Earthquake Hazard Risk Vulnerability Analysis (HRVA) of Navi Mumbai

Final Report

Submitted to

Navi Mumbai Municipal Corporation (NMMC)

by

Ravi Sinha, Alok Goyal, Mahendra Meena and Rohan Shinde

Department of Civil Engineering
Indian Institute of Technology Bombay
Powai, Mumbai - 400 076

January 15, 2016

Executive Summary

The Navi Mumbai Municipal Corporation (NMMC) has initiated a project under Climate Change Adaptation (CCA) program, which has various components including multi hazard mapping and their risk assessment. The main objective of the proposed multi-hazard risk and vulnerability assessment exercise is to evaluate the extent of disaster risk and the vulnerabilities at the ward/node level for Navi Mumbai city. The outcome of the exercise is expected to help identify a set of structural and non-structural measures which can be used by NMMC and other stakeholders to take measures to mitigate the risks associated to various hazards.

The Seismic Hazard Risk Vulnerability Analysis (HRVA) has been carried out by Indian Institute of Technology (IIT) Bombay by using the software RISK.iitb, which has been developed at IIT Bombay on ArcGIS platform. Risk assessment has been carried out for scenario earthquakes by considering moment magnitudes of 6.5 and 6.0, which are consistent with regions of moderate seismic hazard. The city's area is divided in grids of 0.2 km × 0.2 km and the spatial analysis for seismic risk is carried out in each grid. The risk assessment requires several information regarding the city and its built environment. The population and other parameters were provided to IIT at electoral ward levels. These input data are further distributed into the grids based upon the estimated built-up area of the grids. Satellite images from Google Earth have been used to delineate different occupation types such as slum and non-slum areas.

The risk assessment combines the estimated ground shaking due to the scenario earthquake, impact of ground shaking on the built-environment in terms of damage to buildings and the consequence of damage to the occupants. The risk assessment results have been presented in tabular form at electoral ward level as well as easy to understand colour-coded maps. The loss estimation associated with different scenario earthquakes will help various stakeholders to understand the impact of the earthquake and the sensitivity of the size of earthquake on the consequences. The results, presented at ward level, will also help the NMMC and other stakeholder agencies to evaluate the expected demand on them in the aftermath of an earthquake and coping capacity of their organisations. This project report is also expected to be very useful to review the present disaster management plans and to make further improvements to them where necessary.

Based upon the seismic risk assessment of Navi Mumbai, following major recommendations are made among others:

1. The risk assessment shows high impact due to scenario-level earthquake. The results of this study should be shared with organisations managing lifeline systems and important facilities so that impact on rail network, road network, powerlines, pipelines etc. and critical infrastructure such as fire stations, public schools, public health systems, etc. can be assessed by them. Their assessment, from disaster management plan considerations, should also include assessment of damage and restoration times for lifeline systems and critical facilities. Such functionality of these lifeline systems and critical facilities can be very important to get access the disaster struck areas to mobilize rescue teams and provide relief measures.
2. The NMMC can use the results of the seismic risk assessment to prepare their response plan describing all the activities that need to be undertaken in the event of a disaster. It is strongly recommended that, in addition to earthquake risk, the city's disaster management plan also include other hazards such as floods, cyclone, tsunami, terrorism, etc. Action plan should be developed to reduce the risk associated to various hazards by outlining process for different phases of disaster management which includes, response, relief, mitigation, recovery and preparedness. A multi-hazard action plan will help to respond a disaster effectively, which will further help in minimizing loss in the event of future disasters.
3. The Navi Mumbai city has large open spaces. These locations can be utilized as temporary shelters in case of disasters that result in damage to buildings and requiring temporary relocation of occupants into relief camps. The results of risk assessment should be used to prepare the detailed plan for utilization of these spaces. The detailed planning of the relief campus should typically also consider the required infrastructure for water supply, sanitation, medical support, etc. The plan may be prepared ward-wise and these open spaces marked for disaster management purposes in the development plan of the city.

4. Damage to buildings during an earthquake is the primary cause of casualties in an earthquake. The NMMC engineers need to be trained to improve enforcement of the codes. Training may also be provided to architects, planners and engineers in NMMC, CIDCO and other agencies so that they can incorporate earthquake risk parameters in their activities and improve seismic safety.
5. Mock drills as per response plan for scenario earthquakes should be organized for NMMC officers and staff frequently. These mock drills give an opportunity to the different emergency support function agencies to come together and enhance their ability to coordinate their activities. Following disasters, it has been often observed that the response of line departments is more efficient if they frequently practice their roles. Such mock drills provide an opportunity for the agencies to test their ability to deal with the adverse situation and also to improvise the existing system by identifying gaps in their plans.

Acknowledgement

This project was initiated by Navi Mumbai Municipal Corporation (NMMC) in association with United Nations Development Programme (UNDP). Financial support from NMMC is greatly acknowledged. The authors are grateful to NMMC Officials, who are listed below, for their great support throughout the project.

1. Mr. D. T. Waghmare, Municipal Commissioner
2. Mr. Abasaheb Jarhad, Ex-Municipal Commissioner
3. Dr. Bhaskar Wankhede, Ex-Municipal Commissioner
4. Mr. J. N. Sinnarkar, Deputy Municipal Commissioner (Disaster Management)
5. Mrs. Sandhya Ambade, Deputy Municipal Commissioner (Social Development and Slum Rehabilitation)
6. Mr. D.S.Chabukswar, Deputy Municipal Commissioner (Estate, Sports & Cultural, Vehical, Swachha Maharashtra Abhiyan)
7. Mr. Sunil Hazare, Assistant Director Town Planning Department
8. Mr. Gaikwad, Town Planning Department

The authors are also grateful to Mr. Madhukar Sanap, UNDP for the coordination to carry out this project.

Table of Contents

List of Tables viii

List of Figures..ix

Chapter 1. Introduction 10

1.1 GENERAL.. 10

1.2 OBJECTIVES OF THE PROJECT 12

1.3 SEISMIC HAZARD 12

1.4 SEISMIC VULNERABILITY AND EXPOSURE.. 13

1.5 SEISMIC RISK 13

1.6 ORGANIZATION OF THE REPORT 14

Chapter 2. Navi Mumbai Description and Past Earthquakes 15

2.1 NAVI MUMBAI CITY DESCRIPTION 15

2.1.1 Administrative Structure of the City 16

2.1.1.1 Disaster Management Unit 18

2.1.1.2 Fire Department 19

2.1.1.3 Interactions with CIDCO 19

2.1.2 Geographic Information 19

2.1.3 Population Details... 22

2.1.4 Land-Use Pattern in NMMC Area... 22

2.1.5 Building Construction Types... 23

2.2 PAST EARTHQUAKES IN THE VICINITY OF NAVI MUMBAI 23

2.3 DISCUSSIONS.. 27

Chapter 3. Methodology of Seismic Risk Assessment 29

3.1 DETERMINISTIC SEISMIC HAZARD ASSESSMENT 29

3.1.1 Source Characterization... 31

3.1.2 Ground Motion Predictions Equations (GMPE) 31

3.1.2.1 Iyengar and Raghukanth (2004).. 32

3.1.3 Site Characteristics 32

3.1.4 Liquefaction 33

3.1.5 Damage Intensity... 33

3.2 SEISMIC VULNERABILITY 34

3.3 EXPOSURE 35

3.3.1 Population Analysis........ 36

3.3.2 Property Analysis 37

3.4 LOSS ESTIMATION........ 38

3.4.1 Social Losses........ 38

3.5 DISCUSSIONS........ 39

Chapter 4. Seismic Risk Assessment and Loss Estimation........ 40

4.1 SCENARIO EARTHQUAKES 40

4.2 RESULTS OF EARTHQUAKE RISK ASSESSMENT........ 44

4.3 INSIGHTS FROM RISK ESTIMATION 53

4.4 ANALYSIS OF RESULTS........ 61

Chapter 5. Discussions and Conclusions 64

5.1 DISCUSSIONS........ 64

5.2 CONCLUSIONS 65

5.3 RECOMMENDATIONS........ 66

References 69

List of Tables

Table 2.1: Firefighting vehicles (NMMC Fire Mitigation Plan Report, 2012-2013) 19

Table 2.2: Population and area of Navi Mumbai 22

Table 2.3: List of significant historical earthquakes affecting Mumbai and Navi Mumbai (Wenzel et al., 2007 and Joshi, 2007) 24

Table 2.4: Epicentres of earthquakes occurred in 1998 to 2005 in vicinity of Navi Mumbai with magnitude M_c > 2.5 (Mohan, Surve and Tiwari, 2007) 25

Table 3.1: Fatalities as a percentage of injuries in different building types (Coburn and Spence, 1992) 38

Table 4.1: Input parameters of scenario earthquakes 40

Table 4.2 Sensitivity analysis results for earthquake risk assessment assuming 9 epicentres for Mw = 6.5 42

Table 4.3 Sensitivity analysis results for earthquake risk assessment assuming 9 epicentres for Mw = 6.0 43

Table 4.4: Overall casualties from scenario earthquakes 53

Table 4.5 Ward-wise results for earthquake risk assessment for Mw = 6.5 54

Table 4.6: Ward-wise results for earthquake risk assessment for Mw = 6.0 57

List of Figures

Figure 2.1: Navi Mumbai electoral ward boundaries with Ward Numbers 17

Figure 2.2: Flow chart of administrative hierarchy of Navi Mumbai (Tentative) 18

Figure 2.3: Electoral ward map of Navi Mumbai showing land use (NMMC Final Ward Formation File, 2015).. 21

Figure 2.4: Seismicity in the vicinity of Navi Mumbai (Seismotectonic Atlas of India and its Environs SEISAT-27, 2000).. 27

Figure 3.1: Flow chart for DSHA 30

Figure 3.2: Vulnerability curve in terms of damage of different building types (Sinha et al., 2013) 35

Figure 3.3: Methodology for distribution of population to different buildings. 37

Figure 4.1: Assumed epicentres for the scenario earthquakes.. 41

Figure 4.2: Peak Ground Acceleration (PGA) map for scenario earthquake Mw = 6.5......... 45

Figure 4.3: Peak Ground Acceleration (PGA) map for scenario earthquake Mw = 6.0......... 46

Figure 4.4: MSK Intensity map for scenario earthquake Mw = 6.5 47

Figure 4.5: MSK Intensity map for scenario earthquake Mw = 6.0 48

Figure 4.6: Map of estimated injuries for scenario earthquake Mw = 6.5 49

Figure 4.7: Map of estimated injuries for scenario earthquake Mw = 6.0 50

Figure 4.8: Map of estimated fatalities for scenario earthquake Mw = 6.5 51

Figure 4.9: Map of estimated fatalities for scenario earthquake Mw = 6.0 52

Chapter 1. Introduction

1.1 General

India is rapidly urbanizing, and Maharashtra is one of the most urbanized states in the country. In wake of urbanization most of the cities are expanding rapidly, often in an unplanned manner since it is difficult to guide the development in a regulated way. The city of Navi Mumbai was planned in the 1960s to be developed into a satellite counter-magnet to the city of Mumbai and thereby help to decongest Mumbai over time. Navi Mumbai was thus planned as a greenfield city following the best principles of modern town planning. The city has grown from negligible population at its inception to a bustling city of over 1 million people today. The Navi Mumbai Municipal Corporation, headed by the Mayor and Municipal Commissioner, manages the civic affairs of the city.

Western India, including Navi Mumbai, is categorized under Seismic Zone III by the Bureau of Indian Standards. This implies that this region may experience moderate earthquakes, say of magnitude around 6.5. Western India has experienced several earthquakes in the past, the most notable ones being the Bhuj earthquake of 2001, Killari earthquake of 1993 and Koyna earthquake of 1967. There are a number of known earthquake sources in the vicinity of the city, where the occurrence of a moderate earthquake may result in damage to Navi Mumbai. Being a new city, most buildings in Navi Mumbai are expected to be engineered constructions, which are designed and constructed with the involvement of trained professionals. However, there are a number of buildings in the older rural habitations and slums that have not followed the Indian standards. Older buildings may also not be adequately maintained resulting in lower strength that may get damaged due to the earthquake. There are also other contributory factors such as soil conditions that may enhance earthquake motions and cause damage to buildings. Even in buildings that are capable to withstand an earthquake without structural failure, there may be risk to occupants due to interior hazards. Also if engineering codes and practices may not be strictly followed in the construction of buildings, the new buildings may be unable to withstand earthquake forces, as has been seen in during several earthquakes in the last few decades.

As per IS code 1893 - 2002, Western India lies in Zone III and Zone IV. Seismic shaking in terms of Modified Mercalli Intensity (MMI) is expected to be VII and VIII for Zone III and Zone IV, respectively. Most regions of western India, including Navi Mumbai, lie in Seismic Zone III. Western India has experienced several damaging earthquakes, such as the 2001 Bhuj earthquake in the state of Gujarat in 2001, which resulted in over 10,000 casualties. The earthquake badly damaged the urban infrastructure in the towns of Bhuj, Anjar and Bhachau and caused collapse of buildings in Ahmedabad located over 200 km away. Similarly, the 1993 Killari earthquake in Marathwada region of Maharashtra resulted in around 9,000 deaths and caused heavy damage to the region.

In order to take effective steps to manage the earthquake risk, the likely consequences of an earthquake in the region needs to be understood. This can be carried out through developing scientific “scenario” of the occurrence of the hazard. The scenario simulates the consequences such as earthquake wave propagation, and evaluates its impact on the built environment.

Navi Mumbai Municipal Corporation (NMMC) initiated a project under Climate Change Adaptation (CCA) which has various components including multi hazard mapping and their risk assessment. The main objective of the proposed multi-hazard risk and vulnerability analysis exercise is to assess the extent of risk and the vulnerabilities at the ward/node level for Navi Mumbai City. The outcome of the exercise is expected to help identify a set of structural and non-structural steps that can be used by NMMC and other stakeholders to take measures to mitigate the risks associated to various hazards. The Risk associated to earthquake hazard has been evaluated by Indian Institute of Technology (IIT) Bombay.

In this project, the seismic risk assessment scenario analysis has been carried out for Navi Mumbai city. The results of the earthquake scenario have been prepared at ward/node level, that presents assessment results such as the peak ground acceleration (PGA), intensity of earthquake, expected damage to buildings, expected injuries and fatalities, etc. Colour coded risk maps to quickly understand the key results in visual form are also developed. This information can be useful to the city in the context of this project, since major cities vulnerable to earthquakes typically consider earthquake risk as the foundation for planning their risk management or mitigation efforts.

The Earthquake Hazard Risk Assessment study includes the following components:

- Estimation of peak ground acceleration, earthquake intensity and other ground motion parameters if required,
- Seismic risk assessment of the city of Navi Mumbai at ward/node level,
- Loss estimation: expected injuries, deaths and economic losses in terms of structural and non-structural losses, and
- Development of color coded risk maps including information regarding population exposure.

The seismic risk consists of three components: (1) Seismic hazard, or the potential size of earthquakes in future, (2) Seismic structural vulnerability, or the capacity of the built environment to withstand ground shaking, and (3) Exposure, or the consequences of an earthquake and its impact on the built environment.

1.2 Objectives of the Project

This study is a part of “Multi Hazard Mapping Analysis” which have following objectives inter alia:

- To identify and review relevant data sources to be used for conducting the seismic hazard assessment in the study,
- To develop the exposure database at city level,
- To evaluate ground shaking and to evaluate social losses; e.g. scenarios for loss to various categories/types of buildings, residential, industry, commercial, infrastructure and other facilities,
- To identify high risk areas, and
- To generate the mortality and injury scenarios.

1.3 Seismic Hazard

Seismic Hazard is defined as an estimation of ground motion parameters, a scenario event can produce, in the proximity of an engineering site. Seismic hazard analysis consists of characterizing the sources of the hazard i.e. the size and spatial location of postulated earthquakes and characterizing the natural effects these sources would have at a particular location.

The probability that social or economic consequences of earthquakes will equal or exceed specified values at a site, at several sites, or in an area, during a specified exposure time. Historically the term seismic risk has been used to describe an assortment of earthquake effects that range from ground shaking, surface faulting, and earthquake-induced land-slides to economic loss and casualties. As more quantitative methods for estimating the effects of earthquakes have been developed, terminology has become more precise. Although the term seismic risk is still sometimes used in a general sense to mean the potential for both the occurrence of natural phenomena and the economic and life loss associated with earthquakes, it is useful to differentiate between the concepts of seismic hazard and seismic risk. Seismic hazard may be defined as any physical phenomena (for example, ground shaking or ground failure) that are associated with an earthquake and that may produce adverse effects on human activities.

1.4 Seismic Vulnerability and Exposure

Seismic vulnerability can be described as a structure's susceptibility to damage by ground shaking caused by earthquakes. A vulnerability assessment needs to be made for a particular characterization of the ground motion, which will represent the seismic demand of the earthquake on the building.

The exposure time is the time duration of interest for seismic hazard or risk assessments. In practical applications, the exposure time may be considered to be the design lifetime of a building or the length of time over which it is of interest to estimate numbers of casualties. For example, the risk that a certain number of casualties will occur is the probability associated with all combinations of seismic hazards that may result from the earthquakes and all possible numbers of casualties resulting from those hazards.

1.5 Seismic Risk

In general, risk can be defined by probability of occurrence of a seismic event, exposure of people and property to the event, and consequences of that exposure. Risk analysis incorporates estimates of the probability of various levels of injury and damage to provide a more complete description of the risk from the full range of possible hazard events in the area.

1.6 Organization of the Report

Detailed earthquake risk assessment has been carried out for the city of Navi Mumbai at the electoral ward level. This report includes the methodology which is adopted to carry out the earthquake risk assessment for scenario earthquakes. The elements of the built environment considered for the assessment are buildings. Though the whole area of the city is divided into small grids of 0.2 km × 0.2 km size, the results have been aggregated at the city electoral ward level.

The report has been organized into *five* chapters. The *Second* chapter gives a brief description of Navi Mumbai, its geographic information, administrative structure, land use details, population information etc. Seismicity around Navi Mumbai region also presented along with significant earthquake affecting Navi Mumbai. The *Third* chapter contains the methodology of deterministic seismic risk assessment. *Fourth* chapter highlights the earthquake risk assessment results of multiple scenario for two earthquake magnitudes 6.5 and 6.0. Discussions and conclusions along with recommendations are presented in the *Fifth* chapter of the report.

Chapter 2. Navi Mumbai Description and Past Earthquakes

2.1 Navi Mumbai City Description

The first post-independence development plan for Bombay, formulated by the Mayer-Modak Committee in 1948, suggested satellite towns north of Bombay. Ten years later, the Barve committee suggested the formation of a township on the mainland across the Thane Creek as a counter-magnet to draw away population from the already overcrowded city. This proposal was accepted by the BMC. Although the plan lay dormant for a long time, this was the beginning of New Bombay (NMMC, 2016).

The growth of Mumbai city is constrained by sea at south, east and west. As a result total land area available for development of Mumbai is limited. To avoid the haphazard development of Mumbai, Plan for Mumbai Metropolitan Region (MMRP) was prepared under the provision of Maharashtra Regional and Town Planning (MRTP) act 1966, which was sanctioned by Govt in 1973. Hence, developmental planners, in late 1960s started exploiting alternative for dispersal and control of Mumbai population and Navi Mumbai was proposed as an alternative to Mumbai. City and Industrial Development Corporation (CIDCO) prepared developmental plan for Navi Mumbai covering 95 villages from Thane and Raigad district. This was approved by the Government of Maharashtra in August 1979.

Further, for catering to the requirements of 29 villages in CIDCO project and 14 villages from Kalyan notified area, NMMC was formed in December 17, 1991. NMMC came in to existence on January 1, 1992. However, 14 villages from Kalyan notified were deleted from NMMC jurisdiction vide Government dated June 8, 2007. The Maharashtra Government industrial promotion policy leads to development of industrial belt in Navi Mumbai. These industries, in turn, attracted a large population as workers.

Also, the cost of real estate and housing in Navi Mumbai is much less than costs in Mumbai and sub-urban areas. Many government and corporate offices have been shifted from

Mumbai to Navi Mumbai. Chemical, Pharmaceutical, Engineering, Textile Processing, Petrochemical, Electronics, Oil and Processing, Paper, Plastic, Steel and Food Industries in the Taloja and Thane Belapur Industrial Belt of Navi Mumbai offer job opportunities of every conceivable kind - from engineers to mechanics to clerks to peons. As a result a large population of service class and middle class population shifted to Navi Mumbai.

Thus, Navi Mumbai has been developed as a planned city, a counter magnet for Mumbai. It has been developed as an independent, fully self-contained metro city. Navi Mumbai is the world's large, totally planned, well-balanced, environment friendly, modern city with beautifully landscaped area with parks, gardens and promenades along waterfronts. Care has been taken to preserve the mountainous terrain, lakes and green spaces in Navi Mumbai, which cover nearly half of its total area.

2.1.1 Administrative Structure of the City

The Navi Mumbai Municipal Corporation has an area of 162.5 sq. km under its supervision. The population of the city as per the census 1991 was 3,87,206 which had increased to 7,03,947 as provided in the census figures in 2001 and furthermore to 11.2 lakhs in 2011 (Census, 2011).

CIDCO has planned to develop 14 nodes in Navi Mumbai out of which 8 nodes were handed over to NMMC (Navi Mumbai Municipal Corporation) in 1991 for its administration (NMMC, 2015). Each of these 8 nodes is under the control of one administrative officer. Theses 8 nodes are given as below:

1. Digha
2. Airoli
3. Ghansoli
4. Koper Khairne
5. Vashi
6. Turbhe
7. Nerul
8. Belapur

Each of the nodes is divided into groups. These groups are blocks of one or more sector in each of the node. Each group is further subdivided into bits. The administration work is then controlled on a bit basis. Each bit has a supervisor who is required to ensure that all the facilities provided by the NMMC are in order.

These nodes are further divided into wards in the form of electoral wards totalling 111. A corporator is elected in each of the wards. The administrative bits lie in one of the wards. The electoral ward boundaries along with the ward numbers are shown in Figure 2.1.

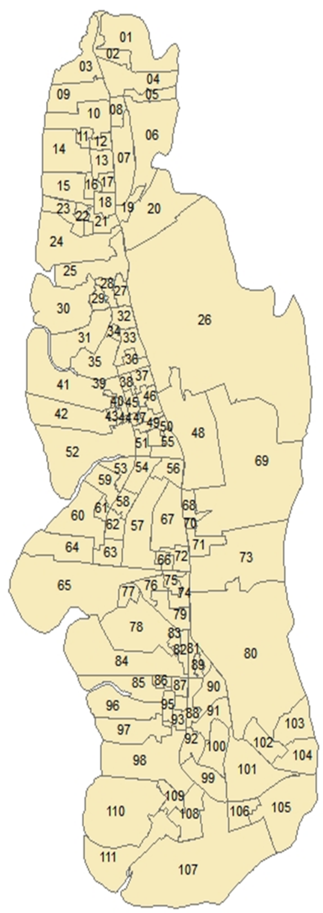

Figure 2.1: Navi Mumbai electoral ward boundaries with Ward Numbers

The municipal corporation is headed by a municipal commissioner and an elected mayor with its headquarter at Belapur. The Mayor is supported by a Deputy Mayor. The day-to-day affairs of Navi Mumbai are governed through various committees. A representative flow chart of administrative hierarchy in NMMC is shown in Figure 2.2.

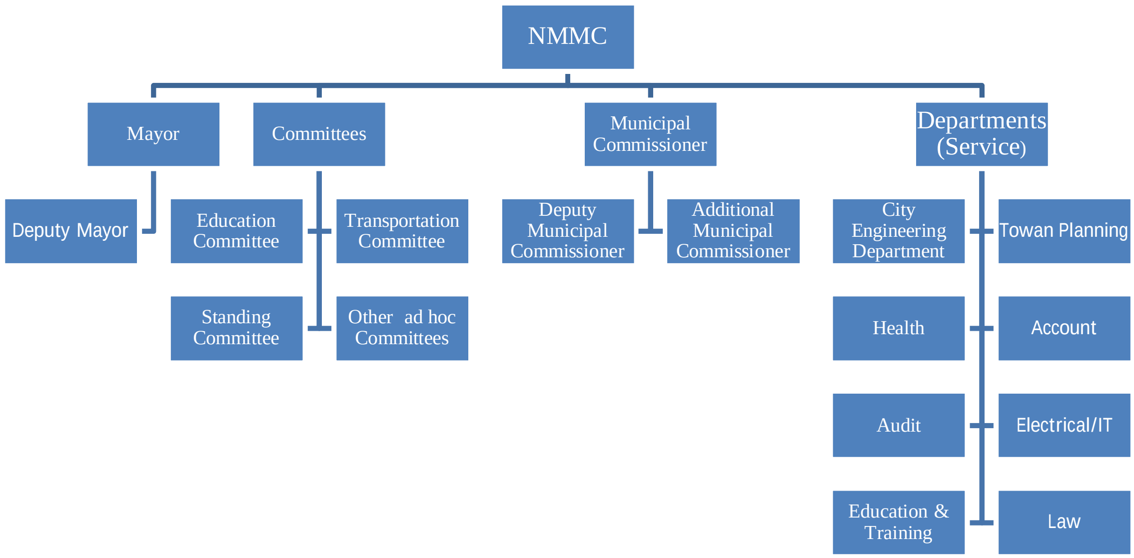

Figure 2.2: Flow chart of administrative hierarchy of Navi Mumbai (Tentative)

The NMMC has 8 departments. These departments are classified based on the services that they offer to the citizens.

2.1.1.1 Disaster Management Unit

Navi Mumbai Municipal Corporation has established a disaster management unit headed by the Municipal Commissioner. The Municipal Commissioner is assisted by a disaster management committee.

Disaster management committee has the following objectives:

- To ensure effective inter-departmental co-ordination between all departments,
- To provide policy decisions when required,
- To keep the government informed about disaster situation,
- To review disaster related activity reports received from NMMC, and
- To co-ordinate the activities of lateral, and Central Government agencies like Defence services, SRP, RPF, Coast Guards etc.

2.1.1.2 Fire Department

Fire department, being the first respondent to disasters, NMMC has established its own firefighting cell. There are 4 firefighting stations at CBD Belapur, Vashi, Airoli and Nerul. One other emergency centre is also established at Koper Khairane for Thane Belapur industrial area.

The details of firefighting equipments are given below:

Table 2.1: Firefighting vehicles (NMMC Fire Mitigation Plan Report, 2012-2013)

Sr. No.	Name of Vehicle	Nos.
1.	Fire Engine	2
2.	Foam Tender	1
3.	Rescue Tender	1
4.	D.C.P. Tender	1
5.	Branto Skylift	2
6.	Water Tanker	2
7.	Ambulance	4
8.	Fire Jeep	4
Total		**17**

NMMC is also planning to procure latest fire fighting vehicles to improve its firefighting capability.

2.1.1.3 Interactions with CIDCO

Since, Navi Mumbai has been planned by CIDCO (City and Industrial Development Corporation), it has already put a lot of planning into its development. CIDCO has its own disaster management unit which works in tandem with NMMC to deal with issues such as water logging, solid waste management, outbreak of disease due to floods, etc.

2.1.2 Geographic Information

Navi Mumbai Municipal Corporation (NMMC) region lies in Thane and Raigarh districts of Maharashtra. The extent of the region lies between 19° N to 19.25° N in North-South direction and 72.95° E to 73.05° E in East-West direction. Navi Mumbai development plan is being implemented by City and Industrial Development Corporation (CIDCO) and NMMC.

The government of Maharashtra had identified total area of 343.70 sq. km for Navi Mumbai. Out of this 162.5 sq. km area is under the administrative control of NMMC. This area includes residential, industrial, commercial, depots and warehouses, administrative areas, education campuses, roads, railways, parking spaces, open spaces for public use, gardens, crematorium, water supply, sewerage, electric supply facilities (NMMC, 2015). In Figure 2.3, the area of Navi Mumbai as divided in residential, commercial, industrial and green area is shown.

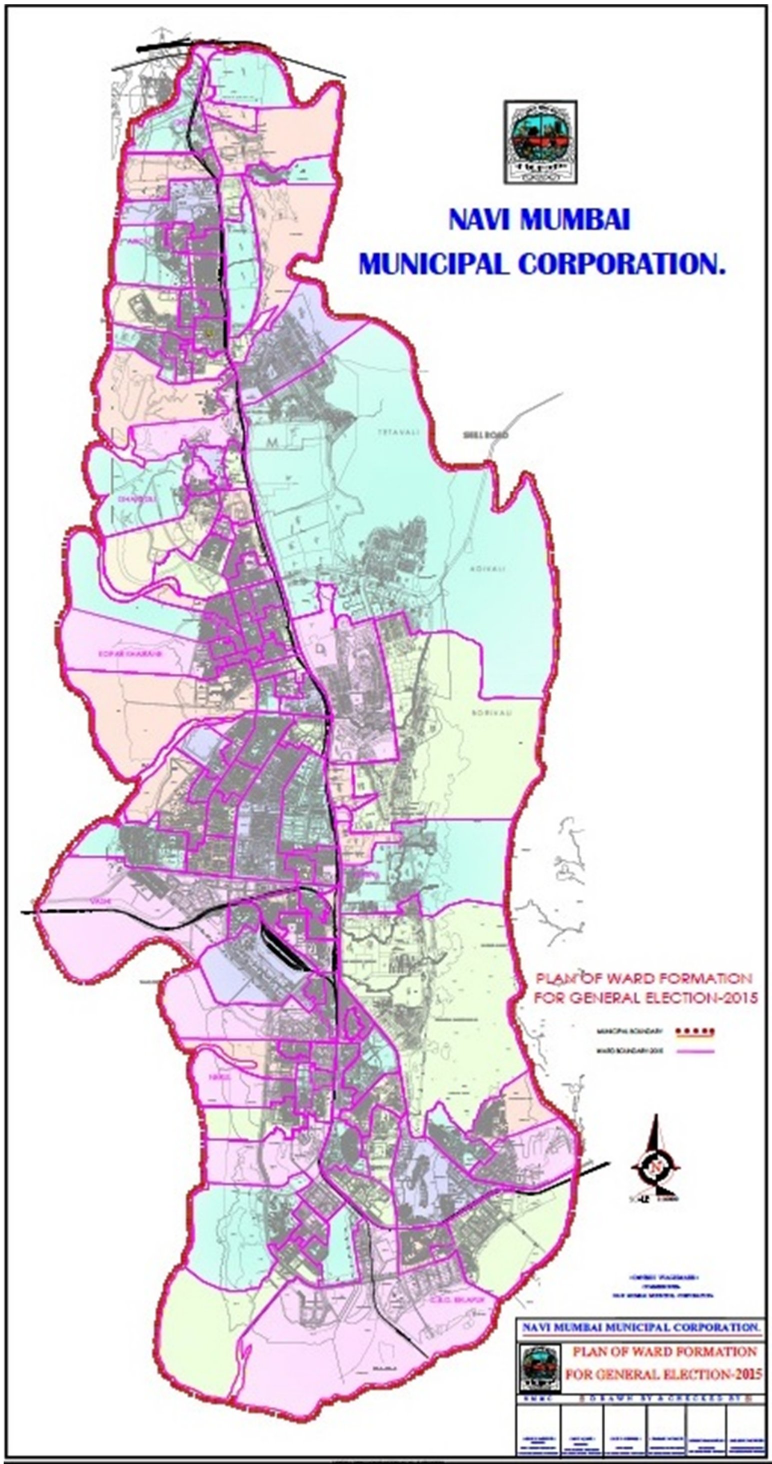

Figure 2.3: Electoral ward map of Navi Mumbai showing land use (NMMC Final Ward Formation File, 2015)

2.1.3 Population Details

The population residing within NMMC area has increased from 3.18 lakhs in 1991 to 11.2 lakhs in 2011 (Census, 2011). The total population and area in 2011 are given in Table 2.2.

Table 2.2: Population and area of Navi Mumbai

Navi Mumbai Municipal Corporation (NMMC)	**Population (2011)**	**Area (Sq. km) (2011)**
	11,20,547	162.5

The population as per census 2011 is 11.2 lakhs and the area is divided into 89 wards. However, as shown Figure 2.3, whole area is divided into 111 electoral wards in 2015.

As per census data of 2011, more than 20% population of Navi Mumbai lives in slums. The slum areas are more vulnerable to natural as well as man-made hazards such as earthquakes, floods, fire etc. Mostly, these slums have weak building stocks and are located at the base of the hills, seashore, under the electrical power lines, on sides of the nalas, vacant locations in industrial areas, etc. These locations also make the slums more vulnerable to disasters.

2.1.4 Land-Use Pattern in NMMC Area

The NMMC area includes various land use types such as residential, industrial, commercial, depots and warehouses, administrative areas, education campuses, roads, railways, parking spaces, open spaces for public use, gardens, crematorium, water supply, sewerage and electric supply facilities, etc.

Out of the total developed area of NMMC, 60.79% area is used for urban, commercial, industrial, administrative areas and infrastructure such as crematorium, water supply and sewage disposal, roads, railways etc. 20.35% of total NMMC are is covered by forests. At present, agricultural activity in Navi Mumbai area is extremely limited. There are forests in the north-east area of Navi Mumbai.

The Thane-Belapur Industrial Belt (TBIA) of Maharashtra Industrial Development Corporation (MIDC) across Trans Thane Creek (TTC) Industrial area is also in the jurisdiction of NMMC. There were over 2,68,614 lakh registered properties in 2012 in

NMMC (NMMC Environmental Status Report, 2012-2013), which are used for different occupancy purposes.

2.1.5 Building Construction Types

The building stock in Navi Mumbai region exhibits a rich mix of several different building technologies. Construction of new buildings is going on in various zones. During year 2012-2013 over 1160 permissions to start new construction were granted. Review of records reveals that Koparkhairane, Airoli and Nerul are the most preferred zones for construction of new buildings (NMMC Environmental Status Report, 2013).

The most commonly used model building types are:

1) Reinforced Cement Concrete Buildings
2) Brick Masonry Buildings
3) Steel Buildings
4) Non-Engineered Buildings

Buildings that are constructed without the involvement of engineers are generally considered as non-engineered constructions. Construction that use a mix of materials for structural members are also categorised as non-engineered since such constructions typically occur when the building height is increased over time, often in an unauthorised manner and without the involvement of engineers.

These building categories can further be distributed to various occupancy types as specified below.

1) Residential
2) Commercial
3) Industrial

Out of total NMMC area (162.5 sq. km), around 70 percent is used for abovementioned occupancy classes viz. residential, commercial and industrial.

2.2 Past Earthquakes in the Vicinity of Navi Mumbai

From earthquake hazard considerations, the country has been divided into four seismic zones (zone II, III, IV and V) by the Bureau of Indian Standards, with Zone V having the largest hazard. As per IS:1893-2002, Navi Mumbai is situated in seismic zone III, that denotes moderate seismic hazard. As per this code, structures need to be designed in Seismic Zone III for earthquake force corresponding to damage intensity of VII on MSK-64 scale.

The list of significant earthquakes that have affected the Navi Mumbai region is given in Table 2.3.

Table 2.3: List of significant historical earthquakes affecting Mumbai and Navi Mumbai (Wenzel et al., 2007 and Joshi, 2007)

Year	Month	Intensity (MMI) / Magnitude (R)
1618	May	IX
1832	October	VI
1906	March	VI
1929	February	V
1933	July	V
1951	April	VIII
1966	May	V
1967	April	4.5
1967	June	4.2
1993	September	6.4

The epicentres of earthquakes that have occurred between 1998 and 2005 in peninsular region having $M_c > 2.5$ are listed in Table 2.4, where M_c is coda magnitude.

The M_c is calculated from measurements of seismic signal durations on records from short-period. Here it is given in terms of intensity which is calculated by following expression (Mohan, Surve and Tiwari, 2007):

$$M_c = (2/3) * I + 1 \quad (2.1)$$

Table 2.4: Epicentres of earthquakes occurred in 1998 to 2005 in vicinity of Navi Mumbai with magnitude M_c > 2.5 (Mohan, Surve and Tiwari, 2007)

Year	Latitude (°N)	Longitude (°E)	$M_c = (2/3) * I + 1$
1998	19.49	73.261	2.9
1998	19.29	73.685	2.5
1998	18.776	73.326	2.5
1998	19.33	73.759	2.5
1999	19.735	73.525	3.5
1999	18.863	73.255	2.7
1999	18.851	73.436	2.7
1999	18.622	72.718	2.5
1999	18.746	73.448	2.5
1999	20.096	73.165	2.6
2000	20.006	72.916	2.8
2000	18.744	73.578	2.5
2001	19.526	72.894	3
2001	18.859	73.233	2.5
2001	18.479	73.627	3
2001	19.807	72.932	3.3
2003	19.081	73.144	2.5
2004	18.932	72.607	2.7
2004	19.18	73.532	3
2005	19.273	73.189	3.3
2005	19.265	73.165	3.1
2005	20.09	73.127	3.3
2005	20.002	73.013	3.3
2005	20.069	73.185	3.3

Year	Latitude (°N)	Longitude (°E)	$M_c = (2/3) * I + 1$
2005	18.952	73.072	2.8

The damaging earthquakes that have occurred in Seismic Zone III of peninsular region in the last few decades include Killari earthquake (M_w=6.3) in 1993 that occurred at a very shallow estimated depth between 5-15 km (Sinvhal et al., 1994 and Joshi, 2000) and is considered to be a typical Seismic Zone III-level earthquake.

Another recent earthquake in Seismic Zone III was the Jabalpur earthquake (M_w=5.8) in 1997. This earthquake was also not recorded on any strong motion instrument. However, this earthquake was estimated to have occurred at moderate depth (36 km). This was the first event in the Indian peninsular shield region to be well recorded by a newly installed, 10-station, broadband seismographic network (Singh, et al., 1999). The experience of the earthquake was also collected extensively, and was combined with damage information to determine the damage intensity. This earthquake was found to have its maximum damage corresponding to Intensity VIII in a relatively large area considering the magnitude of the event (Martin and Szeliga, 2010).

As described above, earthquake activity in peninsular India indicates that different parts of the region are characterized by low to moderate level of seismic activity on regular basis. However, some larger and damaging earthquakes have occurred in the region such as Koyna (1967), Killari (1993), Jabalpur (1997), and Bhuj (2001) which have attracted the attention of many experts in India and abroad. Unlike the earthquakes related to plate boundaries, demarcated by mid-oceanic ridges, transform faults and island arcs, these earthquakes belong to a class called intraplate earthquakes. Panvel and Koyna are the seismic zones identified around Navi Mumbai.

There are following major faults/lineaments are identified by Geological Survey of India (GSI) (Seismotectonic Atlas of India and its Environs, 2000).

1. Koyna Region Source Zone
2. Panvel Flexure Source Zone
3. West Coast Fault

4. Chiplun Fault

The abovementioned seismic sources and other minor lineaments in and around Navi Mumbai region are shown in Figure 2.4. The figure also shows the epicentre of some recent earthquakes that have occurred in this region.

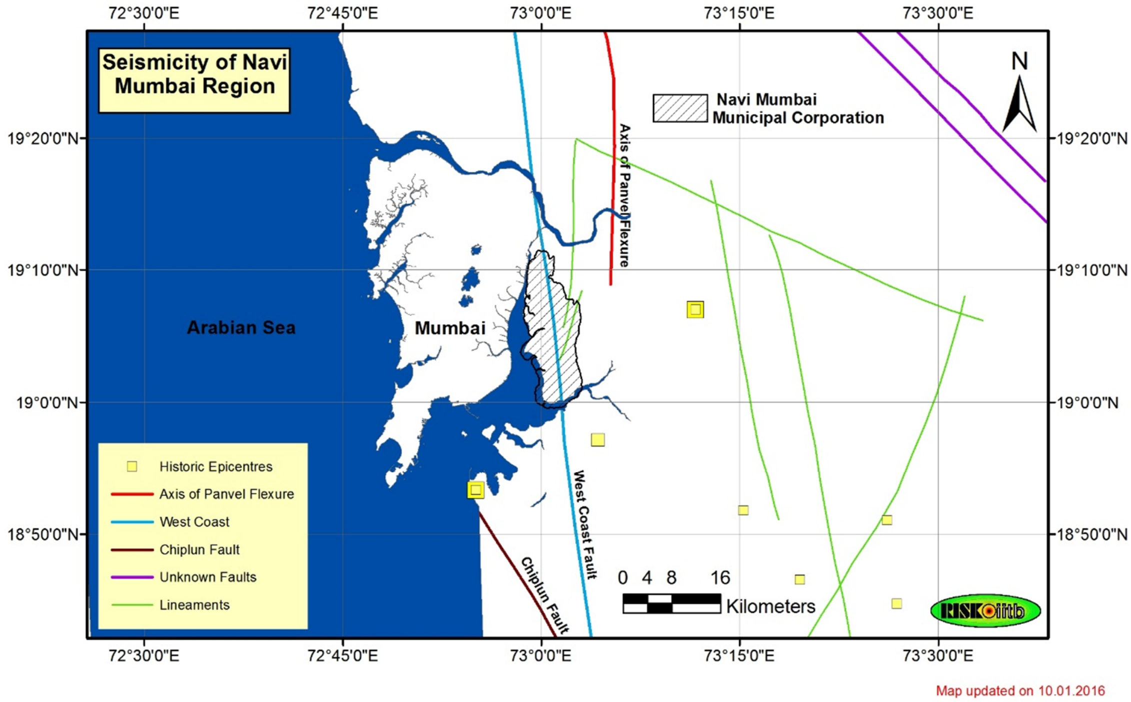

Figure 2.4: Seismicity in the vicinity of Navi Mumbai (Seismotectonic Atlas of India and its Environs SEISAT-27, 2000)

2.3 Discussions

Navi Mumbai Municipal Corporation (NMMC) is headed by Mayor, which is an elected position. The Municipal Commissioner is appointed by the state government and leads the Corporation. The disaster management unit of NMMC is in place, which is also headed by the Municipal Commissioner. Navi Mumbai is equipped with 4 fire stations at different locations. Navi Mumbai disaster management is also complemented by CIDCO which is credited with planning and developing Navi Mumbai.

However, Navi Mumbai has not experienced any significant earthquake since its development in 1960s. Historic seismicity in the region shows that moderate to large earthquake may occur in this region in future affecting the city. The earthquake of May 1618 is the most significant earthquake to strike the region. This earthquake is believed to have damaged significant part of Mumbai City. Thus, it is imperative to plan for a scientifically plausible earthquake which can affect Navi Mumbai.

Chapter 3. Methodology of Seismic Risk Assessment

The assessment of seismic risk involves the estimation of consequences of an earthquake in terms of expected damage and loss from a given hazard. For this purpose, the risk assessment involves evaluation of seismic hazard, vulnerability of structures, exposure and finally loss estimation.

3.1 Deterministic Seismic Hazard Assessment

Seismic Hazard is defined as an estimation of ground motion parameters such as PGA, a scenario earthquake can produce, at the site under consideration. It can be estimated by probabilistic seismic hazard assessment (PSHA) and deterministic seismic hazard assessment (DSHA).

A PSHA for specific site consists of determining the frequency with which an earthquake characteristic takes on a defined range of values during some fixed time 't' in the future. Here earthquake characteristic is quantified by the variable C and the range of values is typically defined as an exceedance of a specific value c. Characteristic C may be peak acceleration of earthquake ground motion at the site, a level of Intensity, the duration of seismic shaking, the displacement caused by a fault beneath a facility's foundation, etc.

In deterministic seismic hazard assessment, the ground motion parameters are estimated for the maximum credible earthquake, assumed to occur at the closest possible distance from the site of interest, without considering the probability of its occurrence during a specified exposure period.

The steps involved in deterministic hazard analysis have been represented in the following flow chart.

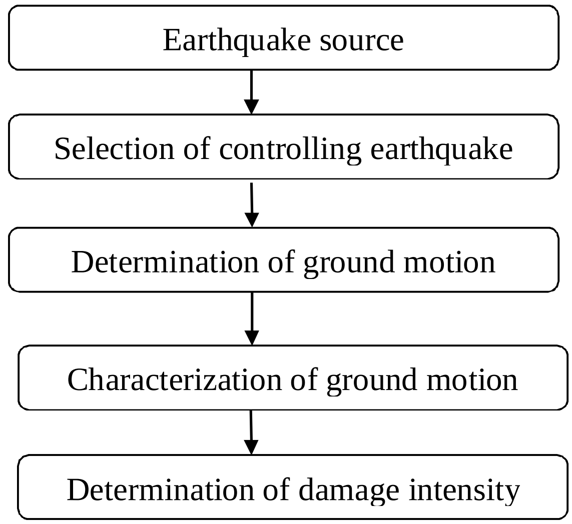

Figure 3.1: Flow chart for DSHA

Step 1 is the definition of an earthquake source or sources. Sources may be in the form of point, line or area sources.

Step 2 is the selection of controlling earthquake. The earthquake potential of each source described in the step 1 is defined in terms of a maximum earthquake. This could be the earthquake, which is reasonably expected, the maximum credible earthquake, or some other type of earthquake description. The specific criteria chosen are one of the most important elements in determining the general level of conservation. Earthquake magnitude or epicental intensity is usually used to define the earthquake size. Along with each of these earthquake source size pairs, there is an associated distance, which represents the appropriate distance between the source and the site. One of these postulated earthquakes will be the controlling earthquake that is the earthquake whose ground motion or other quantity being estimated will dominate the effects of all the earthquake source size pairs being considered. There may be more than one controlling earthquake at this stage. Since it is not always obvious which event is associated with largest ground motion at the site of interest, there may be more than one controlling earthquake at the conclusion of analysis.

Step 3 is the determination of the earthquake effect, usually some type of ground motion parameter at the site. Typically, this is done by means of earthquake ground motion attenuation relationship, which provides the estimates of ground motion for an earthquake of a given magnitude at different distances by means of a curve fitted to observed data. If not determined in step 2, the controlling earthquake is defined considering the one that produces the largest value of the selected ground motion parameter. The most common ground motion parameter used are peak ground acceleration or peak ground velocity.

Step 4 is the definition of the hazard at the site. In most cases it is the direct output of the step 3. This is usually a simplest statement to the effect that the hazard at the site is specific ground acceleration, velocity or other measures that describes earthquake effects (Krammer 2003).

3.1.1 Source Characterization

The source for the scenario earthquake can be taken as a point source or line source. For a point source model, epicentre and hypocentral depth (focal depth) need to be specified. For a line source model, epicentre, fault orientation and type of fault is required for source characterization.

3.1.2 Ground Motion Predictions Equations (GMPE)

The ground motion prediction equations describe how ground motions or intensity measures i.e. acceleration and velocities decrease as a function of distance from the earthquake source.

GMPEs are developed by regression analysis performed on a large number of records which were developed in compatible geomorphic regions. Most of these relationships are updated as new strong ground motion data becomes available and many now include additional parameters such as fault type and site soil conditions.

The functional form of ground attenuation relationships can be given as:

$$\ln Y = C_1 + C_2 M + C_3 MC_4 + C_5 \ln [R + C_6 e^{C7M}] + C_8 R + f(source) + f(site) \quad (3.1)$$

where, Y is ground motion parameter, M is magnitude of earthquake and R is distance of source from site.

There is only one published attenuation relationship that has been developed to fit the above regression relationship using some data recorded in western India (Iyengar and Raghukanth, 2004). Due to the absence of strong motion data in peninsular India in general and western India in particular, that relationship was developed by extracting information from Structural Response Recorders following the Bhuj earthquake of 2001, and further carrying our regression analysis on an ensemble of synthetic ground motions.

It is apparent from the data used to develop the local attenuation relationship that it is unlikely to be very reliable until validated from strong motion records in future. As per the standard practice where highly reliable attenuation relationships are not available, such relationships from other regions of the world with similar seismo-tectonic setting can be used. Some other prominent regions of the world with similar seismo-tectonic setting include Central and Eastern United States (CEUS) and Western Australia (Jaiswal and Sinha, 2007). The description of the applicable attenuation relationships for the Western Indian region is given below.

3.1.2.1 Iyengar and Raghukanth (2004)

This relationship has been proposed for peninsular India. It gives PGA in terms of acceleration due to gravity. It is given by the expression:

$$\ln PGA\ (g) = 1.6858 + 0.9241 \times (M-6) - 0.076 \times (M-6)^2 - \ln(R) - 0.0057 \times R + \ln \in \quad (3.2)$$

Where, $\ln \in$ is the error in the estimation of PGA whose standard deviation is given as $\ln \in$ = 0.468, R is the hypocentral distance and M is moment magnitude. The above attenuation relation is valid for hard rock exposed on the surface, with V_s nearly equal to 3.6 km/s.

Iyengar and Raghukanth (2004) used the earthquake data from intra-plate earthquakes that took place in India. Wherever the strong motion data was not available, they have used synthetically generated data using Boore (2003) model. On stratified regression of this data, the constants for the relationship given in equation 3.1 were determined.

3.1.3 Site Characteristics

Site characteristics include soil, sediments and weathered rock affecting the ground shaking experienced during an earthquake. Amplification factors may be used to include site effects. These amplification factors are usually proposed with each attenuation relationships to modify the ground motion parameter.

Local site characteristics can dramatically alter the intensity and to some degree the frequency content of the ground motion at a site. Shaking intensity in a given area reflects the local surface geology, as ground motion intensities vary in part due to these geological properties.

3.1.4 Liquefaction

When an earthquake strikes an area that is saturated with groundwater, the shaking can cause the soil to lose its stiffness due to increased water pressure, and in some cases behave like a heavy liquid. When this happens, the soil loses its capability to support structures. Buildings can suddenly tilt or even topple over as the ground beneath them becomes liquefied. Pipelines and ducts can surface, and as the liquefied soil shifts, it can break buried utility lines.

Liquefaction is more likely in areas with granular soils that have poor drainage and are saturated with water. An example would be silty sands, which are found along riverbeds, beaches, dunes and other areas where sands have accumulated. If the saturated soil lies underneath a dry crust, the ground motion can crack the top dry soil allowing the liquefied sand to erupt through the cracks, creating sand boils. Sand boils can spread through utility openings into building, and damage the building.

3.1.5 Damage Intensity

The PGA obtained from attenuation relations is used to determine the damage intensity using empirical relations available. The damage intensity of an earthquake is a measure of the destructive effects of the earthquake on the facilities. Many attempts have been made to correlate intensity to specific physical parameters of ground motion, especially peak ground acceleration. For the present study, the approximate empirical relationship presented by Wald et al. (1999) based on data from California has been used to obtain the Intensity (I_{mm}) from the PGA at any location.

For $I_{mm} \leq V$,

$$I_{mm} = 2.20 \log(PGA) + 1.00 \qquad (3.3)$$

For $I_{mm} > V$,

$$I_{mm} = 3.66 \log(PGA) - 1.66 \qquad (3.4)$$

At present there is little data to correlate lower intensity values and recorded ground motions since most of the ground motion data are for larger earthquakes, and intensity data are not typically collected for smaller events.

Since MMI and MSK levels are quite similar in definition, MMI values are considered to be equivalent to MSK values in the present study. The resulting errors are expected to be smaller than or of similar order to those due to other factors such as error in hazard characterization etc.

3.2 Seismic Vulnerability

Vulnerability is the extent of damage suffered by a constructed facility due to a given level of a hazard. The extent of damage to structural, non-structural components and contents of a building is described by one of five damage states: None, Slight, Moderate, Extensive, and Complete. These damage states may either be defined in the form of actual physical damage to individual building components or in the form of inter-story drift, mean damage factor, etc.

The building stock can be divided into building classes based on their material of construction. Each building belonging to a building class can further be classified based on height of the building and adherence to seismic design codes or seismic design level. In general, every building has three types of components: structural, non-structural drift sensitive components and non-structural acceleration-sensitive components. Thus, to quantify the vulnerability of a building stock, we need to classify the building stock into model building types based on material of construction, height, adherence to design codes, and then define vulnerability for each component of model building type. On the basis of height of the building, the built-up area of each building can be calculated. Separate model for such assessment is prepared. Since the built-up area for each building is not available for the project investigations, vulnerability assessment of the buildings is done based on the model building types defined using the material of construction. These types are: 1) Reinforced Concrete 2) Masonry 3) Steel 4) Non-Engineered buildings (strong) 5) Non-Engineered buildings (weak).

There are a number of different factors that affect the overall vulnerability of a structure besides construction type. These factors are generally applicable to all types of structures, both engineered and non-engineered as well as structures with and without earthquake resistant design.

In the methodology, each damage state represents a mean damage probability corresponding to different earthquake intensities indicating the mean loss. The percentage of loss in total value corresponding to different damage intensities for each building type is obtained from loss functions which are based on the data available from previous earthquakes. The vulnerability function relating the earthquake damage intensity to damage state according to the model building type would be used in this study is based on Sinha et al. (2013) and is given in Figure 3.2.

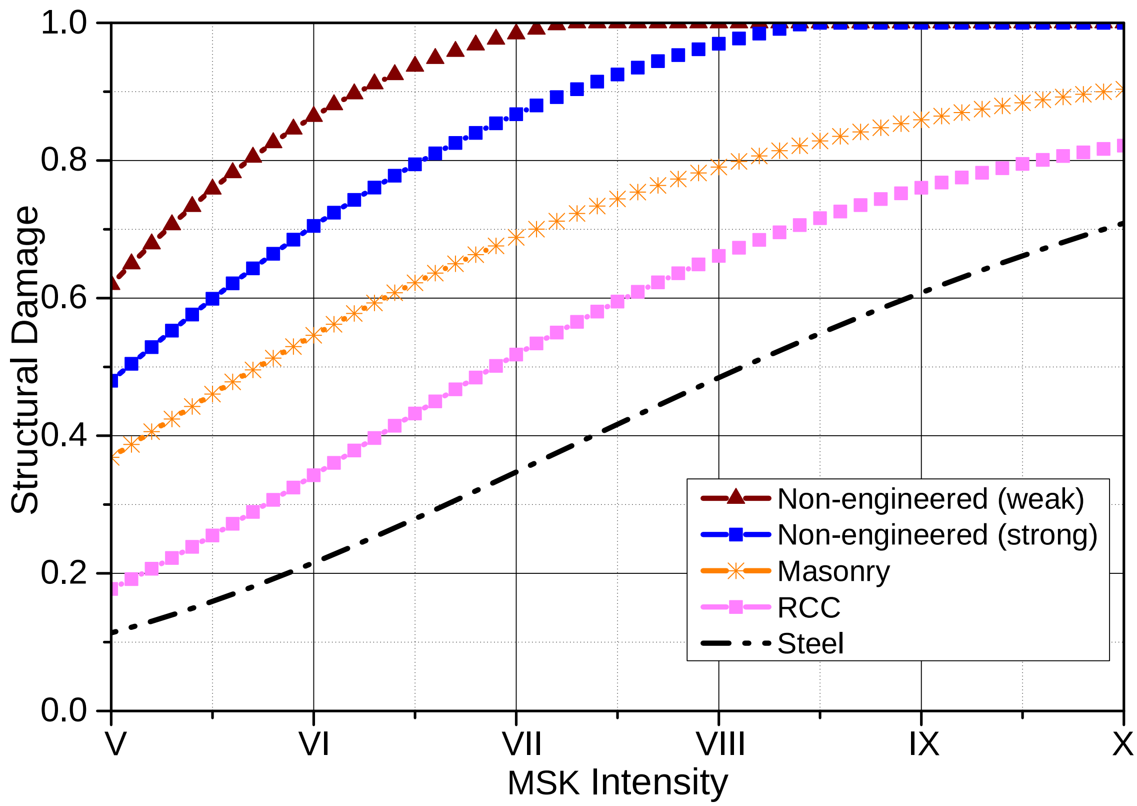

Figure 3.2: Vulnerability curve in terms of damage of different building types (Sinha et al., 2013)

3.3 Exposure

Exposure is the relative amounts of assets, resources and population exposed to natural hazard like earthquake hazard. It also includes property, i.e. the inventory (structural and non-structural) value of the buildings and building contents at the risk of being exposed to the damaging earthquake. The assessment of the consequences of an earthquake on exposure requires the assessment of each component separately. Thus accordingly, exposure analysis is needed.

Exposure Analyses is broken down into two main analyses namely, the Population and Property Analysis. Both allows us to look at the geographic distribution and time variation of population and estimated building property value, aggregated at various geographic resolutions. In the present study depending on the type of an area four different occupancy classes are observed and depending on the construction type.

3.3.1 Population Analysis

The population analysis evaluates the total population of the region that is exposed to the earthquake, and distributes it grid-wise to different building types. In this study, the total night population i.e. population during 1900-0830 hrs, and floating population i.e. the population which accounts for the number of people coming to the area under study during the day-time, expressed as a percentage of night population, are used.

Thus, if scenario earthquake occurs during day (0830 to 1900 hrs), then,

$$\text{Total Population} = \text{Population (Day)} + \text{Population (Float)} \tag{3.5}$$

If scenario earthquake occurs during night, then

$$\text{Total Population} = \text{Population (Night)} \tag{3.6}$$

The population distribution depends on the occupancy types, model building type (material of construction) of the buildings under study and the time of day/night at which the scenario earthquake occurs. Coburn and Spence (2002) temporal occupancy model, which gives the distribution of population during different times of the day, has been used to obtain the population in different building types at the time of earthquake.

Thus, the total population in all buildings of a given Occupancy Type is given by the following relationship:

$$PO = F \times \text{Total Population} \tag{3.7}$$

Where, F is percentage of population residing in a given occupancy type at a particular time. F is specified in Gupta (2006) for night population and is obtained from Table 3.1 for the floating population.

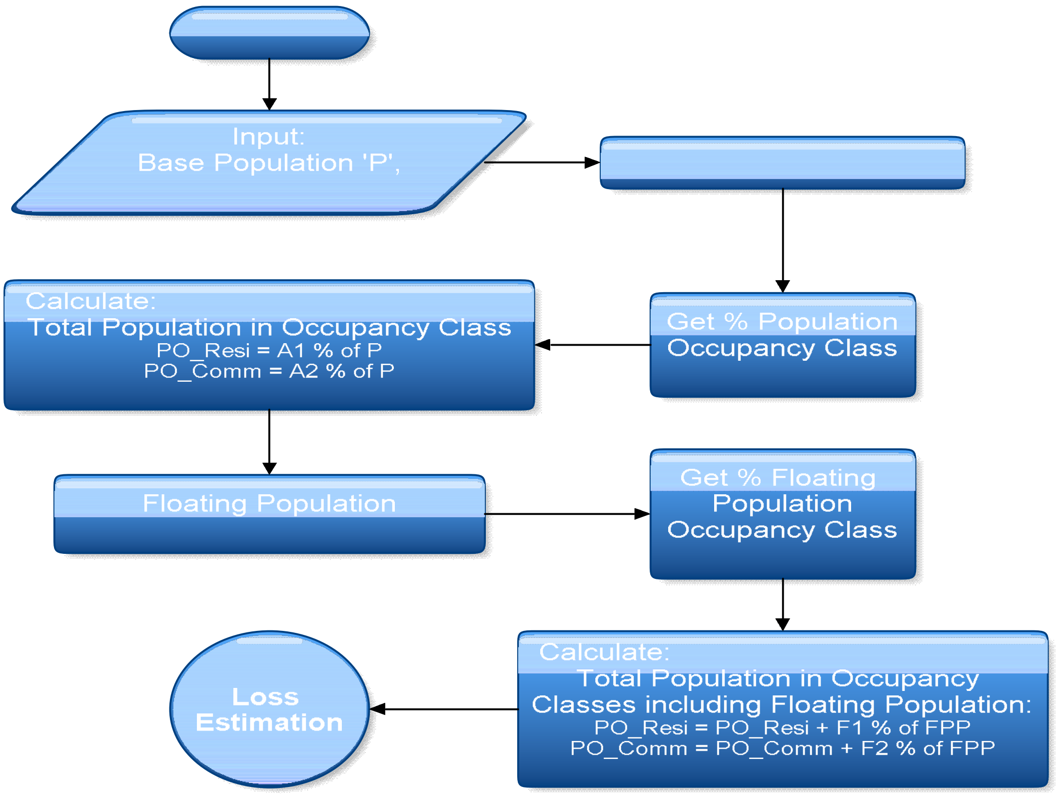

Figure 3.3: Methodology for distribution of population to different buildings.

3.3.2 Property Analysis

The aim of Property analysis is to obtain the Property values for the building stock in the each grid under consideration. Property value refers to estimated building property values in currency. It includes evaluation of structural and non-structural components and the contents of all the buildings in the grid. The value of the structural and non-structural components of a building has been assumed to depend on model building type and the occupancy class of the building.

The worth of structural, non-structural and content is calculated using building repair and replacement values (expressed in terms of rupees per square area) for each combination of model building type and occupancy class.

After completing Population and Property analysis, one can now proceed to the loss estimation.

3.4 Loss Estimation

Loss estimation refers to the evaluation of social and economic losses that are likely to be experienced during the scenario earthquake. The methodology for the assessment of these losses is described below.

3.4.1 Social Losses

Social losses refer to the losses due to number of people likely to be injured and number of fatalities in the scenario earthquake. The methodology involves the estimation of number of people likely to be injured with different severity. For this evaluation purpose, the population under each grid at the time of the earthquake, the model building type and the earthquake damage intensity is considered. The evaluation is carried out as per the building type as each building information is not available.

Fatalities are taken as percentage of injuries. Various building types have different percentages which are shown in Table 3.1.

Table 3.1: Fatalities as a percentage of injuries in different building types (Coburn and Spence, 1992)

Building Type	Deaths (%)
RCC	40
Masonry	20
Steel	50
Non-engineered	10

Thus, for a model building type, or corresponding building area, the number of casualties in a particular severity level due to collapse of building can be expressed as (Coburn and Spence, 2002).

$$Ks = C \times [M_1 \times M_2 \times M_3 \times M_4] \qquad (3.8)$$

Where, C is the percentage of building damage due to earthquake. This is obtained from mean damage factor corresponding to the intensity of damage suffered by the building, M_1 is the occupancy rate, Factor M_2 is the probability of the occupancy at time of earthquake, Factor M_3 represents the probability occupants trapped or otherwise injured by the collapse, Factor M_4 gives the probability of the injuries being fatal, or the fatality rate.

The total number of injuries during the scenario earthquake is obtained by summation of injuries in all the building types.

3.5 Discussions

The methodology used to calculate losses due to a scenario earthquake in the region has been described in detail. The results of seismic risk assessment depend upon the availability of the required data.

Deterministic seismic risk assessment is chosen over probabilistic risk assessment as it is quite helpful to check the resiliency of community and institutional capacity of various institutes associated to disaster management. Deterministic risk assessment provides scenario based results which fulfill the need of an organisation to evaluate the institutional capacity. Scenario based results are easy to communicate with different organisation or departments of an organisation which leads to an efficient coordination mechanism to reduce associated risk.

Chapter 4. Seismic Risk Assessment and Loss Estimation

Based upon the seismicity of the region as discussed in earlier chapters, scenario earthquakes have been considered as illustrated in the following sections.

4.1 Scenario Earthquakes

Scenario earthquakes have been chosen considering the seismic hazard of the Navi Mumbai region. Navi Mumbai lies in seismic zone III. It is common practice to consider maximum earthquake of upto 0.5 magnitude greater than the maximum recorded earthquake in catalogue to take into account insufficient catalogue record duration. Hence, the moment magnitude of the scenario earthquake is considered as 6.5 for the present study of deterministic seismic hazard assessment. However, to check the sensitivity of the region, magnitude 6.0 scenario earthquake has also been considered along with varying epicentre locations. Hence, results are produced for both the scenario earthquakes. The earthquake occurrence has been considered to be on the Panvel flexure which is shown in Figure 2.4. Parameters of scenario earthquakes are shown in Table 4.1.

Table 4.1: Input parameters of scenario earthquakes

M_w	6.5 and 6.0
Depth	10 km
Modelling Parameters	
Fault	Panvel Flexure
GMPE	Iyengar and Raghukanth (2004)
Source	Line Source
Rupture Model	Coppers well & Smith (Strike Slip)
Simulation Grid Size	0.002 degrees (200 m approximately)

For each of the above scenario earthquakes, total 9 epicenters are considered. These epicenters are taken on Panvel flexure in the latitudinal extent of Navi Mumbai, which are shown in Figure 4.1.

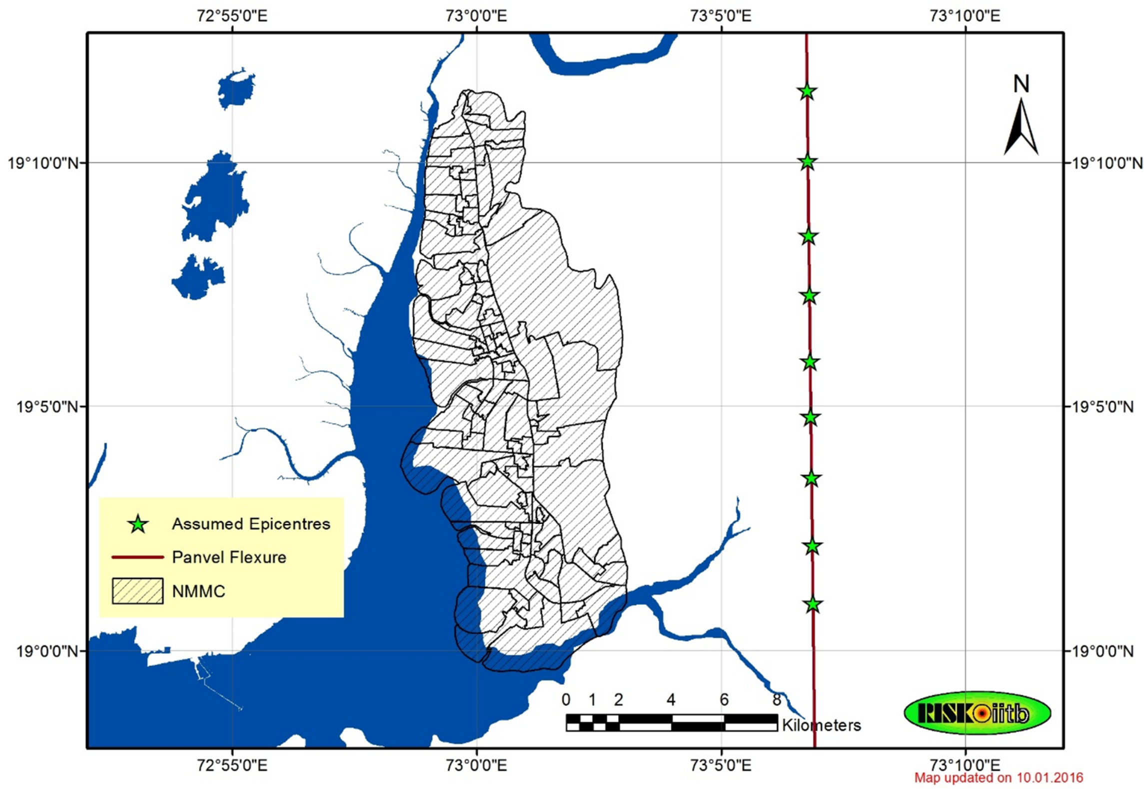

Figure 4.1: Assumed epicentres for the scenario earthquakes

For the city of Navi Mumbai, the electoral ward map is used which is shown in Figure 2.1. This latest map has been used to carry out the simulation. As per latest map total population is 11,20, 925 which is few hundred higher than 2011 census data which is redistributed into 111 wards instead of 89 wards.

The total area of Navi Mumbai is divided into small grids with size of 0.2 km × 0.2 km. This distribution is used to assign the different occupancy of built-up area in each grid by using high resolution google earth map for analysis purposes. Further based upon the land use pattern total area divided into residential, commercial, industrial and green area. Thus, for grid-wise simulation, this distribution is used to assign occupancies to various grids.

The model used in this study does not consider built-up area for each building since this is a first level study and data for building-wise analysis is not required or available. The total built-up area per capita assumed to be 10 m^2 in a residential occupancy type based on other studies. Using this value, the built-up area in commercial and industrial occupancy types is calculated.

The built-up area and population is further divided depending on slum and non-slum areas. Slum areas in the Navi Mumbai are identified based on high resolution Google Earth data by overlaying the generated grid files on the google earth map. Further the built-up area in each occupancy class is distributed to different model building types such as RCC, Masonry, Steel and Non-Engineered. Using vulnerability and loss functions based on the damage intensity of the building and its model building type, the percentage injuries and fatalities of the total population were obtained.

Results of the risk assessment for scenario earthquakes are produced for all the epicentres. Tables 4.2 and 4.3 show the sensitivity analysis of the earthquake risk assessment results for both scenario earthquake magnitudes. Table 4.2 presents earthquake risk assessment results in terms of estimated injuries and casualties for Mw = 6.5 scenario earthquake. Mean and standard deviation of the results are also tabulated.

Table 4.2 Sensitivity analysis results for earthquake risk assessment assuming 9 epicentres for Mw = 6.5

Sr. No.	Epicentre No.	Injuries	Deaths
1	1	50,200	15,900
2	2	50,200	15,900
3	3	51,800	16,200
4	4	51,300	16,300
5	5	52,400	16,400
6	6	51,500	16,400
7	7	51,400	16,300
8	8	51,000	16,300
9	9	50,300	16,100
Mean		**52,500**	**16,400**
Std. Deviation		**718.9**	**192.9**

Table 4.3 Sensitivity analysis results for earthquake risk assessment assuming 9 epicentres for Mw = 6.0

Sr. No.	Epicentre No.	Injuries	Deaths
1	1	33,300	9,200
2	2	35,500	10,100
3	3	36,600	10,900
4	4	35,800	10,100
5	5	38,000	11,500
6	6	35,500	10,100
7	7	33,800	10,100
8	8	34,500	9,800
9	9	35,900	10,450
Mean		**37,000**	**10,100**
Std. Deviation		**1355.9**	**573.6**

It is found that results for epicentre No. 5 are most critical and hence it is considered as our primary epicentre to carry out the detailed risk assessment. These results of the detailed risk assessment for epicentre No. 5 are presented in next section in Tables 4.5 and 4.6.

After comparison of both scenario earthquakes for various epicentres as presented in Tables 4.2 and 4.3, it can be observed that for magnitude 6.0, the variation in the casualties is quite significant as compared to magnitude 6.5 scenario earthquake for different epicentres along the Panvel flexure. It is due to the difference in the length of rupture which is generated on the Panvel flexure. Rupture length for magnitude 6.5 is around 18 km which is almost equal to the North-South extent of NMMC region. Thus minimum distance from the rupture to the centroid of the grid do not vary much for various epicentres whereas for magnitude 6.0, rupture length is around 8 km which cause more variation in distance from the rupture to centroid of grids along the Panvel flexure. However, epicentre No.5 is most critical for both scenario earthquake magnitudes as it is along the centre line of the NMMC region which have most of the grids nearest to rupture.

4.2 Results of Earthquake Risk Assessment

Based upon parameters used for scenario earthquakes, results of the seismic risk assessment are presented in colour coded maps in Figures 4.2 to 4.9 for both scenario earthquakes (Magnitudes 6.5 and 6.0).

Peak Ground acceleration (PGA) map is shown in Figures 4.2 and 4.3 for moment magnitude 6.5 and 6.0 respectively. Maximum peak ground acceleration for moment magnitude 6.5 is 0.65g whereas it is 0.41g for moment magnitude 6.0. This parameter is calculated to find out the MSK intensity to calculate the losses in the region.

Figures 4.4 and 4.5 shows the MSK intensity map of Navi Mumbai for scenario earthquake magnitudes of 6.5 and 6.0 respectively. It can be seen in Figures that for magnitude 6.0, NMMC region experience MSK intensity between VII and VIII and MSK intensity lies between VIII and IX for magnitude 6.5.

Figures 4.6 to 4.9 shows the colour coded maps of expected injuries and deaths across NMMC region. Average injuries for magnitudes 6.5 and 6.0 in a grid is approximately 40 and 29 respectively. Similarly in the proportion of injuries, expected average number of casualties are 12 and 8 in a grid for magnitude 6.5 and 6.0 respectively. Grids which have higher concentration of population and slum pockets are expected to experience higher casualties in terms of injuries and deaths. The area of Digha and Ghansoli records more casualties because of the slum dwellings which have more than 70 percent of total population as slum population as per census data of 2011. Electoral ward No. 6 would experience highest number of casualties. This ward also has higher proportion of slums along with the higher population concentration.

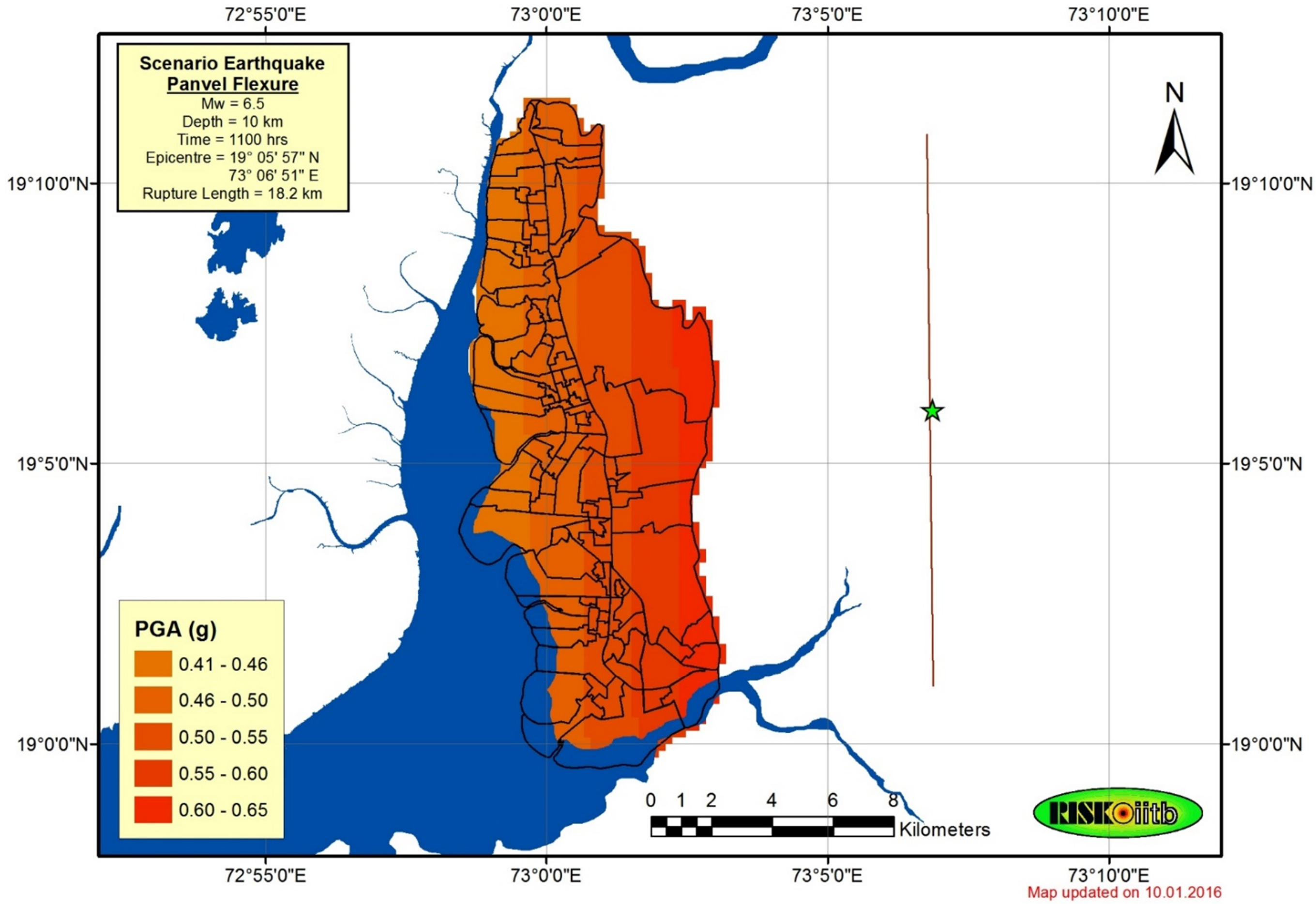

Figure 4.2: Peak Ground Acceleration (PGA) map for scenario earthquake Mw = 6.5

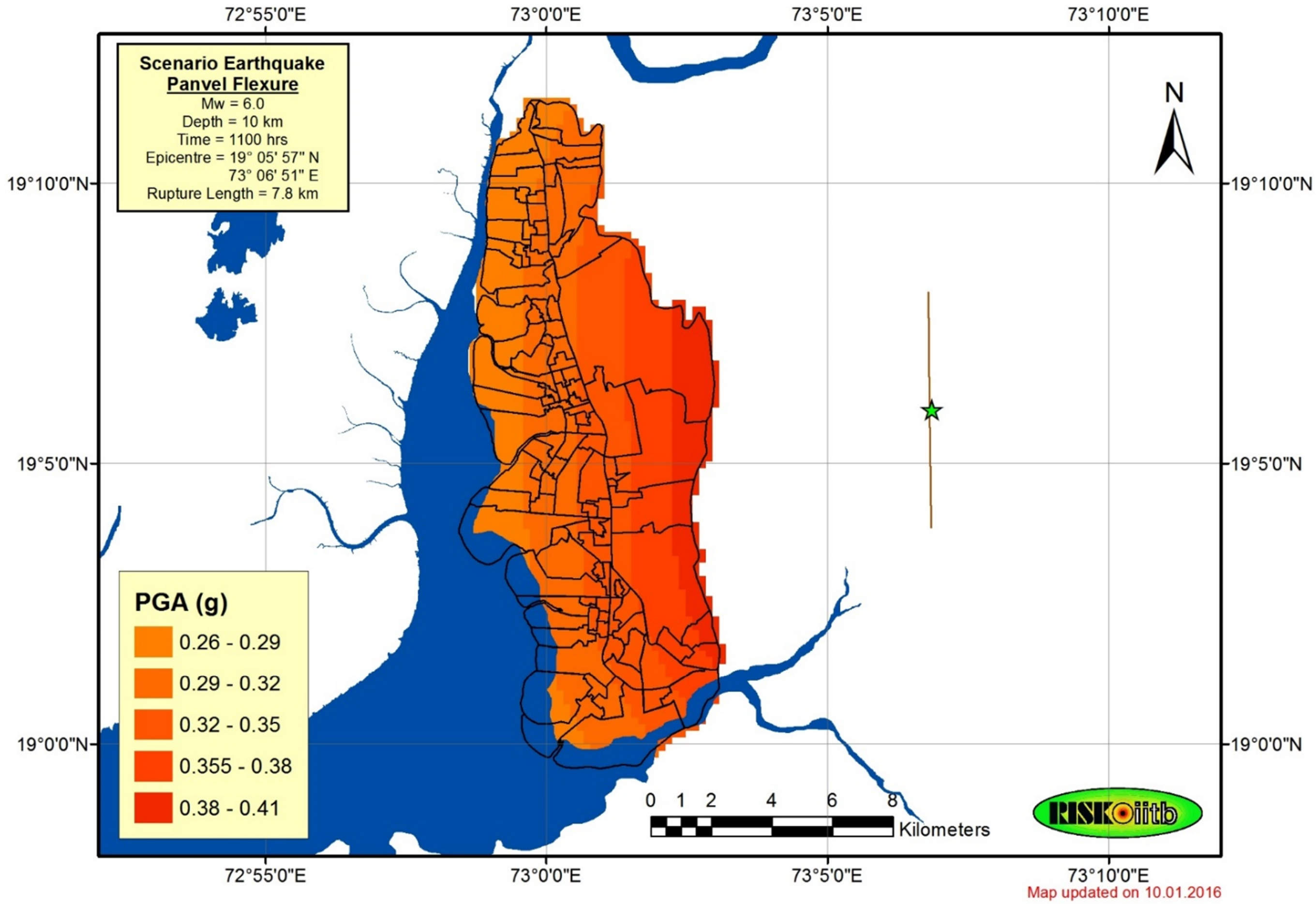

Figure 4.3: Peak Ground Acceleration (PGA) map for scenario earthquake Mw = 6.0

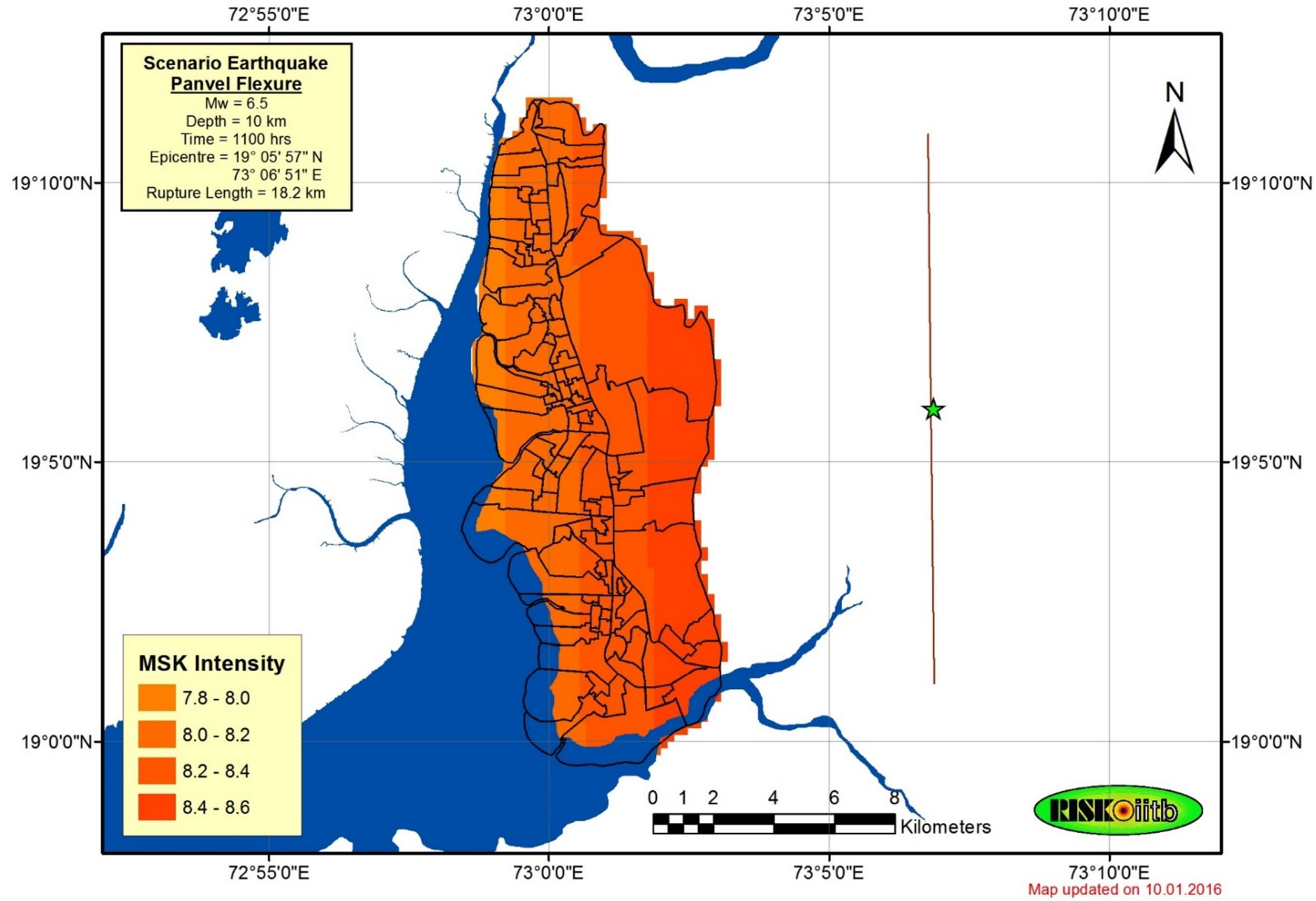

Figure 4.4: MSK Intensity map for scenario earthquake Mw = 6.5

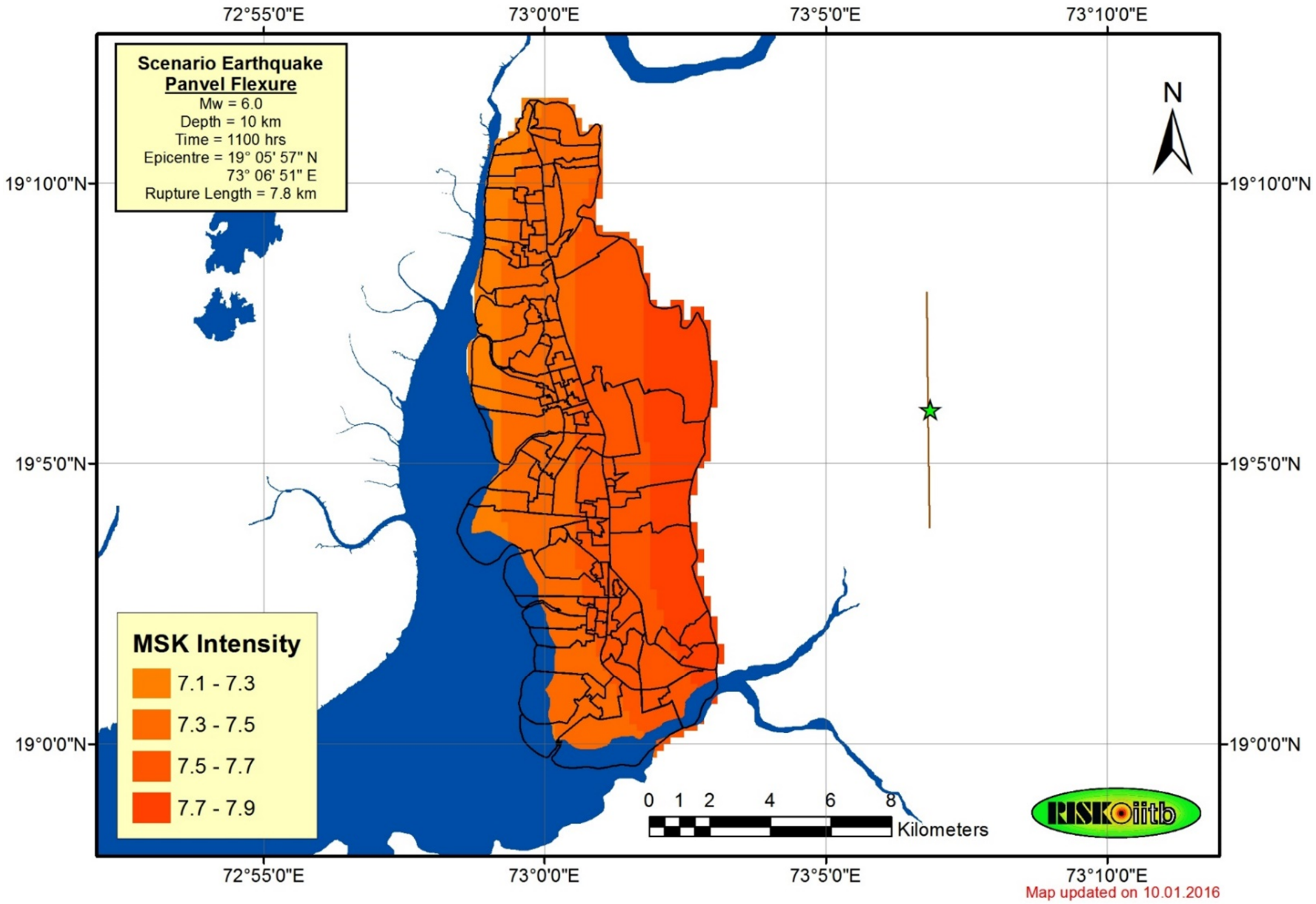

Figure 4.5: MSK Intensity map for scenario earthquake Mw = 6.0

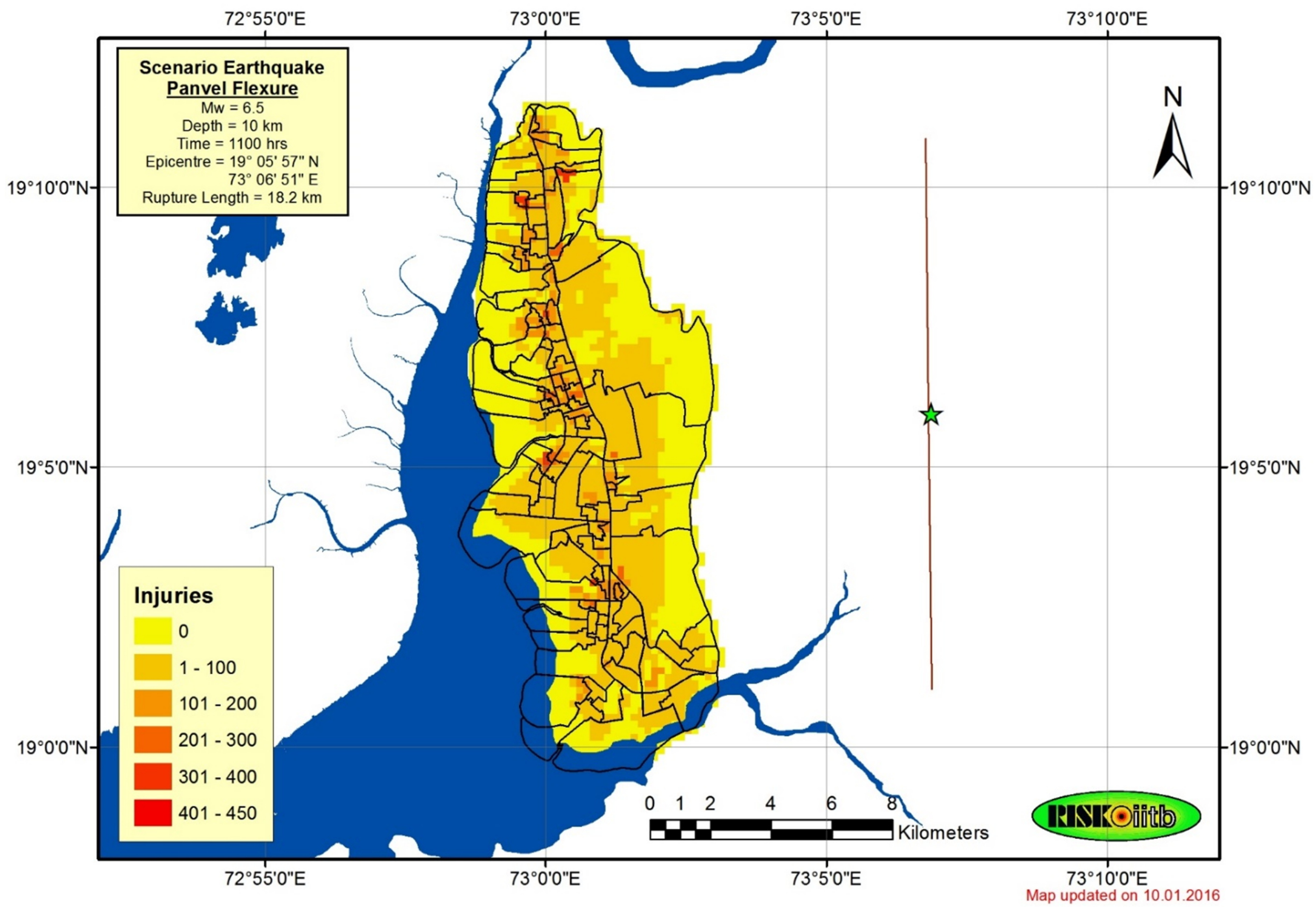

Figure 4.6: Map of estimated injuries for scenario earthquake Mw = 6.5

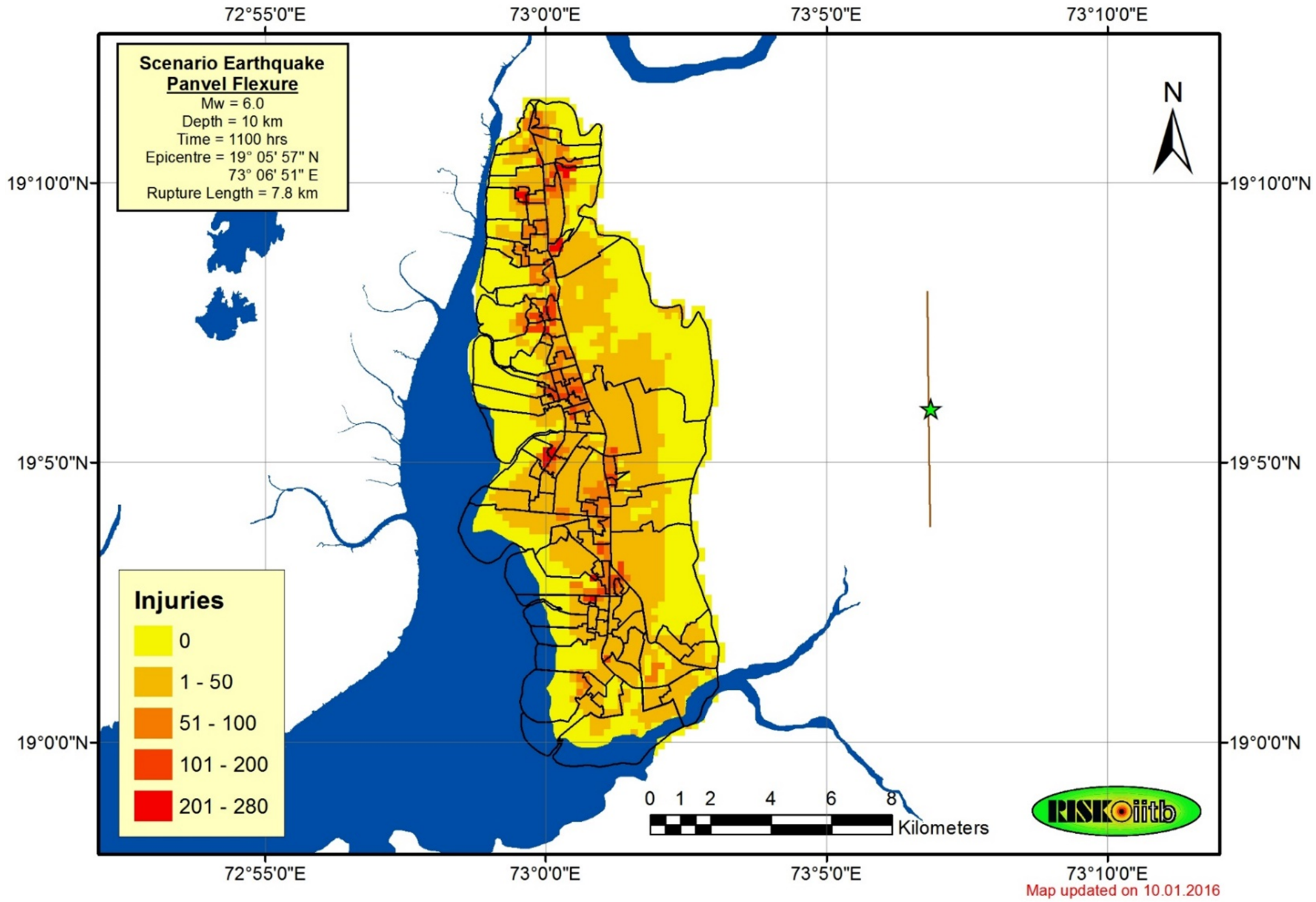

Figure 4.7: Map of estimated injuries for scenario earthquake Mw = 6.0

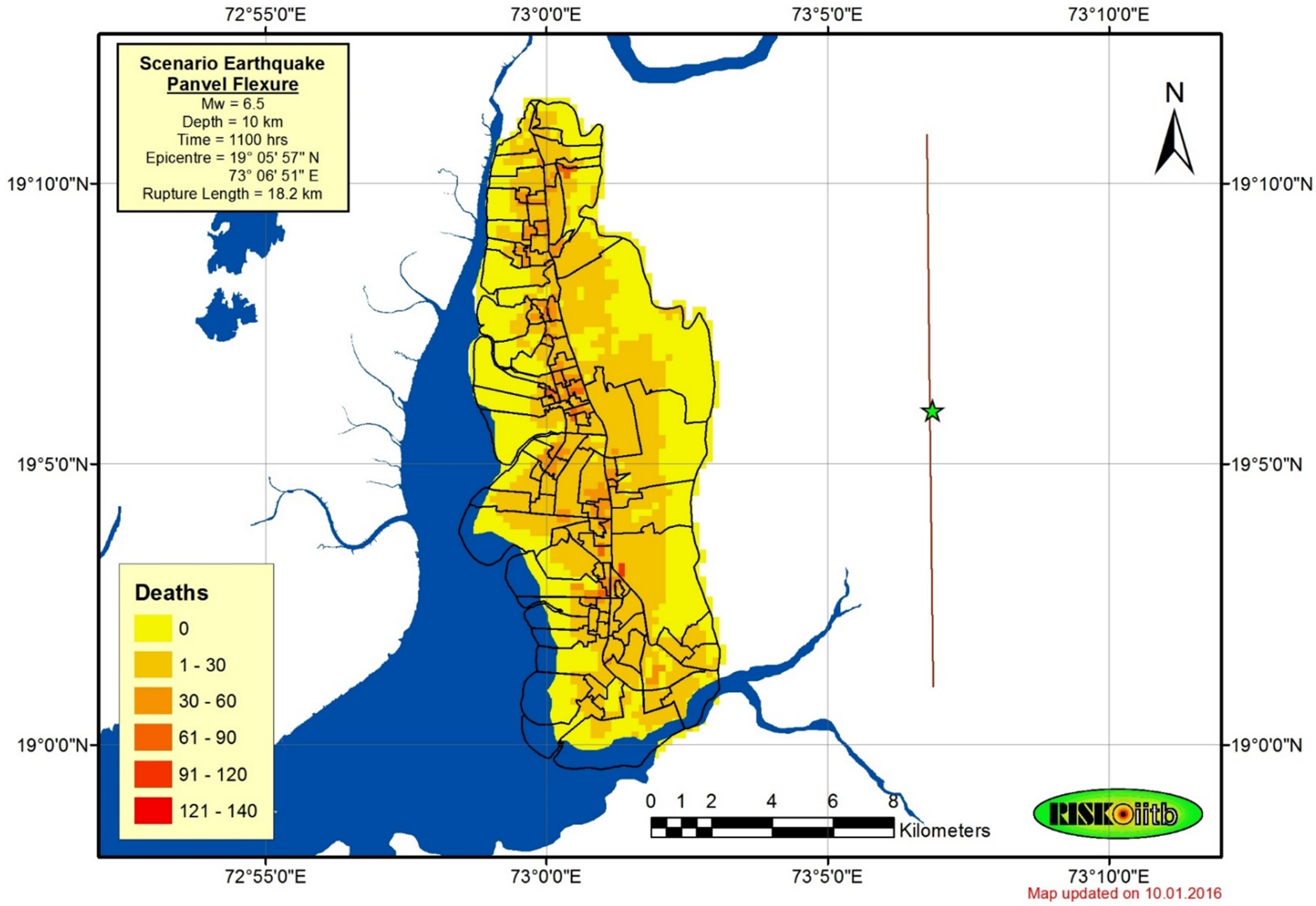

Figure 4.8: Map of estimated fatalities for scenario earthquake Mw = 6.5

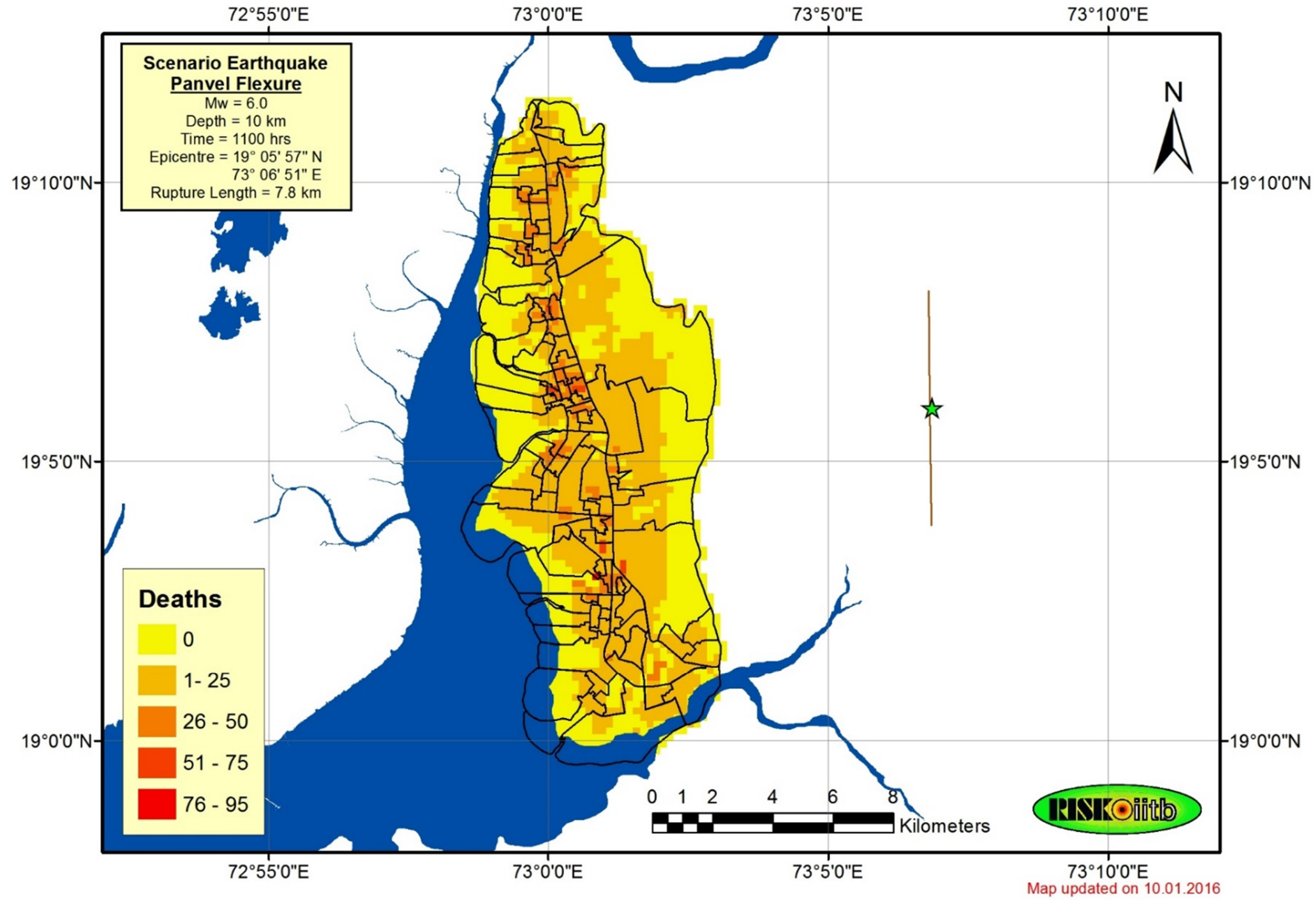

Figure 4.9: Map of estimated fatalities for scenario earthquake Mw = 6.0

Table 4.4 presents the overall results of earthquake risk assessment in terms of injuries and deaths for Navi Mumbai for both scenario earthquakes. It can be observed from the table that for scenario earthquake with magnitude 6.5, around 4.6 percent of the total population would face some kind of injuries which would require medical attention. Similarly 3.3 percent of the total population would require medical attention if earthquake with magnitude 6.0 strikes in the city.

Table 4.4: Overall casualties from scenario earthquakes

Sr. No.	Mw	Injuries	Deaths
1	6.5	52,400	16,400
2	6.0	38,000	11,500

This table also shows the fatalities for both scenario earthquake magnitudes. These fatalities include the likelihood of people who trapped in the debris and fatalities from building collapse. Number of fatalities show that it is almost one third of the injured population for both scenario earthquake magnitudes. These fatalities can be minimized by providing medical care and by putting other emergency care measures at place before the earthquake.

4.3 Insights from Risk Estimation

As the whole region is divided into 0.2 km × 0.2 km grids and input is provided at ward level. Some wards have built up areas in as less as 10 to few hundred grids (after excluding the grids which have green area or water bodies i.e. zero built up area). Ward level results are generated in terms of casualties. Results of the same are tabulated in Tables 4.5 and 4.6 for both scenario earthquake magnitudes.

Tables 4.5 and 4.6 present results at the electoral ward level for all 111 wards for Mw = 6.5 and Mw = 6.0 respectively. The maximum casualties occur in electoral ward No. 6 which has densely populated slum area. Injuries are also more in the areas close to the epicentre and have weak structures. A few wards have negligible social losses (injuries less than 100), so results for such wards have not been presented in both Tables. Injuries and deaths results are also tabulated in terms of percentage of total population of respective wards.

Table 4.5 Ward-wise results for earthquake risk assessment for Mw = 6.5

Sr. No.	Ward No.	Population	Injuries	Injuries (%)	Deaths	Deaths (%)
1	0001	9,257	700	7.6	160	1.7
2	0002	9,435	500	5.3	90	1.0
3	0003	10,815	500	4.6	120	1.1
4	0004	9,142	800	8.8	200	2.2
5	0005	11,471	300	2.6	50	0.4
6	0006	10,985	2,000	18.2	430	3.9
7	0007	9,476	1,300	13.7	340	3.6
8	0008	9,671	600	6.2	140	1.4
9	0009	9,875	500	5.1	140	1.4
10	0010	10,865	500	4.6	170	1.6
11	0011	10,905	900	8.3	190	1.7
12	0012	10,749	600	5.6	180	1.7
13	0013	11,097	400	3.6	140	1.3
14	0014	11,063	400	3.6	140	1.3
15	0015	10,741	400	3.7	150	1.4
16	0016	10,784	400	3.7	130	1.2
17	0017	10,567	300	2.8	120	1.1
18	0018	9,799	600	6.1	230	2.3
19	0019	10,982	800	7.3	180	1.6
20	0020	13,357	800	6.0	230	1.7
21	0021	9,777	500	5.1	180	1.8
22	0022	11,180	200	1.8	80	0.7
23	0023	9,234	300	3.2	130	1.4
24	0024	9,092	700	7.7	100	1.1
25	0025	9,318	800	8.6	180	1.9
26	0026	11,112	800	7.2	290	2.6
27	0027	9,070	600	6.6	120	1.3
28	0028	9,197	1,100	12.0	260	2.8
29	0029	9,740	400	4.1	90	0.9
30	0030	9,192	700	7.6	170	1.8
31	0031	9,426	800	8.5	200	2.1
32	0032	9,340	800	8.6	200	2.1

Sr. No.	Ward No.	Population	Injuries	Injuries (%)	Deaths	Deaths (%)
33	0033	9,148	600	6.6	240	2.6
34	0034	9,225	100	1.1	50	0.5
35	0035	9,908	200	2.0	90	0.9
36	0036	9,908	500	5.0	200	2.0
37	0037	9,875	600	6.1	200	2.0
38	0038	9,102	400	4.4	140	1.5
39	0039	10,200	400	3.9	140	1.4
40	0040	9,306	400	4.3	130	1.4
41	0041	9,421	500	5.3	190	2.0
42	0042	9,957	200	2.0	60	0.6
43	0043	10,228	100	1.0	40	0.4
44	0044	10,696	100	0.9	30	0.3
45	0045	9,199	600	6.5	200	2.2
46	0046	9,689	800	8.3	300	3.1
47	0047	9,926	300	3.0	100	1.0
48	0048	10,571	800	7.6	300	2.8
49	0049	9,117	600	6.6	200	2.2
50	0050	11,415	200	1.8	100	0.9
51	0051	9,172	400	4.4	100	1.1
52	0052	9,725	200	2.1	90	0.9
53	0053	10,662	500	4.7	100	0.9
54	0054	11,129	600	5.4	200	1.8
55	0055	9,078	400	4.4	100	1.1
56	0056	10,338	100	1.0	30	0.3
57	0057	9,362	700	7.5	300	3.2
58	0058	10,975	600	5.5	200	1.8
59	0059	10,734	1,000	9.3	200	1.9
60	0060	10,867	400	3.7	150	1.4
61	0061	10,783	200	1.9	60	0.6
62	0062	11,148	400	3.6	140	1.3
63	0063	11,075	100	0.9	30	0.3
64	0064	11,369	100	0.9	60	0.5
65	0065	10,519	500	4.8	200	1.9

Sr. No.	Ward No.	Population	Injuries	Injuries (%)	Deaths	Deaths (%)
66	0066	9,393	300	3.2	120	1.3
67	0067	9,124	1,200	13.2	440	4.8
68	0068	11,067	900	8.1	300	2.7
69	0069	10,725	900	8.4	310	2.9
70	0070	10,415	200	1.9	30	0.3
71	0071	9,244	200	2.2	60	0.6
72	0072	9,616	300	3.1	110	1.1
73	0073	10,951	500	4.6	170	1.6
74	0074	11,142	300	2.7	110	1.0
75	0075	11,304	600	5.3	200	1.8
76	0076	10,233	100	1.0	50	0.5
77	0077	9,793	-	-	-	-
78	0078	9,640	800	8.3	300	3.1
79	0079	10,278	700	6.8	300	2.9
80	0080	10,018	1,600	16.0	600	6.0
81	0081	10,795	800	7.4	200	1.9
82	0082	9,264	700	7.6	240	2.6
83	0083	9,282	-	-	-	-
84	0084	9,141	1,000	10.9	300	3.3
85	0085	9,172	400	4.4	150	1.6
86	0086	9,017	500	5.5	110	1.2
87	0087	9,405	200	2.1	60	0.6
88	0088	10,992	200	1.8	90	0.8
89	0089	11,144	200	1.8	40	0.4
90	0090	10,779	700	6.5	270	2.5
91	0091	10,150	300	3.0	120	1.2
92	0092	10,941	300	2.7	90	0.8
93	0093	10,216	300	2.9	70	0.7
94	0094	9,054	-	-	-	-
95	0095	9,037	-	-	-	-
96	0096	9,606	100	4.6	40	1.1
97	0097	10,108	100	8.8	40	2.2
98	0098	9,983	600	2.6	190	0.4

Sr. No.	Ward No.	Population	Injuries	Injuries (%)	Deaths	Deaths (%)
99	0099	9,874	400	18.2	130	3.9
100	0100	9,188	400	13.7	140	3.6
101	0101	10,378	900	6.2	300	1.4
102	0102	9,747	200	5.1	80	1.4
103	0103	9,580	400	4.6	100	1.6
104	0104	9,348	200	8.3	70	1.7
105	0105	10,661	300	5.6	90	1.7
106	0106	11,780	-	-	-	-
107	0107	9,826	200	3.6	60	1.3
108	0108	9,017	100	3.7	30	1.4
109	0109	9,431	100	3.7	30	1.2
110	0110	10,957	700	2.8	180	1.1
111	0111	9,568	-	-	-	-
Total	**NMMC**	**1,120,925**	**52,400**	**7.3**	**16,400**	**1.6**

Table 4.6: Ward-wise results for earthquake risk assessment for Mw = 6.0

Sr. No.	Ward No.	Population	Injuries	Injuries (%)	Deaths	Deaths (%)
1	0001	9,257	500	5.4	120	1.3
2	0002	9,435	400	4.2	70	0.7
3	0003	10,815	400	3.7	90	0.8
4	0004	9,142	600	6.6	150	1.6
5	0005	11,471	200	1.7	40	0.3
6	0006	10,985	1500	13.7	320	2.9
7	0007	9,476	1000	10.6	250	2.6
8	0008	9,671	500	5.2	100	1.0
9	0009	9,875	400	4.1	100	1.0
10	0010	10,865	200	1.8	100	0.9
11	0011	10,905	700	6.4	140	1.3
12	0012	10,749	500	4.7	130	1.2
13	0013	11,097	300	2.7	90	0.8
14	0014	11,063	300	2.7	100	0.9
15	0015	10,741	300	2.8	100	0.9

Sr. No.	Ward No.	Population	Injuries	Injuries (%)	Deaths	Deaths (%)
16	0016	10,784	300	2.8	90	0.8
17	0017	10,567	200	1.9	80	0.8
18	0018	9,799	400	4.1	160	1.6
19	0019	10,982	700	6.4	100	0.9
20	0020	13,357	600	4.5	160	1.2
21	0021	9,777	300	3.1	50	0.5
22	0022	11,180	100	0.9	50	0.4
23	0023	9,234	200	2.2	90	1.0
24	0024	9,092	600	6.6	110	1.2
25	0025	9,318	600	6.4	130	1.4
26	0026	11,112	500	4.5	200	1.8
27	0027	9,070	500	5.5	90	1.0
28	0028	9,197	800	8.7	200	2.2
29	0029	9,740	300	3.1	70	0.7
30	0030	9,192	500	5.4	130	1.4
31	0031	9,426	400	4.2	100	1.1
32	0032	9,340	600	6.4	150	1.6
33	0033	9,148	600	6.6	170	1.9
34	0034	9,225	100	1.1	30	0.3
35	0035	9,908	200	2.0	60	0.6
36	0036	9,908	300	3.0	120	1.2
37	0037	9,875	400	4.1	100	1.0
38	0038	9,102	300	3.3	100	1.1
39	0039	10,200	300	2.9	100	1.0
40	0040	9,306	300	3.2	100	1.1
41	0041	9,421	400	4.2	140	1.5
42	0042	9,957	100	1.0	40	0.4
43	0043	10,228	100	1.0	30	0.3
44	0044	10,696	100	0.9	20	0.2
45	0045	9,199	400	4.3	160	1.7
46	0046	9,689	500	5.2	200	2.1
47	0047	9,926	200	2.0	70	0.7
48	0048	10,571	600	5.7	190	1.8

Sr. No.	Ward No.	Population	Injuries	Injuries (%)	Deaths	Deaths (%)
49	0049	9,117	400	4.4	150	1.6
50	0050	11,415	200	1.8	50	0.4
51	0051	9,172	300	3.3	100	1.1
52	0052	9,725	200	2.1	60	0.6
53	0053	10,662	400	3.8	100	0.9
54	0054	11,129	400	3.6	150	1.3
55	0055	9,078	300	3.3	100	1.1
56	0056	10,338	500	4.8	190	1.8
57	0057	9,362	500	5.3	130	1.4
58	0058	10,975	800	7.3	160	1.5
59	0059	10,734	300	2.8	110	1.0
60	0060	10,867	300	2.8	100	0.9
61	0061	10,783	100	0.9	50	0.5
62	0062	11,148	300	2.7	100	0.9
63	0063	11,075	100	0.9	20	0.2
64	0064	11,369	100	0.9	40	0.4
65	0065	10,519	400	3.8	140	1.3
66	0066	9,393	200	2.1	90	1.0
67	0067	9,124	900	9.9	310	3.4
68	0068	11,067	600	5.4	190	1.7
69	0069	10,725	600	5.6	220	2.1
70	0070	10,415	100	1.0	20	0.2
71	0071	9,244	200	2.2	40	0.4
72	0072	9,616	200	2.1	80	0.8
73	0073	10,951	400	3.7	120	1.1
74	0074	11,142	200	1.8	70	0.6
75	0075	11,304	400	3.5	140	1.2
76	0076	10,233	100	1.0	30	0.3
77	0077	9,793	-	-	-	-
78	0078	9,640	600	6.2	200	2.1
79	0079	10,278	500	4.9	180	1.8
80	0080	10,018	1100	11.0	400	4.0
81	0081	10,795	600	5.6	120	1.1

Sr. No.	Ward No.	Population	Injuries	Injuries (%)	Deaths	Deaths (%)
82	0082	9,264	500	5.4	170	1.8
83	0083	9,282	-	-	-	0.1
84	0084	9,141	600	6.6	230	2.5
85	0085	9,172	300	3.3	100	1.1
86	0086	9,017	400	4.4	80	0.9
87	0087	9,405	100	1.1	40	0.4
88	0088	10,992	200	1.8	60	0.5
89	0089	11,144	200	1.8	30	0.3
90	0090	10,779	500	4.6	180	1.7
91	0091	10,150	200	2.0	80	0.8
92	0092	10,941	200	1.8	70	0.6
93	0093	10,216	200	2.0	60	0.6
94	0094	9,054	-	-	-	-
95	0095	9,037	-	-	-	-
96	0096	9,606	100	1.0	30	0.3
97	0097	10,108	100	1.0	30	0.3
98	0098	9,983	300	3.0	100	1.0
99	0099	9,874	300	3.0	90	0.9
100	0100	9,188	200	2.2	80	0.9
101	0101	10,378	600	5.8	200	1.9
102	0102	9,747	100	1.0	50	0.5
103	0103	9,580	300	3.1	100	1.0
104	0104	9,348	100	1.1	40	0.4
105	0105	10,661	200	1.9	60	0.6
106	0106	11,780	-	-	-	-
107	0107	9,826	100	1.0	40	0.4
108	0108	9,017	-	-	-	-
109	0109	9,431	100	1.1	20	0.2
110	0110	10,957	600	5.5	100	0.9
111	0111	9,568	-	-	-	-
Total	**NMMC**	**1,120,925**	**38,000**	**3.4**	**11,500**	**1.0**

4.4 Analysis of Results

Seismic risk assessment results are provided in previous sections. This section provides an analysis of the results.

Ground motion has been evaluated in terms of Peak Ground Acceleration (PGA). PGA is converted to MSK intensity to evaluate the damage caused because of scenario earthquake. The whole city is likely to experience MSK intensity between VIII – IX for scenario earthquake 6.5 and VII – VIII for earthquake magnitude 6.0.

In the previous section, from Table 4.5, it can be seen that the likelihood of injuries is varying from a few to 2000 despite not much difference in the population among various wards. It can also be noted that highest loss is not in the ward which is having highest population. Electoral ward Number 20 has the highest population but the corresponding number of likelihood injuries is 800 which is quite less than the injuries in ward Number 6 which is likely to experience highest injuries. Ward Number 6 has high density of the population and also has the high concentration of slum population. Similar trend can be seen in Table 4.6 for magnitude 6.0 scenario earthquake.

Ward Nos. 6, 7, 28, 59, 67, 80 and 84 are expected to experience more than 10 percent of their total population to be injured during scenario earthquake of magnitude 6.5. Ward Nos. 6, 7, 28, 59 have slum population as 56 percent, 30 percent, 50 percent and 50 percent of total ward population respectively. Other three wards have one of the highest population density. Due to the high proportion of slum population and weak construction practices, ward 6 likely to experience highest number of losses for the assumed scenario earthquake magnitudes.

Thus, it can be inferred that high density areas in the city which is having weak construction are more vulnerable compare to areas which have sparse population and supported by good construction practices.

Loss estimation results can be used in different phases of disaster management in following manner:

1. Loss estimation results presented here are expected to help various stakeholders/ organisations to check the capability to deal with such seismic risk which can be faced. For example, estimated injuries can help to check the capacity of hospitals in

terms of number of beds, availability of required number of doctors to attend injured persons during the disaster, etc.

2. Earthquakes occur suddenly and without warning, so it needs quick and sudden response for post disaster management. These scenario earthquake results are useful to develop quick response and Planning for post-earthquake response. It is imperative to develop a response mechanism for a scenario earthquake for an organisation, as significant earthquakes are rare and people do not have firsthand experience of it so people are unaware of how to respond to such situations.
3. Once response mechanism is developed then these response plans can be tested using tabletop exercise by using the scenario results.
4. These scenario results are also provide the scope of damage and estimate resource potential needs. For example, fire stations and number of fire engines can be identified to the high risk areas.
5. It provides results which can be used to sensitize people and to conduct mock drills which would ultimately help in resiliency.
6. Scenario identify the locations where losses are quite high, these areas can easily be identified through color coded maps. It can be seen in the casualties' map that hot spots are along the industrial belt, this is due to the location of informal settlements along the industrial belt. This can help to devise a strategy to rehabilitate the people living in informal settlement.
7. The MSK intensity maps help to identify high seismic shaking maps which can be used to do the safety assessment of existing buildings to withstand such ground shaking. The whole area would experience MSK intensity VIII – IX if earthquake with magnitude 6.5 strike the NMMC area.
8. These scenario maps can be used for search and rescue team as well by identifying the hot spots in the region. If the rescue team is mobilized toward high density area where damage is also high which ultimately help to maximize the effort to save maximum people. Thus, based upon these maps, effectiveness and efficiency of search and rescue operations can be increased drastically.
9. Standard Operating Procedure (SOP) can be developed by various organisations to develop a centralized Emergency Operation Centre (EOC).
10. By using loss estimation results, planners can see the distribution of different vulnerable populations that are in the disaster area along with the applicable information.

11. Disaster Risk Reduction strategies can be formed by using the scenario earthquake maps. Estimated injuries and casualties would help in mock drills also which can help to prepare the community to deal with such disaster.
12. Scenario earthquake provides realistic picture which can strike a chord in common people who are otherwise ignorant to earthquake disaster as they might not have experienced a real earthquake. By this manner community resiliency can be developed.

Chapter 5. Discussions and Conclusions

5.1 Discussions

Seismic risk assessment assessment has been carried out for earthquake scenarios that can affect Navi Mumbai region. Since Panvel flexure is much active fault near Navi Mumbai, so the epicenter of the hypothetical earthquakes is assumed on Panvel flexure for the scenario earthquakes. Subject to the available ward/node wise data, simulation has been conducted by considering electoral ward as input. However, the region divided into small (0.2 km × 0.2 km) grids to divide the electoral ward into small grids. After overlaying the grids on Google Earth maps, the slum and non-slum built-up areas have been identified and different occupancy types have been assigned for slum and non-slum areas. The soil type has been taken as hard soil across the Navi Mumbai due to the low reported depth of rock.

Peak Ground Acceleration (PGA), MSK intensity, strutural damage, expected injuries and fatalities have been evaluated for two scenarios having earthquake magnitude 6.5 and 6.0. The epicenties have been taken at different locations on the fault-plane and the location resulting in most several consequences has been considered for further investigations.

These results of this study are expected to help various stakeholders/organisations in developing their plans for all the phases of disaster i.e. Response, Mitigation and disaster risk reduction. Results are provided at ward level so that these can be used by ward officers to identify the high risk areas and to prioritize risk mitigation strategies by grading risk areas in a ward. Loss estimation results are also provided in colour coded forms which can be useful to identify the hotspots in the wards.

Estimation of Peak Ground Acceleration and MSK intensity would help engineers and architects to understand the ground shaking and expected damage levels to buildings. This can help to ensure design and construction of earthquake-resistant buildings. This information can also help to frame guidelines to strengthen existing buildings to the required safety level.

The key findings of seismic risk assessment from this study can enable public authorities, businesses, NGOs, and the general public to reach a common understanding of the risks faced as an urban community. By improving the awareness and understanding of disaster risks, earthquake risk in this case, decision makers, stakeholders and emergency managers are in a better position to decide on priorities to undertake preventative measures to take and to prepare ways to avoid the adverse consequences of damaging earthquakes that may occur.

5.2 Conclusions

Earthquakes occur infrequently but their impact can last for decades. The city of Navi Mumbai has moderate earthquake risk. In this study, seismic risk assessment for Navi Mumbai is carried out. A complete analysis is done which includes results for ground motion parameter in terms of Peak Ground Acceleration (PGA), damage intensity as well as social loss estimation in terms of injuries and deaths based on the available exposure data and other input data.

From the estimation, it is found that casualties in slum areas are greater than those in non-slum areas. This is because of poor construction practices in slum areas and also due to the concentration of households in the slums. The expected casualties in slum and non-slum areas have been presented.

Results of the assessment are also produced in color-coded maps to make the understanding of risk assessment results easier for various stakeholders who may not possess the necessary technical background that is required to undertake such assessments. In this way, the results presented in the study can be considered as a postulated scenario and are intended to communicate the complex issues of seismic risk to the all stakeholders involved in seismic risk management. These results can also be used for sensitisation and as an important element of advocacy tools for sustainable risk reduction measures.

The results retain the accuracy of a typical scientific endeavor, while also providing the ability to communicate with various stakeholders in a simple yet accurate manner. Thus, it helps to bridge the varying requirements of scientists, policy-makers, executing bodies and public in terms of understanding earthquake risk and its consequences.

The earthquake risk assessment is expected to contribute to ensure that policy decisions are prioritised in ways to address the significant risks with the most appropriate prevention, mitigation and preparedness measures. Loss estimation is extremely helpful to various stakeholders of urban planners and policy/decision makers in creating a dynamic process for integrating earthquake risk evaluations in the management and development of cities.

5.3 Recommendations

Based on the seismic risk assessment of the city of Navi Mumbai, following recommendations are proposed.

1. Using the results of the seismic risk assessment, an action plan addressing all relevant disaster risk management activities can be prepared for Navi Mumbai. Along with earthquake hazard, such action plan should also include other hazards such as floods, cyclone, tsunami, terrorism etc. Action plan should be developed to reduce the risk associated to various hazards by outlining process for different phases of disaster management which includes, response, mitigation and recovery. Multi hazard action plan would help to respond a disaster effectively which would further help in minimizing loss due to such disasters.
2. Scenario results for earthquake disaster presented herein should be used to check the institutional capacity of various institutions, stakeholders etc.
3. Social losses such as injuries and deaths can be used to evaluate the requirement of critical infrastructure such as open spaces, hospitals, fire stations etc. These would help to evaluate the capacity of institutions to address the disaster.
4. Arrangement should be made to mainstream the risk management activities in the city by framing an organisational policy which clearly defines the roles and assign the responsibilities to plan the risk management strategies. This can be carried through effective communication of the information regarding disaster risk after identifying relevant stakeholders.
5. The comprehensiveness and accuracy of the results of seismic risk assessment largely depends on the availability of the data. Unfortunately, the process of data procuring was very cumbersome and very less data was provided by NMMC. It was felt that insufficient inter-departmental communication and coordination were the main

reasons for it. This area needs a priority attention in order to derive full benefit in case of follow-up studies in future.

6. It is seen that the area under NMMC has a large open spaces. These places can be utilized as temporary shelters in case of an earthquake disaster. These places need to be identified in each ward and marked for such purposes. The catchment areas of people who will be relocated to these temporary shelters also needs to be identified and included in the discussions.
7. In order to produce realistic results and raise awareness of the community on the seismic risk, representatives of various sectors of the society can be involved in such projects in the future. They can contribute to improve resiliency of the community and city as a whole.
8. Most casualties during earthquakes are caused by the collapse of buildings, both engineered and non-engineered, so it is imperative to take measures towards construction of earthquake resistant buildings to make a significant impact towards earthquake safety in Navi Mumbai. These have to be incorporated in the planning process at the developmental stage itself. For effective earthquake mitigation, it has to be ensured that all new constructions are compliant with the latest codes. The techno legal regime in the city has to be strengthened for this purpose. The regulatory agencies and departments should be capable enough both in terms of availability of manpower and technical competence, to enforce/ implement these standards/ codes in construction. Few measures to reduce the seismic vulnerability of buildings include strengthening of existing buildings, control over the construction of new buildings in high risk prone areas.
9. The Municipal engineers should be trained to refresh their knowledge regarding building codes so that they are able to enforce the codes. Institutional arrangements need to be made for training of the Municipal engineers. Training may also be provided to planners and other agencies so that they can incorporate earthquake risk parameters in their activities and contribute to ensuring safety from future seismic activities.
10. Emergency Operation Centre (EOC) should be fully equipped for better response in case of disasters. EOC can be equipped by state of art technologies, centralized information system which can receive and store critical information effectively along with common response system. Emergency communication system should be able to withstand

11. Coordination mechanism within the department and among all line departments should be efficient enough to respond to an emergency situation. Incident Response System (IRS) can be developed to respond an emergency by developing a protocol to identify the line department for a specific disaster incident.
12. Mock drills for earthquakes should be organized frequently as they give an opportunity to the different emergency support function agencies to come together and to be able to coordinate. In case of a disaster it has been observed that it becomes very difficult to identify line departments and their responsibilities. Such mock drills provide an opportunity for the agencies to test their ability to deal with any adverse situation and also to improvise the existing system.
13. Multi-hazard assessment should be carried out which can help organisations to check their capacity with respect to any hazard which can occur in the city. Evaluation of institutional capacity would help to identify the gaps and it would also help to assess those gaps.
14. The next phase of earthquake risk assessment may further include assessment of damage for transportation systems such as bridges and flyovers and lifelines systems such as rail network, road network, power lines, pipelines etc. as well as critical infrastructure such as fire stations, public schools, public health systems etc. These lifelines and critical infrastructures plays crucial role during the disasters so it is imperative to make them resilient enough to withstand a disaster. Such lifelines and critical facilities are very important to get access the disaster struck areas to mobilize rescue teams and other relief measures.

References

Aditya, K. S. P. (2007). "Seismic Risk Assessment of Urban Areas Using GIS." *M.Tech Thesis*, IIT Bombay, India

ArcGIS Desktop Help, ESRI (2015).

Chandra, U. (1977). "Earthquakes of peninsular India – A seismotectonic study." *Bull. Seismol. Soc. Am.*, 67, 1387-1413.

City and Industrial Development Corporation ⟨http://www.cidco.maharashtra.gov.in⟩ accessed on June, 10, 2015.

Coburn, A. and Spence, R. (2002). "Earthquake Protection." *John Wiley and Sons Ltd*., 2nd Edition, Chichester, England.

Dessai A.G., Bertrand H. (1995). "The Panvel Flexure along the Western Indian continental margin: an extensional fault structure related to Deccan magmatism." *Tectonophysics,* 241, 165-178.

Gupta, A., (2006). "GIS Based Seismic Risk Assessment System." *M.Tech Thesis*, IIT Bombay, India.

Joshi, A. (2000). "Modelling of rupture planes for peak ground accelerations and its application to the isoseismal map of MMI scale in Indian region." *Journal of Seismology*, 4, 143-160.

Mohan, G., Surve, G. and Tiwari, P.K. (2007). "Seismic evidences of faulting beneath the Panvel flexure." *Current Science*, 93(7), 991-996.

Navi Mumbai Municipal Corporation (2016). ⟨http://www.nmmconline.com⟩ accessed in January, 2016.

Navi Mumbai Municipal Corporation (NMMC) (2015). "Navi Mumbai Final Ward Formation File" ⟨http://www.nmmconline.com/ward-map⟩

Navi Mumbai Municipal Corporation (2015). "Environmental Status Report of Navi Mumbai Municipal Corporation 2014-15", Navi Mumbai Municipal Corporation, Navi Mumbai.

Navi Mumbai Municipal Corporation (2013). "Environmental Status Report 2012-2013", Navi Mumbai Municipal Corporation, Navi Mumbai.

Iyengar, R. N., and Raghukanth, S. T. G. (2004). "Attenuation of strong motion in Peninsular India." *Seismological Research Letters*, 75, 530-540.

Jaiswal, K. and Sinha, R. (2007). “Spatial variation of maximum considered and design basis earthquakes (MCE and DBE) in peninsular India,” *Current Science*, **92**(5), 639-645.

Kircher, C.A., Whitman, R.V., Reitherman, R.K., and Arnold, C.A., (1997), “Estimation of Earthquake Losses to Buildings.” *Earthquake Spectra*, EERI, 13, 703-720.

Martin, S. and Szeliga, W. (2010). “A catalog of felt intensity data for 570 earthquakes in India from 1636 to 2009.” *Bulletin of the Seismological Society of America*, 100, 562–569, doi: 10.1785/0120080328.

Registrar General and Census Commissioner of India (2011). “Census of India, office of Registrar General and Census Commissioner of India, Government of India, New Delhi.

Seismotectonic atlas of India and its environs, GSI (2000).

Sinha, R., KSP Aditya and Gupta A. (2008). “GIS-based Seismic risk assessment using RISK.iitb.” *ISET Journal of Earthquake Technology*, 497(45), 41–63.

Sinha et al. Technical Document (Tech-Doc) on Seismic Vulnerability Functions of Building Types in India, National Disaster Management Authority (NDMA), New Delhi, India, 2013. ⟨http://ndma.gov.in/ndma/rsva.html⟩

Sinha, R. and Goyal, A. (2004). “A national policy for seismic vulnerability assessment of buildings and procedure for rapid visual screening of buildings for potential seismic vulnerability.” Report to Ministry of Home Affairs, Government of India.

Sinvhal, A., Bose, P.R. and Dubey, R.N. (1994). “Damage report of Latur-Osmanabad earthquake of September 30, 1993.” *Bulletin of Indian Society of Earthquake Technology*, 31, 15-54.

Subrahmanyan, V.(2001) “Seismic signatures in the Kalu River Basin, Thane district and Mumbai”, *In Research Highlights in Earth System Science, Indian Geol. Cong.*, 201–204.

Sungh, S.K., Ordaz, M., Dattatrayam, R.S and Gupta, H.K., “A spectral analysis of the 21 May 1997, Jabalpur, India, earthquake (Mw = 5.8) and estimation of ground motion from future earthquakes in the Indian shield region.” Bulletin of the Seismological Society of America, 89, 1620-1630.

Wald, D. J., Quitoriano, V., Heaton, T. H. and Kanamori, H. (1999). “Relationships between peak ground acceleration, peak ground velocity, and modified Mercalli intensity in California.” *Earthquake Spectra*, 15(3), 557-564.

Wenzel, F., Bendimerad, F., Sinha, R., (2007). “Megacities — megarisks.” *Natural Hazards* 42,481–491.