An Earthquake Risk Management Master Plan for Mumbai: Risk Assessment and its Mitigation

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SUMMARY:
Mumbai city is one of the largest megacities in the world and is located in a region with moderate seismic hazard. The city is highly vulnerable to disasters and experiences both natural and man-made disasters on regular intervals. The city has experienced at over 25 earthquakes with intensity of IV or greater during the last 400 years; however, the city has not experienced a devastating earthquake during this period. As a result, the issues of earthquake risk mitigation are not fully understood by the city's various stakeholders. Mumbai has recently taken the lead in developing a Disaster Risk Management Master Plan (DRMMP), making this the only such initiative in India. Earthquake risk assessment presented herein forms an important part of the DRMMP and provides results which are useful for policy-making, public policy and disaster management application. The discussions in the paper can thus provide a blueprint for contextualising scientific issues that have broad public policy implications.

Keywords: urban risk, disaster management, earthquake risk scenario, risk management master plan.

1. INTRODUCTION

Historically the term earthquake risk has been used to describe risk of an assortment of earthquake effects that range from ground shaking, surface faulting, and earthquake-induced landslides to structural damage, economic loss and casualties. It is now well established that seismic risk consists of the combined effect of the following three components: (1) Seismic hazard, or the potential size of earthquakes in future, (2) 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, including economic and social impact. High risk, thus does not only depend on high hazard; even moderate hazard can result in high seismic risk due to high vulnerability and exposure.

Mumbai is one of the megacities of the world, and is India's economical and financial capital. The frequent natural and man-made disasters such as the recent terrorist attack on Mumbai's population, institutions, cultural and economic infrastructure has demonstrated the urgent need for the Municipal Corporation of Greater Mumbai (MCGM) to enhance internal competency to prepare, manage and eventually reduce its exposure to disaster risks both naturally and human caused. The inevitability of the occurrence of major hazard events including natural hazards such as earthquakes and floods, and human-made hazards such as terrorist attacks and industrial accidents, coupled with the complex urban infrastructure and environment of the city makes the risk very high. In order to implement a comprehensive and holistic urban Disaster Risk Management (DRM) and Disaster Risk Reduction (DRR) program for the city, it is thus imperative to understand the risk due to the various hazards. A project was recently undertaken to develop a Disaster Risk Management Master Plan (DRMMP) for Mumbai, which included earthquake risk management.

This paper presents the brief description of the earthquake risk profile of Mumbai and the risk management issues. The issues pertaining to megacities, which exacerbate the risk, are also discussed herein.

2. MUMBAI: A MEGACITY

Mumbai is one of the complex megacities in the world. It is the capital of Maharashtra State in India and is located on its west coast along the Arabian Sea. As per the 2001 census, the population of Mumbai city (consisting of the area under the Municipal Corporation) has increased from 9.93 million in 1991 to 11.91 million in 2001. However, city officials estimate that an additional 2-3 million 'floating population' also travel to work in Mumbai from the urban agglomeration. The estimated population of the city in 2009, when the study was initiated, was around 13.9 million. Mumbai has a land area of approximately 482 sq km. The population density of Mumbai (over 28,000 people per km^2) is one of the highest in the world.

Informal settlements are a major problem in megacities. In case of Mumbai, about 55% population of the city lives in slums. An increasing number of citizens do not have either permanent or temporary access to land and adequate shelter. Dwellers in slum areas have no sanitation facilities and inefficient rainwater drainage systems. This situation has serious consequences on the environment and public health. The concentration of inhabitants increases the risk of man-made and natural disasters. These informal settlements tend to encroach into the most vulnerable areas.

The city's Development Plan has divided the city into different zones and has recommended land use for each zone. As per the Development Plan, separate residential and commercial zones have not been designated, and most areas of the city have been designated as combined residential and commercial areas. The zoning map of Mumbai as per the Development Plan is shown in Fig. 2.1. The MCGM has divided the city into 24 administrative wards. The ward map of the city is shown in Fig. 2.2.

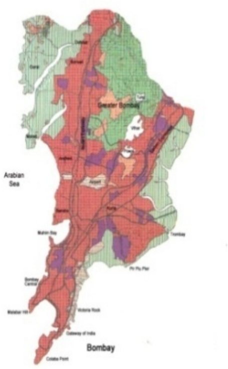

Figure 2.1. Development plan of Mumbai (www.mcgm.gov.in)

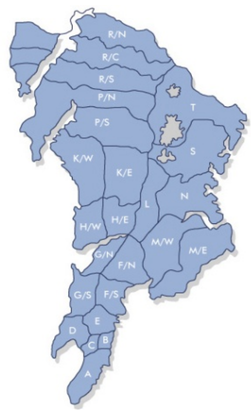

Figure 2.2. Ward Map of Mumbai (www.mcgm.gov.in)

Administrations in megacities like Mumbai are often confronted with a multitude of key problems, like high urban densities, transport, traffic congestion, energy inadequacy, unplanned development and lack of basic services, illegal construction both within the city and in the periphery, informal real estate markets, creation of slums, poor natural hazards management in overpopulated areas, crime, water, soil and air pollution leading to environmental degradation, climate change and poor governance arrangements. Thus, good governance is one of the greatest challenges for megacities. Mumbai is no exception. It has a complex administrative structure with Municipal Corporation of Greater Mumbai (MCGM) as its main administrative body. Several other state government organizations like Mumbai Metropolitan Region Development Authority (MMRDA), Maharashtra State Road Development Corporation (MSRDC), Maharashtra Housing and Area Development Authority (MHADA) are involved in the development of the city. As a result, the city has problems with unclear and overlapping responsibilities amongst internal and external agencies, leading to operational complexities.

Megacities are highly vulnerable to natural and man-made disasters. Mumbai faces several natural hazards such as earthquakes, floods, landslides, etc. The Panvel flexure, a seismically active zone is about 25 km away from the city, exposing the city to earthquake risk. Infrastructure constitutes a major component of the vulnerability of a megacity if disasters strike. In Mumbai, basic infrastructure facilities such as railway networks, water supply, sewage and sewerage and health care are overloaded even in normal times.

Thus, given these characteristics of Mumbai, one of the key challenges is to obtain up-to-date, city wide information in a very timely manner to support more proactive decision making that encourages more effective sustainable development. It is also clear that solutions to problems facing a megacity like Mumbai require concerted response from many internal units and regional and national agencies in areas such as planning, infrastructure, development and land use controls, transportation, environmental management and water management. These can be facilitated through a common understanding of the risk to various hazards, their consequences and the possible actions that can either mitigate the risks or reduce their impacts. A DRMMP can provide these within the framework of the city's legal and institutional structure to enable timely and sustainable risk management programs.

3. DISASTER RISK MANAGEMENT MASTER PLAN (DRMMP) FOR MUMBAI

The development of Mumbai's DRMMP was started in April 2009 and completed in June 2011. The project envisages following main goals:
1. To establish a competent emergency management system for Mumbai that is based on the international standards of practice,
2. To institutionalize a DRM practice, operation and function for Mumbai by which hazards, vulnerability and risks are understood and competently managed, and
3. To develop a coherent set of objectives and recommendations to reduce disaster risk within Mumbai and consequently in the country.

The DRMMP consists of a menu of priority actions which encompass the key and essential components of a sound DRM system and the processes necessary to implement and sustain them. The important components of the DRMMP process are Risk identification and assessment, Legal and institutional system (governance), Capacity building and community preparedness (awareness, response, relief, recovery capability), Risk reduction and prevention, Financial protection and Development and application of knowledge and technology. Many of these components of the DRMMP are based on scientific and technical knowledge which require the inputs of earthquake engineering experts.

The DRMMP considered earthquake and flood hazards to Mumbai. Detailed risk assessment for the two hazards were carried out, which went beyond the traditional risk assessment found in scientific publications, and also considered the requirement for emergency management, response, rehabilitation, etc. The risk assessments were also used to assess the likely impact on the governance and administrative structure of the city.

4. SEISMIC HAZARD OF MUMBAI

Mumbai is located in Seismic Zone III as per IS:1893-2002 (BIS, 2002) signifying that the city may be subjected to intensity VII damage as per MSK64 Intensity Scale. A review of the historical as well as the recent earthquake activity in peninsular India indicates that different parts of the region are characterized by low to moderate level of seismic activity (Jaiswal and Sinha, 2007). Occasionally some large and damaging earthquakes, such as the Koyna (1967), Killari (1993), Jabalpur (1997), and Kachchh (2001) earthquakes have occurred in the region. Unlike the earthquakes occurring on plate boundaries, demarcated by mid-oceanic ridges, transform faults and island arcs, these are intraplate earthquakes and are thus more rare. Fig. 4.1. shows various faults and lineaments within 100 km of the city. Mumbai is located near the Panvel seismic source zone, which is known to be seismically active (Nandy, 1995 and Dessai, 1995).

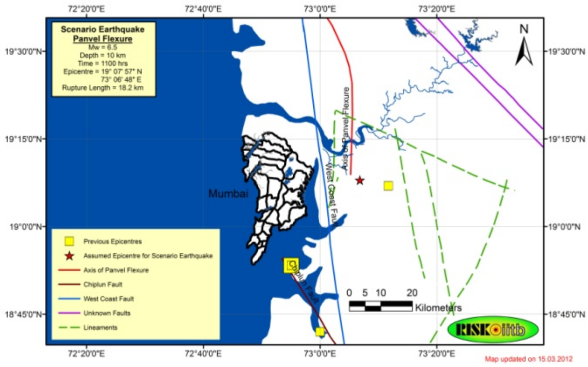

Figure 4.1. Lineaments of the west coast of India near Mumbai, adapted from Seismotectonic Atlas of India (GSI, 2000)

Seismic hazard quantifies ground motions generated due to an earthquake in terms of peak ground acceleration (PGA) or other similar parameters associated with a scenario earthquake (Kramer, 1996). In this paper, a deterministic seismic hazard assessment has been carried out, where hazard in terms of the peak ground acceleration is evaluated at the centre of each grid after dividing the city into a number of small grids.

Very few Ground Motion Prediction Equations (GMPEs) have been developed for stable continental regions such as peninsular India, where Mumbai is located. For the purposes of this study, the Iyengar and Raghukanth (2004) GMPE has been used. The relationship for PGA in terms of acceleration due to gravity is given by

$$\ln PGA = 1.6858 + 0.9241\times(M-6) - 0.076\times(M-6)2 - \ln R - 0.0057R + \ln \varepsilon \qquad (4.1)$$

where PGA is in g, and ln ε is the error in the estimation of ln PGA. The standard deviation of the error estimation is $\sigma(\ln \varepsilon) = 0.468$; R is the hypocentral distance; and M is the moment magnitude. In this study, the effect of soil amplification has been incorporated by assigning an amplification factor of 1.2 to the PGA in non-rock regions.

For the present study, the approximate empirical relationship by Wald et al. (1999) based on data from California has been used to obtain the Modified Mercalli Intensity I_{mm} from the PGA at any location:

$$\text{For } I_{mm} \leq V,\ I_{mm} = 2.20 \log(PGA) + 1.00 \qquad (4.2)$$

$$\text{For } I_{mm} > V,\ I_{mm} = 3.66 \log(PGA) - 1.66 \qquad (4.3)$$

The Indian Standard code (BIS, 2002) specifies damage intensity in terms of the MSK64 intensity scale. Expressions relating MSK and MMI intensity levels have been proposed (for example, ASK, 1977), which show that these levels are similar in the range of interest (i.e., between the damage intensity levels IV and IX). Since MMI and MSK levels are quite similar in definition and range of expected structural response at each level, considering the uncertainty in assigning damage levels based on visual observation of structural behaviour, MMI and MSK values are considered equal in the present study.

5. SEISMIC VULNERABILITY OF BUILDINGS

The building stock in Mumbai exhibits a rich mix of several different building technologies and construction materials. The most commonly used model building types are: (1) Reinforced cement concrete buildings, 2) Brick masonry buildings, (3) Steel buildings, and (4) Non-engineered buildings. In Mumbai's construction practice, it has been found that most non-engineered constructions occur in slums. In the past, non-engineered constructions were also prevalent when authorized masonry buildings were constructed. In the present study, those construction that use a mix of materials for structural members are also categorized as non-engineered since such constructions typically occur when the building height is increased over time, often in an unauthorized manner. These building categories have been further categorized to various occupancy types: (1) Residential, (2) Commercial, and (3) Industrial.

Seismic vulnerability quantifies the possibility of a building or a type of buildings to be damaged due to earthquake ground motions (Karnik et al., 1984). Several methods are available for performing the vulnerability analyses. The type of method chosen depends on the objective of the assessment and the availability of data (Lang, 2002). In the present study, vulnerability of the buildings implied in macro seismic intensity scales has been considered. The method utilizes damage probability matrices (DPMs) that provide the mean level of damage corresponding to ground motion intensity as a conditional probability factor. The vulnerability function, relating the earthquake damage intensity to damage state, used in this study is based on Sinha and Adarsh (1999) and is given in Fig. 5.1. It may be noted that the graphs have not been smoothened to a log-normal curve, as is the normal practice, in this study.

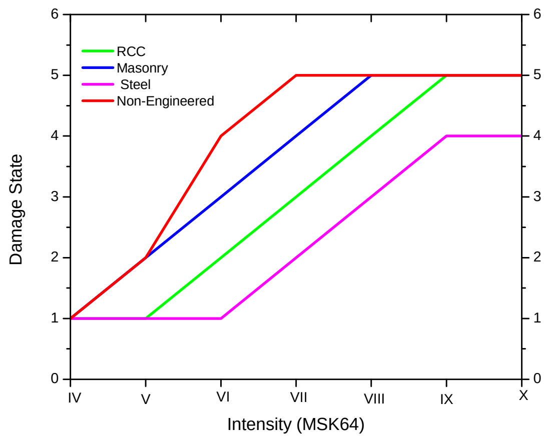

Figure 5.1. Vulnerability Curves for different building types (Sinha and Adarsh, 1999)

To estimate the built-up area in various building types, the per capita residential built-up area in the city has been taken as 10 m^2 based on several urban development studies. The total built-up area of the city has been distributed into the four building types, viz. RCC, masonry, steel and non-engineered, based on Housing Census data of 2001.

6. EXPOSURE AND LOSS ESTIMATION

The population exposure analyzes the total population of the region exposed to the scenario earthquake. In this study, the population distribution is done based on the time of scenario earthquake, occupancy classes, model building types, and area of various buildings present in the city. The temporal occupancy model by Coburn and Spence (2002), which gives the distribution of population during different times of the day, has been used to obtain the population in different buildings at the time of the earthquake as an alternative. The floating population of people from outside the city limits during the daytime is taken as 15% of the night population.

The property exposure analysis has been carried out for the city as used for hazard estimation, and has considered the structural components, non-structural components and the contents of the buildings. The value of the structural and non-structural components of a building has taken based on model building type and the occupancy class of the building. The loss estimation refers to the evaluation of social and economic losses that are likely to be experienced during the scenario earthquake. Social loss involves the estimation of number of people likely to be injured with different severity. This evaluation considers the population in buildings at the time of the earthquake, the earthquake intensity, the vulnerability of the buildings, and is obtained using a casualty model as shown in Figs. 6.1 and 6.2**.**

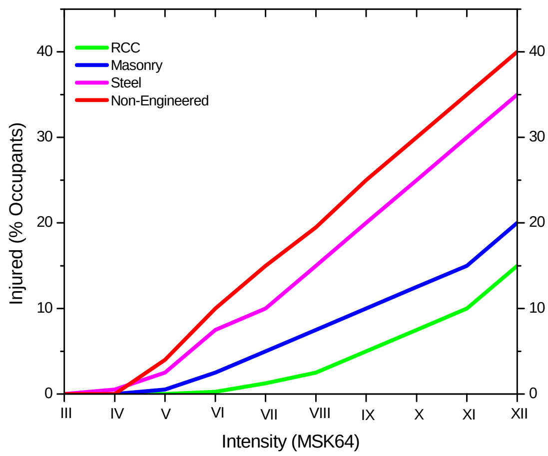

Figure 6.1. Percentage of population likely to be injured during different earthquake intensities (Gupta, 2006)

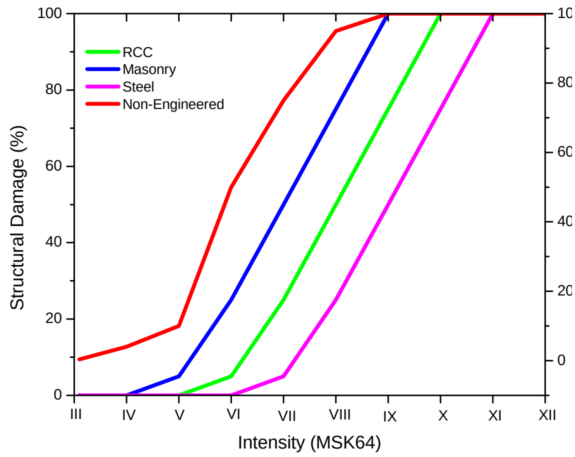

Figure 6.2. Extent of likely structural damage during different earthquake intensities (Gupta, 2006)

The evaluation has been carried out for all buildings of each building type and is carried out for each grid that the city has been divided into for hazard assessment.

7. EARTHQUAKE SCENARIO AND RISK ASSESSMENT

Several different scenario earthquakes have been considered for the DRMMP project, and the results for a typical scenario earthquake (M_w=6.5) are presented herein. The focal depth of 10 km has been chosen for the scenario. The epicentre has been taken on Panvel flexure, and the rupture length has been estimated using Wells and Coppersmith (1994) relationship to be 18.2 km.

Table 7.1. Input parameters for the scenario

Input	**Value**
Time of Occurrence	1100 hrs
Moment Magnitude	6.5
Focal Depth	10 km
Epicenter	19°7'57" N, 73°6'48" E
Population	13.9 million
% Floating Population	15
Soil Type	Rocky and Soft Soil
Fault	Panvel Flexure
Fault Type	Strike Slip
Fault Orientation	3 Degrees East of North
Estimated Surface Rupture Length	18.2 km
GMPE	Iyengar and Raghukanth (2004)

Table 7.2. Estimated casualties and economic losses for the scenario earthquakes

	Injuries	**Deaths**	**Economic Loss***
Slum	537,000	82,000	329.15
Non-Slum	226,000	77,000	709.80
Total	**764,000**	**159,000**	**1038.95**

* Economic loss is in Rs. billion.

As discussed earlier, a grid-based seismic risk assessment of the city has been carried out. The whole area of the city is divided into small grids of 0.25 km × 0.25 km size. The results for developing the DRMMP have been aggregated at the ward level, which is the smallest administrative unit of the city. The input parameters provided for the simulation are given in Table 7.1, while the results of social and economic losses are given in Table 7.2.

The analysis results are also presented in maps to make the understanding of risk assessments easier for various stakeholders who may not possess the necessary technical background. The ground motion is displayed in terms of PGA as shown in Fig. 7.1. It is seen that the PGA value varies from 0.26*g* to 0.66*g*. The injuries, deaths and economic losses are estimated for each grid and presented in terms of easy-to-understand maps of injuries, deaths and economic losses in Figs. 7.2 to 7.4. From Fig. 7.2, it can be seen that in most of the grids the number of people injured vary from 0 to 200. These grids have less concentration of injuries because they cover non-slum areas of the city. On the other hand, the remaining grids cover slum areas of the city and have more concentration of injuries. Such results have been obtained because the population density of slum area is much higher than that of non-slum areas.

These simulation results are being used for sensitisation as well as an important element of advocacy tools for sustainable risk reduction measures. While the risk assessment has been carried out considering the variation of earthquake hazard in 0.25 km × 0.25 km grids, several data are only available at coarser resolution. Some input information such as housing data, slum and non-slum population, construction information, etc., are available only at ward-level. Several quantitative results have been aggregated at ward-level to enable integration of risk results within the city's administrative structure.

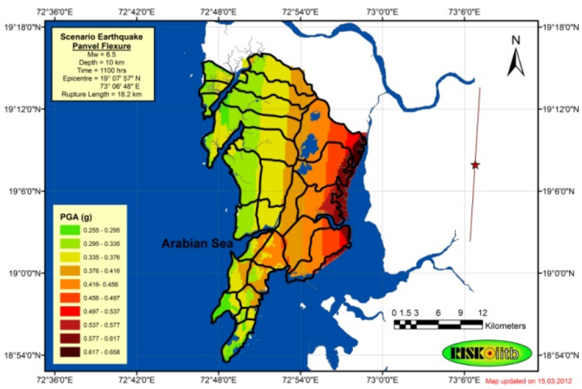

Figure 7.1. PGA intensity map for scenario earthquake with M_w = 6.5

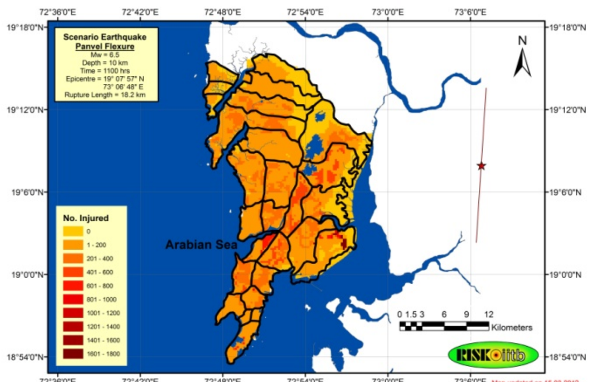

Figure 7.2. Map of estimated injuries for scenario earthquake with M_w = 6.5

8. INTEGRATION OF EARTHQUAKE RISK ASSESSMENT TO DRMMP

Integration of disaster risk parameters into the master planning processes to make urban planning risk-sensitive is an essential part in any policy making process to ensure proper and efficient implementation. The current urban master plan is based on socio-economic development strategies, and has not explicitly considered disaster risk. Risk-sensitive urban development and land use plans can provide opportunity to implement proactive disaster risk reduction in the form of comprehensive plans, zoning, and building regulations.

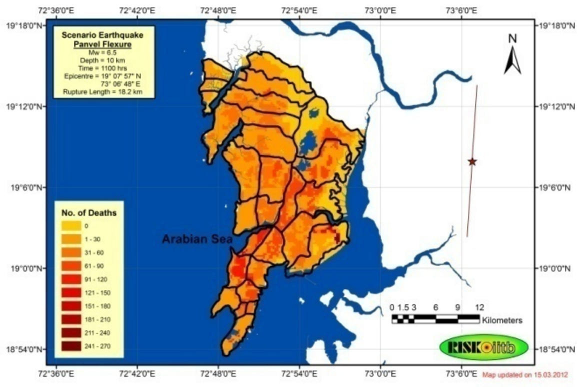

Figure 7.3. Map of estimated fatalities for scenario earthquake with $M_w = 6.5$

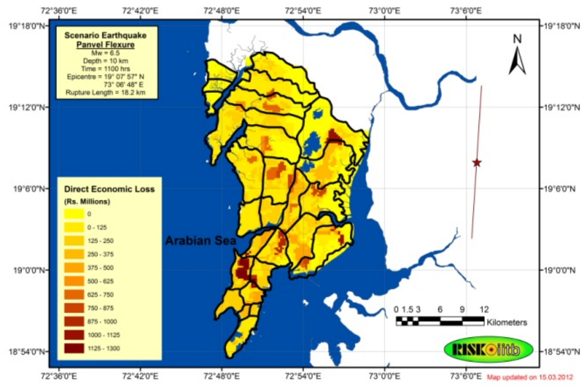

Figure 7.4. Map of estimated economic losses for scenario earthquake with $M_w = 6.5$

The earthquake risk assessment is expected to contribute in ensuring that policy decisions are prioritised in ways to address the most severe risks with the most appropriate prevention and preparedness measures. The results of the study, such as shown in Figs. 7.3 and 7.4, have lead to a series of policy recommendations, strategies and action plans, that have been incorporated in the DRMMP Framework. This earthquake risk assessment study also provides results to meet requirements of various focus groups working in DRMMP project.

For example, the number of houses that are badly damaged and number of people requiring shelters in slum as well as non-slum have been estimated. This information is being used for disaster resiliency of slum shelters, and housing policies and slum reduction programs. For land use planning, the results have been prepared in terms of various grades of damage to the buildings in different areas of the city. These results are helpful for estimation of post-disaster debris generation.

The key findings of seismic risk assessment can enable public authorities, businesses, NGOs, and the general public to reach a common understanding of the risks faced as a 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 agree on the preventative measures to take and to prepare ways to avoid the most severe consequences of damaging earthquakes that may occur near Mumbai in the future.

9. CONCLUSIONS

Mumbai is one of the megacities of the world, and has one of the highest population density in the world. The city experiences complex problems and frequently faces disasters due to natural and human-made causes. The city recently undertook the development of a Disaster Risk Management Master Plan to develop policies, strategies, programs and action plans to improve its disaster risk management capability. The earthquake risk assessment conducted as a part of the DRMMP has been presented in the paper. The assessment presents results in terms of number of casualties, economic loss, etc. Separate analysis has been carried out for slum and non-slum areas considering the difference in population, construction types and economic profile in these areas. The casualties at different severity levels are also estimated. Several different types of results have been generated as per the requirements of various stakeholders involved in the DRMMP project. The results are also presented in the maps to provide better understanding of the non-technical stakeholders. These results are not considered to be an absolute assessment, but postulated scenarios that are intended to communicate the complex issues of seismic risk to the stakeholders and thus promote a common understanding of the issues.

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.

AKCNOWLEDGEMENT

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