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A POSTULATED EARTHQUAKE DAMAGE SCENARIO FOR MUMBAI

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ABSTRACT

Mumbai is known as the commercial capital of the country and is the main centre for economic activities. Due to the city's strategic and economic importance, it is essential to estimate the likely consequences of potential earthquakes so that suitable mitigation measures may be developed and implemented. The earthquake damage scenario for Mumbai has been developed based on the seismic hazard and vulnerability of the building stock in the city. From these investigations, it is found that the extent of damage and destruction due to code-level earthquake affecting the city of Mumbai would be larger than the biggest disasters faced elsewhere in the recent times. The study also considers the effect of mitigation measures and shows that improvement in the design and construction practice is imperative if the likely consequences are to be reduced.

KEYWORDS: Earthquake Hazard, Disaster Mitigation, Damage Scenario, Urban Hazard, Mumbai.

INTRODUCTION

India is highly susceptible to frequent damaging earthquakes. Regions in Northern India, particularly the Himalayan belt, have experienced earthquakes at regular intervals that have caused immense damage in the past. The central and south India were hitherto assumed to be relatively safe from major seismic activities. However, the damaging earthquakes of Koyna, Killari and Jabalpur have all occurred in central India over the last 30 years, raising the possibility that no area of our country may be safe from such earthquakes. So far, all the major recent earthquakes have occurred away from major cities, and have severely affected relatively sparsely populated areas (Chandra, 1977; Sinha and Goyal, 1994; Jain et al., 1994; Iyengar et al., 1994). This has limited the human casualty and the economic losses. However, the Killari earthquake has amply demonstrated that inappropriate construction technology may lead to high casualty levels even for moderate earthquakes (Sinha and Goyal, 1994). A strong earthquake affecting a major urban centre like Mumbai may result in damage and destruction of massive proportions and may have very severe long-term consequences for the entire country.

Mumbai is known as the commercial capital of the country and is the centre of its economic activities. Like most major urban centres in our country, Mumbai has grown tremendously in the last few decades due to unabated migration from the smaller towns and rural areas. As a result, the city has developed in a haphazard fashion with little consideration for proper town-planning norms. This has resulted in most areas of the city lacking in basic civic amenities. In fact, almost 50% of Mumbai population lives in informal houses (often illegal and of very poor quality) in slums. Even in the non-slum areas, the basic amenities may be lacking and the structures may be of poor quality. Any long-term disruption of normalcy in this city may have extremely adverse consequences for the entire nation. There is, consequently, a need to be prepared against all possible natural and man-made disasters that are likely to occur in Mumbai. For this purpose, it is essential to have realistic understanding of the consequences of likely damage in Mumbai due to different disasters. This will permit rational planning of mitigation efforts in order to minimise effects of these disasters (Sinha and Adarsh, 1997b).

The earthquake risk at any location depends on the seismic hazard as well as the vulnerability of its structures. The seismic hazard evaluation considers the likelihood of earthquake of a particular magnitude or intensity affecting a site, and the evaluation of seismic risk in any city requires proper consideration of the strength of likely earthquakes in future. The seismic hazard for Mumbai has been quantified based on the hazard level described in the relevant earthquake-resistant design code (IS:1893, 1984). The seismic vulnerability, on the other hand, depends on the construction practice in the city and is related to quality of the building stock. For old cities like Mumbai, a larger proportion of buildings is very old and consequently more vulnerable when compared to the housing stock of relatively new cities such as Chandigarh. The local construction practice also has a very strong bearing on the seismic vulnerability since the use of inherently strong building materials will result in structures showing better resistance to earthquakes. In this investigation, the seismic vulnerability of different construction practice in Mumbai has been established using the expert evaluation method (EAEE, 1995), and represents the average behaviour of different types of structures. This method considers the relative strengths and weaknesses of buildings using different building materials, but does not attempt to quantify the difference in behaviour of different structural forms using same building materials. The expert evaluation method does not require explicit evaluation of information such as expected earthquake sources and their characteristics or the fragility curves for different structures and lifelines. GIS-based tools for evaluation of earthquake risk using detailed analyses have also been recently developed (for example, NIBS, 1997) but cannot be applied to Indian cities due to non-availability of required data. The expert evaluation method, on the other hand, is less precise but gives "order of magnitude" information that is invaluable for development of earthquake disaster management policies. In the present study, the likely behaviour of the different structure types have been assessed based on the senior author's experience following the Killari and Jabalpur earthquakes and also based on the published earthquake damage reports following several earthquakes in other developing countries (Sinha and Goyal, 1994; Yegian et al., 1994a and 1994b; Hayes, 1996; Jain et al., 1997; Hassan and Sozen, 1997; and Sadek, 1997).

The seismic hazard and vulnerability assessments have been combined to determine the seismic risk of future earthquakes affecting Mumbai. Risk assessment has been used to determine the extent of likely damage or destruction of buildings of different types. This analysis is further extended to determine the likely casualty levels based on a multi-parameter morbidity model. The final results of this investigation are the number of buildings that are likely to be damaged due to earthquakes of different magnitudes and the number of people who may be injured and perish. The risk scenario has been developed based on the 1991 census data for Mumbai. As a result, the damage and casualty figures in a future earthquake, when the population is larger may be greater than that estimated in the present study.

The effect of introduction of structural mitigation measures on the seismic risk has also been postulated. The structural mitigation measures increase the inherent strength of buildings to withstand earthquakes. Since these measures can only be incorporated to those buildings constructed in future, the consequence of earthquakes several years after these measures are implemented has also been developed. This investigation has helped in the assessment of the effectiveness of mitigation measures in reducing earthquake risk.

SEISMIC HAZARD

The seismic hazard is typically determined using a combination of seismological, morphological, geological and geotechnical investigations, combined with the history of earthquakes in the region. The landmass making up the state of Maharashtra is geologically very old, and the Deccan Traps cover ancient rocks that make up the main land mass. Consequently, the Traps hide most of the geological features of the underlying rocks. As a result, investigation of potential seismic activities in this region has been a difficult task. Only the major relevant geological features have been accurately identified and efforts are currently underway to use a combination of direct and indirect methods to map the most important features, particularly those that may affect Mumbai (Vatsa, 1997; and Seeber, 1998).

The major lineaments that have been mapped in Maharashtra are shown in Figure 1. As seen in this figure, the lineaments can be divided into three major groups: (1) N-S lineaments near the coast (Sahyadri group); (2) NW-SE lineaments (Godavari group); and (3) ENE-WSW lineaments in the eastern part of the state (Satpura group). Of these, the Godavari and Sahyadri groups of lineaments, if active, would pose risk of earthquake damage to the Mumbai region. For example, the Koyna earthquake of 1967 (M 6.7) has been associated with the Sahyadri group of lineaments. The lineaments shown in Figure 1 do not indicate the presence of any major features very close to the Mumbai region. However, some recent studies using deep seismic sounding profiles and geo-magnetic anomaly investigations have indicated the presence of several smaller lineaments below the Deccan Traps (Arora and Reddy, 1990). These lineaments may represent an extension of the major groups described above, or may form a part of inter-group lineaments. Not much is currently known about the level of activity along these lineaments. It is, however, quite clear from the lineament traces that their movement (if possible) may pose significant seismic risk to the city (Subramanyan, 1995).

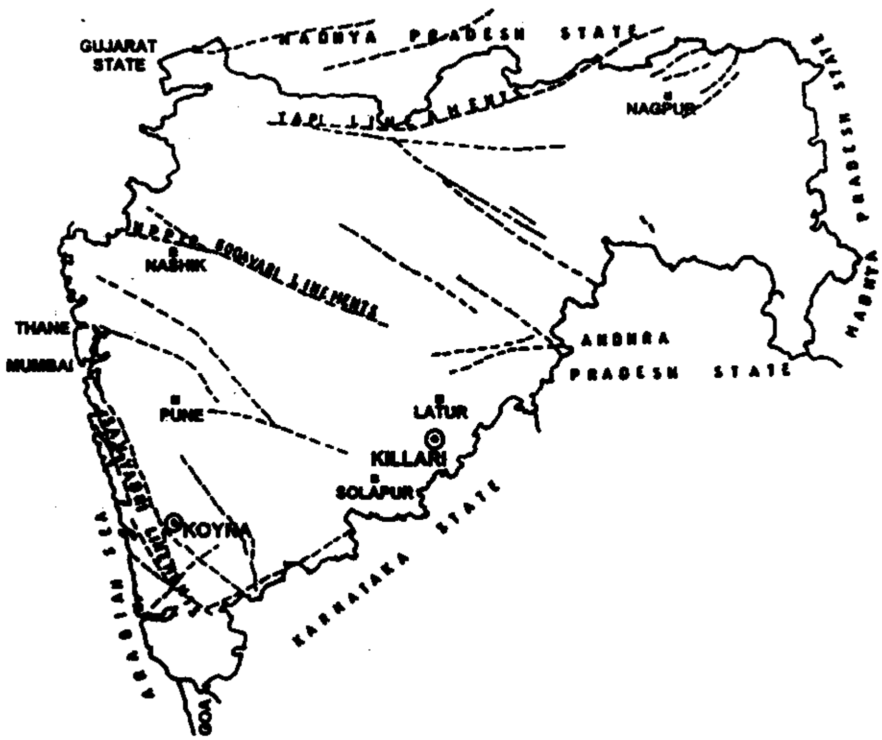

Fig. 1 Map of Maharashtra showing major lineaments

There are also concerns of increase in seismic hazard in peninsular India due to human activities. Recent research has indicated that some activities such as creation of large reservoirs, extraction of hydrocarbon and extensive mining activities may trigger damaging earthquakes in relatively stable regions (Gupta et al., 1972; Gupta, 1992; Simpson, 1986). As a result, there may also be a need to re-examine the seismic hazard assigned to this region based on historical records.

Reliable historical data for seismic activity affecting the Mumbai region is available only for the last 400 years (GOM, 1998; based on the data available from IMD, EPRI, NGRI and MERI). The most prominent recent earthquakes affecting Mumbai have been listed in Table 1. It is seen that this region has been experiencing low-intensity earthquake ground motions at frequent intervals. So far, only one record of an earthquake associated with very severe damage and destruction is currently available, and that too is of dubious reliability. However, large earthquakes in the stable continental regions such as the Deccan region are known to have long return periods (> 500 years) (Seeber and Armbruster, 1987). The lack of information of large earthquakes may therefore be due to paucity of historical data rather than low seismic hazard.

The Indian Standard code (IS:1893, 1984) has placed Mumbai in seismic zone III. The seismic zones in the IS code are not based on analytical assessment of seismic hazard and are largely based on historical data (for example, see Kaila et al., 1972; Chandra, 1977; Rao and Rao, 1984). The seismic zones in

IS:1893 are based on expected damage intensity in the event of code-level earthquake and do not denote consistent ground motion criterion such as equal peak ground acceleration levels. As per IS:1893, the design level earthquake in zone III is expected to result in damage corresponding to MSK Intensity VII. Since major earthquake events in the Deccan and south Indian region have long return periods, the earthquake zoning maps may be biased in favour of the recent large earthquakes (for instance, the Great Gujarat and Koyna earthquakes). This would imply that the areas of central and south India with lower seismic zones in the earthquake code may not necessarily represent areas of lower seismic hazard. However, these may also include areas with greater seismic hazard but with paucity of historical data.

Table 1: Some Major Historical Earthquakes in Mumbai Region*

Year	Month	Intensity (MMI) / Magnitude (R)
1594	--	IV
1618	May	IX**
1678	--	IV
1832	October	VI
1854	December	IV
1865	December	IV
1877	December	IV
1896	April	III
1906	March	VI
1910	September	III
1924	January	IV
1928	November	III
1929	February	V
1933	July	V
1935	September	III
1937	January	III
1941	May	IV
1951	April	VIII
1961	January	III
1963	March	IV
1964	November	III
1965	July	III
1965	December	IV
1966	May	V
1967	April	4.5
1967	June	4.2
1998	May	3.6

*Source: Compiled from catalogues of IMD, NGRI, EPRI and MERI.

**There is some uncertainty about this damage being caused due to an earthquake.

The recent earthquakes in the Deccan region (Koyna, Latur and Jabalpur) have all resulted in extensive damage to the structures close to the epicentre (in the near-field). In all three earthquakes, a small region very close to the epicentre experienced damage of intensity VIII or higher (see, for example, Tandon and Chaudhury, 1968; Sinha and Goyal, 1994; and Jain et al., 1997). Based on the philosophy behind the seismic zoning and experience from recent earthquakes, it can reasonably be assumed that a major earthquake event in the Deccan region is capable of higher damage than that assumed in the zoning map of IS:1893 (1984).

The earthquake history of Mumbai presented in Table 1 shows evidence of damaging earthquakes at frequent intervals; there have already been a few earthquakes with intensity VI+ damage during the last 400 years. Based on this historical data, and due to the non-availability of seismo-tectonic data on lineaments and their level of activity, it is conceivable that the Mumbai region may experience earthquakes with damage greater than intensity VII, the level assumed by the IS code for design purposes. In this investigation, three different earthquake scenarios have been investigated: those resulting in maximum damage corresponding to intensity VI, VII, and VIII.

CONSTRUCTION TECHNOLOGY

The Mumbai region is 100% urban and the building stock exhibits a rich mix of several different building technologies. The most commonly used building categories are: (1) reinforced-concrete frame buildings with partition walls; (2) brick masonry buildings with reinforced concrete roofs and using cement mortar; (3) informal brick masonry buildings (which may or may not use cement mortar); (4) buildings made of other materials such as tin sheets, thatch and other light-weight elements. The first two categories typically constitute engineered constructions in which the assistance of qualified engineers is usually taken at each stage. The last two categories are non-engineered constructions, wherein the services of skilled engineers may not have been employed. In Mumbai, however, it has been observed that several reinforced concrete and brick masonry buildings have been constructed without the assistance of qualified engineers. Due to this reason, these buildings are also not engineered since they may be improperly designed or constructed resulting in lower strength.

During the 1991 census housing survey, the city was found to have a total of 2,768,910 dwellings, including both residential as well as commercial and industrial establishments. Of these, only 9.08% of dwellings were made of reinforced concrete, while 31.35% of dwellings were engineered masonry constructions. As can be deduced, 59.57% of all constructions, even in Mumbai, are non-engineered. A very high percentage of non-engineered constructions can probably be explained due to the very large percentage of population residing in slums. It is expected that the relative percentage of engineered and non-engineered constructions will be similar in most other mega-cities in our country.

The behaviour of the different building types has been quantified in terms of its damage intensity index. This damage intensity index describes the probable percentage of buildings of any type that may be damaged due to an earthquake of particular strength. Based on the expected performance of buildings, it is possible to develop tables of damage intensity index for the prevalent construction practice in Mumbai. The salient features of the behaviour of both categories of constructions and their damage intensity index are discussed next.

1. Engineered Constructions

Those buildings and other structures that are designed and constructed using the services of qualified engineers are categorised as engineered constructions. In urban India, these structures are typically made of reinforced concrete or brick masonry with cement mortar. In some cases, engineered constructions may also employ other building materials such as lightweight roofs of GI sheets designed using qualified technical assistance. In the present investigation, due to paucity of relevant data, masonry buildings that do not have reinforced concrete slab roofs have not been included in this category. The engineered constructions are expected to comply with the appropriate codes and standards. These buildings are also expected to be safe for dead and superposed loads over the entire life of the structure. For the design level earthquake, these buildings are not expected to suffer major damage. For much higher intensity of earthquake, these buildings are expected to collapse in such a manner as to minimise the injury to the occupants.

Since Mumbai is an old city, several engineered constructions are also very old and were constructed decades ago. These buildings have already exceeded their useful service life and several of them have deteriorated badly. These buildings, even though they may be engineered, are not expected to perform as well as the newer similar constructions during an earthquake. In addition, several engineered buildings are designed and/or constructed improperly and may perform worse than expected during earthquakes. A recent study (Schierle, 1996) has shown that quality control during design and construction is a serious issue for aseismic design even in developed countries. Several buildings are lost every year in Mumbai due to natural causes (when the load exceeds the capacity due to loss of strength caused by ageing etc.). The year-wise break-up of the number of major buildings that have collapsed during the last decade is given in Table 2. As can be seen, a considerable number of buildings (most of which are already very old) collapse every year, mainly during the monsoon season. For damage assessment, the impact of earthquake on these types of buildings has been considered by increasing the damage intensity index for all engineered construction categories.

Table 2: Number of Major Engineered Buildings to Collapse during 1984-95

Year	Building Collapses
84-85	382
85-86	395
86-87	391
87-88	346
88-89	406
89-90	274
90-91	319
91-92	254
92-93	242
93-94	236
94-95	257

2. Non-engineered Constructions

Most buildings that are found in Mumbai are non-engineered. These structures are typically designed and/or constructed by people without appropriate technical qualifications. Most such buildings are designed without any detailed analysis and may also be of poor quality. From the census data, it is found that 59.57% of all buildings in Mumbai are non-engineered. Some non-engineered buildings are made from brick masonry with lightweight roof. The performance of these buildings is expected to be at par with the corresponding engineered buildings since most such constructions have also used cement mortar. Most other non-engineered buildings are made of light and informal materials such as thatch, GI sheets, and plastic. These buildings are naturally expected to behave very poorly due to an earthquake. However, due to the lightweight nature of these structures, they are expected to trap fewer people, leading to lower casualty. A similar phenomenon was also observed after Killari earthquake wherein the loss of life among the poorest section of inhabitants, who mainly lived in thatch houses, was found to be the lowest.

SEISMIC VULNERABILITY

The assessment of seismic vulnerability can be carried out using the data of building stock and the evaluation of the behaviour of different types of buildings. In order to simplify the analysis and determine the damage levels, several approximations have been made. Most of these approximations can be eliminated by a more detailed investigation requiring the availability of more detailed data. The approximations are (Sinha and Adarsh, 1997a):

1. About 10% of the city area is expected to experience the most severe level of earthquake damage, and another 30% of the area is expected to experience the next level of damage (as described using MSK intensity isoseismals). For moderate earthquakes affecting Mumbai, in which the near-field effects of fault movement are not significant, this approximation is a reasonable estimate of the isoseismal areas. This distribution of isoseismals (and the corresponding area enclosed under each isoseismal) is similar to that observed after recent moderate earthquakes in urban areas of US and Japan.

2. The building stock under the earthquake excitation is expected to behave as per the known performance of each structure type. For example, an earthquake with MSK Intensity VII is expected to result in the damage pattern described in IS:1893 for different types of structures and with damage intensity described in Table 3.
3. The secondary effects of earthquake damage to buildings are ignored. Based on this approximation, the possibility of debris of a weak building damaging the better quality adjoining buildings will not be considered. Similarly, the consequences of an earthquake causing building damage due to other disasters such as fire are ignored.
4. The micro effects of population and building concentrations have not been considered. Due to this assumption, the entire population and the building stock are considered to be uniformly distributed throughout the city area. In most large Indian cities, with intense demographic pressure and high population density, this assumption closely approximates the habitation pattern.
5. The average family size is assumed to be five. This information has been used to estimate human casualty from the assessment of building damage. This average family size has been obtained from the 1991 census data for Mumbai.
6. The occupancy rate at different times of the day is estimated based on the investigations by Coburn et al. (1992). It is assumed that these occupancy rates are also applicable to Mumbai where the residents follow similar living patterns.

Based on these assumptions, earthquake damage in the city can be divided into three intensity zones. The highest intensity zone covers approximately 60 km^2 (10% of the city area). The next intensity zone covers 30% of the city area (approximately 200 km^2) while the remaining portions of the city (340 km^2) experience lowest seismic intensity. The effect of earthquakes of different magnitudes on the buildings depends on the building category (and quality).

Table 3: Proposed Damage Intensity Index for Different Building Types in Mumbai

	MSK V	MSK VI	MSK VII	MSK VIII
Reinforced Concrete Building	0.00	0.05	0.25	0.50
Engineered Masonry Building	0.05	0.25	0.50	0.75
Non-Engineered Masonry Building	0.05	0.25	0.50	0.75
Non-Engineered Constructions Using Other Materials	0.10	0.50	0.75	0.95

The seismic damage index based on the discussions in previous section is given in Table 3. The reinforced concrete buildings show the best behaviour during an earthquake while the non-engineered buildings using alternative materials show the worst performance. The vulnerability of concrete structures have been based on the definition of MSK intensity scale (see IS:1893, 1984), and the values have been slightly increased to account for very large number of poor quality and old concrete structures in the city. The intensity index for the masonry buildings (both engineered as well as non-engineered) is also based on the definition of MSK intensity scale. However, these values have been modified based on the damage surveys carried out by the senior author following the Killari and Jabalpur earthquakes, and also based on survey reports published after major earthquakes in other developing countries (for example, Sadek, 1997). Following the Killari and Jabalpur earthquakes, it was observed that both engineered as well as non-engineered masonry structures behaved in similar manner. This was possibly due to poor design and prevalent construction quality of the masonry buildings. In view of this observation, the same damage intensity has been kept for both engineered and non-engineered buildings. The intensity index for non-engineered buildings is also based on the expected behaviour of these buildings as defined in the MSK intensity scale and the observations following the Killari and Jabalpur earthquakes. It is interesting to note that a much larger proportion of buildings, than that estimated using MSK intensity definition, were *damaged during the recent Izmit, Turkey, earthquake (Shah, 1999), clearly showing the impact of low* quality of engineering practice on structural vulnerability.

EARTHQUAKE RISK

The information on earthquake hazard and structural vulnerability has been combined to determine the risk to different building types. The procedure for determining the damage and casualty is schematically shown in Figure 2 (Murakami, 1992). Based on the damage index, the total numbers of buildings that may be damaged in Mumbai (based on 1991 census data) due to earthquakes of different maximum magnitude are given in Table 4. As can be seen, the number of buildings that may be damaged are extremely high and their repair and rehabilitation is likely to impose a heavy burden on the economy of our nation. It is interesting to note that over 100,000 houses experienced medium to severe damage in Los Angeles city alone due to Northridge earthquake (EERI, 1996). Since Mumbai is a much larger city and the building stock is of poorer quality, the expected damage is consequently much higher.

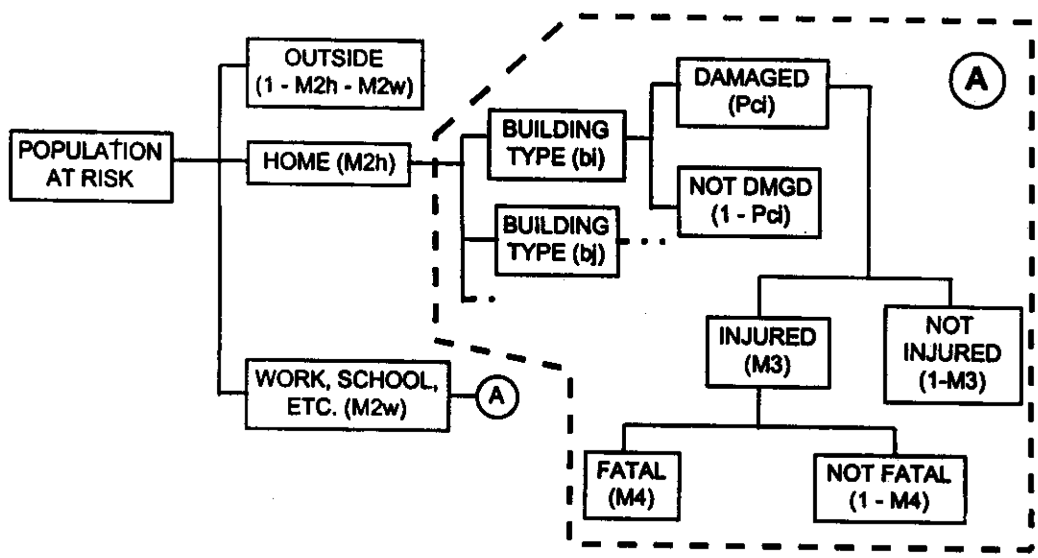

Fig. 2 Model for estimation of human casualty due to building damage and collapse (adapted from Murakami, 1992)

Table 4: Estimated Number of Buildings Damaged due to Earthquake in Mumbai

	MSK VI	MSK VII	MSK VIII
Reinforced Concrete Building	1,300	10,700	39,000
Engineered Masonry Building	34,700	134,500	325,500
Non-Engineered Masonry Building	31,100	120,500	291,600
Non-Engineered Constructions Using Other Materials	69,800	248,400	540,500

In order to assess the human casualty levels due to the earthquake, the estimates of average fatality and injury levels have been used. These figures have been derived by using a mortality prediction model for different categories of structures. This prediction model is based on investigation of casualty due to several major earthquakes that have occurred during this century (Coburn et al., 1992). The total number of people that may be killed due to damage of each building type can be represented by:

$$Ks_b = D_b \times [M1_b \times M2_b \times M3_b \times M4_b] \quad (1)$$

where D_b is the total number of damaged structures of building type b, $M1$ is the occupant density and $M2$ to $M4$ are conditional probability factors to modify the potential casualty figures. The factor $M1$ represents the population per building. For this investigation, $M1$ is taken as 5. $M2$ is the occupancy of buildings at the time of earthquake. The occupancy cycle proposed by Coburn and Spence (1992) has been presented in Figure 3 for residential and business structures. Depending on the time of the earthquake, the occupancy rate can been found from this figure. $M3$ is the proportion of occupants who are trapped by collapse of buildings. This depends on the type of building. For all types of non-engineered buildings, this has been taken to be 20%, for engineered masonry buildings 10% and for reinforced concrete buildings 5%. These figures are derived from typical observations from damaging earthquakes. $M4$ is the proportion of injured occupants who are killed in the earthquake. It has been observed that collapsed reinforced concrete buildings lead to death of a large number of trapped occupants, while collapsed non-engineered light-weight buildings lead to death of very small number of trapped occupants. Based on the quantitative information available from several earthquakes (Coburn et al., 1992), $M4$ is taken as 0.4 for reinforced concrete buildings, 0.2 for masonry buildings and 0.1 for informal non-engineered buildings.

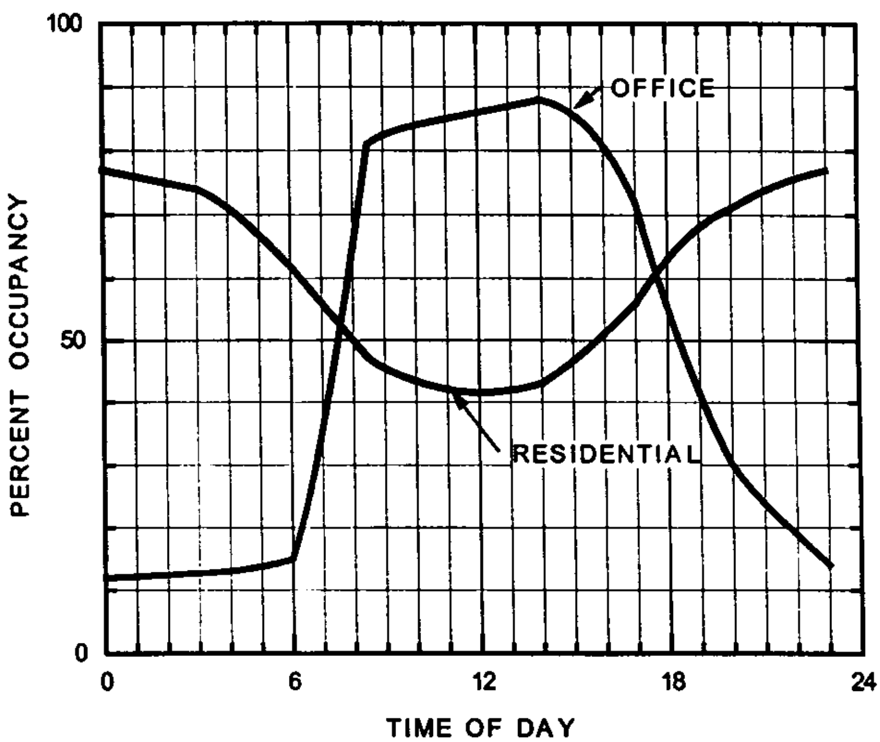

Fig. 3 Building occupancy at time of earthquake (Coburn et al., 1992)

The Mumbai census information, earthquake hazard and vulnerability data and the mortality information have been combined to estimate the number of possible injuries (Table 5) and the corresponding deaths (Table 6) that may occur due to earthquakes of different strengths. It should be noted that an investigation had been conducted by Arya (1992) to estimate the mortality due to a major earthquake in Himachal Pradesh. However, the predictions in that investigation were based on observations during earlier earthquake of similar magnitude in the same area. As a result, that approach can not be extended to other areas with insufficient earthquake information. The predictions in the current investigations are based on consistent mortality prediction models and can be applied to any area with sufficient hazard, vulnerability and demographic information.

Table 5: Estimated Number of Injuries due to Different Maximum Earthquake Intensities Occurring in Mumbai

Time	MSK VI	MSK VII	MSK VIII
Midnight	31,400	118,400	277,600
6 A.M.	25,000	94,600	222,100
12 Noon	18,800	71,000	166,500

Table 6: Estimated Number of Fatalities due to Different Maximum Earthquake Intensities Occurring in Mumbai

Time	MSK VI	MSK VII	MSK VIII
Midnight	11,200	42,600	100,100
6 A.M.	9,000	34,000	80,000
12 Noon	6,700	25,500	60,100

MITIGATION MEASURES

The extent of damage to structures and casualty level due to an earthquake in the future can be reduced by the introduction of suitable mitigation measures. These mitigation measures can be categorized as structural and/or non-structural. The structural measures are those that directly influence the performance of building stock through strengthening of code provisions and the prevalent construction practice. The vulnerability of any building type can be reduced by incorporating the appropriate structural mitigation measures. The non-structural mitigation measures include improvement in the state of preparedness before a disaster, and the infrastructure related to response following a disaster. The non-structural measures help to reduce the severity of casualty levels following an earthquake. In order to reduce the consequences of a major earthquake in Mumbai, it is necessary that appropriate structural as well as non-structural measures be undertaken. In this paper, the impact of structural measures on the future earthquake risk has been considered.

Only a small fraction of the total dwellings in Mumbai are made of reinforced concrete. Almost all such buildings have been designed and detailed using the prevalent design code for reinforced concrete structures (IS:456, 1978). This design code is primarily intended for safe design of reinforced concrete structures for typical static loads, and does not include any ductile detailing and other special earthquake-resistant provisions. As a result, these buildings may be vulnerable to sudden and catastrophic failure if the loads exceed the carrying capacity of some critical members. The structural measures that are required for improving the seismic performance of such buildings are: (1) ductile detailing of members, (2) design for strong column and weak beam frames, and (3) rigorous construction supervision and quality control to ensure compliance with the design specifications. These measures will improve the safety margins of the building, and will also ensure that the failure causes least casualty to the occupants. The vulnerability of new buildings after inclusion of the structural mitigation measures will be similar to that expected for buildings designed according to earthquake-resistant design codes (IS:13920, 1993). The damage intensity index for reinforced concrete structures with reduced vulnerability has been given in Table 7. As can be seen, the mitigation measures result in reduction of vulnerability by about 30%-40%. During the

Northridge earthquake, large difference in vulnerability between buildings that were compliant and non-compliant was also observed (Burby et al., 1998).

The vast majority of the buildings in Mumbai consist of engineered and non-engineered masonry buildings. Inspection of the typical construction practice in Mumbai has shown that essential earthquake-resistant features such as lintel-band are seldom used in these constructions. Based on the evaluation of performance of typical masonry buildings in Killari and Jabalpur earthquakes, the authors feel that the inclusion of lintel band is the most effective and the only practical mitigation measure. The presence of lintel band ties the peripheral walls of the building together and leads to considerable improvement in the building performance when subjected to ground motions. In fact, close to the epicentre of the Killari earthquake, the performance of building with lintel band has been found to be at par with that of reinforced concrete buildings without ductile detailing (Sinha and Goyal, 1994). Other commonly proposed measures such as reinforcement of masonry at corners and near the openings may pose practical difficulty in their implementation. Based on these considerations, the damage index for new masonry structures with lintel band has been taken to be the same as that of ordinary reinforced concrete buildings that was presented earlier in Table 2.

The buildings and other dwellings that are constructed from informal materials usually belong to the most economically disadvantaged people. All such constructions are unauthorised. Many such structures are constructed by the residents themselves due to economic reasons. Implementation of structural mitigation measures for these dwellings may be difficult due to their unauthorised nature and the extra financial resources required for these measures. In this investigation, it has been assumed that these structures will be excluded from the implementation of structural measures, and the likely effect of mitigation measures for these structures has not been included. The damage intensity index for these constructions is kept same as that given earlier.

The damage intensity index for different types of buildings after the mitigation measures have been implemented is given in Table 7. Same damage intensities have been taken for both engineered as well as non-engineered masonry constructions since both typically use similar construction techniques for the load-bearing walls.

Table 7: Proposed Damage Intensity Index for Different Building Types after Mitigation Measures are Implemented in Mumbai

	MSK V	MSK VI	MSK VII	MSK VIII
Reinforced Concrete Building	0.00	0.03	0.15	0.30
Engineered Masonry Building	0.00	0.05	0.25	0.50
Non-Engineered Masonry Building	0.00	0.05	0.25	0.50
Non-Engineered Constructions Using Other Materials	0.10	0.50	0.75	0.95

The introduction of structural mitigation measures will affect the new constructions that are designed and built in future. Due to economic reasons, it is unrealistic to expect that the existing building stock will be retrofitted to comply with the mitigation measures. In order to estimate the effect of an earthquake in future, it can be assumed that only 50% of the new-engineered structures shall comply with the mitigation measures. It is further assumed that 50% of the non-engineered masonry buildings shall also comply with the mitigation measures. The remaining reinforced concrete and masonry buildings and all non-engineered buildings using informal materials shall exhibit similar behaviour as the existing building stock.

EARTHQUAKE RISK AFTER MITIGATION

The population of Mumbai is expected to grow to approximately 12.9 million by the year 2011 (BMRDA, 1996) from the 9.9 million recorded in 1991. This increase of population by 3.0 million (i.e. by 30%) will be accommodated through the new constructions that are likely to be built. Past national studies have also found that about 1% of the building stock is lost every year. If this rate of building loss is also taken to be applicable to Mumbai, then about 20% of the building stock will be lost (and replaced) by the year 2011. This is in addition to the new constructions likely to be built in order to accommodate the increasing population. By combining the rate of increase in demand for housing stock with the annual renewal rate, it can be seen that by the year 2011, the city will have approximately 50% new constructions (built since 1991) when compared with the total housing stock in 1991.

The morbidity model presented earlier has been used to estimate the casualty figures for a damaging earthquake in 2011 (Tables 8 and 9). The casualty levels have been estimated both when the mitigation measures discussed above have been implemented and when no structural measures have been implemented (i.e., status quo in construction practice is maintained). It can readily be seen that the implementation of mitigation measures results in a significant reduction in the number of injuries and fatalities. There is a similar decrease in the extent of building damage.

Table 8: Estimated Number of Injuries due to Different Maximum Earthquake Intensities Occurring in Mumbai in 2011

	Mitigation					
Time	Yes	No	Yes	No	Yes	No
	MSK VI		MSK VII		MSK VIII	
Midnight	36,500	40,800	139,700	153,900	333,600	361,000
6 A.M.	29,200	32,600	111,800	123,100	266,900	288,700
12 Noon	21,900	24,500	83,800	92,300	200,200	216,500

Table 9: Estimated Number of Fatalities due to Different Maximum Earthquake Intensities Occurring in Mumbai in 2011

	Mitigation					
Time	Yes	No	Yes	No	Yes	No
	MSK VI		MSK VII		MSK VIII	
Midnight	13,200	14,700	50,700	55,500	121,100	130,400
6 A.M.	10,600	11,700	40,600	44,300	96,900	104,300
12 Noon	7,900	8,800	30,400	33,300	72,700	78,200

CONCLUSIONS

In this paper, a method for determination of earthquake risk to Mumbai has been presented. This method requires information on the seismicity of the region and detailed information of the city population and building stock. In case where the seismicity information is not available, approximate estimates based on the seismic zoning map given in IS:1893 can be used. The vulnerability of the building stock is determined based on observed damage of similar constructions due to past earthquakes in other developing countries and the senior investigator's assessment of the performance of structural systems during the Killari and Jabalpur earthquakes. The procedure developed in this investigation can be readily applied to any urban region of our country in order to assess the necessity of more detailed investigation of earthquake risk. The information can also be used for planning disaster mitigation measures based on realistic estimate of damage potential due to the postulated earthquakes.

In the analysis presented herein, the demographic and census information have been used to estimate the existing building stock and to determine the likely level of damage to the building stock. For this analysis, the effect of earthquake on the large number of very old buildings in Mumbai has also been implicitly included. The analysis procedure has also been combined with a mortality prediction model to estimate the level of human casualty due to earthquakes of different magnitudes.

The analysis has been further extended to investigate the impact of mitigation measures on the consequences of an earthquake. Only the impact of structural mitigation measures, in which the design and construction procedures are improved to make the buildings less vulnerable, have been considered. The analysis has considered the possibility of improper compliance with the mitigation measures, and only 50% of the dwellings constructed after 1991 have been assumed to satisfy the mitigation measures. Based on this analysis, the probable casualty levels have been estimated. The corresponding casualty levels if no mitigation measures have been implemented has also been evaluated, in order the estimate the impact of the mitigation measures.

The following conclusions can be drawn from this investigation:

1. The occurrence of code-level earthquake (MSK Intensity VII) at Mumbai may lead to massive loss of life and damage of buildings. Depending on the time of the day, between 25000 to 42000 people may perish due to structural collapse and damage in the earthquake. The numbers of serious injuries may also range between 71,000 to 1,18,000, possibly placing a very severe strain on the emergency relief and health-care infrastructure. Similarly, a very large number of buildings (in millions) may be damaged or lost. The likely impact of an earthquake more severe and less severe than the code-level earthquake has also been presented. These give the likely range of human casualty due to earthquakes of different strengths.
2. The results from seismic risk assessment provide the necessary information that is required to develop realistic mitigation policies. The risk assessment results can help the state and city administrations in developing appropriate earthquake disaster management policy for Mumbai. This analysis also clearly demonstrates the need for further investigations so that quantitative tools similar to HAZUS97 can be developed for Mumbai and other Indian cities.
3. There is a need to realise the consequences of inappropriate choice of construction materials and technology. Structural systems that comply with the appropriate codal provisions are found to behave much better during earthquakes than deficient structural systems. There is an urgent need to encourage earthquake-resistant constructions in order to reduce the devastating consequences. This should form the basis of developing any earthquake mitigation strategy.
4. The impact of implementation of structural mitigation measures has been considered in order to estimate the consequence of an earthquake in 2011. It is found that if mitigation measures are implemented in half of all the engineered buildings and in half of the masonry non-engineered buildings that are built after 1991, it will lead to over 10% reduction in the casualty levels. Obviously, if the structural mitigation measures are implemented more effectively than that assumed in this analysis, the losses in future earthquake will be further reduced.
5. In these investigations, it has been assumed that mitigation measures are not implemented in buildings made from informal materials. This assumption has been made due to the observed weakness of typical constructions of this type. Since almost one-third of all dwellings in Mumbai are from this category, it is essential that the number of such dwellings be brought down through appropriate long-term planning and development control policies. This measure will also increase the proportion of building stock with earthquake mitigation measure, leading to further lowering of the expected casualty level.
6. This investigation clearly shows that implementation of structural mitigation measures is not sufficient to drastically reduce the extent of human casualty due to earthquakes of different magnitudes. This is mainly due to the expected poor performance of existing building stock that shall last for several more decades. In order to reduce the impact of an earthquake, it is therefore essential that suitable non-structural measures also be implemented to complement the structural measures.
7. There is a need to take up development of similar earthquake damage scenario on other large cities in order to determine the necessity of developing appropriate earthquake mitigation strategy.

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