SEISMIC RISK ASSESSMNET DUE TO SCENARIO EARTHQUAKE: A CASE-STUDY FOR BIHAR-NEPAL EARTHQUAKE-1934

A DISSERTATION

Submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
DISASTER MITIGATION AND MANAGEMENT

By

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CENTRE OF EXCELLENCE IN DISASTER MITIGATION AND MANAGEMENT
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
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MAY 2016

CANDIDATE'S DECLARATION

I, hereby ,declare that the work which is being presented in the dissertation entitled "**Seismic Risk Assessment due to Scenario Earthquake: A case-study for Bihar-Nepal Earthquake-1934**",in partial fulfilment of the requirement for the award of the degree of Master of Technology in Disaster Mitigation and Management, submitted in the Centre of Excellence in Disaster Mitigation and Management , Indian Institute Of Technology –Roorkee, Roorkee ,is an authentic record of my own work carried out under the guidance of **Dr. M.L. Sharma, Professor**, Department of Earthquake Engineering, Indian Institute of Technology Roorkee.

I have not plagiarized or submitted the same work for the award of any other degree. In case this undertaking is found incorrect, I accept that my degree may be unconditionally withdrawn.

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Dated: 16-05-16 **(ANKITA PRASUN)**

Place: Roorkee

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ACKNOWLEDGMENT

I take this opportunity to express my gratitude to **Dr. M. L. Sharma**, Professor, Department of Earthquake Engineering, Indian Institute of Technology Roorkee, India, for giving me an opportunity to work under his esteemed guidance. His superb guidance with enriched knowledge, regular encouragement and valuable suggestions at every stage of the present work has proved to be extremely beneficial to me. I consider myself fortunate to have had the opportunity to work under his able guidance and enrich myself from his depths of knowledge. Also, I would like to thank **Prof. B. K. Maheshwari**, The Head, Centre of Excellence in Disaster Mitigation and Management, IIT Roorkee; for allowing me to carry on with the official formalities for this project. In addition to this, I would definitely like to extend my gratitude towards **Prof. Ajay Gairola and Prof. D. K. Paul** for constantly encouraging me for this work. I am thankful to **Prof. Kamal Jain**, Chairman Academic Programme Committee, CoEDMM, IIT Roorkee and other faculty members for their valuable criticisms and advice during each and every stage of this dissertation.

I consider myself fortunate enough to have gained ample knowledge related to the topic of dissertation during my internship at BSDMA (Bihar State Disaster Management Authority). I am greatly thankful to **Sri. Anil Sinha Sir**, Vice – Chairman, BSDMA; **Sri. Barun Kant Mishra**, Senior Technical Advisor; **Dr. Anand Bijeta**, Project Officer; **Mr. Vishal Vasvani**, Project Officer; **Dr. Madhubala**, Project Officer; **Mr. Asif Shahab**, Project Officer and **Ms. Sumbul Afroz**, Senior Technical Assistant; for their precious advice and tremendous support. I must thank **Dr. A. S. Arya**, member at BSDMA; for motivating me to perform this dissertation work. I would definitely like to extend my gratitude to **Dr. Amir Ali Khan**, Assistant Professor; **Dr. Chandan Ghosh**, Professor and **Prof. Santosh Kumar**, Executive Director for involving me in the important discussions relating the topic at NIDM (National Institute of Disaster Management).

I am also grateful to Mr. Tahir Hussain, Steno to the Head, CoEDMM, IIT Roorkee; for facilitating me with the official services and formalities.

I must acknowledge the help and support which I have been provided with, by few of my friends- Pratyasha Patnaik, Prashansa Dixit, Richa Gupta, Deepshikha Singh, Shivani Mam, Praveen Kumar, Abhishek Kumar, Kuldeep, Irfan H Khan and Suryendu Das Gupta.

Last but never the least,it is all owed to the blessings of my respected and loving **parents** and **family members** for supporting me in every possible sense that I have come up with this work in due time . Ultimately, I thank the almighty for making everything possible for me to complete my work positively.

Ankita Prasun.

ANKITA PRASUN

Enrollment. No: 14552001

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NOMENCLATURE

CBD_i	Cost of building damage in occupancy i
$FAMBT, i$	Percentage floor area of a MBT (*Model Building Type*)
TBA_i	Total built-up area of occupancy i
$\sum P(Grj)_{\mathrm{MBT}}$	Probability of damage grade j in a MBT
LR_j	Building loss ratio for damage grade j
$\mathrm{RV}_{\mathrm{MBT}}$	Building Replacement value for a MBT
NG5_V	Number of buildings suffering Damage Grade 5 which lie in the seismic zone V of the region.
NG5_IV	Number of buildings suffering Damage Grade 5 which lie in the seismic zone IV of the region.
NG5_III	Number of buildings suffering Damage Grade 5 which lie in the seismic zone III of the region.
NG4_V	Number of buildings suffering Damage Grade 4 which lie in the seismic zone V of the region.
NG4_IV	Number of buildings suffering Damage Grade 4 which lie in the seismic zone IV of the region.
NG4_III	Number of buildings suffering Damage Grade 4 which lie in the seismic zone III of the region.

ABSTRACT

Bihar state sits on a high seismic zone which falls on the boundary of a convergent tectonic plate near the Bihar-Nepal border. Out of 38 districts in Bihar, 8 districts lie in Zone V, 24 districts in Zone IV and 6 districts in Zone III of the seismic zone. The Himalayan tectonic plate is moving towards the Indian Plate slowly and gradually. This dangerous plate tectonic behaviour has already caused a number of devastating earthquakes in the past. The continuous movement of plate projects an alarming picture for the state in future. The state has experienced high levels of destruction each time. The project focuses on the mitigation of the damage caused due to scenario earthquake in the state of Bihar. The Bihar-Nepal Earthquake-1934 has been taken as the scenario earthquake in this study. The term *'Scenario Earthquake'* here refers to a condition in which a hypothetical recurrence of an earthquake is assumed in Bihar; whose magnitude, intensity and epicentre is considered same as of any previous earthquake of the focussed region of study. For the same reason, risk associated with the state has been identified by performing a Seismic Risk Assessment. Total expected direct and indirect losses are calculated in terms of rupees and number of deaths (caused due to the collapse of buildings) respectively. Consequently, the results obtained out of this assessment projects the most vulnerable districts of the state during any scenario earthquake. The project then discusses about the prevailing housing typologies in Bihar state. The most common type of building construction in the region, i.e. Burnt Brick Construction; has been identified and discussed in context of the state. Since, Bihar has witnessed a number of earthquakes in the past; buildings of the state have suffered great damage. In this context, the building deficiencies and damage trend observed in such structures have been laid out. Further, based on scenario studies, the first eight worst affected districts of the state have been projected. The typical types of cracks and building failures observed in burnt brick masonry structure due to the previous earthquakes are also outlined. Eventually, retrofitting recommendations for this typical construction has been given.

CHAPTER 1
INTRODUCTION

1.1 PREAMBLE

Earthquake is a natural disaster, but it can trigger man-made disasters as well. Bihar lies in the Zone IV and Zone V of the seismic zone belt of India. This makes the buildings of Bihar extremely vulnerable to damage in any future earthquake. The state has already witnessed a number of devastating earthquakes in the past. Case-studies of all the major previous earthquakes have been performed in the project report. The damage suffered by the state after every earthquake has been discussed in detail. Later, the building typology of the epicentral tract of Bihar-Nepal earthquake is studied. The major types of buildings are categorized based on their building materials. The percentage number of buildings falling under each category in the state is shown. In order to identify the risk associated with the state, Seismic Risk Assessment for scenario earthquake has been done. The term *'Scenario Earthquake'* refers to a condition in which a hypothetical recurrence of an earthquake is assumed whose magnitude, intensity and epicentre is considered same as of any previous earthquake of the focussed region of study. The case-study of 1934 Bihar-Nepal Earthquake has been considered for the seismic risk assessment. In this procedure, direct and indirect losses have been calculated, which the state may suffer due to any scenario earthquake. Based on the results obtained after seismic risk assessment, the most vulnerable districts of the state have been projected out. Comparison has also been made between the worst affected districts during 1934 Bihar-Nepal Earthquake and the scenario earthquake. Later, peculiar geological condition of Munger district and the reason behind its unique behaviour has been studied.

In the recent Gorkha Earthquake-2015, a large number of buildings got damaged in Bihar and Nepal. It becomes necessary to retrofit the damaged structures in order to prevent further disasters. The Unreinforced and Reinforced Masonry constructions have been discussed in the project. Then the typical construction type which is prevalent in the region has been explained in detail. Focus has been put on the construction style and building components which are common in Bihar. For example: use of poor quality of masonry in economically weaker sections of the society, openings supported by discontinuous lintel band, frequent use of half brick thick internal walls, etc. Then, the performances of both Unreinforced and Reinforced Masonry buildings in the previous earthquakes are shown in this report. For projection of the worst hit districts of Bihar in future, seismic risk assessment due to the scenario earthquake has been performed. A case of 1934 Bihar-Nepal Earthquake is considered for the same. The result of this study highlights the eight districts of Bihar which may suffer the most devastation in case of recurrence of such an earthquake of similar magnitude and intensity. Now that buildings in Bihar have already endured damages in the recent Gorkha Earthquake-2015, study has been carried out in this paper to outline the types of cracks and failures observed in Brick Masonry Buildings of the region. Then, retrofitting measures for the same are recommended for future.

1.2 NEED OF THE STUDY

Bihar lies in the Zone IV and Zone V of the seismic zone belt of India. The state has high local population density, thick alluvium cover and high pace of development. These all reasons bring the need for a seismic risk assessment of the state. For mitigation of the damage caused due to any scenario earthquake disaster, seismic risk assessment is important. It is important to study the built environment and typical building typology of the state. Then, depending upon their vulnerability and damage trend observed in previous earthquakes, it becomes essential to suggest the retrofitting measures for those typical structures. The essence of this study is basically to mitigate the state of Bihar from damage due to any future earthquake.

1.3 AIM AND OBJECTIVES

The aim of this dissertation project is to mitigate the damage which the state of Bihar may suffer due to any scenario earthquake.

Following are the objectives of this study:

- To understand the seismicity of the state and study the previous major and great earthquakes of the region.
- To study the building typology of the state.
- To identify the risk associated with the state and estimate the expected loss to be suffered due to scenario earthquake.
- To project the worst affected districts of Bihar during scenario earthquake.
- To make a comparison between worst affected districts of scenario earthquake and Bihar-Nepal 1934 Earthquake.

- To identify the typical housing typology of the state and suggest retrofitting guidelines for them depending upon the type of damage observed in previous earthquakes.

1.4 SCOPE OF WORK

The scope of work includes taking the case-study of Bihar-Nepal Earthquake-1934 into account and identifying the risk upon the state based on scenario earthquake studies. Suggesting retrofitting guidelines for the common housing typologies of Bihar for the damage caused due to scenario earthquake.

1.5 DISSERTATION OUTLINE

The first chapter of this dissertation gives the introduction of the work with its need, objectives and scope followed by the second chapter which throws light on the damage scenarios of past earthquakes of Bihar. Further, a study has been carried out about the building typologies of the state. In the next chapter, identification of risk associated with the state due to scenario earthquake has been discussed. Consequently, after the estimation of expected loss which the state may suffer; worst affected districts have been projected. The common housing typology is identified and retrofitting measures have been recommended for them.

CHAPTER 2

DAMAGE SCENARIOS DUE TO PAST EARTHQUAKES

2.1 PAST EARTHQUAKES OF BIHAR

Bihar and Nepal share common geographical location. Bihar has always shared the common grief of disasters like earthquake and flood. Also, Bihar is a multi-hazard prone state of India which has witnessed a number of deadly earthquakes till date. Of all the earthquakes from the long history, few of the important and damaging have been discussed here.

1. Bihar-Nepal Earthquake 1833
2. Bihar-Nepal Earthquake 1934
3. Bihar-Nepal Earthquake 1988
4. Bihar-Nepal Earthquake 2015

2.1.1BIHAR-NEPAL EARTHQUAKE 1833

The earthquake occurred on August 26th, 1833. The tremor was felt over a large part of northern India. It triggered just before the midnight shaking around 1 million sq kms region of northern India. The main shock was preceded by the two large foreshocks (5 hrs and 15 minutes before the main shock). This acted as an alarm to alert people and eventually helped in lesser loss of life. Tibet and Nepal mainly suffered huge losses. 4600 houses and many temples were destroyed by the earthquake induced landslides and rockfalls in both the regions *('Damage Scenario Under Hypothetical Recurrence of 1934 Earthquake intensities in various districts in Bihar', BSDMA report).* Less than 500 casualties were reported. India suffered very less damage with less than 10 fatalities.

Table 2.1: Introduction to Bihar-Nepal Earthquake 1833

Date	August 26, 1833
Time	23:35 (Calcutta time)
Magnitude	7.5 to 7.9
Epicentre	Lat. 27.5 N and Long. 86.5 E (around 100kms from Indian border and NE of Kathmandu)
Casualties in India	<10
Building Damages in India	Very less damage, total destruction of very few buildings
Casualties in Nepal and Tibet	<500
Building damages in Nepal and Tibet	4600 dwellings and many temples

The main shock of the earthquake was felt from Delhi to Chittagong. The intensities were observed to be high in mountainous regions of Kathmandu (especially near and north of Kathmandu). The northern end of the southern Tibet experienced very high intensities. In Muzaffarpur, water was observed to be thrown out of the tanks 1.2 m deep. Munger and Muzaffarpur were the most suffered districts of Bihar.

2.1.2 BIHAR-NEPAL EARTHQUAKE 1934

Bihar and Nepal was hit by a devastating earthquake at 14:13 hrs, January 15th in the year 1934. The shock was of very high magnitude of 8.1 which affected a large part of Bihar and Nepal. This was considered as the worst earthquake in the history of India and Nepal. The epicentre of the earthquake lied in the eastern Nepal, about 10 kms south of Mount Everest. The depth of focus was 33 kms. Since, the adjoining boundaries of these two affected regions lie on the divergent plate boundary of Main Boundary Thrust (MBT); the fault type was of Convergent (Destructive) kind. Extreme liquefaction of soil took place over a length of 3 kms in Bihar in which many structures went afloat. The Iso-seismal map of this earthquake is shown below.

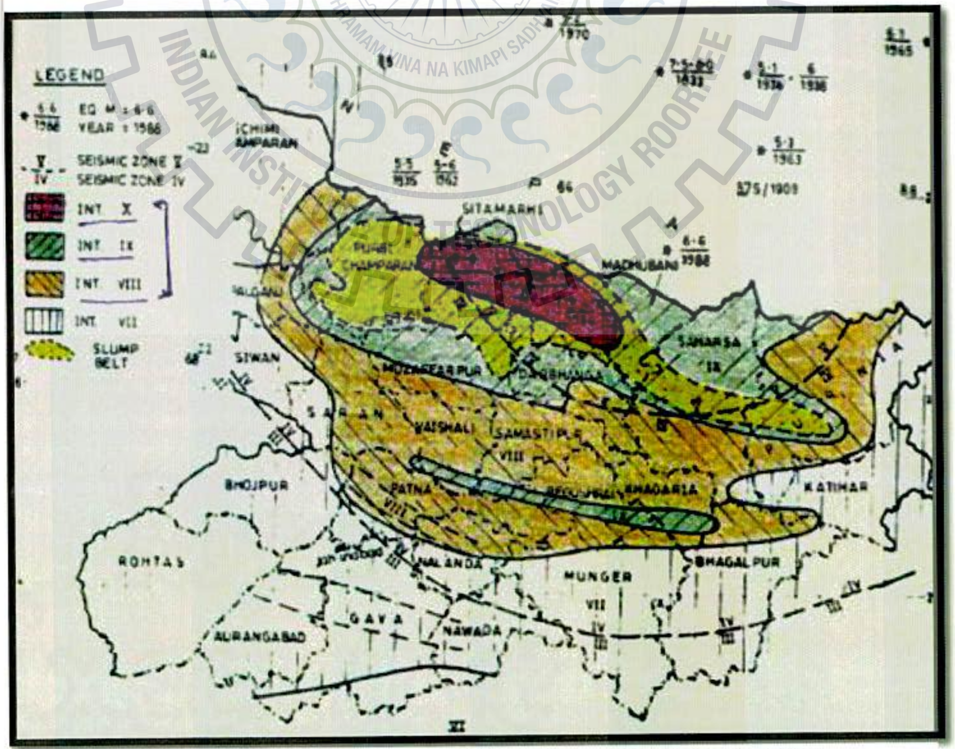


Figure 1: Iso-seismal map of Bihar-Nepal Earthquake-1934

Table 2.2: Introduction to Bihar-Nepal Earthquake 1934

Date	January 15, 1934
Time	14:13 (IST)
Magnitude	7.5 - 8.0
Epicentre	Lat. 26.6o N, Long. 86.2oE
Casualties in India	7153
Worst affected districts in India	Sitamarhi, Munger, Muzaffarpur, Champaran
Casualties in Nepal	8519
Worst affected districts in Nepal	Kathmandu, Bhaktpur, Patan

Sitamarhi and Munger districts in India and Bhaktgaon in Nepal were completely damaged and no buildings remained standing. Other cities of Motihari, Muzaffarpur and Darbhanga city in Bihar were severely affected by the earthquake. Bhaktpur, Patan and Kathmandu in Nepal were the cities which were destroyed completely. A very destructive ground failure was observed in Bihar. Large tract of ground which stretched for 300 kms in length and about 50 kms in width slumped due to liquefaction. Districts like East Champaran, Sitamarhi, Madhubani, Saharsa and Purnia fell on this belt of liquefaction. As a result of this, many buildings went afloat. Sand- fountains and boils were largely observed at many places. Sand fissures erupted at several places in Muzaffarpur town. Buildings in Sitamarhi, Madhubani and Purnia were seen tilted and many sank into the ground. The stretch of slump zone belt is shown in the given map (Figure: 1). Also, the intensity depicted on the map (Figure: 1) in the form of Modified Mercalli Scale explains the effect and severity of the earthquake. Cities sitting on the river bed of The Ganga (Patna, Barh and Jamalpur) also experienced heavy damage to houses and infrastructure (especially roads). Munger town which is situated more than 120 kms from the epicentre suffered more damage than the cities which lie in between. The reason behind this was the peculiar geological condition on which the town sits. The town rests on a thick layer of alluvium which is abutted by Archaean Quartzite.

Figure 2: Navlakha Palace, Madhubani (Bihar) damaged after earthquake

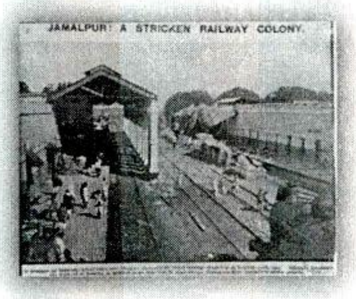


Figure 3: Railway station after earthquake at Munger, Bihar (India)

Table 2.3: Districts lying under different seismic zones and intensities

ZONE	INTENSITY	NUMBER OF DISTRICTS	NAME OF DISTRICTS
V	MSK X	3	Parts of Sitamarhi, Madhubani and East Champaran
IV	MSK IX	8	Sitamarhi, Madhubani, Darbhanga, Saharsa, Supaul, Araria, Kishanganj and Madhepura
IV and III	MSK VIII	20	Gopalganj, Muzaffarpur, Vaishali, Samastipur, Begusarai, Khagaria, Purnia, Katihar, Bhojpur, Patna, Jahanabad, Arwal, Nalanda, Nawada, Shekhpura, Lakhisarai, Jamui, Munger, Bhagalpur and Banka

2.1.3 LITERATURE REVIEW OF ‘DAMAGE SCENARIO UNDER GREAT EARTHQUAKES, A CASE-STUDY OF 1934 BIHAR-NEPAL EARTHQUAKE

Damage scenario under hypothetical recurrence of 1934 Bihar- Nepal Earthquake intensities has been estimated in the literature. The calculations are done using open software tool known as ‘SeisVARA’ (Seismic Vulnerability and Risk Assessment of Housing). The probable damage in Bihar arising due to scenario earthquake, both economic and life loss have been projected for the year 2021. District wise calculations are done, which gives a clear idea about the hot-spot regions of Bihar, i.e. most badly affected regions during future earthquake. The reasons observed behind expected huge loss in some specific districts are:

- High population density
- Places lying under seismic zone V
- Places sit close to the epicenters of past earthquakes
- Construction on the hazardous slump belt area
- Weaker houses in higher intensity zones, not ready to withstand seismic load
- Lack of planning and implementation of guidelines and codes
- Expected higher population in coming years in vulnerable areas

2.1.4 BIHAR-NEPAL EARTHQUAKE 1988

The very two regions were again hit by an earthquake of magnitude 6.6 at 04:39 hrs on August 21st, 1988. This time the magnitude was lesser than the previous one, about 750 times lesser than the 1934 earthquake in terms of energy release. The epicentre was in eastern

Nepal between Udaipur and Dharan with a depth of 57.9 kms. Highest Intensity recorded was IX.

Table 2.4: Understanding Bihar-Nepal Earthquake 1988

Date	August 21, 1988
Time	04:39:10.30
Magnitude	6.6
Epicentre	Lat. 26o 45’ N, Long. 86o 36’ 57.6” E
Casualties in India	282
Casualties in Nepal	1194

The earthquake struck in two instalments of 10 seconds and 15 seconds each and left cracks in 50000 buildings. Northern Bihar and several towns of Nepal were severely damaged. Total number of casualties was 1467 out of which 282 were from Bihar. The number of injured in Bihar reached 3766. Effect was so severe that shocks were felt till Assam, Tripura, West Bengal, Delhi and Roorkee. Major damages were observed in Bhaktpur (Nepal), Munger (Bihar) and areas near epicentre.

Figure 4: A damaged house in Munger district during Earthquake 1988

The number of deaths was surprisingly low in view of the fact that 149334 houses were damaged in Bihar. Number of Pucca private houses collapsed: 11335, major damage: 19141, minor damage 34142, Kutcha houses: Collapsed 13758, major damage 27258 and minor damage 43700. Mostly the damaged houses were built in Unburnt or burnt brick masonry.

The worst affected districts of Bihar were Darbhanga, Madhubani and Saharsa. Munger, again suffered huge destruction due to its special geological and geotechnical feature.

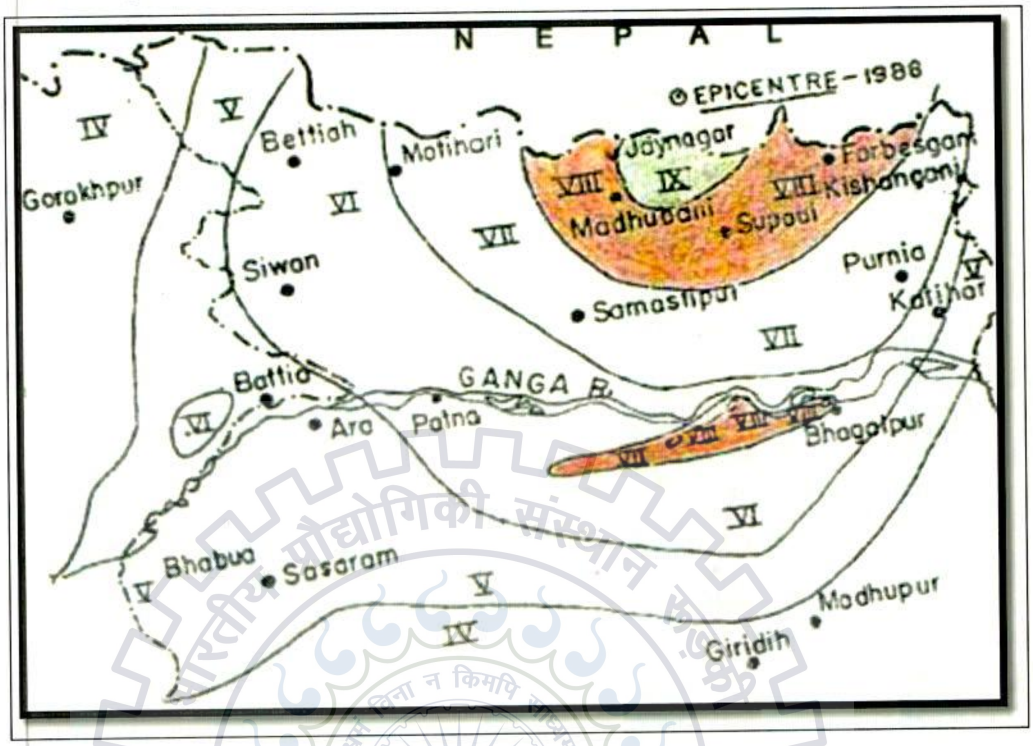


Figure 5: Iso-seismal map of Bihar-Nepal Earthquake 1988

2.1.5 BIHAR-NEPAL EARTHQUAKE 2015

This is the most recent earthquake (also known as Gorkha Earthquake) which struck Nepal and adjoining Bihar region with a magnitude of 7.8 and maximum intensity reaching IX (violent). The deadly disaster occurred on April 25th, 2015 at 11:56:26 NST, 80 kms NW of Kathmandu (east of the district of Lamjung) at a depth of 15 kms (USGS). The tremor lasted for 90-100 seconds followed by four major aftershocks: 6.6 Mw on April 26th 2015, 6.7 Mw on April 26th 2015, 7.3 Mw May 12th 2015, and 6.3 Mw May 12th 2015. The earthquake triggered two major avalanches on Mount Everest and Langtang valley which killed around 20 people and 250 were missing after the catastrophe.

Table2.5: Understanding Bihar-Nepal Earthquake 2015

Date	April 25th, 2015
Time	11:41 IST
Magnitude	7.8
Epicentre	Lat. 28.147° N, Long. 84.708° E

Casualties in India	130
Casualties in Nepal	>8800
Casualties in China and Bangladesh	27, 4
Number of people injured in India	560
Number of people injured in Nepal	17,803 respectively
Number of people injured in China and Bangladesh	383, 200 respectively

The earthquake left devastating impact on buildings and infrastructure. 489500 buildings were completely and 262600 partially destroyed in Nepal. A large part of northern India (UP, Bihar and Bangladesh) was affected by the earthquake; especially the districts of Bihar adjoining Nepal border were severely affected. Bihar witnessed the shaking intensity of VII on MMI scale.

Figure 6: Damaged masonry house in Madhubani, Bihar

Figure 7: Damaged school building in Motihari, Bihar

The effects of earthquake felt in terms of intensities at various places in Nepal and India were:

- Intensity IX: Kathmandu (**Nepal**)
- Intensity VIII and VII: Bhaktpur, Lalitpur, Gorkha, Sindhupalchok, Nuwakot, Hetauda (**Nepal**)
- Intensity VI: Birgunj, Raxaul, Sitamarhi, Motihari (**India**)
- Intensity V: Muzaffarpur, Patna, Kolkata (**India**)
- Intensity IV: Varanasi, Lucknow, Kanpur, New Delhi (**India**)

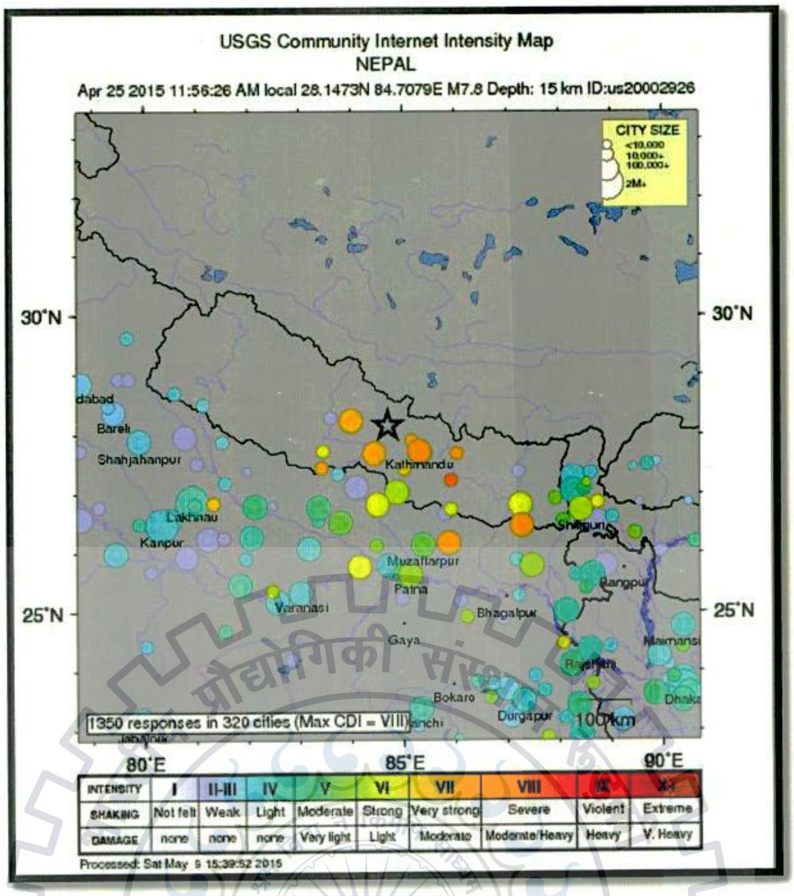


Figure 8: USGS Intensity map of Bihar-Nepal Earthquake 2015

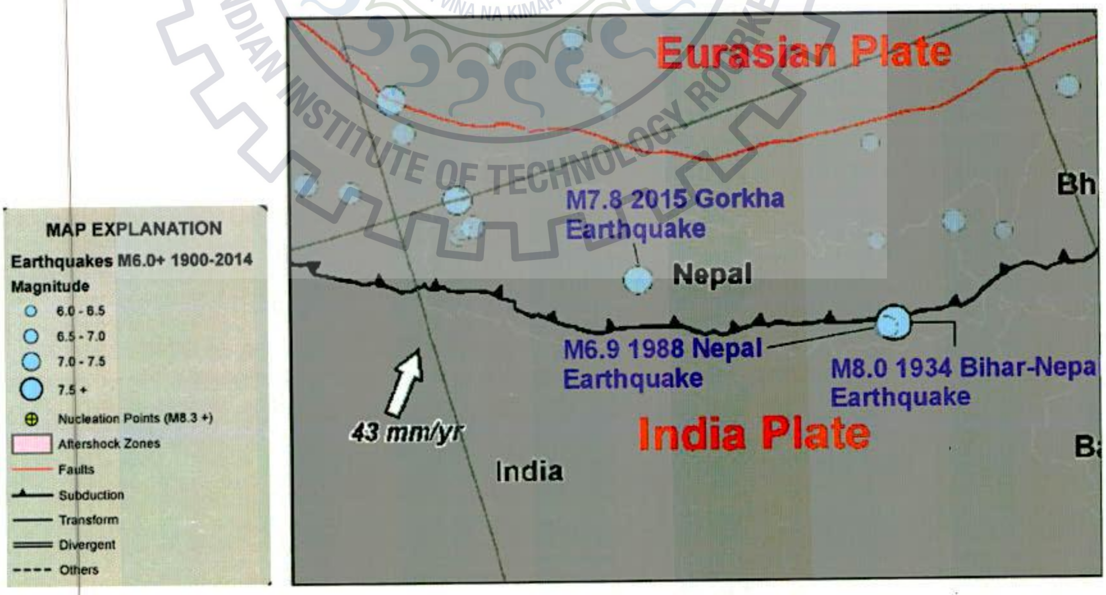


Figure 9: Map showing seismically active region with epicenters along with magnitude depiction of past earthquakes (USGS)

2.1.6 CONCLUSIONS

Bihar has been witnessing a number of major earthquakes including a great earthquake in the last few decades. Earthquakes triggered during the 19th century made dreadful impact on the region. Since then, potential earthquakes have shown and led to a common trend of damage in the state. With the pace of development and population, state has shown increasing tendency of damage during each earthquake. This aggravates the need to study the built environment of the state for mitigation against the earthquake disaster in future.

CHAPTER 3

BUILDING TYPOLOGY OF BIHAR

3.1 SEISMIC ZONES OF BIHAR

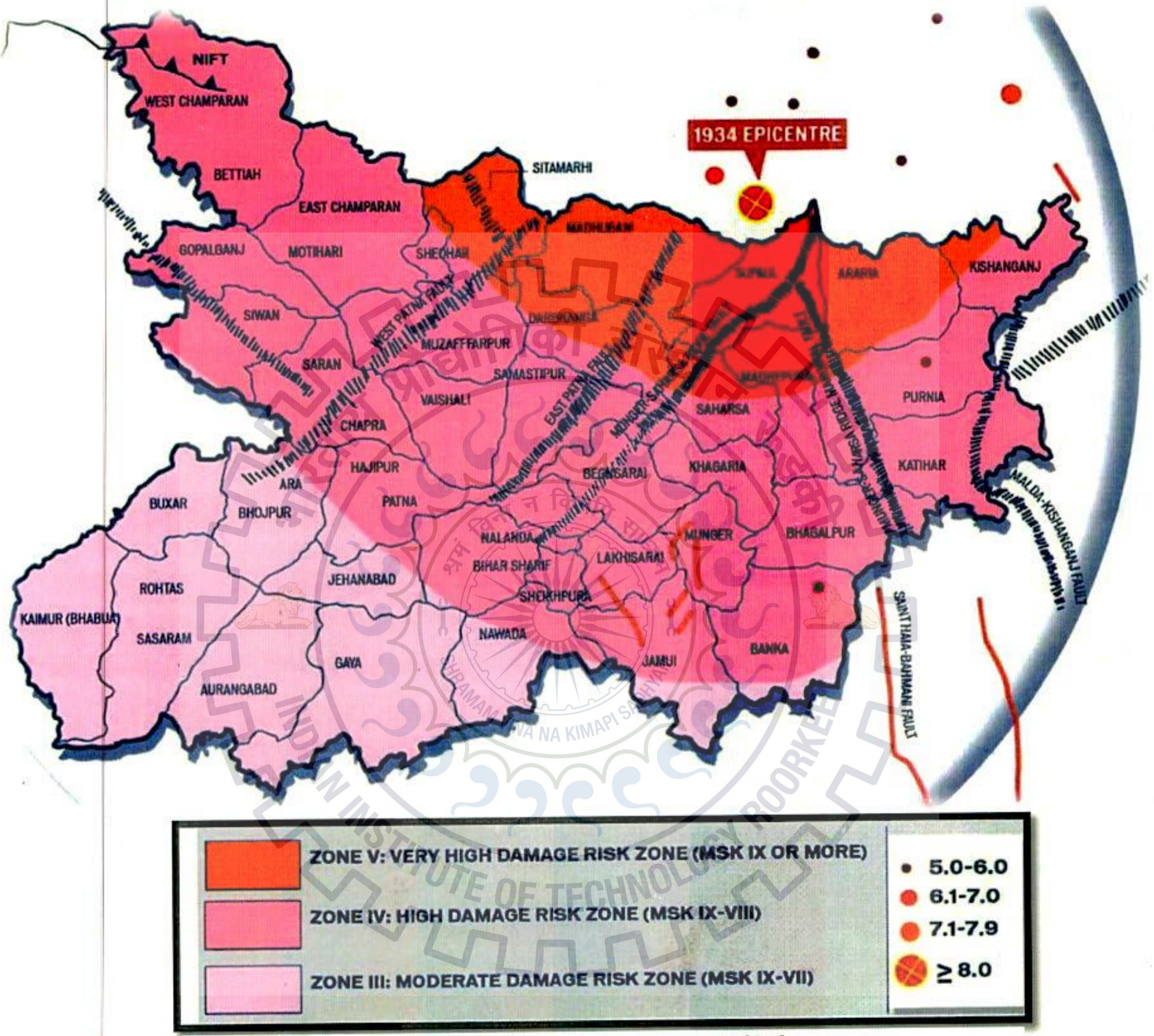


Figure 10: Seismic zone map of Bihar

Eight district zones of Bihar lie in Seismic Zone V of Seismic Zoning Map of India. These districts are Sitamarhi, Madhubani, Saharsa, Supaul, Madhepura, Araria and Kishanganj. In Seismic zone V, MSK Intensity 'IX or higher' are considered probable. Twenty four districts namely East Champaran, West Champaran, Shivhar, Chapra, Siwan, Gopalganj, Muzaffarpur, Vaishali, Samastipur, Begusarai, Khagariya, Purnia, Katihar, Bhojpur, Patna, Jahanabad, Nalanda, Nawada, Shekhpura, Lakhisarai, Jamui, Munger, Bhagalpur and Banka are classified in seismic zone four with probable maximum earthquake Intensity, MSK VIII. Only five districts which are at the South-West corner of the state are placed in seismic zone III where maximum probable Intensity MSK VII is postulated to occur (See Figure: 10). It is important to understand that Bihar-Nepal earthquake 1934 created an area of 120 kms in East-West direction and 30 kms in the South-West direction which lies under Intensity, MM X. This whole are is again surrounded by an elliptical area of 120 kms in the North-South direction and 300 kms in the East-West direction. This particular area lies in Intensity of MM IX which covers both the plains of Bihar and mountainous areas of Nepal. The presently defined area which lies in seismic zone V is classified in the iso-seismal of Intensity MM IX as well as MM X. Similarly, the vast area in Bihar which is covered in seismic zone IV is subjected to an Intensity of MM VIII. The rest of the part which is placed in the Southern part of the state lies in seismic zone III and is subjected to an Intensity of MM VII. This zonation and classification of seismic zones are purely based on the responses of the 1934 Bihar-Nepal Earthquake.

3.2 UNDERSTANDING BIHAR

The state of Bihar is a multi-prone disaster state of India which is predominantly rural in character. It has been witnessing disasters of very cruel nature from quite a long time. Flood, earthquake, landslide, cyclone, tornado, heat wave and cold wave are some of the hazards which keep on occurring time to time (few occur annually) *Figure: 11*. Large part of the state lies in seismic zone V, IV and III. Man-made and human induced hazards like, fire, accidents, stampedes, epidemics are also observed in the region. The growing population and more and more zest for development have led to an increase in the frequency of hazards. This is either directly or indirectly related to each other. Simultaneously, the state has also developed its potential to mitigate and prevent such disasters from happening.

Table 3.1: Understanding Bihar

Country	India
Region	East India
Capital	Patna
Districts	38
Area (in sqm)	94163
Area (in rank)	13th
Population as per Census 2011	103804637
Population rank	3rd
Population density	1106 per sqm
Literacy rate	63.40%

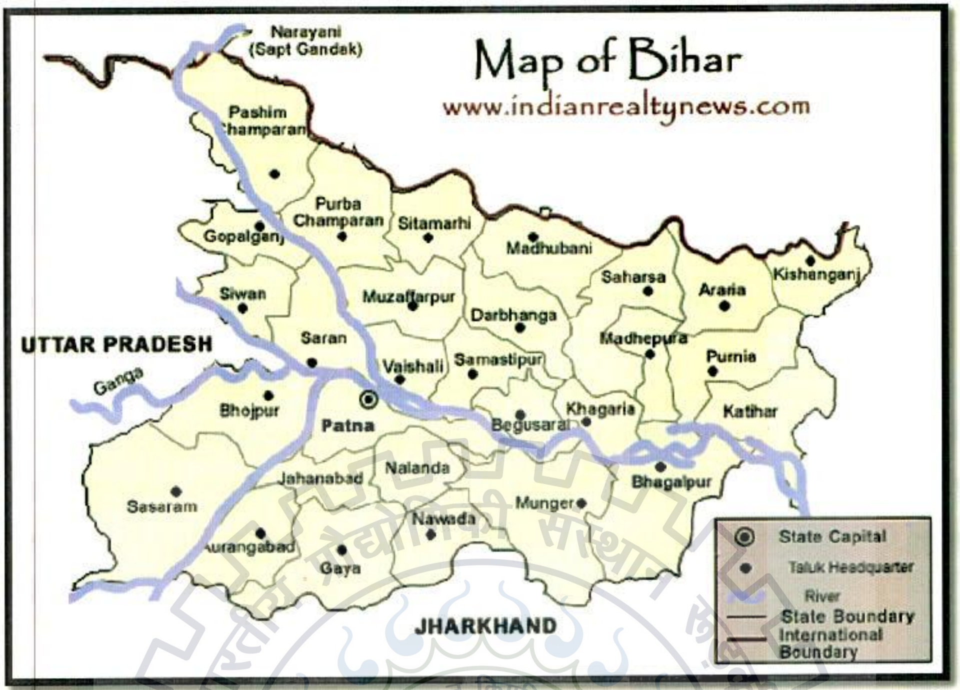
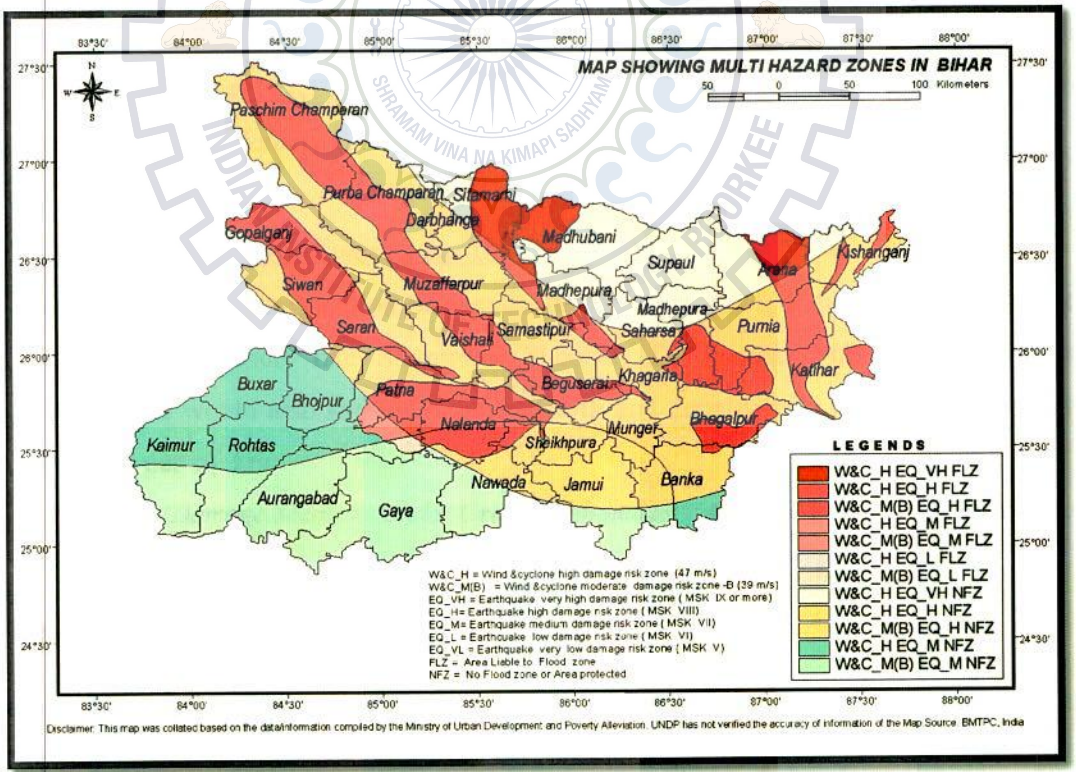


Figure 11: Location map of Bihar



W&C_H = Wind &cyclone high damage risk zone (47 m/s)
W&C_M(B) = Wind &cyclone moderate damage risk zone -B (39 m/s)
EQ_VH = Earthquake very high damage risk zone (MSK IX or more)
EQ_H= Earthquake high damage risk zone (MSK VIII)
EQ_M= Earthquake medium damage risk zone (MSK VII)
EQ_L = Earthquake low damage risk zone (MSK VI)
EQ_VL = Earthquake very low damage risk zone (MSK V)
FLZ = Area Liable to Flood zone
NFZ = No Flood zone or Area protected

Disclaimer: This map was collated based on the data/information compiled by the Ministry of Urban Development and Poverty Alleviation. UNDP has not verified the accuracy of information of the Map Source: BMTPC, India

Figure 12: Map showing multi-hazard zones in Bihar

Demographic Profile

Bihar has a total population of 82,998,509 in which 43,243,795 are male and 39,754,714 are female. Around 85% of the total population is rural and 58% accounts for youth section, i.e. below 25 years age, which is the highest in India. The average population density comes around 881 persons per square km with sex ratio of 919 females per 1000 males (as per Census 2011).

Population Projection for Bihar in coming years based on present data:

- *Population density of Bihar as per Census 2001*

  Patna and Darbhanga districts have the highest population density of 1400 to 1800 persons per sqm till the year 2001. Districts with least population density are West Champaran, Kaimur, Jahanabad, Jamui and Banka with less than 600 persons per sq. km.

- *Population density of Bihar as per Census 2011*

  By the year 2011, population density of Patna district has skyrocketed to about 1823 persons per sq. km. Unlike in previous decade, West Champaran and Banka districts have also grown in terms of population density; while Jamui, Jahanabad and Kaimur still are in least density zone.

- *Population density of Bihar as per Census 2021*

  After completing population projection for the year 2021, Patna still remains at the top. Other districts like Sitamarhi, Sheohar, Darbhanga, Muzaffarpur, Vaishali, Begusarai, would also show a bubble growth and density may reach more than 1800 persons per sq. km.

  *(*Source: 'Damage Scenario Under Great Earthquakes, A Case-Study Of 1934 Bihar-Nepal Earthquake)*

3.3 BUILDING TYPOLOGIES IN BIHAR

Buildings with varied typologies can be found throughout the state of Bihar. 88.4% of the total houses are rural, whereas urban houses accounts for only 11.5%. The typology of housing is decided by the roofing and walling materials used in the construction. The buildings thus are categorized in the following way;

I. *Based on Walling Material*

   a. Type A: Mud wall, Unburnt brick wall and Stone wall

   b. Type B: Burnt brick wall

   c. Type C: Wood wall and Concrete wall

   d. Type X: Walls made of other materials like- grass, thatch, bamboo, plastic, asbestos sheets, GI or metal sheets etc.

II. *Based on Roofing Material*

   a. Type R1: Pitched roofs made of lightweight materials like- grass, thatch, bamboo, wood, plastic, asbestos sheets, GI or metal sheets etc.

   b. Type R2: Pitched roofs made of heavyweight materials like- tiles and slates.

   c. Type R3: Flat roofs which are heavy and made of wooden joists holding earth fill and bricks, stone slabs and Reinforced concrete slabs.

The state carries 23% of Type 'A' houses, 42% of Type 'B' houses, 0.8% of Type 'C' houses and 33% of Type 'X' houses. Also, houses with R1, R2 and R3 Type of roofing accounts for 39%, 34% and 26% respectively. As per this, houses made of lightweight materials are the largest in number; they are not considered while studying damage scenario though (they do not cause any threat to life even if they fail during earthquake). The data clearly shows that besides Type 'X' and 'R1', Type 'B' with 'R3' type of roofing in houses is prominent in the state*(See Figure: 13 and 14)*.

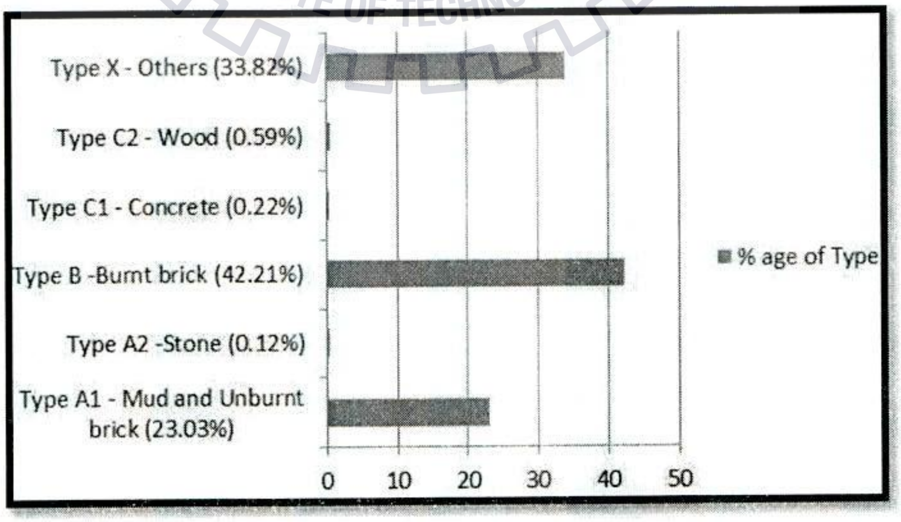


Figure 13: Percentage number of houses based on wall materials in Bihar

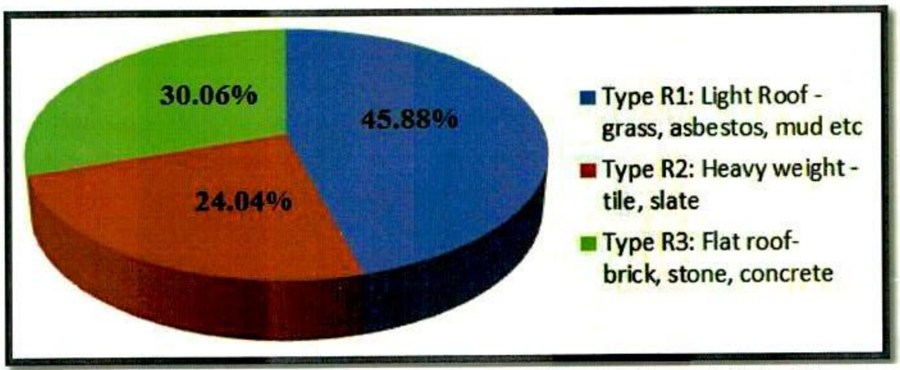


Figure 14: Percentage number of houses based on roof materials in Bihar

3.4 UNDERSTANDING INTENSITIES AND THEIR EFFECTS ON BUILDING TYPES

Damage to buildings depends on their typologies and the Seismic Intensity zones in which they lie. Damage percentage of buildings differs with their typologies, even if they experience same Seismic Intensity during an earthquake. Damage grades of buildings range from Grade 1 to Grade 5, in increasing order of damageability. RC and Masonry buildings show different damageability in same damage grade as they differ in typology. Damage Grade 5 depicts worst stage of damage. The figure *(Figure:15)* below explains this fact in pictorial way.

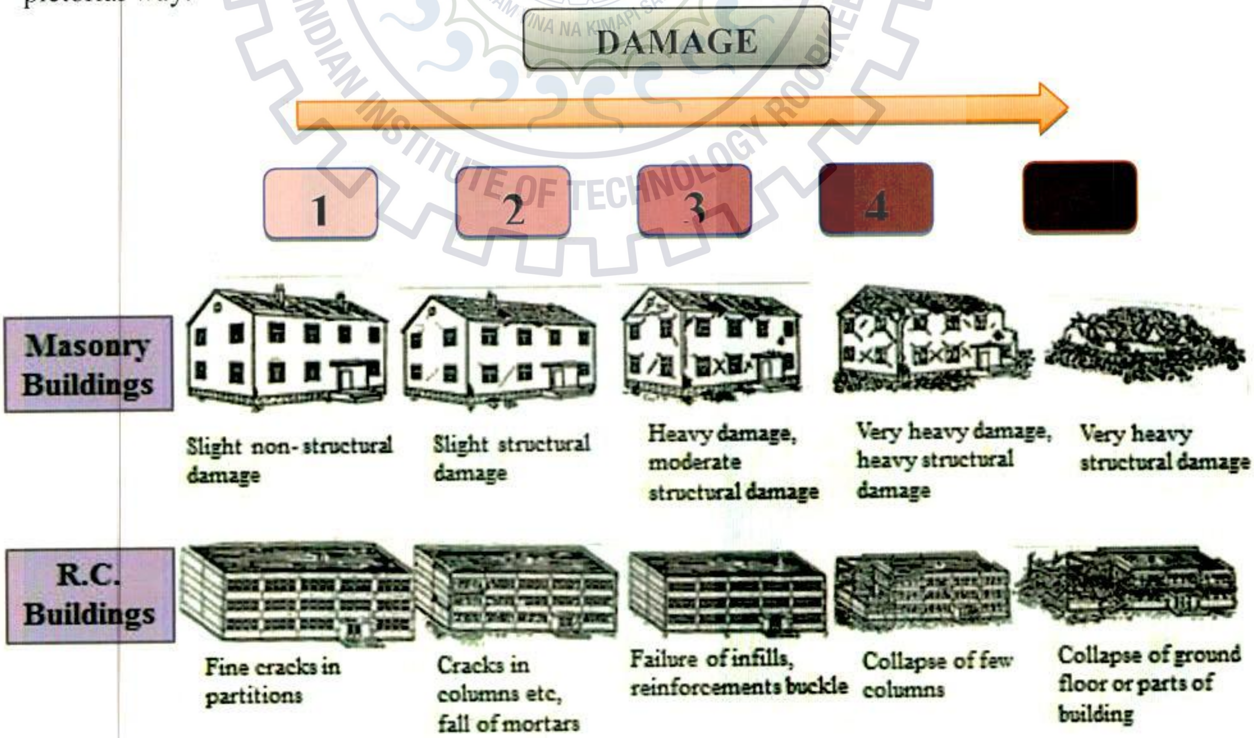


Figure 15: Behaviour of RC Buildings and Masonry Buildings under various Damage Grades

CHAPTER 4

RISK IDENTIFICATION DURING SCENARIO EARTHQUAKE IN BIHAR

Based on various aspects of data, few regions of Bihar with high vulnerability towards earthquake damage would be identified. The parameters deciding the vulnerability level may include these factors:

- Population
- Region lying under different seismic zones
- Majority type of construction in the region (use of building materials)
- Region lying under different intensity zones (based on 1934 EQ data)

Amalgamation of these factors would help in identifying the hot-spots regions of Bihar. Loss calculation for both infrastructure and life loss would be the major parameters for deciding vulnerability against earthquake. Overlapping all the four parameters would produce the worst affected districts of Bihar during future earthquake of similar magnitude (as of Bihar-Nepal Earthquake-1934).

4.1 CALCULATION OF DIRECT ECONOMIC LOSSES

'Direct Economic Loss' refers to the loss suffered in terms of rupees due to the damage of buildings and the contents present inside those buildings. For the calculation of this type of loss, DPM (Damage Probability Matrix) has been used. The Probability from the DPM is multiplied by the Loss Ratio for each category of buildings coming under specific Intensity zone *(See Figure: 37 and 38)*. An example of this method of calculation is shown in *Appendix – A*.

Data required for the calculation:

- Average no. of occupants: **4.77**
- Average floor area:
  - Type A – 20sqm
  - Type B – 60sqm

    - Type C – 100sqm
- Average cost of building replacement:
    - Type A – Rs. 500/sqm
    - Type B – Rs. 1000/sqm
    - Type C – Rs. 1500/sqm
- Number of houses (from Census 2011)
- Intensity in which the particular district lies.

* Values taken from the source: *'Damage Scenario under Great Earthquakes: A case-study of 1934 Bihar-Nepal Earthquake'*

Thus the **total expected economic loss due to building damage** for a given occupancy class can be estimated as:

1. *Structural and Non-structural damage:*

$$\mathbf{CBD_i} = \sum_{MBT=1}^{N}[\, FAMBT_{,i} \times \mathrm{TBA_i} \times \sum_{j=1}^{5}(\, P(Grj)_{MBT} \times \mathrm{LR_j}\,) \times \mathrm{RV_{MBT}}\,]$$

- CBD_i = Cost of building damage in occupancy i
- $FAMBT, i$ = %age floor area of a MBT (*Model Building Type*)
- TBA_i = Total built-up area of occupancy i
- $\sum P(Grj)_{MBT}$ = Probability of damage grade j in a MBT
- LR_j = Building loss ratio for damage grade j
- RV_{MBT} = Building Replacement value for a MBT

2. *Damage of Content:*

The 'Content' here refers to the commodities which remain inside any building; for example: furniture, appliances, machineries, etc. With the damage of buildings, the commodities inside any building also get destroyed. This indirectly turns into economic loss. Thus, it is essential to calculate all such losses while estimating direct economic loss, in order to get more appropriate results for the seismic risk assessment.

The **total expected loss due to damage of content** in a given occupancy class can be estimated as:

Loss = Structural and non-structural damage / 2

4.2 ESTIMATION OF DIRECT SOCIAL LOSSES

'Direct Social Losses' refers to the deaths of human beings which can be caused due to the collapse of buildings after any earthquake. The number of persons dying due to any earthquake is greatly affected by the time of occurrence of earthquake. If an earthquake triggers during daytime, lesser number of people fell prey to it, as it becomes easier for people to escape out of the buildings in which they work or live. Contrarily, more number of deaths is caused in case earthquake hits during night time, as most of the people are not awake at night. They become incapable of leaving their buildings or residences immediately, as ground shaking can't be quickly felt in sleep. Therefore, calculations are done for both the conditions to get more appropriate results. Calculation of life loss during Unfavourable and favourable Time of Occurrences has been performed. Unfavourable time of occurrence may also include, earthquakes triggering during a rainy day or a disaster hit time. For example: during or after any disaster like flood, cyclone etc. Thus, the **total expected life loss due to building damage** for a given occupancy class can be estimated as:

- *During Unfavorable Time of Occurrence*

  i. For Zone V $$\boxed{L \times R \times (0.06 \times NG5\_V + 0.02 \times NG4\_V)}$$

  ii. For Zone IV $$\boxed{L \times R \times (0.06 \times NG5\_IV + 0.02 \times NG4\_IV)}$$

  iii. For Zone III $$\boxed{L \times R \times (0.06 \times NG5\_III + 0.02 \times NG4\_III)}$$

- *During Favorable Time of Occurrence*

  i. For Zone V $$\boxed{F \times L \times R \times (0.06 \times NG5\_V + 0.02 \times NG4\_V)}$$

  ii. For Zone IV $$\boxed{F \times L \times R \times (0.06 \times NG5\_IV + 0.02 \times NG4\_IV)}$$

  iii. For Zone III $$\boxed{F \times L \times R \times (0.06 \times NG5\_III + 0.02 \times NG4\_III)}$$

- **NG5_V** = Number of buildings suffering Damage Grade 5 which lie in the seismic zone V of the region.
- **NG5_IV** = Number of buildings suffering Damage Grade 5 which lie in the seismic zone IV of the region.

- **NG5_III** = Number of buildings suffering Damage Grade 5 which lie in the seismic zone III of the region.
- **NG4_V** = Number of buildings suffering Damage Grade 4 which lie in the seismic zone V of the region.
- **NG4_IV** = Number of buildings suffering Damage Grade 4 which lie in the seismic zone IV of the region.
- **NG4_III** = Number of buildings suffering Damage Grade 4 which lie in the seismic zone III of the region.
- **R** = average population per house for a district

  R = Total Population of the District/ Total Census Houses
- **F** = Favorable Condition Factor

  F = {0.3 x Rural housing + 0.5 x Urban Housing} / Total Housing
- **L** = Light Roof Reduction Factor

  L = (10% of R1 + 30% of R2 + R3) / Total Housing

Buildings suffering damage grade 5 and 4 are considered for the calculation of life loss, as other damage grades are not as severe that may cause deaths.

4.3 RESULTS

After calculating each type of losses in every district of Bihar, the total expected economic loss due to building damage, content damage and estimated life loss have been shown below. The results obtained after the calculations are as follows:

- **Total expected infrastructural loss due to building damage = Rs. 98, 389 Crores**(Ninety eight thousands three hundreds and eighty nine Crores)
- **Total expected loss due to damage of content = Rs. 49, 194** (Forty nine thousands one hundred and ninety four Crores)
- **Total expected life loss due to building damage :**
  - **During Unfavourable Time of Occurrence =2, 22, 337 persons**(Two lakhs twenty two thousands three hundred and thirty seven)
  - **During Favourable Time of Occurrence =86, 248 persons**(Eighty six thousands two hundred and forty eight)

The losses for each district of Bihar have been calculated and dealt in detail in *Appendix – B* and *Appendix – C* of this report.

CHAPTER 5

PROJECTION OF RISK DUE TO SCENARIO EARTHQUAKE IN BIHAR

5.1 PROJECTION OF WORST AFFECTED DISTRICTS OF BIHAR IN FUTURE EARTHQUAKE

On the basis of loss calculation and few other important parameters, the districts possessing highest risk during any scenario earthquake in Bihar, have been projected. Parameters for this risk projection are as follows:

- Infrastructure and content loss of each district
- Life loss of each district
- Districts lying under high seismicity
- Districts with high intensity (as of Bihar-Nepal Earthquake 1934)

Separate district maps for the state have been developed for each parameter. Districts with highest level of infrastructure, content loss and life loss are shown in decreasing order of their dominancy or severity *(See Figure: 16 and 17).*Similarly, another map is developed based on the area of districts lying under highest seismic zone in decreasing order of their land cover*(see Figure: 18).* Considering the intensity of the scenario earthquake similar to the intensity experienced during Bihar-Nepal Earthquake 1934, a map has been prepared which shows the severity of intensity in the decreasing order among the districts of the state *(See Figure: 19).*

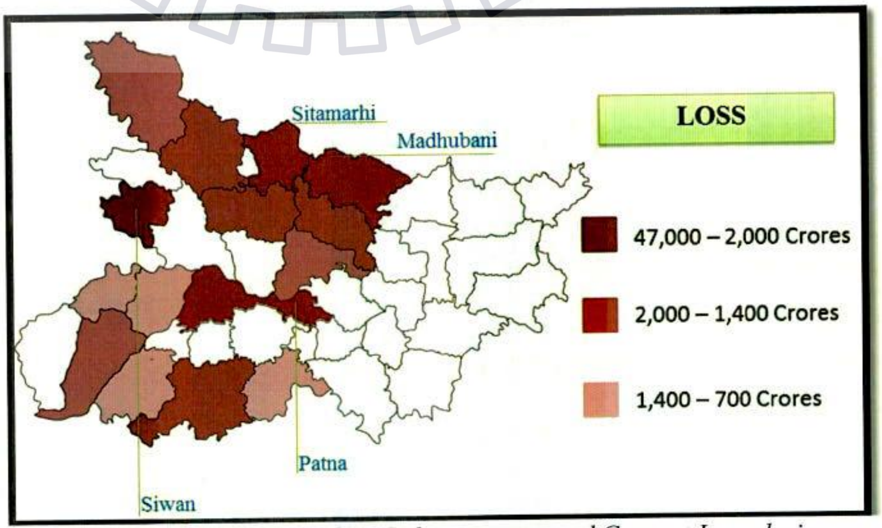


Figure 16: Districts of Bihar with highest Infrastructure and Content Loss during scenario earthquake

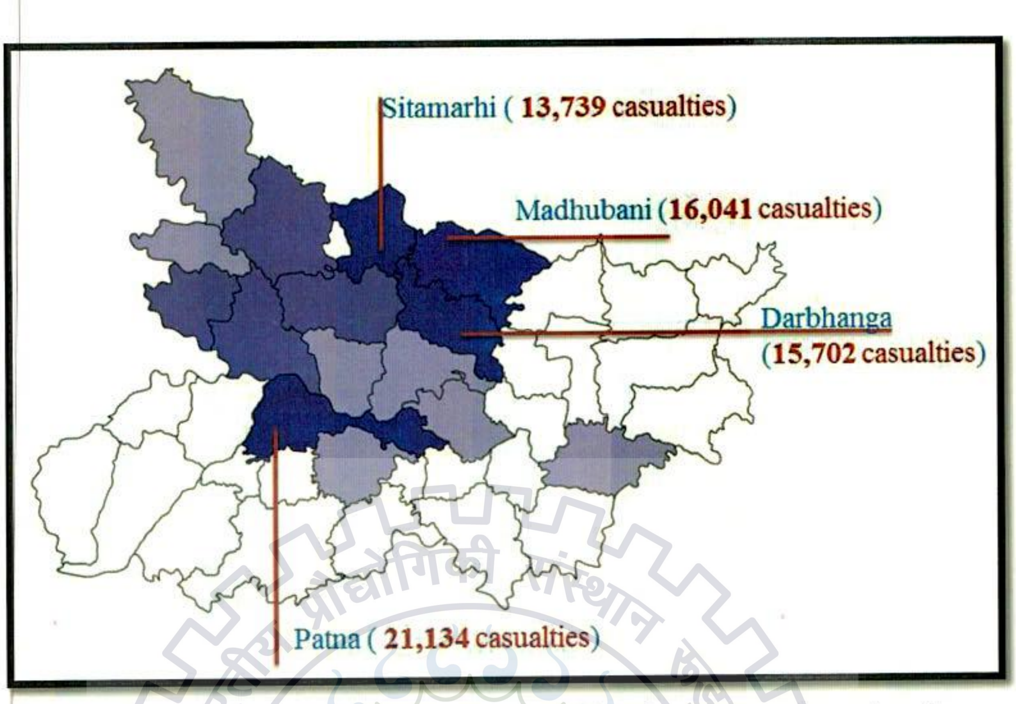


Figure 17: Districts of Bihar with highest Life loss during scenario earthquake

**Darker shade depicts greater severity and lighter shade depicts lesser severity.*

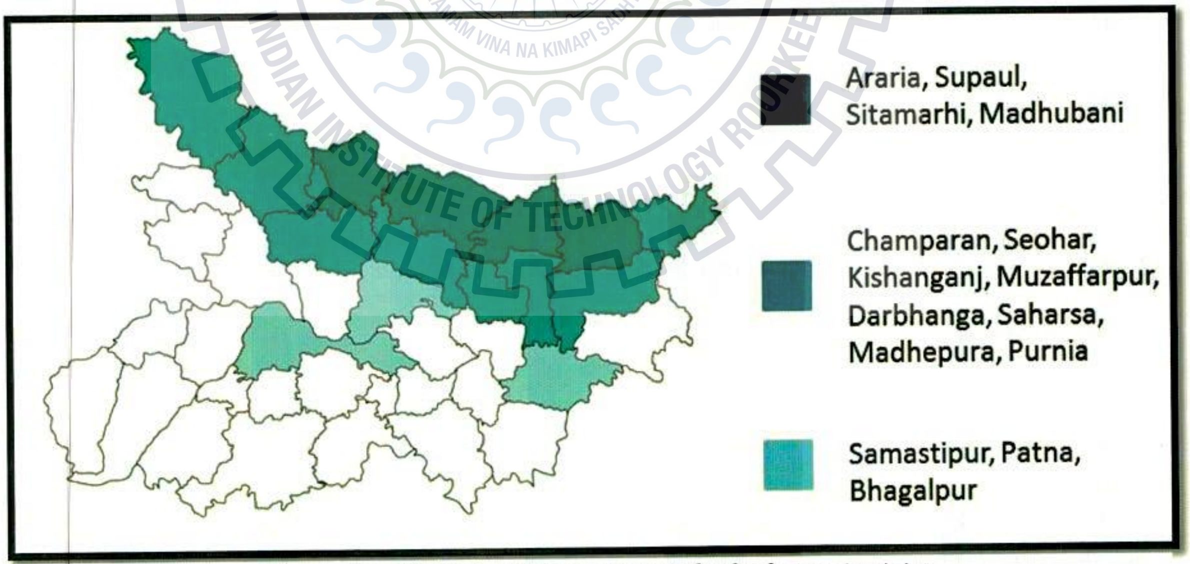


Figure 18: Districts of Bihar lying under highest seismicity

**Districts which are sharing two different seismic zones have been considered into the zone in which major portion of the region is lying.*

**Darker shade depicts greater severity and lighter shade depicts lesser severity.*

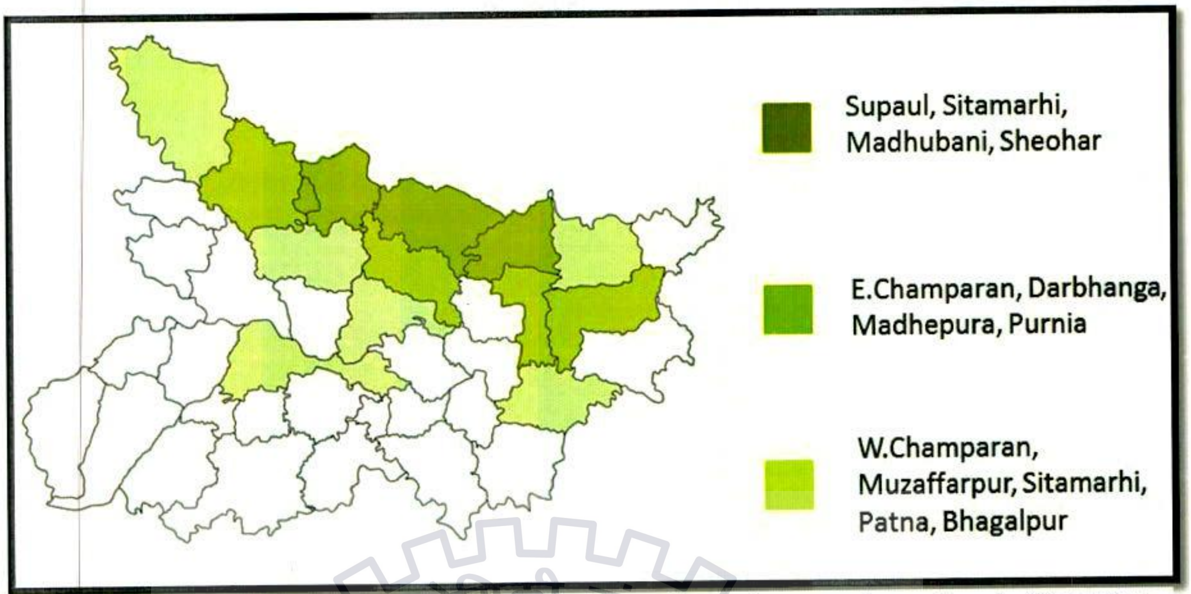


Figure 19: Districts of Bihar lying under highest Intensity during scenario earthquake (Assuming Intensity similar to that of Bihar-Nepal Earthquake 1934)

After considering all the four possible parameters (or aspects) and overlapping the maps, we get the worst affected districts of Bihar during any scenario earthquake. The districts which are common in all the four maps are the districts with highest threat. Accordingly, the next four districts possessing risk has been depicted with lighter shade of the colour. Darker shade depicts greater severity. **Thus, the first four worst affected districts due to scenario earthquake in Bihar are** *(See Figure: 20)***:**

Sitamarhi, Madhubani, Muzaffarpur and Darbhanga

Next four badly affected districts are:

East Champaran, West Champaran, Patna and Samastipur

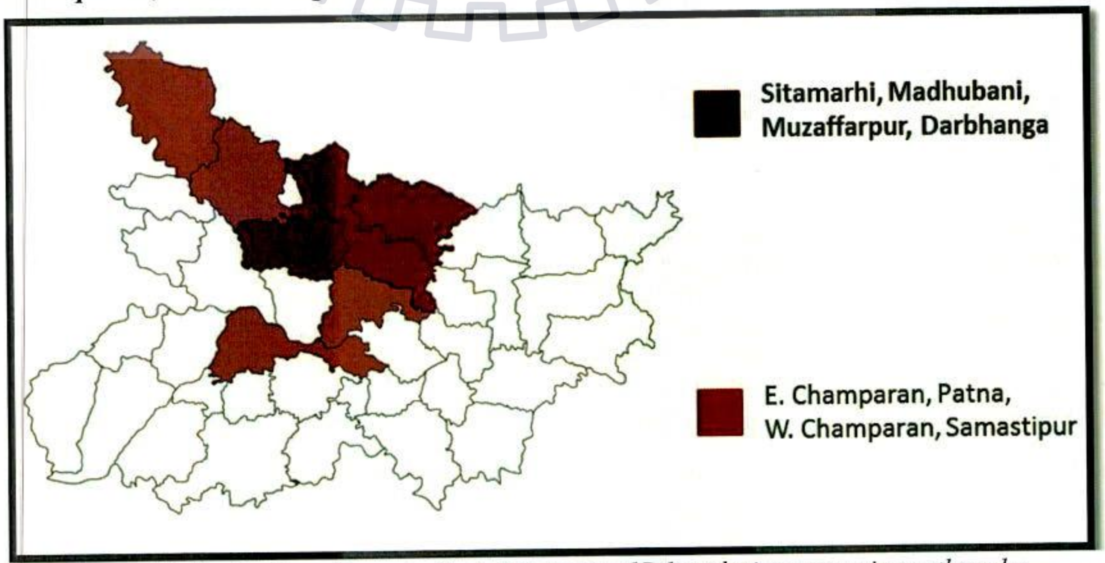


Figure 20: Projection of worst affected districts of Bihar during scenario earthquake

5.2 COMPARISON OF WORST AFFECTED DISTRICTS BETWEEN BIHAR-NEPAL EARTHQUAKE – 1934 AND SCENARIO EARTHQUAKE

The Bihar-Nepal Earthquake – 1934 had left a dreadful impact on the districts of Nepal and Bihar. The districts suffering most devastation during the disaster were Sitamarhi, Patna, Madhubani (then known as Rajnagar), Muzaffarpur, Champaran (now known as East Champaran and West Champaran) and Munger. A map has been developed showing the worst affected districts of Bihar during the 1934 Bihar-Nepal Earthquake *(see Figure: 21).*

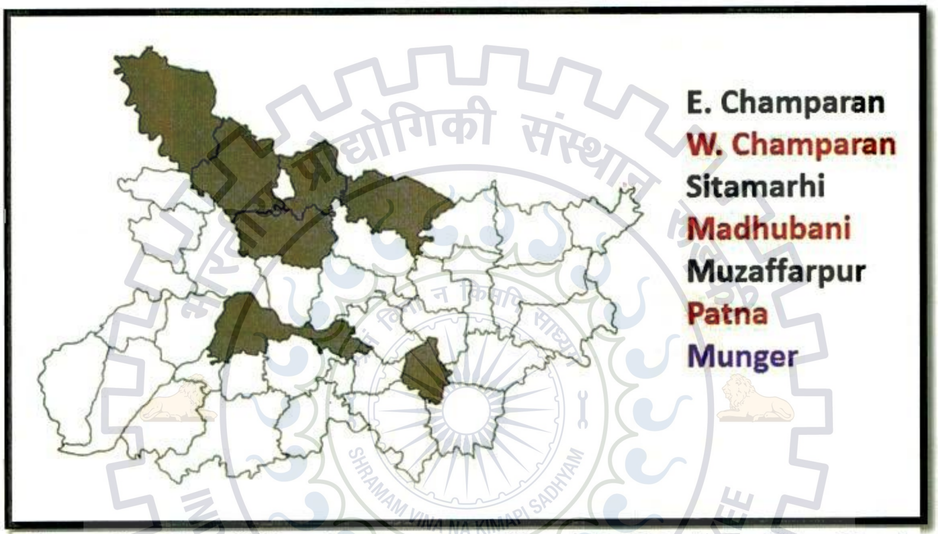


Figure 21: Map of Bihar showing worst affected districts during Bihar-Nepal Earthquake-1934

The worst affected districts during both the earthquakes, i.e. Bihar-Nepal Earthquake-1934and the Scenario Earthquake are compared by overlapping both the maps. As a result, all of the districts are found common during both the earthquakes, except *Darbhanga, Samastipur and Munger*. It is clear from the comparison that unlike Munger, Darbhanga and Samastipur are the districts with emerging threats in future. Munger had witnessed great damage during previous (Bihar-Nepal 1934) earthquake, but will be suffering very lesser in any scenario earthquake. This is a very suspicious outcome. Hence, the reasons behind this are studied carefully.

5.3 PECULIAR BEHAVIOUR OF MUNGER DISTRICT

It has been observed that Munger is situated at 465 kms (300 miles) away from the epicentre of 1934 Bihar-Nepal Earthquake. And, districts lying before Munger suffered lesser damage after the earthquake. The devastation in this district was observed to be much greater than any other part of Bihar *(See Figure: 23)*. Also, same damage trend was observed in the district during 1833 and 1988 earthquakes. Before looking into the reasons behind this peculiar behaviour of the Munger district, it is necessary to know the impacts which the earthquake had left on this district.

Impacts of 1934 Bihar-Nepal Earthquake on Munger: The entire town was reduced to ruins. The direction of movement of seismic waves throughout Munger was from East to West. Vertical and Rotational movements in buildings were also observed. Moreover, many buildings were seen to be lifted a few inches before they collapsed. No sign of *Liquefaction* was observed throughout the district. Ground fissures up to 4 feet were observed.

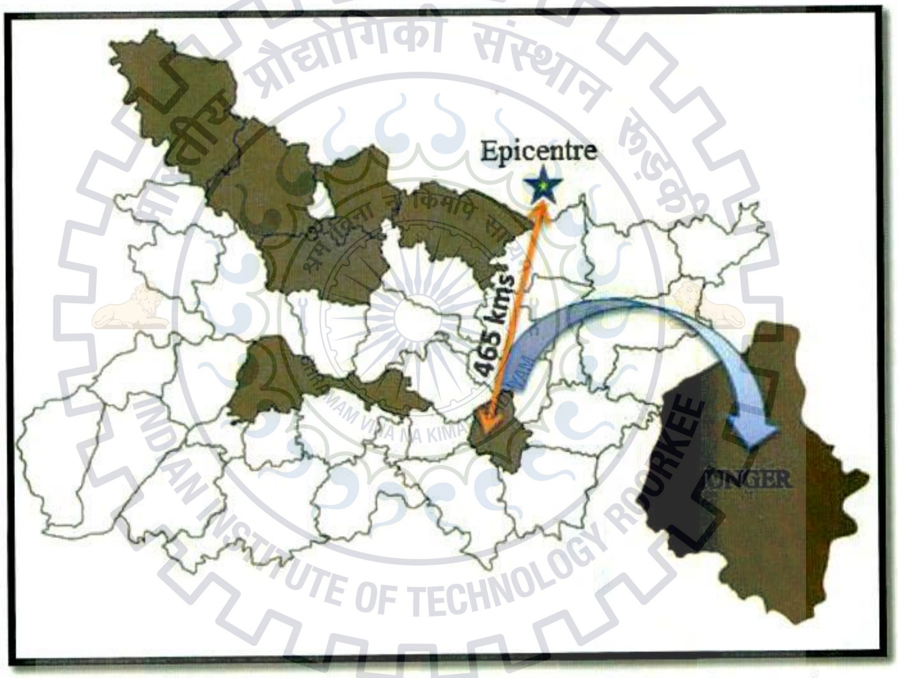


Figure 22: District map of Bihar showing the comparative distance from the epicentre of 1934 earthquake to Munger and other districts.

Reason behind this peculiar behaviour of Munger district: The district Munger has an interesting geological condition. It is bordered by Ganges from North side and stands both on **Alluvium soil** and peninsula of **Archean rock** *(See Figure: 23 and 25)*.Therefore, there is a discontinuity of geological set up throughout the district. Whenever an earthquake hits the region, the seismic waves get affected by this geological setup and eventually amplify the ground motion greatly. Consequently, the whole region experiences severe ground acceleration and this eventually led to large scale destruction throughout the district.

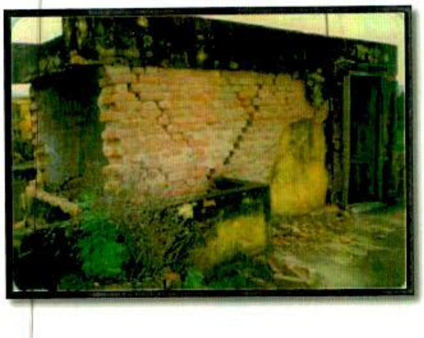


Figure 23: Damaged building at Munger during 1988 Bihar-Nepal Earthquake

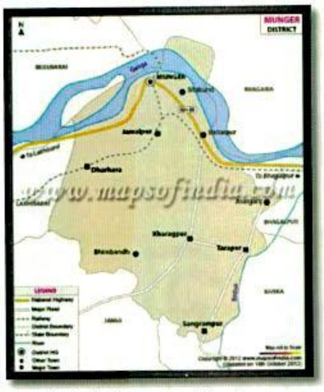


Figure 24: Munger district crowned by the river Ganga from North

As per the results obtained by seismic risk assessment in this research study, Munger is not coming under threat during any scenario earthquake. Contrarily, the damage trend observed in all the past earthquakes show that the district had suffered great loss in every past earthquakes. The reason this contradiction has arose is due to the fact that among all the parameters taken during seismic risk assessment, *geological condition* of the region is not taken into consideration. Interestingly, the ground shaking and PGA (peak ground acceleration) is largely affected by the geological condition of any region. This fact gives a clear picture about the impact which the district might face during future earthquakes. **There is a full possibility of huge damage in Munger during any scenario earthquake.**

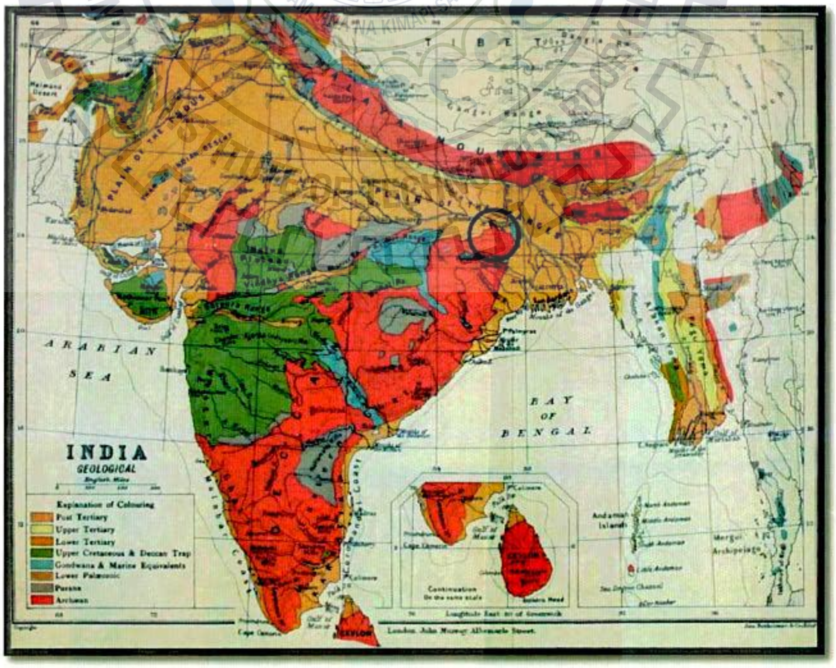


Figure 25: Map of India showing distribution of Archean and various rocks; location of Munger district is shown by a circle

5.4 DISTRICTS WITH EMERGING THREATS

As per the damage trend observed after 1934 Bihar-Nepal Earthquake, Darbhanga and Samastipur were the districts which had suffered very less damage as compared to its surround districts in North (towards the direction of the Epicentre). Now, according to the results obtained after seismic risk assessment of all the districts, the very two districts are coming under great threat in scenario earthquake; i.e. Darbhanga coming under first four and Samastipur as next four worst affected districts *(See Figure: 26).*This arises out the necessity to look into the reasons which has now made these two districts more vulnerable towards damage during any future earthquake.

For looking into the reason, the geological condition, demographic profile and development profile of the two districts has been studied. Geological set up of any region would not change with time. It has been discovered that the population of both the districts has risen unexpectedly during last few decades and they have witnessed high level of urbanization since 1961*(See Table: 5.1 and Figure: 27).*Thus, larger the population; more will be the number of deaths. Similarly, increase in the level of urbanization would further aggravate the infrastructural damage and life loss as well. Therefore, in case of any scenario earthquake, these districts have become more vulnerable towards damage with time.

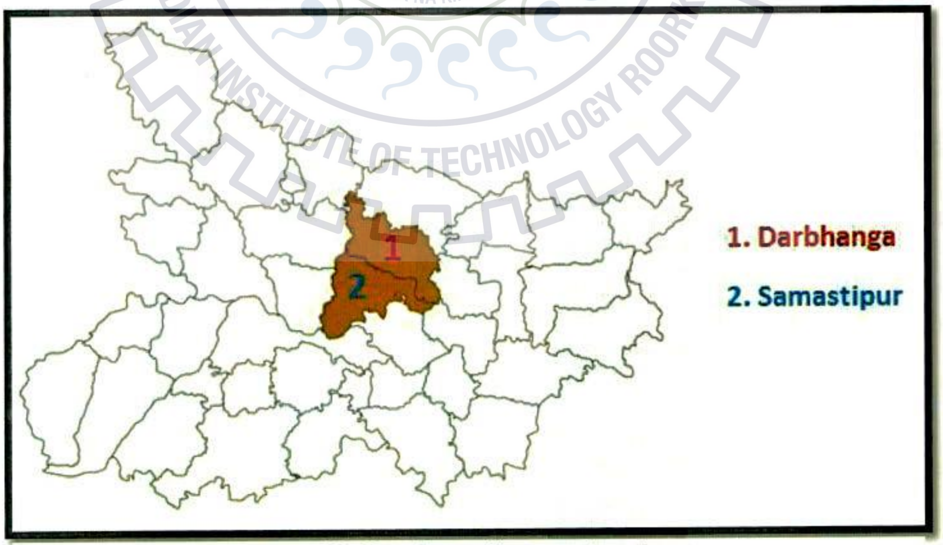


Figure 26: Districts with emerging threats

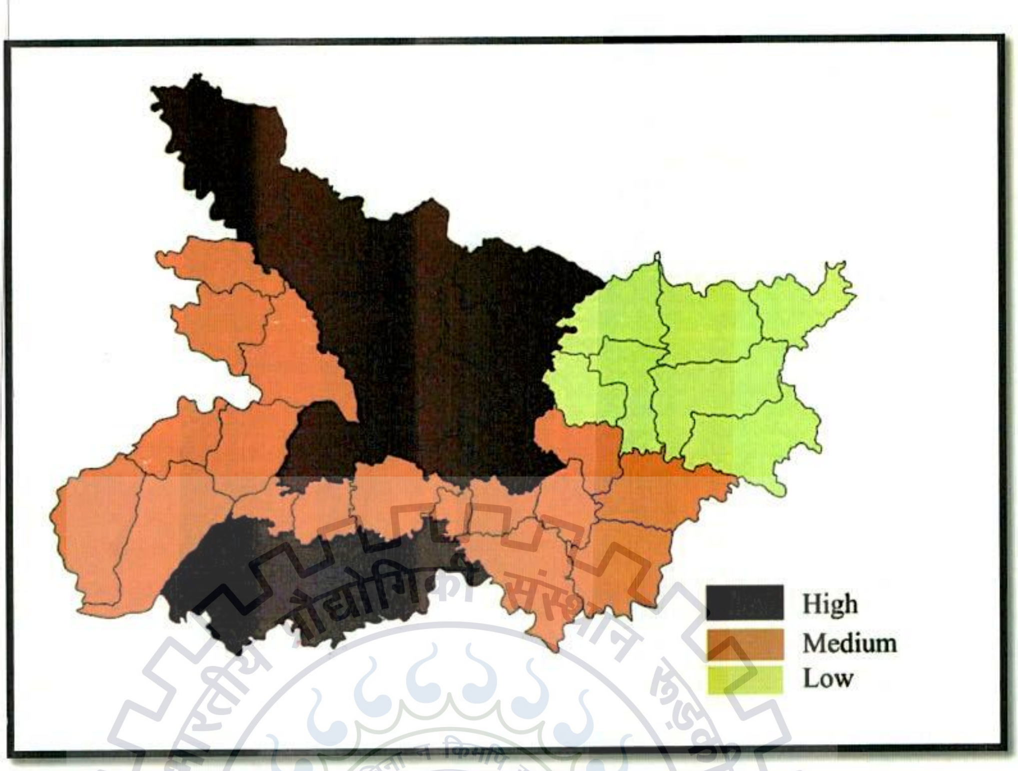


Figure 27: District map of Bihar showing changes in level of Urbanization during 1961-2011

Table 5.1: Population and Urbanization comparison of Darbhanga and Samastipur with time

Population	Darbhanga	Samastipur
Population in 1931	8,869	1,931
Population in 2011	39,21,971	42,54,782
Urbanization (1961-2011)	High	High

CHAPTER 6

RETROFITTING RECOMMENDATIONS FOR DOMINANT BUILDING TYPOLOGY IN BIHAR

6.1 IDENTIFICATION OF THE DOMINANT HOUSING TYPOLOGY IN BIHAR

Buildings with varied typologies can be found throughout the state of Bihar. 88.4% of the total houses are rural, whereas urban houses accounts for only 11.5%. The typology of housing is decided by the roofing and walling materials used in the construction. The buildings thus are categorized in the following way;

I. *Based on Walling Material*
   a. Type A: Mud wall, Unburnt brick wall and Stone wall
   b. Type B: Burnt brick wall
   c. Type C: Wood wall and Concrete wall
   d. Type X: Walls made of other materials like- grass, thatch, bamboo, plastic, asbestos sheets, GI or metal sheets etc.

II. *Based on Roofing Material*
   a. Type R1: Pitched roofs made of lightweight materials like- grass, thatch, bamboo, wood, plastic, asbestos sheets, GI or metal sheets etc.
   b. Type R2: Pitched roofs made of heavyweight materials like- tiles and slates.
   c. Type R3: Flat roofs which are heavy and made of wooden joists holding earth fill and bricks, stone slabs and Reinforced concrete slabs.

The state carries 23% of Type 'A' houses, 42% of Type 'B' houses, 0.8% of Type 'C' houses and 33% of Type 'X' houses. Also, houses with R1, R2 and R3 Type of roofing accounts for 39%, 34% and 26% respectively. As per this, houses made of lightweight materials are the largest in number; they are not considered while studying damage scenario though (they do not cause any threat to life even if they fail during earthquake). **The data clearly shows that besides Type 'X' and 'R1', Type 'B' with 'R3' type of roofing in houses is prominent in the state***(Damage Scenario Under Hypothetical Recurrence of 1934 Earthquake intensities in various districts in Bihar, BSDMA).*

6.2 UNDERSTANDING BURNT BRICK MASONRY CONSTRUCTION

Burnt brick masonry construction with flat roof is the most common type practiced in Bihar since times. There are two types of such construction: Unreinforced Masonry (URM) Construction and Reinforced Masonry Construction. Buildings with load bearing walls which are vulnerable to seismic loads (because of high mass and lack of ductility) and where structural members are absent are termed as Unreinforced Masonry structures. On the other hand, Reinforced Masonry constructions are those constructions in which steel reinforcements are embedded in masonry unit in such a way that they combine to act together and resists tensile, compressive and shear stresses acting upon the building. They are always preferred over URM construction, as they can perform better under seismic loads during any earthquake. Based on engineering point of view, buildings are categorized mainly into three types:

i. Non-Engineered Structures
ii. Semi-Engineered Structures
iii. Engineered Structures

Non-Engineered structures are those structures which are constructed in traditional manner without the supervision of any engineer or architect. Such type of houses becomes the main reason of damage during any earthquake, as they are not designed for gravity loads or seismic loads. Structures which are designed for gravity loads, but seismic loads are ignored are kept under the category of Semi –Engineered structures. They have the potential to get damaged during any high magnitude earthquake. Engineered Structures are those which are designed for gravity loads and seismic loads as well fall under this category. They are considered as the strongest structures during any earthquake, as they can resist seismic loads up to a great extent.

A building has several components. Major components of any building are broadly classified into: Structural Component and Non-Structural Component; former includes columns, beams and foundation whereas the latter includes walls, roof and floor. The behaviour of every component under seismic load is different and thus the damage patterns caused due to earthquake in those component members are also different. The damage pattern of each component in such building types (Burnt Brick masonry structures with flat roof) has been discussed in detail in this paper.

6.3 BUILDING CONSTRUCTION IN CONTEXT OF BIHAR

The socio-economic condition of the family plays a vital role in determining the construction of their houses. As discussed earlier in this paper, the burnt brick construction technology dominates among the rest in the state. The methods of such constructions are also varied, depending upon the capability of the family. There are several examples of existing building components which clearly show the vulnerability of getting damaged or destroyed in case of any earthquake. After doing a close study, several common construction details have been noticed in this particular type of construction in the state. After making foundation, 30-60 cms of brick plinth is common in the state. Further, poor quality of masonry is often used for brick wall construction in the economically weaker sections and low income group of the society. Half brick thick (usually 6 inches) interior walls without any horizontal band are commonly seen. Moreover, window and door openings support lintel bands which are not continuous and aggravate the vulnerability (from earthquake point of view). Load bearing unreinforced brick wall in mud mortar is usually seen in the houses of weaker sections. In most of the buildings, discontinuity in the vertical and structural members is observed. A good number of buildings are reinforced concrete framed structure with brick infill. The buildings in Bihar have mainly three types of roofing. As per the data given by Census 2011, 39% of buildings have R1 type of roofing *(pitched roofs made of lightweight materials like- grass, thatch, bamboo, wood, plastic, asbestos sheets, GI or metal sheets etc.),* 34% have R2 type of roofing *(pitched roofs made of heavyweight materials like- tiles and slates)* and 26% accounts for R3 type of roofing *(flat roofs which are heavy and made of wooden joists holding earth fill and bricks, stone slabs and Reinforced concrete slabs)*.The seismic behaviour of any building is greatly determined by the type of its roof. Light weight roofs are always favoured over heavy weight roofs. Majority of the structures in the state have light weight roofs which rarely possess risk in case of falling. Unfortunately, the other two types also cover remarkable number of buildings. They have the potential to cause severe damage and injury in case of falling. Moreover, they are more susceptible to falling during any earthquake because of their weight. And this further results into collapse of walls. Thus these are the construction details and structural components which are very common in the burnt brick structures of Bihar.

6.4 BUILDING DEFICIENCIES AND DAMAGE TREND OBSERVED IN PREVIOUS EARTHQUAKES

Table 6.1: Performance of URM and RC Framed buildings

Performance of Unreinforced Masonry buildings	***Performance of Reinforced Masonry (RC Framed) buildings***
Out of plane failure of URM walls.	Infill failure – Extensive damage to masonry infill of RC Framed building walls. Diagonal cracks are observed in the pier region between two openings. Inadequate strength due to use of half-brick thick infill. Diagonal and shear sliding cracks at mid-height of infill walls. Horizontal cracks in the infill walls due to differential settlement.
Formation of cracks at the corners of URM building walls *(which decreases out of plane stability drastically).*	Open ground storey failure was common in such buildings.
Cracks around the opening due to the absence of horizontal bands.	Weak ground storey failure was also observed.
Step type shear cracks were formed.	Inadequate size and proportion of building and poor reinforcement detailing of columns results in pancake collapse of a number of buildings.
Weak diaphragms and their poor connection with the masonry walls resulted in the failure of supporting walls and consequently collapse of roofs.	Lateral movement of buildings up to 3 meters was observed *(especially in open ground storey buildings).*
Pancake collapse was also observed in many URM structures.	RC members were found absent at the corners of the building.
	Absence of continuing members around the openings.
	Masonry crushing and plastic hinge formation in columns.
	Cracks in walls projecting beyond column lines.

During any earthquake, the percentage of engineered and non-engineered burnt brick structures suffering various damages are summarized below. The different category of buildings based on walling and roofing type and depending upon their material of construction, the damage varies with the intensity zone under which the area is lying. According to the previous earthquakes (Bihar-Nepal Earthquake-1934), largest part of the area of the state comes under MSK Intensity VII zone, followed by Intensity VII and Intensity IX.

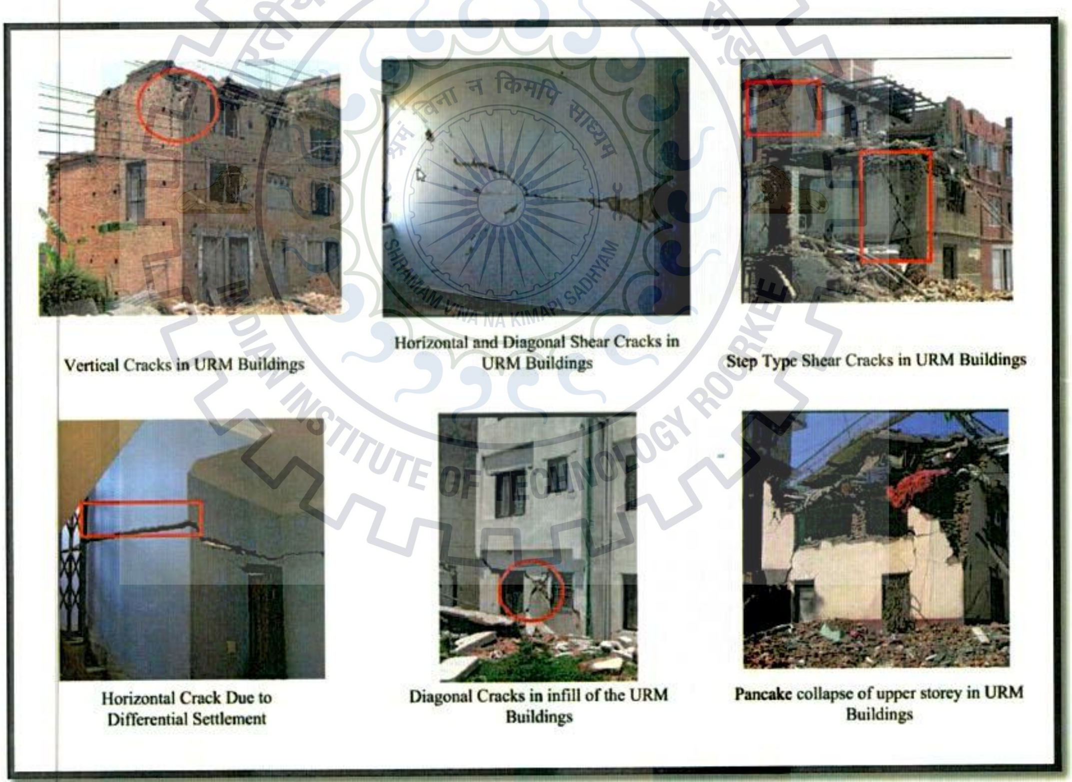
Table 6.2: Damage to different building types depending upon Intensity

Building Type	Intensity VII	Intensity VIII	Intensity IX
Ordinary burnt brick constructions	Many suffer small cracks in their walls.	Most suffer large and deep cracks.	Many suffer partial collapse with few complete collapse
		Few suffer partial collapse.	Few suffer minor cracks.
Reinforced Concrete Framed Structures	Many suffer fine plaster cracks.	Most suffer small cracks in walls.	Many suffer large and deep cracks.
		Few suffer large and deep cracks.	Few may suffer partial collapse.

*As per the International MSK Intensity scale, the quantitative description of terms: 'Most' means 75%, 'Many' means 50% and 'Few' means 15% of the total.

6.5 TYPES OF CRACKS AND BUILDING FAILURES IN BURNT BRICK MASONRY CONSTRUCTIONS DUE TO THE GORKHA EARTHQUAKE-2015

Before discussing the retrofitting guidelines for burnt brick structures, it is important to understand the nature of damage and deficiency, which the buildings have undergone. The burnt brick structures have experienced few similar types of cracks under same intensity. Vertical cracks are often seen in unreinforced masonry buildings. These generally occur at the corners or ends of the wall, as reinforced structural members are absent at those joints in such structures *(See Figure: 28)*. Horizontal and Diagonal shear cracks develop in the brick infill walls *(See Figure: 28)*. Diagonal cracks are mostly developed between two openings *(See Figure: 28)*. Many a times, horizontal cracks are also formed in the infill walls due to differential settlement of the structure. Such an example is shown in (*Figure: 28)*. Shear cracks are also formed in step type. They generally originate from one end of the infill wall to the other or right from the floor till the roof of the building. A similar kind of crack can be seen which has been taken from one of the districts of Bihar *(See Figure: 28)*. Pancake collapse is a very common type of failure in an unreinforced masonry building during any earthquake. In this case, walls of the building fail completely, due to the pressure (or weight) exerted by the heavy roof. This type of failure occurs in soft storeyes. Soft storeyes are those in which number of walls is less than required for supporting the above roof. Similar type of failure is shown *(See Figure: 28)*. Sometimes, the walls are so weak that they fail to bear the weight of roof under little shaking. This usually occurs because the walls lack bonding at corners and as a result under seismic force, they behave individually and collapse eventually. This type of failure is termed as 'out-of-plane' failure. This results in sudden collapse of roof *(See Figure: 29)*. In case of reinforced concrete framed structures, the most common type of collapse happens due to soft storey failure. Buildings on stilts fail first. They act as inverted pendulum. The ground floor of those buildings are supported by stilts and have very less or no walls to bear the load of the superstructure. Such an example can be seen in *Figure: 29*.Mostly, this kind of failure results in lateral displacement of the entire structure. The building shifts completely by the distance which is equal to the height of the ground floor of that structure. Such an example is shown in



Vertical Cracks in URM Buildings

Horizontal and Diagonal Shear Cracks in URM Buildings

Step Type Shear Cracks in URM Buildings

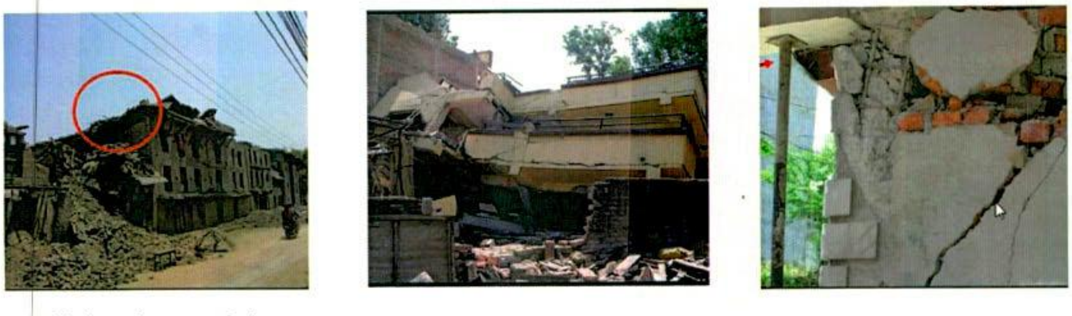
Horizontal Crack Due to Differential Settlement

Diagonal Cracks in infill of the URM Buildings

Pancake collapse of upper storey in URM Buildings

Figure 28: Various types of Cracks and Failures in Brick Masonry Buildings in Bihar after Gorkha Earthquake 2015

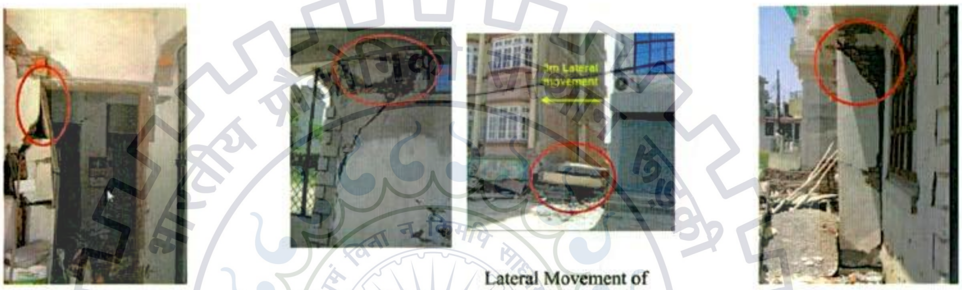
Figure: 29, in which the apartment building has shifted laterally by around 3 meters (equal to the ground floor height).



Roof Collapse due to out-of -plane failure

Soft storey failure of RC Framed structure.

Plastic Hinge formation in column



Absence of Confining member around opening

Masonry Crushing

Lateral Movement of building due to open ground

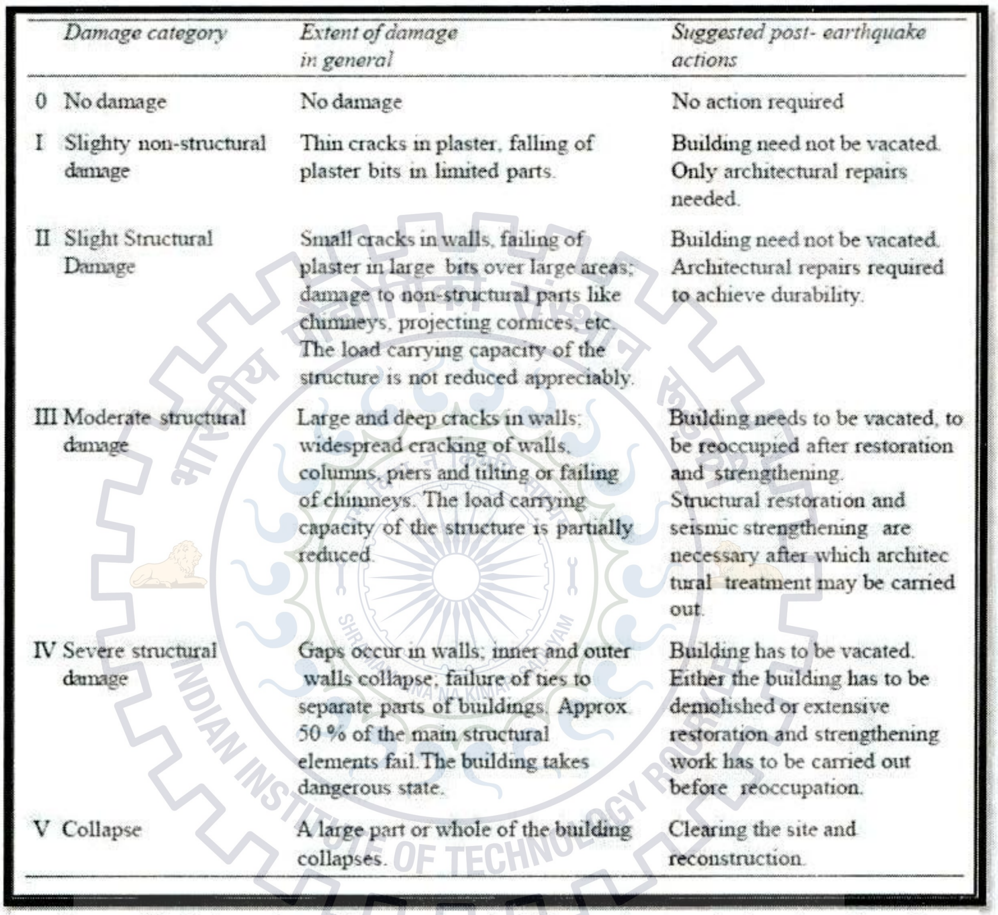
Absence of RC Member

Figure 29: Various types of Cracks and Failures in Brick Masonry Buildings in Bihar after Gorkha Earthquake 2015

Buildings are also damaged due to the absence of certain important structural component at necessary locations. The absence of RC member at the corner, which has led to the detachment of portion of wall from the building, is shown in *(Figure: 29)*. In a similar manner, absence of confining member at the corner of opening has created deformation *(See Figure: 29)*. The structural members fail, if the reinforcement is not done as per the guidelines. An example of plastic hinge formation in column *(See Figure: 29)*. Inappropriate mortar mixture often results in masonry crushing *(See Figure: 29)*.

6.6 RETROFITTING RECOMMENDATIONS FOR STRUCTURES BASED ON OBSERVED DAMAGE TREND

Retrofitting is needed for damaged buildings after any severe earthquake in order to restore their lost strength and make them fit for use again. It becomes essential to identify the severity of damage, as buildings which have undergone failures may induce other disasters by falling either completely or partially. Sometimes, it is required to vacate the building after severe damage for retrofitting works. In case of minor damage, retrofitting works can be performed without vacating the buildings. The table below gives the category and extent of damage with suggested post-earthquake actions *(See Figure: 30)*.



	Damage category	Extent of damage in general	Suggested post- earthquake actions
0	No damage	No damage	No action required
I	Slighty non-structural damage	Thin cracks in plaster, falling of plaster bits in limited parts.	Building need not be vacated. Only architectural repairs needed.
II	Slight Structural Damage	Small cracks in walls, failing of plaster in large bits over large areas; damage to non-structural parts like chimneys, projecting cornices, etc. The load carrying capacity of the structure is not reduced appreciably.	Building need not be vacated. Architectural repairs required to achieve durability.
III	Moderate structural damage	Large and deep cracks in walls; widespread cracking of walls, columns, piers and tilting or failing of chimneys. The load carrying capacity of the structure is partially reduced.	Building needs to be vacated, to be reoccupied after restoration and strengthening. Structural restoration and seismic strengthening are necessary after which architec tural treatment may be carried out.
IV	Severe structural damage	Gaps occur in walls; inner and outer walls collapse; failure of ties to separate parts of buildings. Approx 50 % of the main structural elements fail. The building takes dangerous state.	Building has to be vacated. Either the building has to be demolished or extensive restoration and strengthening work has to be carried out before reoccupation.
V	Collapse	A large part or whole of the building collapses.	Clearing the site and reconstruction.

Figure 30: Categories of damage in a building and suggested post-earthquake actions

**(Source: 'Structural Performance During Earthquakes', IAEE Manual)*

The damages in any Brick Masonry buildings are mainly caused in the listed components of the structure:

- Walls
- Structural Members
- Roof
- Whole building

Different types of damages are caused in each category.

Brick masonry can either be Reinforced Concrete Masonry structures (RC buildings) or Unreinforced Masonry structures (URM buildings). Behaviour of both the types of structures differs under same intensity and magnitude of earthquake. Generally, a well-constructed RC building shows better performance with minor damages, when compared to URM buildings. Few RC buildings may collapse because of several reasons. For example, open ground storey in an RC building, poor reinforcement detail of the structural members, poor geometrical configuration of the building, use of half-brick thick infill walls, extension of walls beyond column lines, etc. The reason RC buildings perform better is mainly because they are framed structures. Therefore, much attention is needed towards URM buildings during retrofitting. In addition to this, materials used for the repair work play a vital role in the entire process. It becomes necessary to make use of advanced materials for their better and effective properties. Few repair materials with their advanced properties are listed in *Chapter 7*.

Table 6.3: Types of damage in Walls and retrofitting recommendations

I. FOR WALLS		
S. No.	**Damages or Failures**	**Reference for Retrofitting Technique**
1	***Cracks*** - Vertical cracks and inclined cracks - Cracks at the corners, end of the walls or at T-junctions. - Horizontal and Diagonal shear cracks in infill, generally developed between two openings. - A number of cracks observed close together.	Refer *Chapter 7, Title I, Subtitle 1*
2	***Masonry Crushing***	Refer *Chapter 7, Title I, Subtitle 2*
3	***Partial or full collapse of wall***	Refer *Chapter 7, Title I, Subtitle 3*

Table 6.4: Types of damage in Structural Members and retrofitting recommendations

II. FOR STRUCTUAL MEMBERS		
S. No.	**Damages or Failures**	**Reference for Retrofitting Technique**
1	***Cracks***	Refer *Chapter 7, Title II, Subtitle 1*
2	***Damaged Reinforcements***	Refer *Chapter 7, Title II, Subtitle 2*

Table 6.5: Types of damage in Roofs (Flat Terraced Roofs: Type-'R3') and retrofitting recommendations

III. FOR FLAT TERRACED ROOFS		
S. No.	**Damages or Failures**	**Reference for Retrofitting Technique**
1	***Falling of roof slab***	Refer *Chapter 7, Title III, Subtitle 1*
2	***Cracks in roof slab***	Refer *Chapter 7, Title III, Subtitle 2*

** Same technique is adopted for similar types of damage in floor.*

Table 6.6: Types of damage in Building as whole and retrofitting recommendations

IV. FOR BUILDING AS A WHOLE		
S. No.	**Damages or Failures**	**Reference for Retrofitting Technique**
1	***Out of plane failure***	Refer *Chapter 7, Title IV, Subtitle 1*
2	***Strengthening of all the walls***	Refer *Chapter 7, Title IV, Subtitle 2*

CHAPTER 7

SPECIFIC TYPES OF DAMAGES AND RECOMMENDATIONS FOR RETROFITTING

I. WALLS

1) CRACKS

- **Repair Materials used for the cracks:**

  Traditionally, the materials which are used for the repair of cracks in brick masonry structures are sand, mud, lime, brick, stone and sometimes steel is used as threaded rods, channels, angles, bolts etc. Generally, cement or lime is mixed with water and sand for the preparation of mortar. There are several advanced materials with better properties like; sulphate resistance, low heat evolution and shrinkage compensation, which can be used for repair of such damages. A few of them is discussed below:

  a. Epoxy Resins

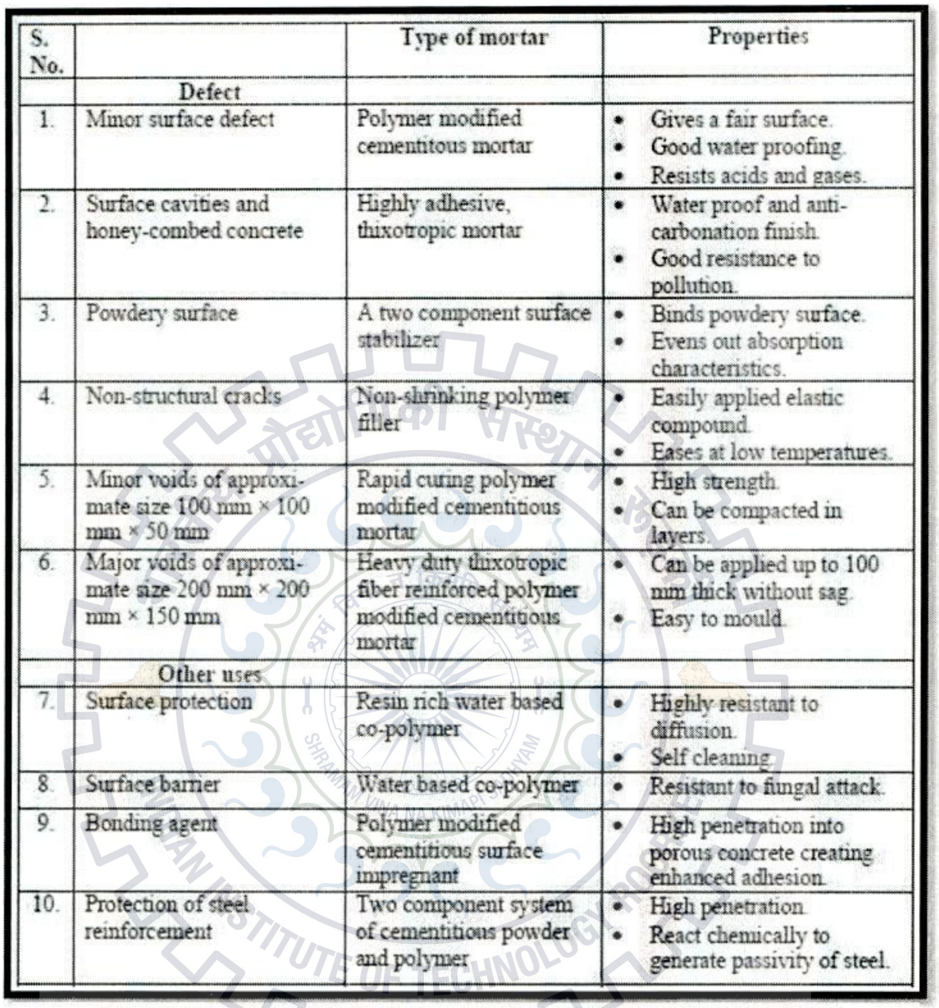
  They are excellent binding agents. They are available with low and high viscosity properties, low viscous resins are mainly used for filling smaller cracks and the latter is applied as coating over concrete surfaces and for filling up larger or wider cracks. Uses of Epoxy Resins include, bonding plastic concrete to a hardened concrete surface, bonding between rigid surfaces etc.

  b. Epoxy Mortar

  Epoxy Resin and sand combine to form Epoxy Mortar. They are high in compressive and tensile strength. Addition of Epoxy Mortar as a second binder in cement mortar increase plasticity, tensile and flexural strength of the mixture.

  c. Quick Setting Cement Mortar

  They are patented and generally contain two components. They are classified as: Unmodified cementitious, Polymer modified, Polyester or Epoxy Resin based, Cement or pozzolanic modified. Various types of mortars with their properties and uses are discussed in below *(See Figure: 31).*



S. No.		Type of mortar	Properties
	Defect		
1.	Minor surface defect	Polymer modified cementitous mortar	• Gives a fair surface. • Good water proofing. • Resists acids and gases.
2.	Surface cavities and honey-combed concrete	Highly adhesive, thixotropic mortar	• Water proof and anti-carbonation finish. • Good resistance to pollution.
3.	Powdery surface	A two component surface stabilizer	• Binds powdery surface. • Evens out absorption characteristics.
4.	Non-structural cracks	Non-shrinking polymer filler	• Easily applied elastic compound. • Eases at low temperatures.
5.	Minor voids of approximate size 100 mm × 100 mm × 50 mm	Rapid curing polymer modified cementitious mortar	• High strength. • Can be compacted in layers.
6.	Major voids of approximate size 200 mm × 200 mm × 150 mm	Heavy duty thixotropic fiber reinforced polymer modified cementitious mortar	• Can be applied up to 100 mm thick without sag. • Easy to mould.
	Other uses		
7.	Surface protection	Resin rich water based co-polymer	• Highly resistant to diffusion. • Self cleaning.
8.	Surface barrier	Water based co-polymer	• Resistant to fungal attack.
9.	Bonding agent	Polymer modified cementitious surface impregnant	• High penetration into porous concrete creating enhanced adhesion.
10.	Protection of steel reinforcement	Two component system of cementitious powder and polymer	• High penetration. • React chemically to generate passivity of steel.

Figure 31: Applications of various types of Mortar for retrofitting

**(Source: 'Handbook on Seismic Retrofitting of Buildings, April 2007)*

d. Micro-concrete

These are ready-made formulations tailored to produce flowable and shrinkage free concrete. They are used at complicated locations and in thin sections.

e. Fibre-reinforced Concrete

They are extensively used for structural strengthening because of their high durability, ductility and tensile strength, as compared to conventional concrete.

f. Fibre-reinforced Polymer

These are made of polymer matrix and fibers. They have high vibration absorption capacity, strength-to-weight ratio, thermal and chemical stability. They are corrosion resistant.

g. Ferro-cement

They are economical even for non-engineered buildings. They are made of cement mortar reinforced with closely spaced layers of small diameters wire mesh (steel or other materials). This is one of the most common materials used for retrofitting of masonry structures.

- **Repair Techniques used for the cracks:**

Cracks basically reduce the strength of load bearing members especially when they are not reinforced. They can be formed in walls due to any earthquake and vary in widths depending upon the ground acceleration and earthquake magnitude. Techniques for treatment of different crack widths are also different.

a. *Minor to medium cracks* (width between 0.5 mm to 5 mm):

They are repaired by Epoxy pressure injection.

Materials Required– Plastic, non-shrink cement, polyester putty, 1:3 cement sand mortar.

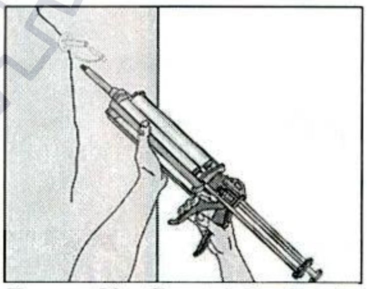


Figure 32: Grout injection in vertical crack of masonry wall

Equipment/Tool Required– Aluminium nipples of 12mm diameter and 30-40mm long, Compressor used for injection of the slurry.

Procedure-The external surfaces are cleaned of properly. The surface along both the sides of the cracks are posted with Plastic or Aluminium ports and secured with polyester putty or 1:3 cement mortar. The center-to-center spacing of theses ports is usually kept equal to the thickness of the wall which has to undergo treatment. After the curing of the sealant, clearing of cracks is done with compressed air or water. The grout injection is performed into one port at a time. In case of vertical cracks, the injection is begun from the lower part of the crack and in case of horizontal cracks; the same is performed from one end to the other *(See Figure: 32)*. The finer the cracks, higher will be the pressure of injection. Complete penetration of the grout material should be done throughout the width and depth of the wall member. Diagonal cracks can also be treated with the similar method of grouting *(See Figure: 33 and 34).This method is suitable for all types of structural elements like, beams, columns, walls and floors of masonry structures.*

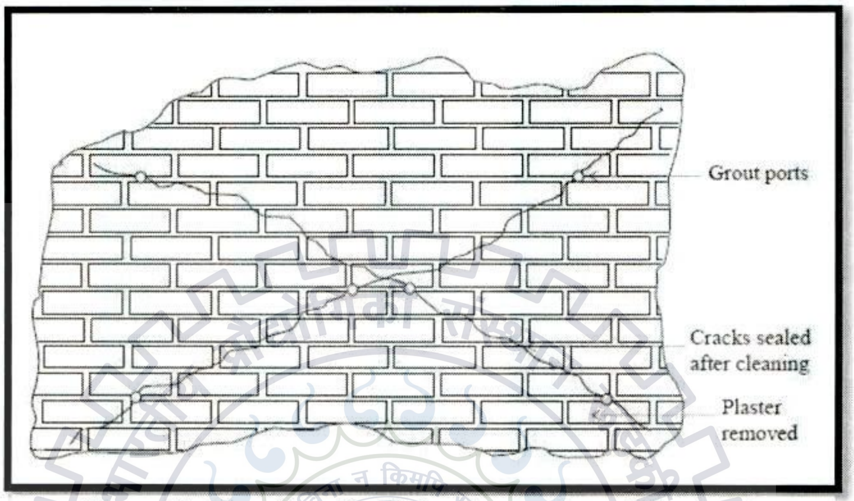


Figure 33: Elevation of wall showing cracks and Grout ports

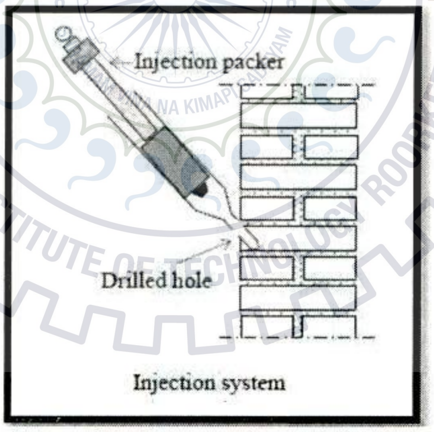


Figure 34: Grout or Epoxy injection

b. *Major cracks* (wider than 5 mm):

For major cracks, a method besides grout injection can be used. The external surfaces are cleaned of properly by removing the loose materials and the gap is filled with any cement mortar discussed earlier *(See Figure: 34).*Flexural or shear reinforcements can be provided, if needed. They can be further covered with plaster for providing better strength and protection to reinforcements. In case of damage to the walls and floors, steel mesh can be provided on the outer side of the surface and bolted or nailed to the wall.

In case a number of cracks are observed close together in the wall, partial demolition of the wall might be required for reconstructing it using 1:6 or richer cement mortar.

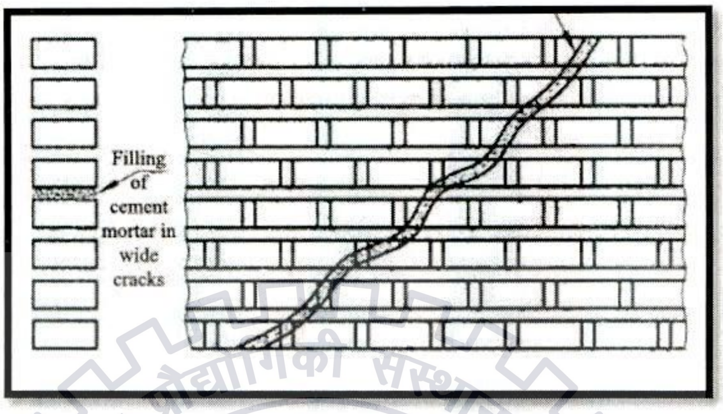


Figure 35: Filling of cement mortar and fine chips in wide cracks

2) MASONRY CRUSHING

For the treatment of this type of damage, the same procedure can be adopted as dealt for the *'Major Cracks'*.

3) PARTIAL OR FULL COLLAPSE OF WALL

In case of partial or full collapse of brick masonry wall, reconstruction of the wall is needed.

II. STRUCTURAL MEMBERS

1) CRACKS

The method of repair discussed in *Chapter 7, Title 1, and Subtitle 1* can be adopted for all types of cracks formed in structural members like, beams and columns of brick masonry structures.

2) DAMAGED REINFORCEMENTS

Buckling and elongation of reinforcements are the most common damages which are caused due to earthquakes. Plastic hinge formation of reinforcements is often observed. In any of such cases, the old portion of the steel reinforcements can be replaced with new steel using butt welding or lap welding. In order to confine the concrete and prevent buckling of reinforcements in future, additional stirrups should be tied in the damaged portions, before concreting. However, in certain cases anchorage of additional steel into existing concrete becomes essential. This is made possible by drilling a hole larger than the diameter of bar. The drilled hole is then injected with epoxy expanding cement or other high strength grouting materials *(discussed in Chapter 7, Title 1, and Subtitle 1)*. The bar is then pushed into the place and held still until the gout sets.

III. ROOFS *(Flat Terraced Roofs: Type-'R3'):*

1) FALLING OF ROOF SLAB

In case of partial or full collapse or falling of roof slab, reconstruction is needed.

2) CRACKS IN ROOF SLAB

The method of repair discussed in *Chapter 7, Title 1, and Subtitle 1* can be adopted for all types of cracks formed in structural members like, beams and columns of brick masonry structures.

IV. BUILDING AS WHOLE

1) OUT-OF-PLANE FAILURE

The external face of the building can be covered with the steel mesh and mortar (or micro-concrete). The continuity of steel at the corners should be maintained simultaneously. The coverings can also be used in the form of vertical splints only between the openings. And, horizontal bands over the spandrel walls can be introduced. This method of wall strengthening is economical when compared to the full covering of external face. This measure integrates all the components of the building more effectively *(See Figure: 36)*. The building thus behaves like a box and prevents out-of plane failure.

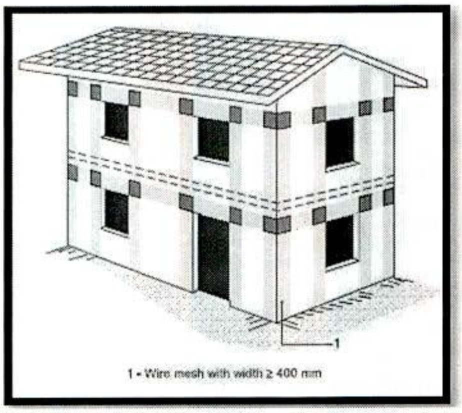


Figure 36: External binding of the building with wire mesh

2) STRENGTHENING OF ALL THE WALLS

For proper strengthening of brick masonry walls and to prevent them from falling, steel plates or angles can be used to provide them with extra support. Each wall member of a building can be supported by such steel plates or angles *(See Figure: 37).*

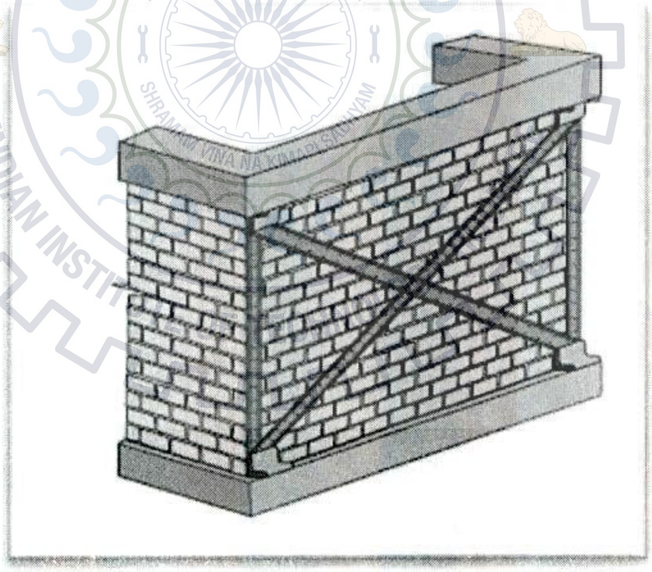


Figure 37: Use of steel plates for strengthening of masonry walls

CHAPTER 8

SUMMARY AND CONCLUSION

The seismic risk assessment has been carried out with the study of damages due to past earthquakes in Bihar. In order to identify the risk associated with the state due to scenario earthquake, estimation of loss has been calculated for each district. Based on this result, probability of damage suffered by the districts has also been shown. In order to mitigate such damage in future, built environment of the state is studied and retrofitting measures have been recommended for the damage trend observed in past earthquakes in a specific building typology, which is found typical in the whole region.

The following conclusions have been drawn from the performed study:

1. The seismic risk assessment of Bihar performed by the calculation method gives a clear picture of threat which the state possesses in today's date. The loss calculation of Bihar under hypothetical recurrence has been done to identify the risk associated with the state. The results are as follows:

2. **Total expected infrastructural loss due to building damage = Rs. 98, 389 Crores** (Ninety eight thousands three hundreds and eighty nine Crores)
   Total expected loss due to damage of content = Rs. 49, 194 (Forty nine thousands one hundred and ninety four Crores)
   Total expected life loss due to building damage:
   a. **During Unfavourable Time of Occurrence =2, 22, 337 persons** (Two lakhs twenty two thousands three hundred and thirty seven)
   b. **During Favourable Time of Occurrence =86, 248 persons** (Eighty six thousands two hundred and forty eight)

3. The projected worst affected districts of Bihar due to scenario earthquake are **Sitamarhi**, **Madhubani**, **Muzaffarpur**, **Darbhanga**, **East Champaran**, **West Champaran**, **Patna** and **Samastipur.**

4. Darbhanga and Samastipur districts have emerged as new threat towards damage due to any future earthquake. Urbanization and population growth of the very two districts have resulted in increased risk.

5. Munger district has an interesting and peculiar geotechnical set up, which makes it more vulnerable towards any future earthquake. The geological set up of the region attracts huge devastation.

6. Burnt Brick Masonry type construction dominates in the state of Bihar. Since, the state is hit by Earthquake in recent time (Gorkha Earthquake-2015), great devastation has occurred. Consequently, few buildings collapsed entirely and many have suffered damage. The damages in burnt brick masonry buildings after the earthquake have been studied and retrofitting measures are recommended for the same.

7. The main types of damages and failures encountered after the Gorkha Earthquake-2015in brick masonry structures of Bihar have been studied. Description of damages and their retrofitting techniques have been categorized in following four major components: for walls, for structural members, for roof and for building as whole. Few of the major damages are as follows:
   - Out-of-plane failure of URM walls.
   - Formation of cracks at the corners of URM buildings.
   - Cracks around the openings.
   - Step type shear cracks were formed.
   - Weak diaphragms and their poor connection.
   - Pancake collapse of the structure.
   - Extensive damage to infill of the masonry walls of RC Framed structures.
   - Diagonal cracks in pier region, between the two openings.
   - Extensive use of half-brick thick wall.
   - Open ground storey failure in RC Framed buildings.
   - Masonry crushing and plastic hinge formation in the columns.

8. Few of the important retrofitting measures recommended for burnt brick masonry buildings which have undergone such failures are as follows:
   - Crack grouting procedure for various types of cracks (minor, medium and major) in walls.
   - Partial demolition of walls and reconstructing it with 1:6 rich mortar (in case of several cracks developed close together).
   - Ferro-cement plates installation at the corner cracks.

- Using steel plates to provide strength to the masonry wall.
- External binding of the building by covering the external face of the building by steel mesh and micro-concrete.
- Introduction of new load bearing members to the columns to reduce the burden of loaded member with the help of jacking.
- Addition of reinforced concrete strips attached to the existing foundation part of the building.

Bihar is developing with a great pace in the field of construction; there is a need to retrofit a large number of structures though. Damaged masonry buildings possess a great threat towards both life and infrastructure. This fact aggravates the need of acknowledging retrofitting measures and its implementation on the damaged structures.

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APPENDIX - A

CALCULATION OF DIRECT AND INDIRECT LOSSES FOR *PATNA* DISTRICT OF BIHAR:

DIRECT ECONOMIC LOSS *(STRUCTURAL AND NON-STRUCTURAL DAMAGE)*:

PROBABILITY * LOSS

Lower bound Calculation:

a) For building Type – A: 275990
Loss = [(0 x 2/100) + (0.18 x 10/100) + (0.17 x 50/100) + (0.55 x 1) + (0.1 x 1)] x (20 x 275990)* x 500*
= (0 + 0.018 + 0.085 + 0.55 + 0.1) x 2759900000
= 2078204700 (Rs.)
{* Floor area x no. of houses of type A}
{* Building Replacement cost}

b) For building Type – B: 7773473
Loss = [(0 x 2/100) + (0.18 x 10/100) + (0.17 x 50/100) + (0.55 x 1) + (0.1 x 1)] x (60 x 7773473) x 1000
= 351205510100 (Rs.)

c) For building Type – C: 27448
Loss = [(0 x 2/100) + (0.18 x 10/100) + (0.17 x 50/100) + (0.55 x 1) + (0.1 x 1)] x (100 x 27448) x 1500
= 3100251600 (Rs.)

Total loss of Type A, B and C = Rs. 35638 Crores

Upper bound Calculation:

a) For building Type – A: 275990

Loss = [(0 x 2/100) + (0 x 10/100) + (0 x 50/100) + (0.8 x 1) + (0.2 x 1)] x (20 x 275990)* x 500*
=(0.8 + 0.2) x 2759900000
= 2759900000 (Rs.)

b) For building Type – B: 7773473

Loss = [(0 x 2/100) + (0 x 10/100) + (0 x 50/100) + (0.8 x 1) + (0.2 x 1)] x (60 x 7773473) x 1000

= 351205510100 (Rs.)

c) For building Type – C: 27448

Loss = [(0 x 2/100) + (0 x 10/100) + (0 x 50/100) + (0.8 x 1) + (0.2 x 1)] x (100 x 27448) x 1500

= 4117200000 (Rs.)

Total loss of Type A, B and C = Rs. 47328 Crores

CONTENT LOSS:

Half of Direct Economic Loss:

Lower Bound = Rs. 17819 Crores

Upper Bound = Rs. 23664 Crores

EXPECTED SOCIAL LOSS (Number of deaths):

- ***During unfavorable time of occurrence***
  = L x R x (0.06 x NG5_IV + 0.02 x NG4_IV)
  = 0.66 x 4.77 [(0.06 x 24745) + (0.02 x 261418)]
  = **21134 persons**

- ***During favorable time of occurrence***
  = F x L x R x (0.06 x NG5_IV + 0.02 x NG4_IV)
  = 0.39 x 0.66 x 4.77 [(0.06 x 24745) + (0.02 x 261418)]
  = **8242 persons**

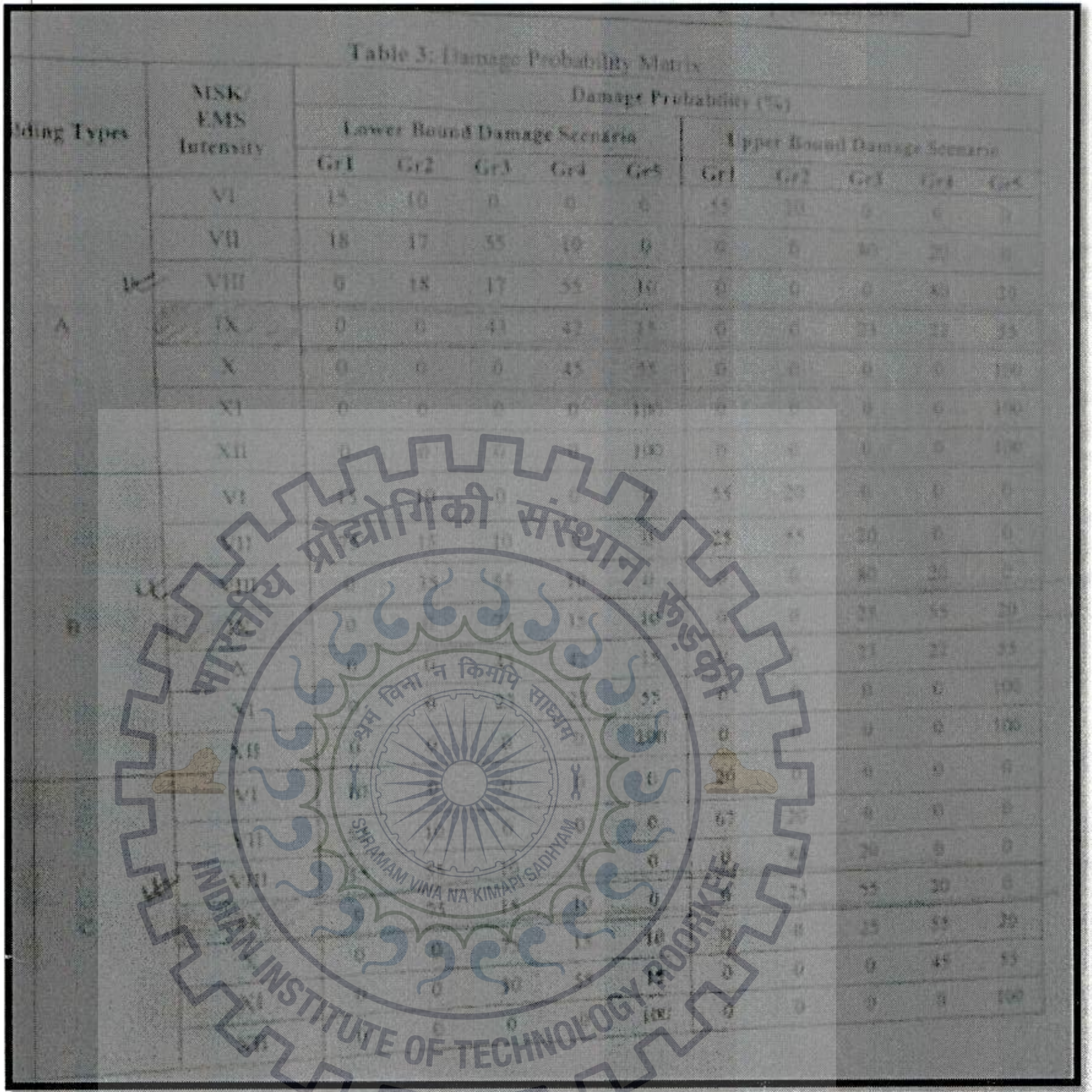

Table 3: Damage Probability Matrix

lding Types	MSK/ EMS Intensity	Damage Probability (%)									
		Lower Bound Damage Scenario					Upper Bound Damage Scenario				
		Gr1	Gr2	Gr3	Gr4	Gr5	Gr1	Gr2	Gr3	Gr4	Gr5
A	VI	15	10	0	0	0	55	20	0	0	0
	VII	18	17	55	10	0	0	0	40	20	0
	VIII	0	18	17	55	10	0	0	0	80	20
	IX	0	0	43	42	15	0	0	23	22	55
	X	0	0	0	45	55	0	0	0	0	100
	XI	0	0	0	0	100	0	0	0	0	100
	XII	0	0	0	0	100	0	0	0	0	100
B	VI	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	55	20	0	0	0
	VII	[illegible]	15	10	[illegible]	[illegible]	25	55	20	0	0
	VIII	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	80	20	0
	IX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	25	55	20
	X	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	23	22	55
	XI	[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]	0	0	100
	XII	[illegible]	[illegible]	[illegible]	[illegible]	100	0	[illegible]	0	0	100
C	VI	[illegible]	[illegible]	[illegible]	[illegible]	0	20	[illegible]	0	0	0
	VII	[illegible]	[illegible]	[illegible]	[illegible]	0	67	[illegible]	0	0	0
	VIII	[illegible]	[illegible]	[illegible]	[illegible]	0	[illegible]	[illegible]	20	0	0
	IX	[illegible]	[illegible]	[illegible]	[illegible]	0	[illegible]	25	55	20	0
	X	[illegible]	[illegible]	[illegible]	[illegible]	10	0	0	25	55	20
	XI	[illegible]	0	30	55	15	0	0	0	45	55
	XII	[illegible]	0	0	[illegible]	100	0	0	0	0	100

Figure 38: Damage Probability Matrix

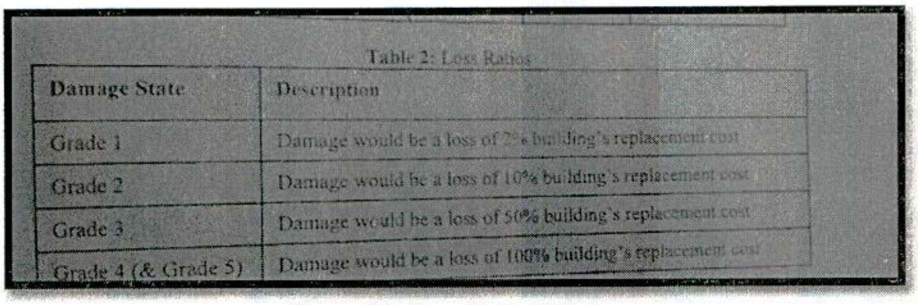

Table 2: Loss Ratios

Damage State	Description
Grade 1	Damage would be a loss of 2% building's replacement cost
Grade 2	Damage would be a loss of 10% building's replacement cost
Grade 3	Damage would be a loss of 50% building's replacement cost
Grade 4 (& Grade 5)	Damage would be a loss of 100% building's replacement cost

Figure 39: Loss Ratio Chart