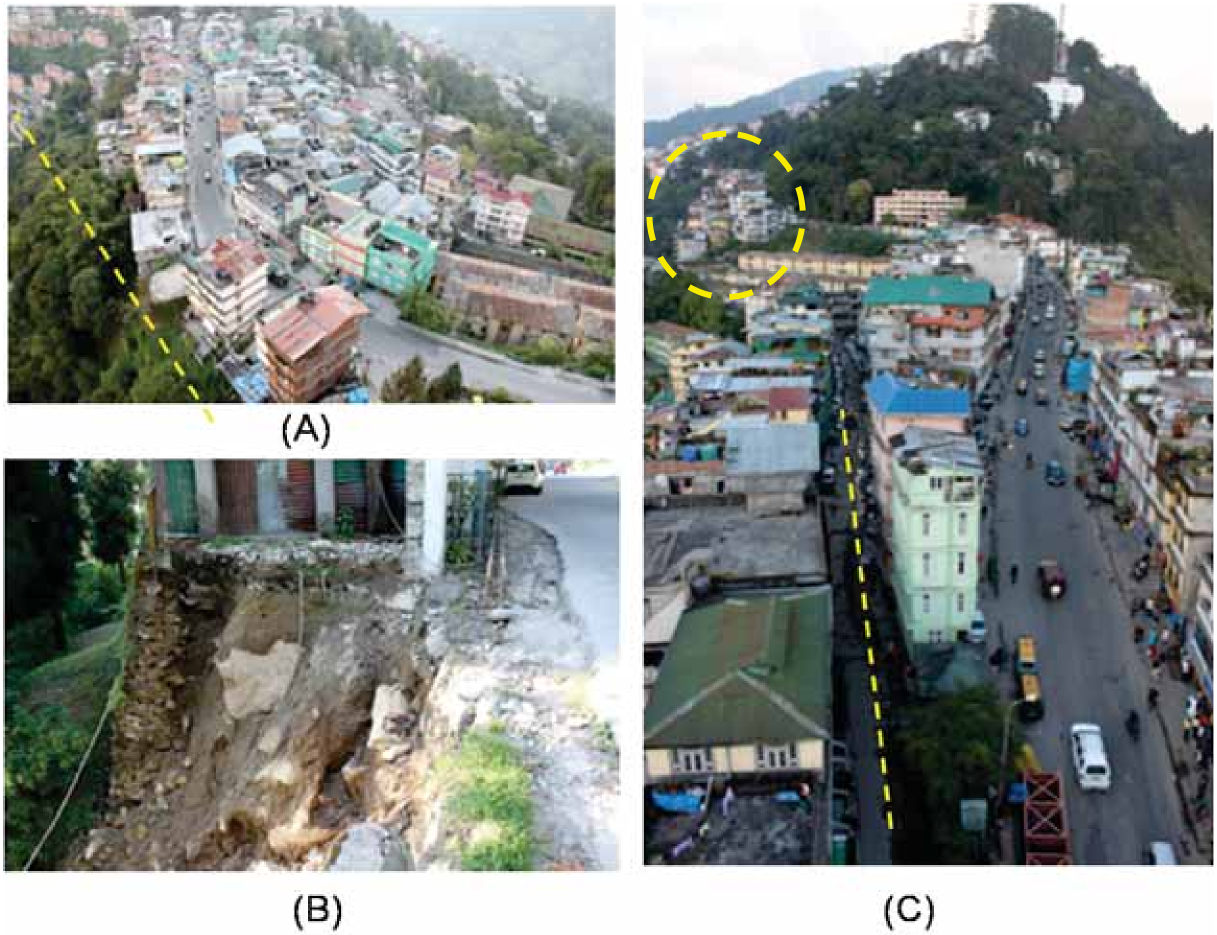


Figure 6-26 Buildings constructed on Unstable slope Areas with High Building Density

Figure 6-26 shows different buildings of Gangtok located on steep slopes. Figure 6-26 A and B show the buildings constructed on the edge of steep slopes. The slope failure at these locations can cause severe damages. Figure 6-26-C shows the narrow roads between tall buildings. Buildings have two different ground levels on either side of the road showing the steepness of the slope. The circular highlighted portion in the Figure 6-26-C shows buildings constructed on steep slopes. So if buildings on up slope fail it can cause severe damage to the buildings on down slope.

Therefore, it order to assess the effect of local ground condition on building damage, Land stability map, building density map and the slope map were integrated. All input maps were reclassified into 6 classes based on their contribution to the vulnerability and exposure in case of building density map. All classes of input maps were given rating from 1-6 where 1 is the low and 6 is highest contribution to vulnerability/exposure. Saaty's Analytical Hierarchy Process (AHP) was used for determining the weights based on their contribution to the total risk. The integrated map can be considered as risk map as it takes into account slope stability hazard, vulnerability of slopes and exposure of buildings, although in a qualitative manner, subsequently for each class, risk can be quantified. A matrix is developed between these three factors and all were given rating on scale of 1-9 based on the pair-wise comparison, and these values were normalised to determine the weights for each factor. The detail steps of determining these weights through AHP are given in Annexure – B. The pair - wise comparison matrix for the three factors is given in Table 6- 29 and the rating was assigned based on Saaty's Analytical Hierarchy Process (AHP) as given in Table 6-28.

Table 6-28 Rating for pair wise comparison

Numerical Rating	Judgments
9	Extremely preferred
8	Very strongly to extremely
7	Very strongly preferred
6	Strongly to very strongly
5	Strongly preferred
4	Moderately to strongly
3	Moderately preferred
2	Equally to moderately
1	Equally preferred

Table 6-29 Pair – wise comparison Matrix

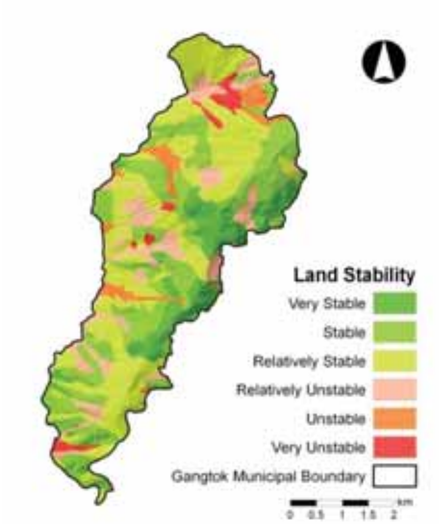
	Land Stability	Building Density	Slope
Land Stability	1.000	1.000	3.000
Building Density	1.000	1.000	5.000
Slope	0.333	0.200	1.000

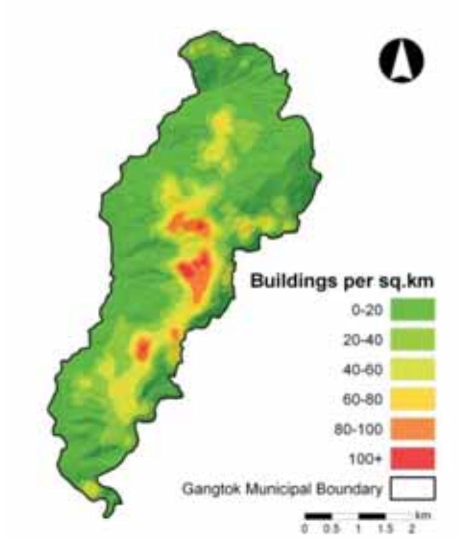
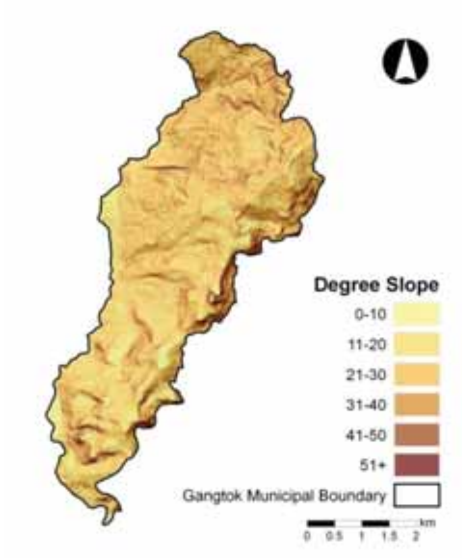
Land stability map was generated by Mines, Minerals and Geology Department, Govt. of Sikkim, Gangtok, to define the number of floors to be permitted based on slope/land stability. The factors and permissible numbers of floors are given in Table 4-1 are and Table 4-2. Since the land stability is generated using many geo-environmental factors such as geology, slope, aspect, rainfall pattern, land-use/land cover, hydrology and land cover, seismicity, soil type and rock erodability and vegetation, which determines the slope stability, it was considered as cumulative effect of all such factors instead of all the individual factors. For finding out the exposure and vulnerability of buildings, the building density and slope were considered.

During field investigation it was observed that the slope is the single most important factor that determines building vulnerability in hilly areas due to uneven weak foundation, distribution of load and force due to lateral spreading. Building density map is considered as exposure of buildings to hazards and secondly on slopes if a single building fails, it is likely to affect buildings in the down slope direction. So these three factors were considered and rated according their importance for risk assessment.

Table 6-30 Normalized Weights and Individual class rating

Map	Weight	Classes	Weight
Land Stability	0.480	Very Stable	1
		Stable	2
		Relatively Stable	3
		Relatively Unstable	4
		Unstable	5
		Very Unstable	6



Building Density	0.405	0-20	1	
		21-40	2	
		41-60	3	
		61-80	4	
		81-100	5	
		100+	6	
Slope	0.115	0-10	1	
		11-20	2	
		21-30	3	
		31-40	4	
		41-50	5	
		50+	6	

Three classified maps were multiplied with their respective weights and were integrated to generate the final risk map.

Risk Map = 0.480 * "Land Stability Map" + 0.115 * "Slope Map" + 0.405 * "Building Density Map

The final output map was then reclassified in to three classes such as High Risk, Medium Risk and Low Risk Areas. Figure 6-27 shows the final classified Map of Gangtok region.

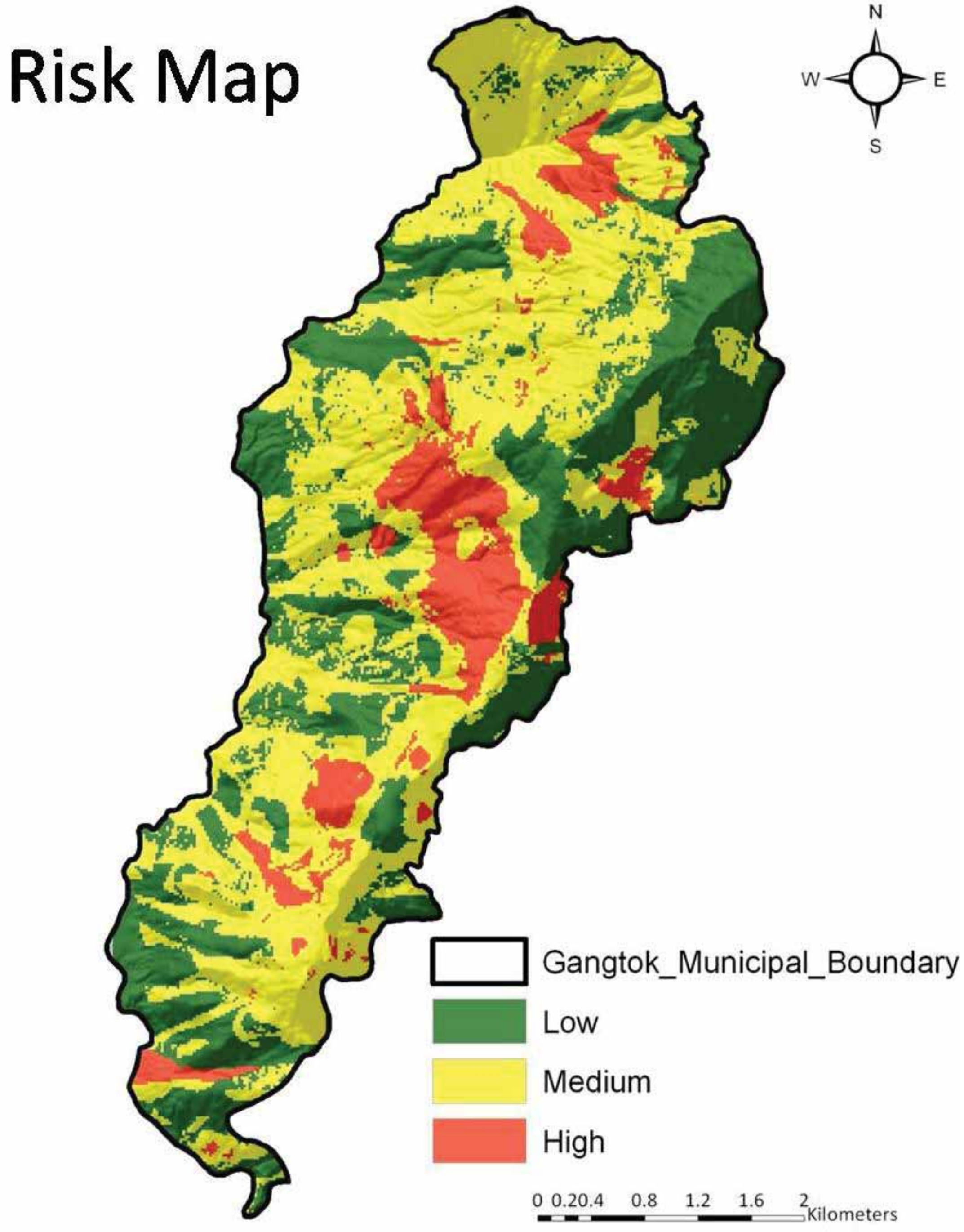


Figure 6-27 Risk Map of Gangtok Region

Discussion

Figure 6-27 clearly shows areas where the land is highly unstable, building density is high and slope is high, is classified as high risk zones. Majority of area falls under moderate and low risk that are either located close to the ridge or to the river in the valley and the centre of the city is located in the high risk zone.

Validation

The location of the damaged buildings which were visited during field investigation was overlaid on the risk map to see the location of buildings with respect to the risk zones. The descriptions of all these buildings are given in the previous chapter.

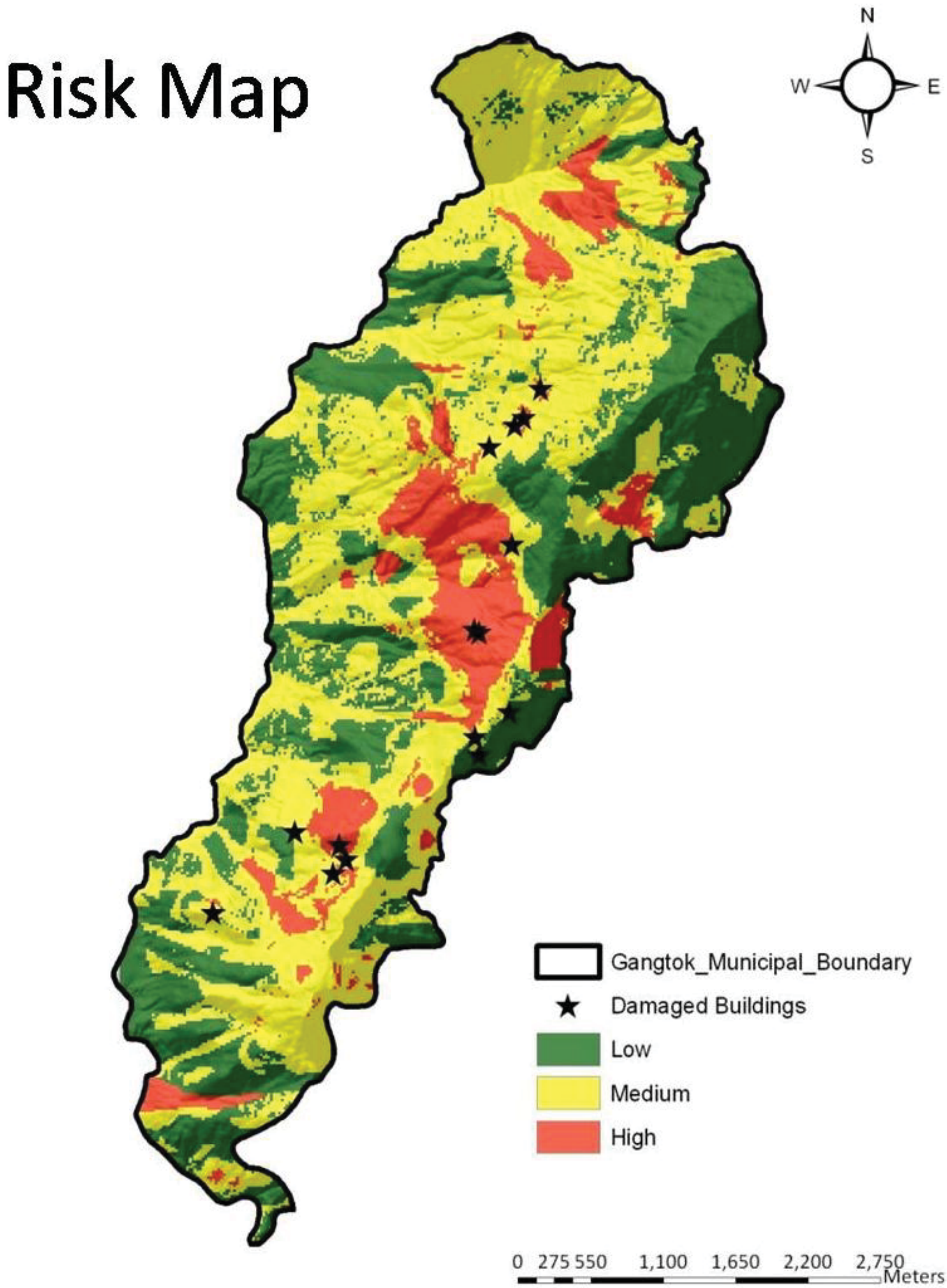


Figure 6-28 Identified damaged buildings on Risk Map

Discussion

Figure 6-28 clearly indicates that most of the damaged buildings are located in the high risk zones or close to the high risk zones. Only two buildings close to the ridge area are in the low risk zone. Few others lie in the moderate risk zones, but are close to the high risk areas.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusion

The main objective of the research was to assess vulnerability of buildings (building response and damage assessment) due to 6.9 Mw earthquake of 18th September, 2011, in Gangtok region which is a very important town with largest number of population closest to the epicentre (located at around 68 km from the epicentre). The study was carried out using HAZUS methodology which was originally developed for US buildings and latter on used elsewhere, and therefore, one of the aim was to compare the generated results with the actual damage occurred in the Gangtok area and assess the level of applicability of the methodology in Indian context. The main of objective of the research was achieved by completing two sub-objectives and third sub objective concentrated on the retrofitting of damaged buildings in the earthquake which results in reduction of vulnerability of buildings to future events. The conclusions derived from each sub objective are discussed in detail below.

Sub objective 1: To identify input parameters of HAZUS methodology for adapting in Indian context.

HAZUS methodology which was originally developed for multi hazard risk assessment of buildings in United States has been used in other parts of world including in India. The earthquake risk assessment module of HAZUS requires four main parameters for seismic risk assessment such as seismic hazard, ground motion, building inventory and damage functions. The seismic risk assessment mainly uses the non-linear structural analysis of buildings for developing damage probabilities. This requires structural properties of buildings along with properties of construction material and method of construction. These values were developed for buildings in US and are not currently available for Indian building types. So to adopt the HAZUS methodology to Indian condition, local building types was matched with the most likely building types as used in HAZUS. The similar mapping methods have been attempted by Prasad et al. (2009). The structural properties of a building are defined by the capacity curves of the building based on their seismic design level. These values are provided by FEMA (2011) in HAZUS technical manual.

Second parameter in the methodology was derived from the characterisation of earthquake scenario by simulating ground motion at the site of consideration. Earthquake magnitude, type of faulting, location of epicentre and depth, type of soil class, shear wave velocity of soil class were identified as the parameters for generating earthquake scenario (ground motion) using the attenuation function developed by Boore et al. (1997).The peak building response is calculated from the earthquake scenario and building structural properties. Using the spectral displacement, median value of spectral displacement at which building reaches the threshold of damage state, and other building parameters, the damage probabilities can be calculated for four levels of damages namely slight, moderate, extensive and complete damage states. It is concluded that the methodology can be adapted for the Indian context and damage results can closely match with real situation. However, without the availability of structural values required for the method, the developed scenarios may not be able to produce exact result due to variation of building type, construction practice, age and local conditions.

Sub objective 2: To estimate building damage in user defined earthquake scenario using adapted HAZUS methodology for Indian context and validate them

The level of applicability of the methodology in Indian context was known by comparing the generated results with actual damage in the field due to the 2011 earthquake. Buildings types in the study area were identified during the field visit and classified according to the HAZUS building types. The building damage data reported in the field by local authorities were collected for validation. Based on the identified building types, damage probabilities were estimated by following the HAZUS method for different possible ground motion scenarios. Four different building types and different shear wave velocities were considered.

The results showed that C3L types of buildings were highly vulnerable and there is a high probability of slight damage to such buildings. These scenarios were matched with the reported damage. So it is concluded that the HAZUS methodology can be used for Indian condition, and HAZUS building types have some similarity with Indian building types. It is also concluded that for generating real scenarios Indian building structural values should be used.

In order to assess high risk areas of the Gangtok region, land stability map, slope map and the building density map were integrated using AHP, in which weights were assigned to these maps and risk map was generated. Most of the visited damaged buildings are located in the high risk areas or close to the high risk areas. So the risk map can be further utilised for locating most probable areas of maximum damage, it can be further improved by incorporating local ground conditions of all the damaged buildings in Gangtok, which can be carried out in further research.

Sub objective 3: To make an general assessment of damage to built environment and comment on various prevention and retrofitting methods for reducing building damage.

From the field visit it is concluded that none of the building have any level of seismic design considerations and most of the buildings violate the local building laws. Poor construction practices were identified in the new constructions and old constructions were maintained in very bad conditions. Damage to different buildings was assessed and possible factors that caused building damages were identified for finding out the possible retrofitting methods. Based on the literature review and local condition, possible retrofitting measures were recommended for reducing the vulnerability. It is also observed that most of government buildings have experienced maximum damage, therefore, as a policy, it may be easier to implement retrofitting measures and better building construction practices in government buildings first followed by private buildings.

7.2. Recommendations

7.2.1. Recommendations for Gangtok City

- As Gangtok is one of the major urban areas and main resource of economy, detailed and sound building damage assessment need to be carried out with respect to building properties and foundation condition.
- It is recommended for developing codes for earthquake resistant designs and details for future constructions.
- Practices which were followed to repair the buildings don't meet the standards and these structures are not strong enough to sustain future earthquakes. So it is recommended to immediately repair, retrofit and strengthen the damaged buildings and make them strong enough to resist future earthquakes.

- As Gangtok lies in the high seismic zone, it is recommended to conduct training programs for all the masons and construction workers regarding the earthquake resistant construction practices.
- It is also recommended that all the building databases developed needed to updated on a regular basis by local authorities for efficient planning and preparedness in emergency situations.
- Gangtok is main tourist destination and it attracts many national and international tourists. It is strongly recommended that assessment of all the hotels, guest houses and other tourist related infrastructure to be carried out immediately and make these earthquake resistant, as damage to these structures can affect the income generated by tourism.
- It is recommended that proper disaster management and emergency management plan needed to be developed as Gangtok is one of highly populated areas of Sikkim and lies in high seismic hazard zone. It is also advised to conduct disaster management workshops and seminars to educate the people on disaster safety measures and prepare them for future events.
- All the hospitals, schools, government buildings have to be immediately made earthquake proof to minimise damage and loss in future events on a priority basis

7.2.2. Recommendations for further research.

- Development of structural parameters can produce more realistic scenario for vulnerability assessment.
- Similar vulnerability assessment is recommended in future when Indian building structural parameters are available for generating realistic scenarios.
- With the present generated damage probabilities, the building replacement costs can be calculated and based on the building vulnerability, population vulnerabilities can also be calculated for the Gangtok region and other areas of Sikkim.
- As the HAZUS methodology closely approximate Indian conditions, it can be used for generating the vulnerability scenarios of buildings in other cities located in high earthquake hazard zones.

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ANNEXURE – A

Generation of Discrete Damage probabilities

Step 1: Generation of Demand Spectrum

Demand Spectrum is generated by the Equation given by Boore et al. (1997) given Below.

$$\mathrm{Ln}(\mathrm{S_A}) = \mathrm{b}_1 + b_2(\mathrm{M}-6) + b_3(M-6)^2 + b_5\,\mathrm{Ln}(r) + b_v\,\mathrm{Ln}\left(\frac{V_s}{V_A}\right)$$

where $$r = \sqrt{r_{jb}^2 + h^2}$$

and

$$b_1 = \begin{cases} b_{1SS} & for\ strike - slip\ earthquakes \\ b_{1RV} & ifor\ reverse\ slip\ earthquakes \\ b_{1ALL} & if\ mechanism\ is\ not\ specified \end{cases}$$

where $\mathrm{S_A}$ is the spectral acceleration to be derived

$b_1, b_2, b_3, b_5, b_v, V_A, h$ are constants provided with the equation

M is the magnitude of earthquake

r_{jb} is the horizontal distance from epicentre

V_s the shear wave velocity of the soil class provided by NEHRP classification

The constants provided with equation by Boore et al. (1997) are

T	b_{1SS}	b_{1RV}	b_{1ALL}	b_2	b_3	b_5	b_v	V_A	h
0	-0.313	-0.117	-0.242	0.527	0	-0.778	-0.371	1396	5.57
0.1	1.006	1.087	1.059	0.753	-0.226	-0.934	-0.212	1112	6.27
0.11	1.072	1.164	1.13	0.732	-0.23	-0.937	-0.211	1291	6.65
0.12	1.109	1.215	1.174	0.721	-0.233	-0.939	-0.215	1452	6.91
0.13	1.128	1.246	1.2	0.711	-0.233	-0.939	-0.221	1596	7.08
0.14	1.135	1.261	1.208	0.707	-0.23	-0.938	-0.228	1718	7.18
0.15	1.128	1.264	1.204	0.702	-0.228	-0.937	-0.238	1820	7.23
0.16	1.112	1.257	1.192	0.702	-0.226	-0.935	-0.248	1910	7.24
0.17	1.09	1.242	1.173	0.702	-0.221	-0.933	-0.258	1977	7.21
0.18	1.063	1.222	1.151	0.705	-0.216	-0.93	-0.27	2037	7.16
0.19	1.032	1.198	1.122	0.709	-0.212	-0.927	-0.281	2080	7.1
0.2	0.999	1.17	1.089	0.711	-0.207	-0.924	-0.292	2118	7.02
0.22	0.925	1.104	1.019	0.721	-0.198	-0.918	-0.315	2158	6.83
0.24	0.847	1.033	0.941	0.732	-0.189	-0.912	-0.338	2178	6.62
0.26	0.764	0.958	0.861	0.744	-0.18	-0.906	-0.36	2173	6.39
0.28	0.681	0.881	0.78	0.758	-0.168	-0.899	-0.381	2158	6.17
0.3	0.598	0.803	0.7	0.769	-0.161	-0.893	-0.401	2133	5.94
0.32	0.518	0.725	0.619	0.783	-0.152	-0.888	-0.42	2104	5.72
0.34	0.439	0.648	0.54	0.794	-0.143	-0.882	-0.438	2070	5.5
0.36	0.361	0.57	0.462	0.806	-0.136	-0.877	-0.456	2032	5.3
0.38	0.286	0.495	0.385	0.82	-0.127	-0.872	-0.472	1995	5.1
0.4	0.212	0.423	0.311	0.831	-0.12	-0.867	-0.487	1954	4.91
0.42	0.14	0.352	0.239	0.84	-0.113	-0.862	-0.502	1919	4.74
0.44	0.073	0.282	0.169	0.852	-0.108	-0.858	-0.516	1884	4.57
0.46	0.005	0.217	0.102	0.863	-0.101	-0.854	-0.529	1849	4.41
0.48	-0.058	0.151	0.036	0.873	-0.097	-0.85	-0.541	1816	4.26

0.5	-0.122	0.087	-0.025	0.884	-0.09	-0.846	-0.553	1782	4.13
0.55	-0.268	-0.063	-0.176	0.907	-0.078	-0.837	-0.579	1710	3.82
0.6	-0.401	-0.203	-0.314	0.928	-0.069	-0.83	-0.602	1644	3.57
0.65	-0.523	-0.331	-0.44	0.946	-0.06	-0.823	-0.622	1592	3.36
0.7	-0.634	-0.452	-0.555	0.962	-0.053	-0.818	-0.639	1545	3.2
0.75	-0.737	-0.562	-0.661	0.979	-0.046	-0.813	-0.653	1507	3.07
0.8	-0.829	-0.666	-0.76	0.992	-0.041	-0.809	-0.666	1476	2.98
0.85	-0.915	-0.761	-0.851	1.006	-0.037	-0.805	-0.676	1452	2.92
0.9	-0.993	-0.848	-0.933	1.018	-0.035	-0.802	-0.685	1432	2.89
0.95	-1.066	-0.932	-1.01	1.027	-0.032	-0.8	-0.692	1416	2.88
1	-1.133	-1.009	-1.08	1.036	-0.032	-0.798	-0.698	1406	2.9
1.1	-1.249	-1.145	-1.208	1.052	-0.03	-0.795	-0.706	1396	2.99
1.2	-1.345	-1.265	-1.315	1.064	-0.032	-0.794	-0.71	1400	3.14
1.3	-1.428	-1.37	-1.407	1.073	-0.035	-0.793	-0.711	1416	3.36
1.4	-1.495	-1.46	-1.483	1.08	-0.039	-0.794	-0.709	1442	3.62
1.5	-1.552	-1.538	-1.55	1.085	-0.044	-0.796	-0.704	1479	3.92
1.6	-1.598	-1.608	-1.605	1.087	-0.051	-0.798	-0.697	1524	4.26
1.7	-1.634	-1.668	-1.652	1.089	-0.058	-0.801	-0.689	1581	4.62
1.8	-1.663	-1.718	-1.689	1.087	-0.067	-0.804	-0.679	1644	5.01
1.9	-1.685	-1.763	-1.72	1.087	-0.074	-0.808	-0.667	1714	5.42
2	-1.699	-1.801	-1.743	1.085	-0.085	-0.812	-0.655	1795	5.85

The other parameters considered in the equation are

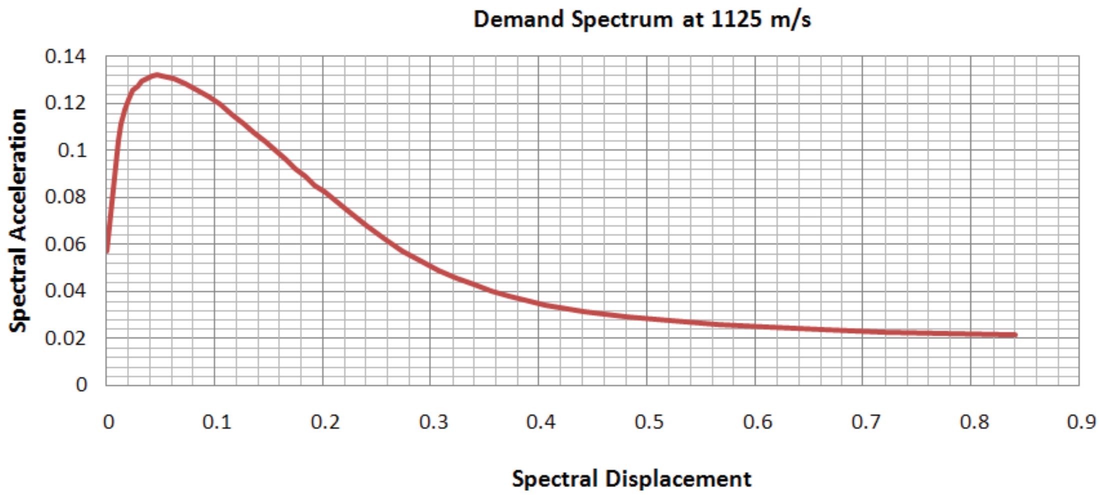
M	6.9
r_{jb}	68.7487 Km
V_s	Site class – B – Average – 1125 m/s

Then from the equation spectral acceleration S_A is derived. Then S_D is calculated from the equation given below

$$S_D = 9.8 \times S_A \times T^2$$

where S_A is the Spectral Acceleration calculated from the first equation
T is the time period in seconds as given in the constants provided with the equation

So we get demand spectrum when we plot the generated S_D in x-axis and S_A in y –axis shown in the graph below.

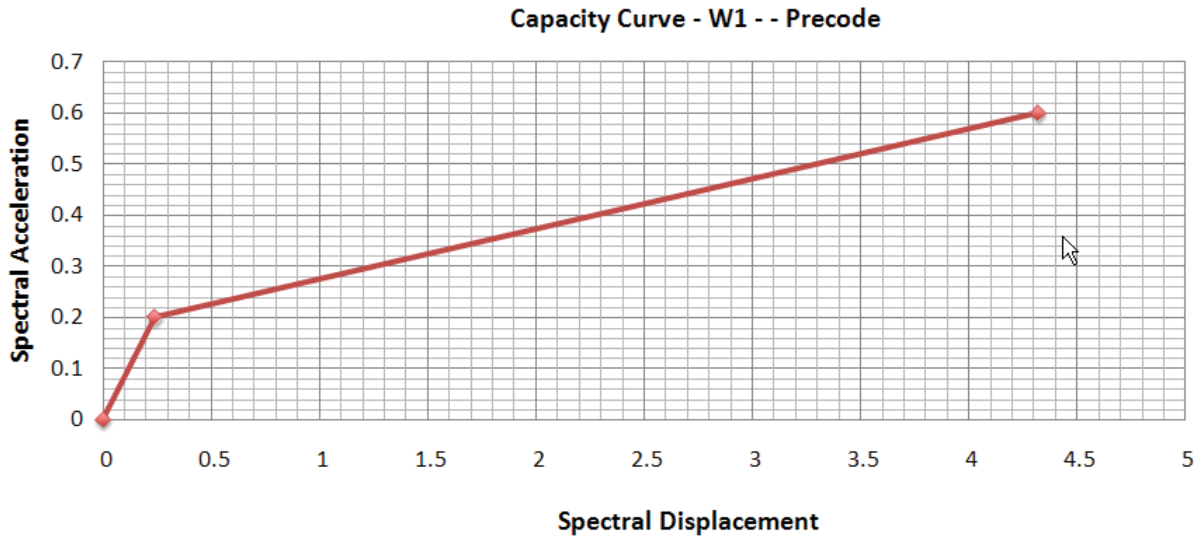


Step 2: Generation of Capacity Curves

The capacity curves of buildings are generated by the parameters given by the HAZUS manual for each building type. The values for wooden building type W1 are given in the table below. Different seismic level design has different values. The values of pre-code design level and taken in the case.

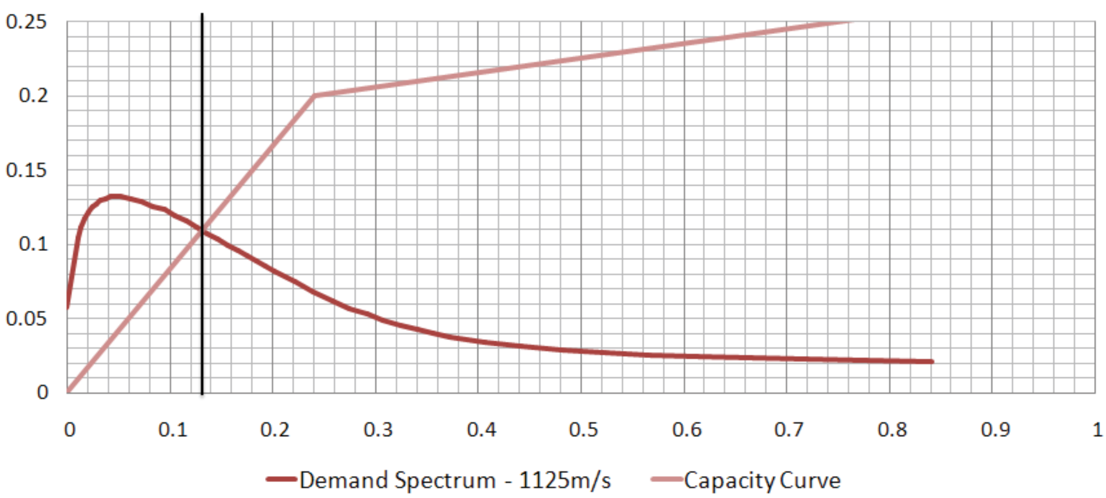
Building Type	Yield Capacity		Ultimate Capacity	
	D_y	A_y	D_u	A_u
	Pre- Code –Seismic Design			
W1	0.24	0.200	4.32	0.600

The plot between the yield capacity points and ultimate capacity points generates the capacity curves.



Step 3: Calculate Peak Building Response (S_D)

By overlaying the capacity curve over the demand spectrum, the value at the intersection point of two graphs gives us the peak spectral displacement or peak building response from which the damage probabilities are calculated. The intersection point is shown in the graph below.



Peak Building Response	
Building Type	W1
Peak Building Response (S_D)	0.12

Step 4: Calculation of Damage Probability

HAZUS manual has given the formula for calculating the damage probability. The damage probabilities are calculated for four damage scenarios, slight, moderate, extreme and complete by the given equation below.

$$P(d_S|S_d) = \Phi\left[\frac{1}{\beta_{ds}}\ln\left(\frac{S_d}{\bar{S}_{d,ds}}\right)\right]$$

where $P(d_S|S_d)$ is the probability of reaching the slight damage state for a given peak building response S_d

$\bar{S}_{d,ds}$ is the median value of spectral displacement at which the building reaches the threshold of damage state,

β_{ds} is the standard deviation of the natural logarithm of spectral displacement for damage state d_s

Φ is the standard normal cumulative distribution function

Median and standard deviation values for each damage state and for seismic design levels are given in the manual. The parameters given for the W1 building, pre-design level code for slight, moderate, extreme and complete are given in the table below.

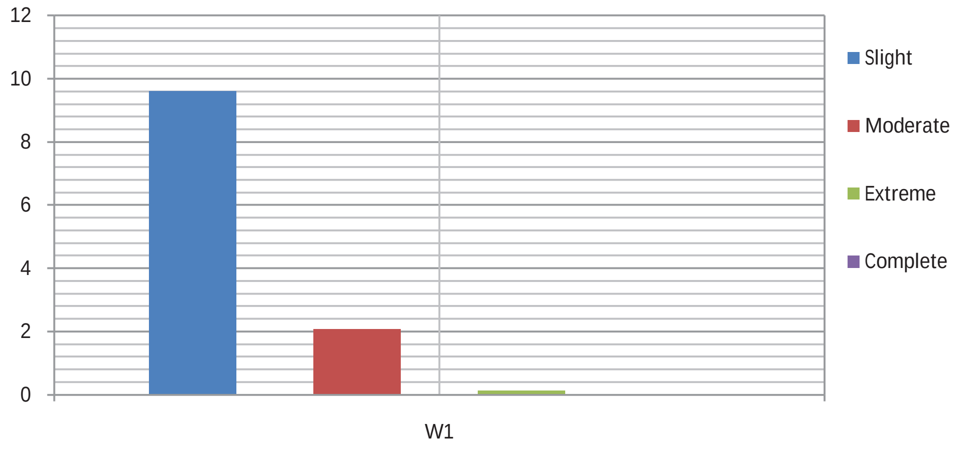
Building Type	Slight		Moderate		Extensive		Complete	
	$\bar{S}_{d,ds}$	β_{ds}	$\bar{S}_{d,ds}$	β_{ds}	$\bar{S}_{d,ds}$	β_{ds}	$\bar{S}_{d,ds}$	β_{ds}
Pre- Code –Seismic Design								
W1	0.40	1.01	1.00	1.05	3.09	1.07	7.56	1.06

By using these values the cumulative damage probabilities for each state are generated. From these cumulative damage probabilities, discrete damage probabilities are calculated from the equations given below.

Probability		
Complete Damage	$P[C]=$	$P(C\|S_d)$
Extensive Damage	$P[E]=$	$P(E\|S_d) - P(C\|S_d)$
Moderate Damage	$P[M]=$	$P(M\|S_d) - P(E\|S_d)$
Slight Damage	$P[S]=$	$P(S\|S_d) - P(M\|S_d)$
No Damage	$P[N]=$	$1 - P(E\|S_d)$

	Slight	Moderate	Extreme	Complete
Cumulative Damage Probability	$P(S\|S_d)$	$P(M\|S_d)$	$P(E\|S_d)$	$P(C\|S_d)$
	0.1166	0.0217	0.0012	0.0000
Discrete Damage Probability	$P[S]$	$P[M]$	$P[E]$	$P[C]$
	0.0960	0.0206	0.0012	0.0000

Percentage	Slight	Moderate	Extreme	Complete
	9.6045	2.0575	0.1153	0.0046



Cumulative Damage Probabilities – Low –code

Cumulative Damage Probabilities – Low Code at 270 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.1887	0.0381	0.0025	0.0001
C3L	0.4791	0.2416	0.0614	0.0029
C3M	0.3901	0.1312	0.0097	0.0030
C3H	0.4266	0.1337	0.0268	0.0038

Cumulative Damage Probabilities – Low Code at 560 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.1103	0.0180	0.0009	0.0000
C3L	0.2284	0.0799	0.0125	0.0002
C3M	0.1189	0.0205	0.0005	0.0002
C3H	0.1329	0.0228	0.0039	0.0004

Cumulative Damage Probabilities – Low Code at 760 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.0855	0.0127	0.0006	0.0000
C3L	0.1445	0.0420	0.0052	0.0000
C3M	0.0659	0.0087	0.0001	0.0001
C3H	0.0759	0.0105	0.0018	0.0002

Cumulative Damage Probabilities – Low Code at 1125 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.0624	0.0084	0.0003	0.0000
C3L	0.0838	0.0200	0.0020	0.0000
C3M	0.0384	0.0041	0.0000	0.0000
C3H	0.0353	0.0038	0.0007	0.0001

Cumulative Damage Probabilities – Low Code at 1500 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.0418	0.0050	0.0002	0.0000
C3L	0.0609	0.0131	0.0011	0.0000
C3M	0.0250	0.0022	0.0000	0.0000
C3H	0.0173	0.0015	0.0003	0.0000

Cumulative Damage Probabilities – Pre-code

Cumulative Damage Probabilities – Pre Code at 270 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.2770	0.0746	0.0068	0.0004
C3L	0.5570	0.3248	0.1047	0.0064
C3M	0.5240	0.2287	0.0420	0.0062
C3H	0.5687	0.2268	0.0501	0.0071

Cumulative Damage Probabilities – Pre Code at 560 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.1821	0.0405	0.0028	0.0001
C3L	0.3121	0.1335	0.0280	0.0005
C3M	0.2022	0.0466	0.0044	0.0004
C3H	0.2187	0.0471	0.0079	0.0007

Cumulative Damage Probabilities – Pre Code at 760 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.1493	0.0306	0.0019	0.0001
C3L	0.2177	0.0793	0.0135	0.0001
C3M	0.1199	0.0209	0.0015	0.0001
C3H	0.1383	0.0240	0.0038	0.0003

Cumulative Damage Probabilities – Pre Code at 1125 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.1166	0.0217	0.0012	0.0000
C3L	0.1417	0.0434	0.0060	0.0000
C3M	0.0773	0.0109	0.0007	0.0000
C3H	0.0679	0.0089	0.0014	0.0001

Cumulative Damage Probabilities – Pre Code at 1500 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.0849	0.0142	0.0007	0.0000
C3L	0.1102	0.0307	0.0038	0.0000
C3M	0.0544	0.0065	0.0003	0.0000
C3H	0.0401	0.0044	0.0007	0.0000

Discrete Damage Probabilities – Low -code

Discrete Damage Probabilities – Low Code at 270 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.1530	0.0357	0.0024	0.0001
C3L	0.2960	0.1831	0.0585	0.0029
C3M	0.2657	0.1245	0.0067	0.0030
C3H	0.3159	0.1108	0.0230	0.0038

Discrete Damage Probabilities – Low Code at 560 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.0932	0.0171	0.0009	0.0000
C3L	0.1609	0.0676	0.0123	0.0002
C3M	0.0987	0.0202	0.0003	0.0002
C3H	0.1136	0.0193	0.0035	0.0004

Discrete Damage Probabilities – Low Code at 760 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.0734	0.0122	0.0006	0.0000
C3L	0.1077	0.0368	0.0052	0.0000
C3M	0.0573	0.0086	0.0001	0.0001
C3H	0.0670	0.0089	0.0016	0.0002

Discrete Damage Probabilities – Low Code at 1125 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.0544	0.0081	0.0544	0.0000
C3L	0.0658	0.0180	0.0658	0.0000
C3M	0.0344	0.0040	0.0344	0.0000
C3H	0.0320	0.0032	0.0320	0.0001

Discrete Damage Probabilities – Low Code at 1500 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.0370	0.0048	0.0370	0.0000
C3L	0.0490	0.0119	0.0490	0.0000
C3M	0.0227	0.0022	0.0227	0.0000
C3H	0.0160	0.0013	0.0160	0.0000

Discrete Damage Probabilities – Pre-code

Discrete Damage Probabilities – Pre Code at 270 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.2086	0.0683	0.0063	0.0004
C3L	0.3305	0.2265	0.0983	0.0064
C3M	0.3311	0.1929	0.0358	0.0062
C3H	0.3848	0.1838	0.0430	0.0071

Discrete Damage Probabilities – Pre Code at 560 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.2086	0.0683	0.0063	0.0001
C3L	0.3305	0.2265	0.0983	0.0005
C3M	0.3311	0.1929	0.0358	0.0004
C3H	0.3848	0.1838	0.0430	0.0007

Discrete Damage Probabilities – Pre Code at 760 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.1206	0.0287	0.0018	0.0001
C3L	0.1519	0.0659	0.0134	0.0001
C3M	0.1005	0.0195	0.0014	0.0001
C3H	0.1178	0.0205	0.0035	0.0003

Discrete Damage Probabilities – Pre Code at 1125 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.0960	0.0206	0.0012	0.0000
C3L	0.1043	0.0374	0.0060	0.0000
C3M	0.0671	0.0102	0.0006	0.0000
C3H	0.0603	0.0076	0.0013	0.0001

Discrete Damage Probabilities – Pre Code at 1500 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	0.0714	0.0135	0.0006	0.0000
C3L	0.0832	0.0269	0.0038	0.0000
C3M	0.0482	0.0062	0.0003	0.0000
C3H	0.0364	0.0038	0.0006	0.0000

Percentage Damage – Low-code

Percentage of Damage – Low Code at 270 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	15.2957	3.5722	0.2415	0.0073
C3L	29.6037	18.3053	5.8530	0.2868
C3M	26.5667	12.4465	0.6718	0.2990
C3H	31.5866	11.0756	2.2968	0.3788
Average	25.76318	11.3499	2.265775	0.242975

Percentage of Damage – Low Code at 560 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	9.3166	1.7084	0.0883	0.0019
C3L	16.0882	6.7564	1.2346	0.0165
C3M	9.8712	2.0217	0.0264	0.0207
C3H	11.3595	1.9330	0.3472	0.0405
Average	11.65888	3.104875	0.424125	0.0199

Percentage of Damage – Low Code at 760 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	7.3353	1.2181	0.0563	0.0010
C3L	10.7689	3.6806	0.5192	0.0036
C3M	5.7272	0.8635	0.0058	0.0068
C3H	6.6999	0.8939	0.1608	0.0169
Average	7.632825	1.664025	0.185525	0.007075

Percentage of Damage – Low Code at 1125 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	5.4381	0.8068	0.0328	0.0005
C3L	6.5761	1.8049	0.1964	0.0007
C3M	3.4362	0.4043	0.0014	0.0027
C3H	3.2039	0.3228	0.0603	0.0057
Average	4.663575	0.8347	0.072725	0.0024

Percentage of Damage – Low Code at 1500 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	3.6953	0.4811	0.0169	0.0002
C3L	4.8970	1.1943	0.1135	0.0003
C3M	2.2727	0.2230	0.0004	0.0013
C3H	1.6012	0.1288	0.0256	0.0022
Average	3.11655	0.5068	0.0391	0.001

Percentage Damage – Pre-code

Percentage of Damage – Pre Code at 270 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	20.8648	6.8305	0.6343	0.0424
C3L	33.0543	22.6463	9.8319	0.6388
C3M	33.1062	19.2890	3.5816	0.6161
C3H	38.4847	18.3830	4.2985	0.7139
Average	31.3775	16.7872	4.586575	0.5028

Percentage of Damage – Pre Code at 560 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	14.4371	3.7775	0.2690	0.0138
C3L	20.6073	10.5980	2.7558	0.0468
C3M	15.9555	4.2678	0.3954	0.0418
C3H	17.8773	3.9951	0.7156	0.0737
Average	17.2193	5.6596	1.03395	0.044025

Percentage of Damage – Pre Code at 760 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	12.0564	2.8739	0.1831	0.0084
C3L	15.1852	6.5896	1.3421	0.0115
C3M	10.0451	1.9482	0.1395	0.0126
C3H	11.7781	2.0516	0.3519	0.0314
Average	12.2662	3.365825	0.50415	0.015975

Percentage of Damage – Pre Code at 1125 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	9.6045	2.0575	0.1153	0.0046
C3L	10.4302	3.7442	0.5955	0.0024
C3M	6.7087	1.0243	0.0611	0.0049
C3H	6.0253	0.7618	0.1281	0.0096
Average	8.192175	1.89695	0.225	0.005375

Percentage of Damage – Pre Code at 1500 m/s				
Building Type	Slight	Moderate	Extreme	Complete
W1	7.1437	1.3506	0.0650	0.0022
C3L	8.3246	2.6905	0.3761	0.0010
C3M	4.8209	0.6166	0.0323	0.0024
C3H	3.6355	0.3752	0.0637	0.0043
Average	5.981175	1.258225	0.134275	0.002475

ANNEXURE – B

Analytical Hierarchy Process (AHP)

Pair-wise comparison scale

Numerical Rating	Judgments
9	Extremely preferred
8	Very strongly to extremely
7	Very strongly preferred
6	Strongly to very strongly
5	Strongly preferred
4	Moderately to strongly
3	Moderately preferred
2	Equally to moderately
1	Equally preferred

Pair- wise comparison matrix

	Land Stability	Building Density	Slope
Land Stability	1.000	1.000	5.000
Building Density	1.000	1.000	3.000
Slope	0.200	0.333	1.000
Row total	2.200	2.333	9.000

Synthesized Matrix

	Land Stability	Building Density	Slope	Priority Vector
Land Stability	0.455	0.429	0.556	0.480
Building Density	0.455	0.429	0.333	0.405
Slope	0.143	0.091	0.111	0.115
			Total	1.000

Weighted sum matrix

$$0.405* \begin{vmatrix} 1.000 \\ 1.000 \\ 0.200 \end{vmatrix} + 0.480 * \begin{vmatrix} 1.000 \\ 1.000 \\ 0.333 \end{vmatrix} + 0.115 * \begin{vmatrix} 5.000 \\ 3.000 \\ 1.000 \end{vmatrix} = \begin{vmatrix} 1.460 \\ 1.230 \\ 0.346 \end{vmatrix}$$

All the elements in the of the weighted sum matrices were divided by theie respective priority vector element.

$$\frac{1.230}{0.405} = 3.044, \quad \frac{1.460}{0.480} = 3.033, \quad \frac{1.000}{0.115} = 3.010$$

The average of all these values were the computed to obtain λ_{max}

$$\lambda_{max} = \frac{3.033+3.044+3.010}{3} = 3.029$$

Consistency Index

$$CI = \frac{\lambda_{max} - n}{n-1}$$

Number of factors n=3

$$CI = \frac{3.029 - 3}{3-1} = 0.015$$

Average Random Consistency Matrix (ARI)

Factors	1	2	3	4	5	6	7	8	9	10
ARI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Consistency Ratio

$$CR = \frac{CI}{ARI}$$

ARI = 0.58

$$CI = \frac{0.015}{0.58} = 0.025$$

As the value of the consistency ratio was less than 0.1, the above weights assigned are. acceptable