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GIS-BASED URBAN SEISMIC RISK ASSESSMENT USING RISK.IITB

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ABSTRACT

The earthquake risk or damage potential of an area is due to a combination of seismic hazard, and vulnerability of the built environment and its exposure. The damage during recent earthquakes worldwide has demonstrated the need for seismic risk assessment for disaster management applications. It is also often observed that the complex risk assessment carried out in the scientific domain does not easily provide information and data amenable to policy making or for disseminating seismic risk to the public. In this paper, a newly developed GIS-based system for seismic risk assessment, namely RISK.iitb, has been described. RISK.iitb quantifies seismic hazard, structural vulnerability, and exposure and loss estimation. This system considers the requirements of disaster management community, and results can be easily understood by the various stakeholders while maintaining scientific rigour. An example analysis has been performed for the Mumbai municipal region to illustrate the uses of RISK.iitb.

KEYWORDS: Disaster Management, Seismic Hazard, Vulnerability, Economic Loss, Mumbai Scenario

INTRODUCTION

The past few decades have witnessed an increase in the number of damaging earthquakes in India, with nine damaging earthquakes occurring during the last two decades itself. The vast extent of damage and the consequent loss of life associated with these events reflect the poor construction practices in India. Before the 2001 Bhuj earthquake, constructions with poor seismic resistance were assumed to be a feature of non-urban areas, with urban structures considered safer due to the use of engineering knowledge and modern construction materials. However, this earthquake shattered the myth of urban seismic safety through widespread damage to modern buildings. The low awareness among the general public towards structural safety and the inability of regulatory bodies and technical professions in maintaining quality standards in constructions has created an urgent need to educate the leaders, public, city planners, architects, and the engineering professionals about the consequences of earthquakes. Advocacy of the importance of seismic safety requires understanding of seismic risk and the adverse consequences of earthquakes by all the stakeholders. This issue assumes particular importance due to the long return period of damaging earthquakes in India, resulting in diminishing public memory of earthquake disasters with time. Recent earthquakes, such as the 2001 Bhuj earthquake that had followed the damaging Anjar earthquake in 1957 in the same area, have shown that the vulnerability of the constructions did not get reduced despite the experiences of the 1957 earthquake. As a result, the same tragic lessons had to be re-learnt in 2001 as during 1957 (Sinha et al., 2001).

The evaluation of consequences of earthquakes using a rigorous scientific approach does not automatically provide useful data for advocacy, policy-making, or for implementation of the earthquake risk management initiatives. These results must be interpreted in a manner that makes the various non-expert stakeholders understand the factors contributing to the damage and losses due to earthquake and their influence on the affected area. One approach that has been successfully used in the recent past is based on developing earthquake scenarios in which losses and other consequences are estimated due to different potential earthquakes. In this the results are presented in the form of charts and colour coded maps, which can be easily understood by the various stakeholders in disaster management without requiring them to understand the intricacies of the mathematical modelling and other scientific details. Some recent scenario studies that have been found useful for advocacy and policy-making include RMS (1995), Chen et al. (1997), and Erdik et al. (2005).

Scientifically realistic earthquake damage scenarios, if available for India, can be invaluable for the advocacy of seismic safety and for disaster management. The disaster scenario information can be used to sensitize various stakeholders regarding the risk and potential consequences of earthquakes. The information can thus overcome some of the limitations due to the absence of earthquake disaster memory in the society. The disaster scenario can also help in identifying the most vulnerable areas and population groups that will require the most assistance in the aftermath of a damaging earthquake. The pros and cons of various disaster management interventions can also be evaluated using earthquake disaster scenario tools by simulating the effectiveness of these measures in reducing the losses over time. The use of disaster scenarios is very useful for both urban and rural areas. Their use for effective disaster management planning is essential in urban areas because of the intense concentration of people, infrastructure, and resources that may be affected by a damaging earthquake. As a result, disaster management plans that are prepared without carrying out rigorous risk assessment and scenario development, such as those described herein, are unable to take advantage of this information for optimal prioritization of resources and for monitoring long-term reduction of risk.

Several methodologies have been developed to estimate the consequences of scenario earthquakes. These methodologies can be probabilistic, wherein the probability of exceeding different levels of losses with corresponding uncertainties are evaluated, or deterministic wherein the losses due to a given scenario earthquake are estimated. The loss estimation can include the extent of damage to the buildings, the number of people injured, the number of fatalities, and the economic losses occurring in the region under study. The probabilistic assessment is often used by insurance companies to manage their risk portfolio. However, the probabilistic assessment does not easily provide information and data useful for policy making or for public advocacy. Recent publications also indicate that deterministic scenario-based assessment can provide a suitable basis for carrying out probabilistic risk assessment (Klügel et al., 2006). Hence, in this study only the deterministic analysis procedure has been considered whose results are realistic and easier to understand by the non-technical stakeholders.

Various efforts have been globally made to develop software systems that quantify the losses caused due to natural hazards like earthquakes, hurricanes, floods, etc. The most well known tools for the estimation of losses associated with earthquakes include HAZUS (NIBS, 1999), RADIUS (IDNDRS, 1999), HAZ-Taiwan (Yeh et al., 2006), and RISK-UE (Spence and Le Brun, 2006).

HAZUS is a tool that can be used for earthquake-related mitigation, emergency preparedness, response and recovery planning, and disaster response operations. It has been implemented on GIS platforms such as Arc View and MapInfo. It provides the user ability to perform different levels of analysis, ranging from estimates based on simplified models using default inventory to very refined studies based on detailed engineering and geotechnical data for a specific study region. Its methodology is comprehensive, and it generates maps and calculates losses with different probabilities. Various US agencies use HAZUS for earthquake risk management. The HAZUS approach has been used for HAZ-Taiwan and RISK-UE projects with modifications based on local hazard and vulnerability in Taiwan and Europe, respectively.

RADIUS is a risk assessment tool, which has been implemented in MS-Excel software. The user selects rectangular meshes, which roughly represent the area under study. Properties are assigned to each mesh, and the tool estimates the losses due to a scenario earthquake using factors, the default values of which are provided in the tool. The user has the freedom to change the values of these factors as per the area under study. However, the tool gives very approximate estimates for losses, and the results are also not properly displayed. RADIUS has been widely used for simulation training of engineers, architects and public officials, particularly in developing countries, since it is freely available and requires minimal computing resources.

Even though the software tools such as HAZUS give very detailed results, those are not suitable for loss estimation simulations from earthquakes in India because the hazard and vulnerability assessment in HAZUS has been carried out using the data applicable for USA, Taiwan, and Europe. Further, the financial models for determining the damage to social and economic losses are not applicable to India. Another problem with the HAZUS method is that it requires extensive urban data regarding buildings, population, and economic activities that are typically not available in India. On the other hand, even though the method is simple requiring limited inputs, RADIUS does not have advanced processing capabilities and only gives approximate loss estimates. Earthquake risk assessment tools that consider the special requirements of India and other similar developing countries are not available in the public domain.

The authors have recently developed a seismic risk assessment system known as RISK.iitb at the Indian Institute of Technology Bombay (Gupta and Sinha, 2006; Aditya and Sinha, 2006). This risk assessment system uses Geographical Information System (GIS) kernel and is amenable to convenient graphical inputs and outputs. The physical inventory data for carrying out risk assessment can be specified for each structure as individual objects or grid-wise inventory after dividing the entire study area into small-square grids. The simulation capabilities where each structure is considered as a separate object is not very useful for policy-making and public advocacy due to its excessive detail. In this paper, the methodology for seismic risk assessment and loss estimation in RISK.iitb for grid-wise simulation, which is more useful for policy-making, public policy and disaster management applications, is described. Various options for specification of inputs are also described. The procedure for estimation of injuries, deaths, and economic losses is also briefly presented. It may be noted that RISK.iitb is undergoing constant enhancement, and additional mathematical models for hazard, vulnerability, and losses are being implemented. The main aim of this paper is to illustrate the importance of disaster scenario studies using GIS platform for advocacy and policy-making and for the preparation of disaster management plans.

RISK.iitb has been used for carrying out seismic risk assessment of an urban area for a scenario earthquake. The city of Mumbai has been selected for the example assessment and to illustrate the features of the risk assessment system. The results have been presented in tables and easy-to-understand figures to demonstrate the effectiveness of using RISK.iitb for advocacy and to communicate with decision-makers and other non-technical stakeholders. The results presented here are in form of a postulated scenario for a given earthquake on the basis of available data, which can be improved further by using RISK.iitb based on more detailed inputs as and when those become available.

METHODOLOGY FOR SEISMIC RISK ASSESSMENT

The assessment of seismic risk involves the estimation of consequences of an earthquake in the chosen area in terms of the expected damage and loss from a given hazard to a given element at risk. For deterministic risk assessment, the estimation is typically carried out for a hazard event, such as an earthquake of a particular magnitude at a specified location. For probabilistic risk assessment, the consequences can be assessed over a specified period in future (Bendimerad, 2001). The risk assessment involves evaluation of seismic hazard, vulnerability of structures, exposure, and finally loss estimation. Thus, the total risk can be expressed simply in the following pseudo-mathematical form:

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \times \text{Exposure} \tag{1}$$

The methodology has been outlined in Figure 1. Various components used in risk assessment in RISK.iitb have been explained below.

1. Seismic Hazard

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 is evaluated at the centre of each grid. The ground-motion parameters in deterministic assessment are estimated for the specified earthquake event that is assumed to occur at the specified location and depth. The computation of seismic hazard requires the following inputs (Gupta and Sinha, 2006):

i) Source characterization, which includes (a) point source model—epicentre and hypocentral depth, or (b) line source model—epicentre, fault orientation (or bearing), and type of fault. For strike-slip fault, the fault rupture model based on Wells and Coppersmith (1994) has been implemented.

ii) Attenuation relationships that define how ground motions decrease as a function of distance. The following attenuation relationships that have been found to be suitable for Deccan and peninsular India have been implemented in RISK.iitb:

   a) The relationship by Iyengar and Raghukanth (2004) for PGA in terms of acceleration due to gravity is given by

$$\ln \text{PGA} = 1.6858 + 0.9241 \times (M-6) - 0.076 \times (M-6)^2 - \ln R - 0.0057R + \ln \varepsilon \tag{2}$$

where $\ln \varepsilon$ is the error in the estimation of ln PGA, whose standard deviation is given as $\sigma(\ln \varepsilon) = 0.468$; R is the hypocentral distance; and M is the moment magnitude. The above attenuation relationship is valid for hard rock exposed on the surface, with shear wave velocity V_s exceeding 3.6 km/s.

b) The relationship by Atkinson and Boore (1995) for PGA in terms of cm/s^2 is given by

$$\ln \mathrm{PGA} = 3.79 + 0.298 \times (M-6) - 0.0536 \times (M-6)^2 - \ln R - 0.00135R + \ln \varepsilon \tag{3}$$

where $\ln \varepsilon$ is the error in the estimation of ln PGA, whose standard deviation is given as $\sigma(\ln \varepsilon) = 0.250$; R is the hypocentral distance; and M is the moment magnitude. The relationship is derived from an empirically based stochastic ground motion model. The expression is valid for hard rock sites with shear wave velocity V_s exceeding 3.8 km/s.

c) The relationship by Toro et al. (1997) for PGA in terms of acceleration due to gravity is given by

$$\ln \mathrm{PGA} = 2.20 + 0.81 \times (M-6) - 1.27 \times \ln R + 0.11 \times \max[\ln(R/100), 0] - 0.0021R \tag{4}$$

where R is the source-to-site distance, i.e., $R = \sqrt{R_{jb}^2 + C_7^2}$, with R_{jb} taken as the closest horizontal distance to the earthquake rupture in kilometres, and C_7 = 9.3, while M is the moment magnitude. This expression is valid for hard rock sites with shear wave velocity V_s exceeding 1.8 km/s at the surface.

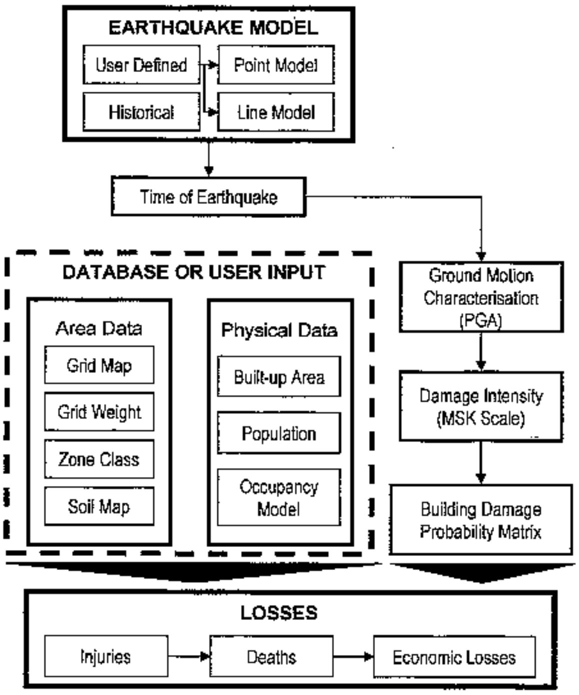

Fig. 1 Methodology for loss estimation using grid-wise assessment in RISK.iitb

iii) Site characteristics, which include soil, sediments, and weathered rock affecting the ground shaking experienced during an earthquake. Amplification factors are usually proposed with each attenuation relationship; those modify the ground motion parameter appropriately to include the site effects. Mathematical relationships for the amplification have not been implemented in this version of RISK.iitb so far, and the amplification factors can be specified by the user for each soil type, if required, using the interactive input option of the software tool.

The uncertainties associated with each of the above factors may be quantified. However, this has not been taken into account in the present implementation of RISK.iitb, since it is based on deterministic risk assessment. The hazard assessment thus determines the median peak ground acceleration based on the selected earthquake attenuation model.

2. Damage Intensity

The intensity of an earthquake at a place is a measure of the destructive effects of the earthquake on buildings and other structures at that place. Several attempts have been made to correlate earthquake intensity (on intensity scale) to specific physical parameters of ground motion, especially peak ground acceleration (PGA). 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:

$$I_{mm} = 2.20 \log(\mathrm{PGA}) + 1.00 \tag{5}$$

The Indian Standard code (BIS, 2002) specifies damage intensity in terms of the MSK intensity scale, and not the Modified Mercalli Intensity (MMI) 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 intensity levels IV and IX). Since MMI and MSK levels are quite similar in definition and range of expected structural response at each level on considering the uncertainty in assigning damage levels based on visual observation of structural behaviour, MMI values are assumed to be equal 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, data on structural vulnerability, etc. The authors also intend to implement local-damage-intensity-to-PGA relationships, as and when those become available, which can improve the intensity assessment and consequently loss estimation in RISK.iitb by incorporating the local data that considers the effect of parameters, such as ground motion duration, frequency content, etc.

3. Seismic Vulnerability

Seismic vulnerability quantifies the propensity of a building or a type of buildings to be damaged during 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 level of damage corresponding to ground motion intensity as a conditional probability factor.

Different buildings vary in their degree of vulnerability as a function of geometrical or qualitative characteristics (such as height, plan dimensions, elevation configurations, age, etc.), and structural characteristics (such as mass, stiffness, quality of construction, strength, intrinsic ductility, state of stress, seismic displacements, non-linear behaviour parameters, and other structural information). Hence, there is a need to classify the structures by their types and uses. In the present study, the types of buildings have been defined on the basis of the material used for construction and are (1) reinforced concrete, (2) steel, (3) masonry, and (4) non-engineered buildings. Each building type is further classified based on whether the building has been designed as per the code, i.e., complying with the earthquake-resistant provisions or without complying with the code provisions. In the present study, five damage states have been defined based on BIS (2002), Sinha and Adarsh (1999), and Musson (2000). Each damage state has been assigned a mean damage probability, indicating the mean loss, corresponding to different earthquake intensities. 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. By using appropriate loss functions one can assess the potential damage loss suffered by a grid for a given scenario earthquake. 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 Figure 2.

When using grid-wise simulation, where the region under study is divided into small-square grids, each grid may contain several buildings of different building types. Therefore, the total built area of all buildings of a specified building type in a grid is considered in this study. The vulnerability of a building type is quantified by assigning a damage state based on the MSK intensity at the centroid of the grid.

4. Exposure

Exposure includes property, i.e., the inventory (structural and non-structural) value of the buildings and building contents, and the human population at risk, of being exposed to the damaging earthquake.

The assessment of the consequences of an earthquake on exposure requires the assessment on each component separately as described below.

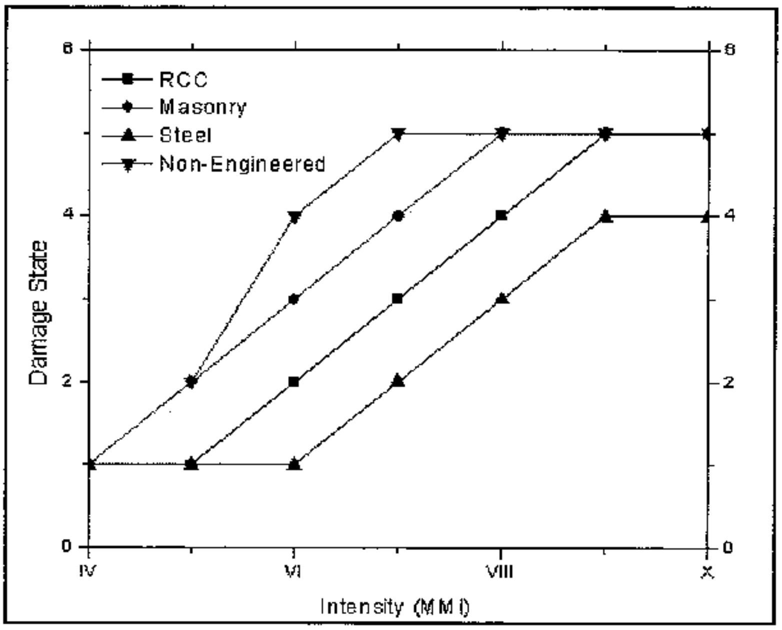

Fig. 2 Vulnerability curves for different building types (Sinha and Adarsh, 1999)

4.1 Population Analysis

A population analysis evaluates the total population of the region exposed to the earthquakes and distributes it to different building types. This evaluation is carried out grid-wise. 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 grid (see Table 1). 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. This model is based on the data obtained from developed countries. However, it may be noted that the range of commercial activities in Mumbai closely resembles that in major cities of developed countries in terms of typical office timings, presence of operations on 24×7 basis, and typical commuting time. Based on these considerations, and in view of the absence of temporal occupancy models based on Indian data, the temporal occupancy model by Coburn and Spence (2002) has been implemented in RISK.iitb.

The total population in all buildings of a given occupancy type is given by the following relationship:

$$\text{PO} = F \times \text{Total Population} \tag{6}$$

where F is the percentage of population residing in a given occupancy type at a particular time. This is specified in Gupta (2006) for the night population and is obtained from Table 1 for the floating population.

Table 1: Distribution of Floating Population in Different Building Types (Gupta, 2006)

Building Type	Population (%)
Residential	0
Commercial	90
Industrial	5
Non-engineered (and mixed occupancy)	5

4.2 Property Analysis

The property analysis in each grid refers to the evaluation of structural and non-structural components and the contents of all 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 occupancy classes included in the system are (a) residential, (b) commercial, and (c) industrial (Gupta, 2006).

5. 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.

5.1 Social Losses

This process involves the estimation of number of people likely to be injured at different severity levels. This evaluation considers the population in each building of the grid at the time of the earthquake, its model building type, the earthquake intensity, and is obtained using the casualty model. Since building-wise information is not available, the evaluation is carried out for the sum of all buildings of each building type in a grid. The computation uses a series of partial probability factors that are applied to each building or area with buildings. For a particular model building type, the number of injuries at a particular severity level can be expressed as (Coburn and Spence, 2002)

$$K_s = C \times (M1 \times M2 \times M3 \times M4) \tag{7}$$

where C is the percentage of buildings of that type and damaged due to the scenario earthquake. This is obtained from the mean damage factor corresponding to the intensity of damage suffered by the buildings, as explained earlier. The factor $M1$ is the probability of occupancy of the building type, or its occupancy rate, $M2$ is the probability of occupancy at the time of earthquake, or its occupancy factor, $M3$ represents the probability of occupants trapped or otherwise injured in the building, or injury rate, while the factor $M4$ represents the probability of the injuries being fatal, or the fatality rate. The social loss conditional probability factors, $M3$ and $M4$, have been taken from Coburn and Spence (2002), who determined these factors considering a large number of earthquakes from both developing and developed countries. Since India-specific factors are not available to assess the "lethality" of the collapse mechanisms of typical constructions, the use of these factors for $M3$ and $M4$ is considered as a reasonable approximation. It may also be noted that the poor quality of typical construction practices in the urban areas of India is reflected through the Damage Probability Matrix of each construction type and does not require further modification in $M3$ and $M4$. The injury factors are given in Figure 3, and the fatality factor is given in Table 2.

5.2 Economic Losses

Economic losses are estimated by taking into account five types of losses, which include structural building loss (i.e., loss due to structural damage), non-structural building loss (i.e., loss due to non-structural damage), building content loss, loss due to injuries, and loss due to deaths. Those depend on various model building types, occupancy classes, and extent of damage to buildings in the affected grids. The damage factors for structural and non-structural components and contents are given in Figures 4 and 5.

The loss to structural, non-structural, or content value is evaluated using the following equation:

$$\text{Loss}_i = \sum_{j=1}^{5} C_{ij} \times V_j \tag{8}$$

where, Loss_i is the loss to the parameter *i*, viz., structural, non-structural, or content value; C_{ij} is the mean damage ratio of the *i*th parameter due to the *j*th damage state or mean damage ratio; and V_j is the total worth of the structural, non-structural, or content value of the buildings of the same building type in a grid. The worth of structural/non-structural/content value of the buildings has been modelled depending on the size of the building and its occupancy type (Gupta, 2006) and is given in Tables 3 and 4.

The losses due to human injuries or fatalities are evaluated in Rupees per person for each injury category, or for death as per the compensation policy of Government of India (Aditya, 2007).

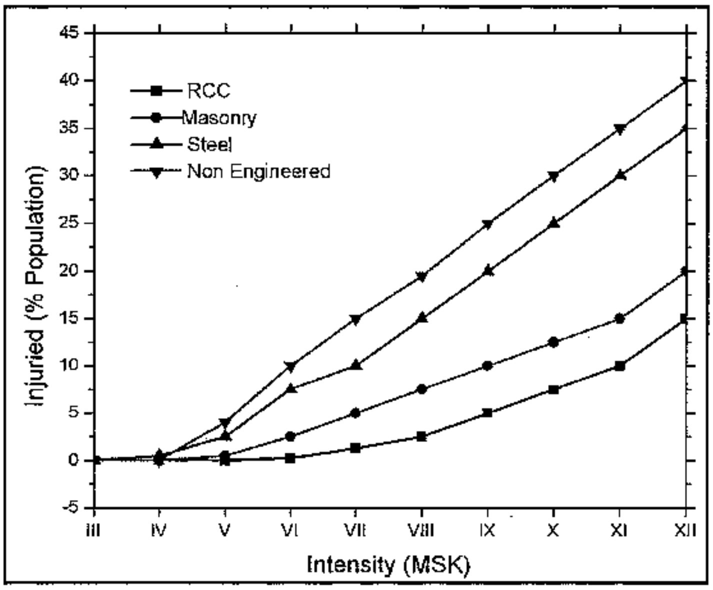

Fig. 3 Percentage of population likely to be injured during different earthquake intensities (Gupta, 2006)

Table 2: Fatalities as a Percentage of Injuries in Different Building Types

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

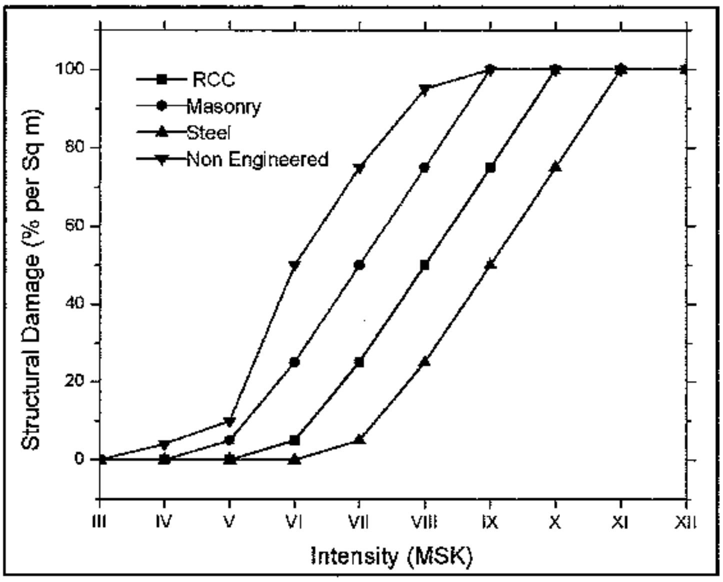

Fig. 4 Extent of likely structural damage during different earthquake intensities (Gupta, 2006)

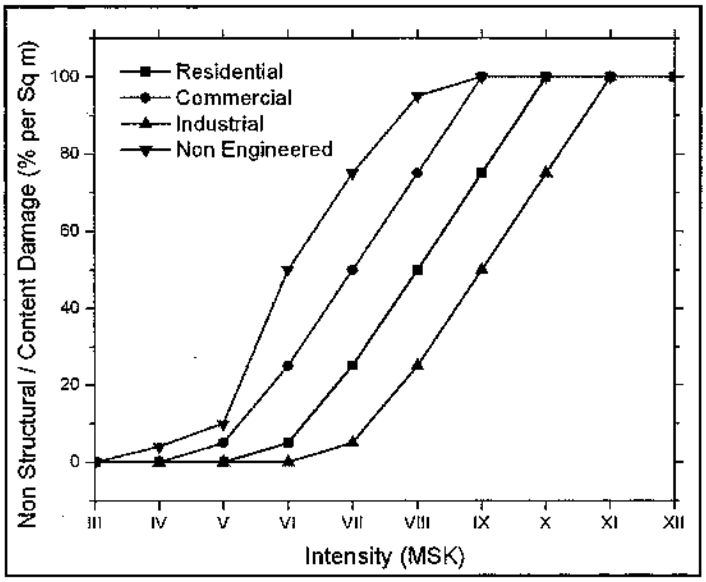

Fig. 5 Extent of likely non-structural and content damage during different earthquake intensities (Gupta, 2006)

Table 3: Structural Worth of a Building in Terms of Replacement Cost of the Built-up Area

Building Type	Structural Worth per m^2 (Rs.)
RCC	1000
Masonry	600
Steel	1000
Non-engineered	300

Table 4: Non-structural and Content Worth of a Building in Terms of Replacement Cost of Built-up Area Considered for the Example Simulation

Occupancy Category	Non-structural Worth per m^2 (Rs.)	Content Worth per m^2 (Rs.)
Residential	1000	150
Commercial	3000	500
Industrial	5000	1000
Non-engineered	1000	150

IMPLEMENTATION ON GIS PLATFORM

The methodology outlined above has been implemented in RISK.iitb on a GIS platform. Due to the immense flexibility in its use, and considering the multi-sectoral requirement of GIS platform for urban governance by municipal authorities, ArcGIS has been used as the GIS platform for implementation (ESRI Developer Network[1], accessed on November 10, 2005). RISK.iitb has been developed using VBA as the programming environment. The software performs various calculations as indicated earlier in the methodology. Since a large number of data values are required for various calculations, the data is stored in database files in .dbf format. The software also allows interactive modifications to the data during risk evaluations. The results for the risk assessment are presented in maps as well as in a table, indicating the total losses under the given scenario earthquake.

When the software is executed, the master user interface is presented to the user as shown in Figure 6. The interface consists of several command buttons which, when clicked, perform the calculations of

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[1] Website of ESRI Developer Network, http://edn.esri.com

different steps of the methodology. The following steps describe the procedures for carrying out the risk assessment.

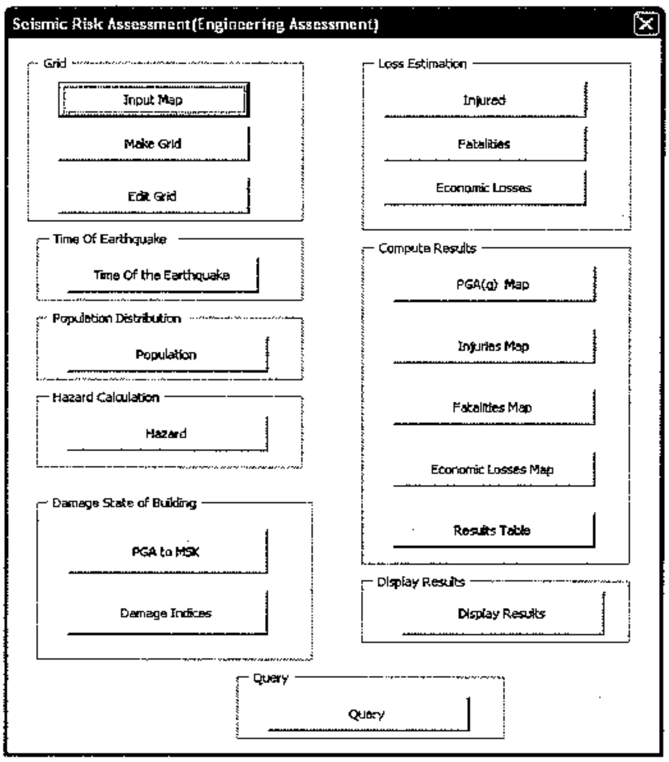

Fig. 6 User interface for starting seismic risk assessment using RISK.iitb

1. Basic Inputs and Evaluation Details

The first step is to input the data required to perform the risk assessment of the area under study. This information can be collected from the target area or city for the earthquake scenario simulation. Following steps are performed for the seismic risk assessment using RISK.iitb:

a) Input a geo-referenced image of the area under study. The map may be a scanned map of the urban area under study in case grid-wise assessment is to be carried out. If the same is already available as a GIS map, it can also be used after converting to a geo-referenced image format. GIS maps in ArcGIS compatible file format can be directly read by the software. RISK.iitb uses the geo-referenced image to create a layer of grids, of the grid-size specified by the user, to overlay the map.
b) Edit the grid map, to exclude the grids that do not lie within the urban area under study.
c) Input the grid weight for each grid. The available grid-weight classifications are given in Table 5. For each grid, the weight chosen depends on the land area in that grid. For grids that include major water bodies, the grid weight is suitably reduced.
d) Input soil type information for each grid.
e) Specify zone classification and population weight for each grid. The various occupancy classes have been described earlier. The default values are given in Tables 6 and 7.
f) Specify the proportion of total built-up area in each grid that belongs to different building types and occupancy classes. The buildings are classified into four model building types and three occupancy types in the example study presented herein. However, the tool has the ability to accommodate fifteen model building types and fifteen occupancy classes. The use of additional building types requires the user to update the database files accordingly.
g) If the basic data described above is available from other studies or previous simulations, then that database file may be optionally provided wherein the grid data in the area under study can be directly added to the attribute table of the grid map. Steps b–f are not required under this situation.
h) Input the total built-up area of the buildings in the area under study. This is the total area of all the buildings of each type, and is distributed grid-wise based on the zone classification and population weight.
i) Specify the time at which the scenario earthquake takes place.

j) Input the total population (i.e., night and floating population) of the region under study. Alternately, the base population can be specified and occupancy estimated as described earlier.

All these inputs are required during the different stages of seismic risk assessment. It may be noted that most of the basic geographical and physical data would also be required for the assessment of risk to other hazards, and RISK.iitb has been developed considering the possibility of extending it to other hazards in a seamless manner.

Table 5: Grid Weight Classification for the Computation of Land Area

Area Class	Grid Weight
Class 1	0.01
Class 2	0.1
Class 3	0.25
Class 4	0.5
Class 5	1

Table 6: Zone Classification Based on the Usage of Constructed Area

	Residential (%)	Commercial (%)	Industrial (%)
Zone 1	5	15	80
Zone 2	45	45	10
Zone 3	45	45	10

Table 7: Population Weight of Each Zone Based on the Land Usage

	Population Weight
Zone 1	1
Zone 2	1
Zone 3 (No-Development Zone)	0.01

2. Seismic Hazard

RISK.iitb allows the user to define a deterministic scenario event. Following two methods are available to estimate the peak ground acceleration (PGA):

i) The predefined earthquake option gives the user the option of selecting a historical earthquake and an attenuation relationship. The software tool allows the user to choose from a few major earthquakes, which had occurred in peninsular India in the past.

ii) The user-defined earthquake option asks the user to define the parameters for the scenario earthquake, like latitude and longitude of the epicentre of the earthquake, moment magnitude of the earthquake, and the hypocentral depth of the earthquake, and to select an appropriate attenuation relationship. An alternative option for the specification of earthquake on the basis of epicentre, orientation of fault plane, and rupture length is also available.

The GIS platform allows direct calculation of the source-site distance from the grid map, for use in the attenuation relationships. The PGA is calculated at the centroid of each square representing a grid.

If soil map is present or soil data is defined, the PGA at each centroidal point is modified to take into account the amplification due to soil characteristics at the site.

These inputs are used to evaluate the PGA at the centroid of each grid. These results are saved in the attribute table in the database in .dbf format.

3. Earthquake Intensity and Damage Levels

Based on the PGA, the damage intensity for different types of building is determined for each grid. The damage probability matrix (DPM) that specifies the relationship between damage intensity, seismic hazard, MSK, and damage levels, is based on the Indian data from Sinha and Adarsh (1999) and Gupta (2006) and is shown in Figure 2. These values can be interactively modified by the user, if required, to account for any special characteristics of the area under study or other special simulation requirement.

In order to evaluate losses, population distribution in different building types in each grid is required. RISK.iitb provides the user with two options for distributing the total population to each grid depending on the zone class and grid weight. This step evaluates the number of people in each building at the time of earthquake and adds it to the attribute table of the building map. Several factors that are needed for the population distribution are kept in the database files. These values can be interactively modified by the user to account for any special characteristics of the area under study or other special simulation requirements.

Following calculations are made during the evaluation. Built-up area of a grid, AG, is calculated as

$$\mathrm{AG} = \frac{A}{N} \times \mathrm{GW} \times \mathrm{ZP} \tag{9}$$

where, A is the total built-up area; N is the total number of grids; GW is the grid weight (see Table 5); and ZP is the zone population weight (see Table 7). For each occupancy type in a grid, the built-up area AGO is determined from the following expression:

$$\mathrm{AGO} = \mathrm{AG} \times \mathrm{ZOP} \tag{10}$$

where ZOP is the percentage of a specified occupancy class in a zone (see Table 6). The total built-up area for each occupancy class, AO, is then determined from all grids as

$$\mathrm{AO} = \sum^{\text{All Grids}} \mathrm{AGO} \tag{11}$$

It may be noted that Zone 3 has a ZP of 0.01, because of which the total built-up area will be reduced. The difference is added to Zone 2 equally among all the grids.

The population per occupancy class, PGO, is estimated for each grid as

$$\mathrm{PGO} = \frac{\mathrm{PO} \times \mathrm{AGO}}{\mathrm{AO}} \tag{12}$$

It may be noted that buildings of different construction types can have the same occupancy class (see Table 8). The population in every occupancy type is distributed among different construction types. The summation of this population over all occupancies gives the total population in a construction type in a grid as

$$\mathrm{AGB} = \sum^{\text{All Occupancies}} \mathrm{AGO} \times \mathrm{FB} \tag{13}$$

$$\mathrm{PGB} = \sum^{\text{All Occupancies}} \mathrm{PGO} \times \mathrm{FB} \tag{14}$$

where, AGB is the built-up area of each building type in a grid; PGB is the population of each building type in a grid; and FB is the percentage building type in a given occupancy class and is obtained from Table 8.

Table 8: Distribution of Building Types for Each Occupancy Class

	RCC (%)	Masonry (%)	Steel (%)	Non-engineered (%)
Residential	80	10	9	1
Commercial	80	10	9	1
Industrial	80	10	9	1

4. Loss Estimation

In this step, the number of people injured and the number of fatalities are evaluated, and this data is added as new fields to the attribute table of the grid map. For estimating the economic losses, the software evaluates the cost of structural components, non-structural components, and the cost of contents of each grid. The data values, which give cost per unit area of each component and contents, are stored in the database files. Using the cost of structural, non-structural components, contents, and the damage level, this step evaluates the economic losses, and a new field is added to the attribute table of the grid map. The models (based on the Indian data) relating seismic intensity with different types of losses are used in the analysis and are described in Aditya (2007). The values obtained from these models are stored in the database files. Values in the database files can be interactively modified by the user depending upon the region of study and to provide other loss models as additional features.

The details of various calculations carried out for the exposure analysis are described below. If the total number of persons injured and the total number of fatalities in a grid are denoted as Inj and D, respectively, these quantities can be determined as

$$\mathrm{Inj} = \sum^{\text{All Building Types}} \mathrm{PGB} \times \mathrm{FI} \tag{15}$$

$$D = \mathrm{Inj} \times \mathrm{FD} \tag{16}$$

where FI is the percentage of population injured due to a particular damage intensity and is obtained from Figure 3, and FD is the percentage of injured population that results in fatalities. The total number of injuries and fatalities is determined from the summations of Equations (15) and (16) over all grids. For the monetary value of loss calculations, the losses in rupees per person injured and per death are taken as Rs. 50,000 and Rs. 2,00,000, respectively, based on the recent data of compensation following some natural disasters in the country.

If SL is the loss due to damage to structural members in a grid, NSL is the loss due to damage to non-structural members in a grid, and CL is the loss of content due to structural damage in a grid, these losses have been evaluated using the following expressions:

$$\mathrm{SL} = \mathrm{AGB} \times \mathrm{F1} \times \mathrm{SW} \tag{17}$$

$$\mathrm{NSL} = \mathrm{AGO} \times \mathrm{F2} \times \mathrm{NSW} \tag{18}$$

$$\mathrm{CL} = \mathrm{AGO} \times \mathrm{F3} \times \mathrm{CW} \tag{19}$$

where $\mathrm{F1}$, $\mathrm{F2}$, and $\mathrm{F3}$ are percentage structural, non-structural, and content damages, respectively, at a given earthquake intensity, and are obtained from Figures 4 and 5. SW, NSW, and CW are the replacement costs for structural, non-structural, and content components, respectively, per square meter for a given building type and occupancy type, and are obtained from Tables 3 and 4. The total economic loss is estimated as the sum of all losses.

5. Generation of Result Maps and Table

The risk assessment as described above results in the addition of new fields (or layers) containing the values of PGA, MSK, and losses to each grid on the grid map of the city. Colour coded maps with the results are automatically generated by the software. A colour code is assigned for each range of injures, fatalities, and economic losses, which help to quickly spot the heavily damaged areas. The generated maps include PGA contour maps, damage intensity maps, injuries maps, fatalities maps, and economic losses maps. Besides generating the above maps, a table of results is also generated. This table is stored as a database file, and it contains three columns indicating the values of total number of injuries, total number of fatalities, and total economic losses suffered in the area under study due to the given scenario. These values are computed by the summation of the injuries, fatalities, and economic losses associated with each building type in each grid on the grid map. The results are stored as an output data file in the output directory.

6. Query Results

RISK.iitb allows the user to perform complex queries on the results computed. The user has the option of single-condition query or multi-condition query. When a query is performed, the grids satisfying the query criterion, as defined by the query expression, are highlighted and the map is stored as a layer file in the output directory.

EXAMPLE SCENARIO DEVELOPMENT AND LOSS ESTIMATION FOR MUMBAI

The risk assessment of an example area has been performed using RISK.iitb. The city of Mumbai (within its municipal limits), which is India's most populous city and has an area of approximately 470 km^2, has been selected to illustrate the use of RISK.iitb. The closest significant active fault is considered to be the Panvel flexure that runs to the east of the city across Thane creek and is oriented approximately in the N-S direction (see Figure 7). A preliminary seismic risk assessment of Mumbai was carried out earlier by Sinha and Adarsh (1999), and the basic data regarding the structural vulnerability of different construction types has been considered in this study. Various parameters and inputs used for the loss estimation are given below:

i) The geo-referenced map of Mumbai city has been extracted from the scanned image of the master plan of Mumbai Metropolitan Region and is shown in Figure 8.

ii) The risk assessment has been carried out using three different grid sizes, viz., 2.0, 1.0, and 0.5 km. Detailed results are shown only for the grid size of 0.5 km, while the economic losses and the table of final results are shown for all grid sizes to illustrate the robustness of the procedure and convergence of results.

iii) The grid weight and zone classification are used as per the data available from the master plan of Mumbai Metropolitan Region. In the absence of reliable data on soil properties, soil amplification has not been considered in the simulations, i.e., soil amplification factor has been taken as unity for all grids.

iv) The occurrence time of the scenario earthquake has been considered as 3:00 p.m.

v) Total night (or resident) population in the example area has been taken as 13 million based on the census data and more recent estimates. The floating population of people from outside the city limits during the daytime is taken as 15% of the night population, i.e., 1.95 million based on the recent estimates.

vi) A user-defined earthquake is considered. The parameters for the earthquake are taken as given below (with the epicentre on Panvel flexure):

   a) latitude of hypocentre: 19°7'57"N;
   b) longitude of hypocentre: 73°6'48"E;
   c) moment magnitude: 6.0; and
   d) focal depth: 10.0 km.

   Since Mumbai is located in the seismic zone III as per the Indian Standard code (BIS, 2002), representing moderate seismic hazard, the earthquake moment magnitude $M = 6.0$ has been selected for this simulation to represent a typical moderate earthquake. The focal depth of 10 km has been chosen assuming the earthquake to be shallow. The epicentre has been taken on Panvel flexure, which is considered to be the closest significant active fault near Mumbai (Dessai and Bertrand, 1995). The resulting rupture length is 7.8 km, with the epicentre taken at its mid-length.

vii) The attenuation relationship by Iyengar and Raghukanth (2004), which has been estimated using the local data for the Bhuj earthquake of 2001, has been chosen for the estimation of seismic hazard.

The remaining inputs, which pertain to the physical data of the example area, have been described in Aditya (2007). The results from loss estimation of the example area are shown in Tables 9 and 10. It can be seen that the total area under the grids increases as the grid size becomes larger (or the grid becomes coarser). This is expected since larger grids have greater error due to the inclusion of the entire area of the boundary grids. However, the actual physical area does not change significantly due to the software feature of defining grid weight based on the grid class that considers the land area in each grid (see Table 5).

The physical and economic losses for the above scenario assessment, which have been generated in RISK.iitb, are shown in Table 10. The results are of similar order as those presented in Sinha and Adarsh (1999), thus clearly demonstrating the accuracy of the results for a preliminary assessment of seismic risk. It can be also seen that the results of loss estimation are convergent as the grid size is reduced. This indicates that a grid size of 2×2 km is adequate for carrying out the risk assessment of an area of the size of Mumbai. However, smaller grid sizes give more refined local distributions of the losses, which are of immense importance in developing disaster management strategies and for evaluating spatial variation of risk in the city.

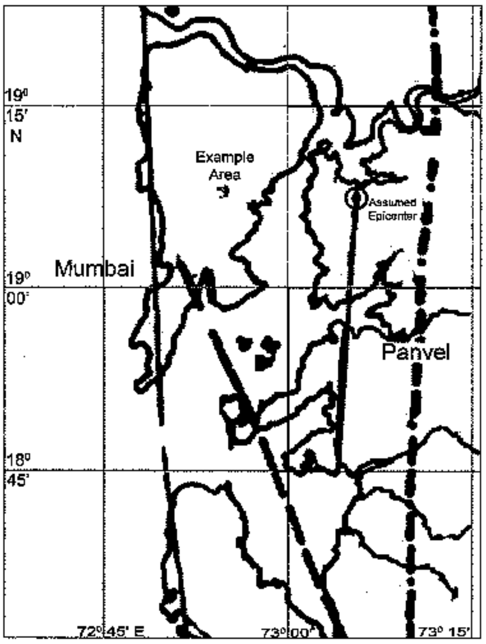

Fig. 7 Fault trace map showing the example area (of Mumbai) considered for scenario development and the lineament under consideration (Dessai and Bertrand, 1995)

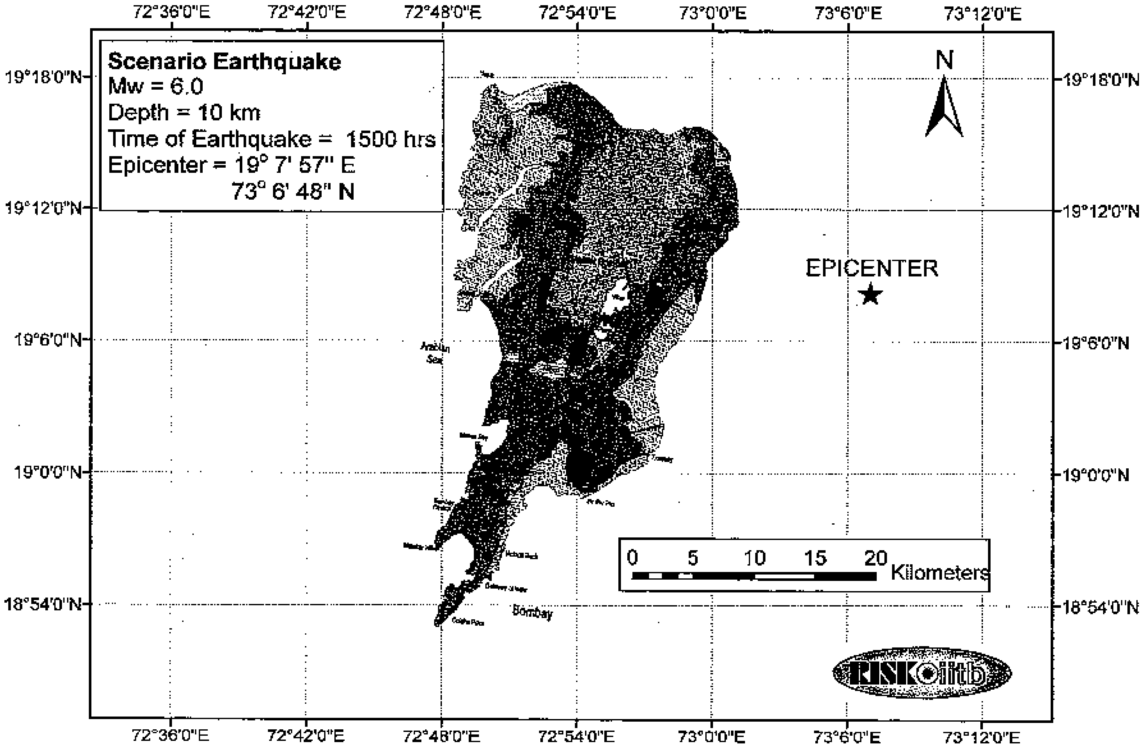

Fig. 8 Geo-referenced map of Mumbai used for the seismic risk assessment

Table 9: Land Area under Different Damage Intensity (on MSK Scale) for the Scenario Earthquake

Grid Size (km)	Area (km^2)		
	MSK VI	MSK VII	MSK VIII
0.5×0.5	331.50	237.75	0.00
1.0×1.0	356.00	249.00	0.00
2.0×2.0	392.00	272.00	0.00

Table 10: Estimated Physical and Economic Losses for the Scenario Earthquake

Grid Size (km)	Number of Injuries	Number of Deaths	Economic Losses (Million Rs.)
0.5×0.5	128825	15212	87230
1.0×1.0	129617	15331	87800
2.0×2.0	130860	15416	88210

Following maps are generated after the analysis:

- Grid maps (2×2, 1×1, and 0.5×0.5 km); the grid map for 0.5×0.5 km grid is shown in Figure 9.
- Grid weight map; the grid weight map for 0.5×0.5 km grid is shown in Figure 10.
- Occupancy zone classification map; the occupancy zone classification map for 0.5×0.5 km grid is shown in Figure 11.
- Soil grid map.
- PGA grid map.
- Damage intensity grid map; the damage intensity map for 0.5×0.5 km grid is shown in Figure 12.
- Injury map (grid-wise or total); the grid-wise injury map for 0.5×0.5 km grid is shown in Figure 13.
- Fatality map (grid-wise or total); the grid-wise fatality map for 0.5×0.5 km grid is shown in Figure 14.
- Economic loss map (grid-wise or total); the grid-wise economic loss maps for all three grid sizes are shown in Figures 15–17.

It is evident that the thematic display of inputs of the analysis and maps of the results, as shown in Figures 8–17, can be easily understood even by the non-technical stakeholders. These maps illustrate the unique advantage of developing a seismic risk assessment system on the GIS-based platform, since the results retain the accuracy of a typical scientific endeavour, while also providing the ability to communicate with various stakeholders in a simple yet accurate manner. Since several major urban areas in India are in the process of updating their records on a GIS-based platform, RISK.iitb provides an opportunity to interface with the municipal database to directly extract the relevant input information from the municipal records as and when it becomes available.

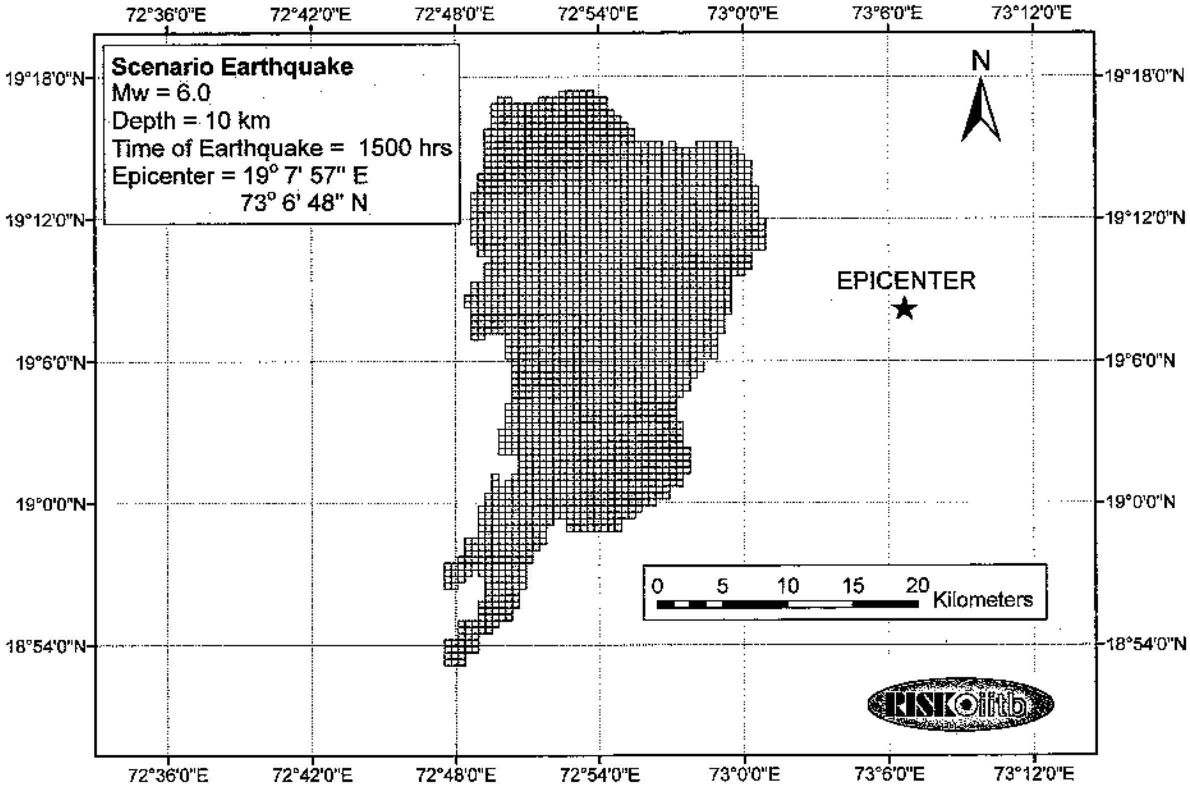

Fig. 9 Grid map of Mumbai with 0.5×0.5 km resolution

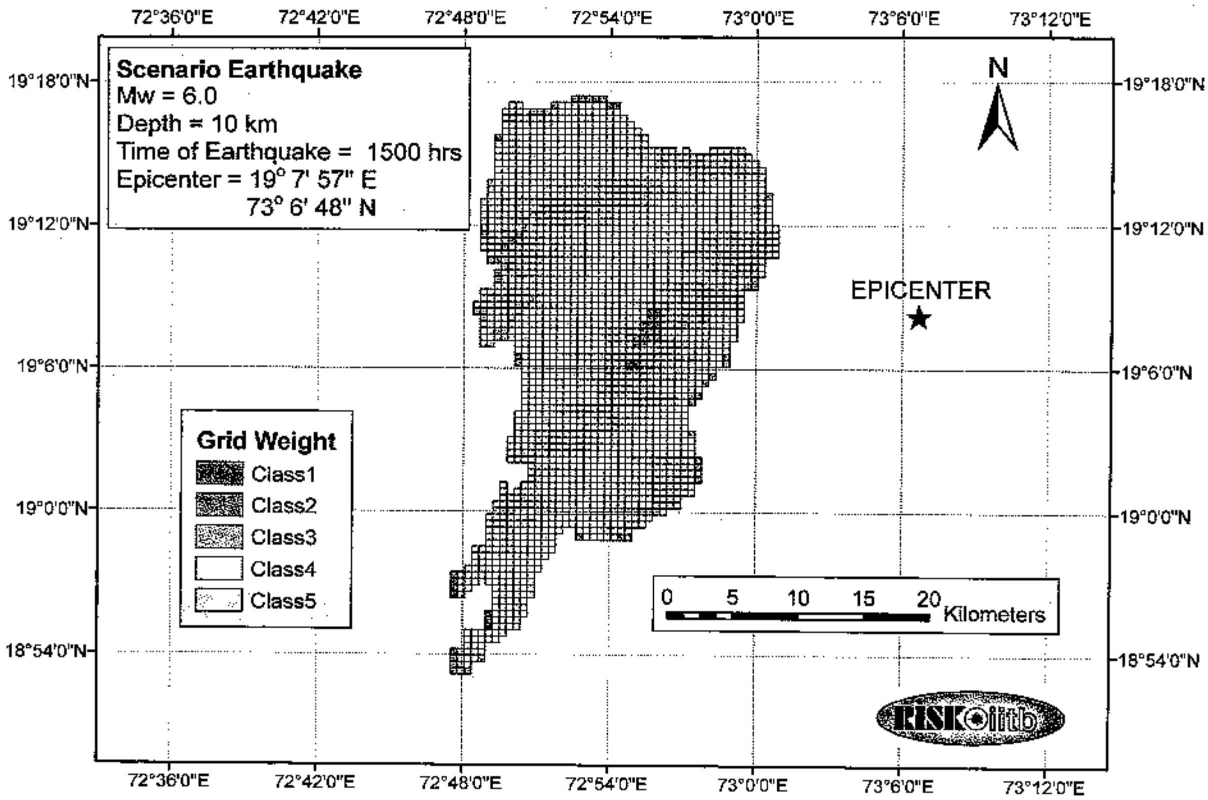

Fig. 10 Grid weight map of Mumbai with 0.5×0.5 km resolution

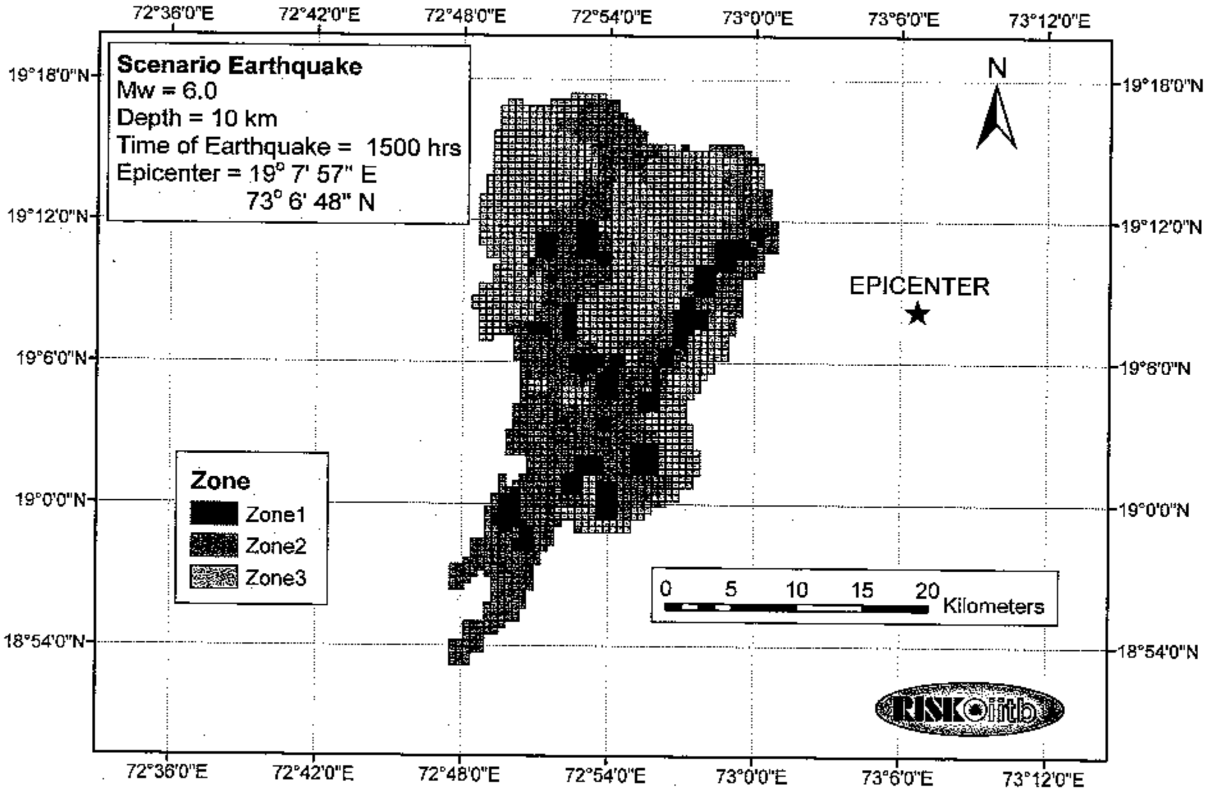

Fig. 11 Occupancy zone map of Mumbai with 0.5×0.5 km resolution

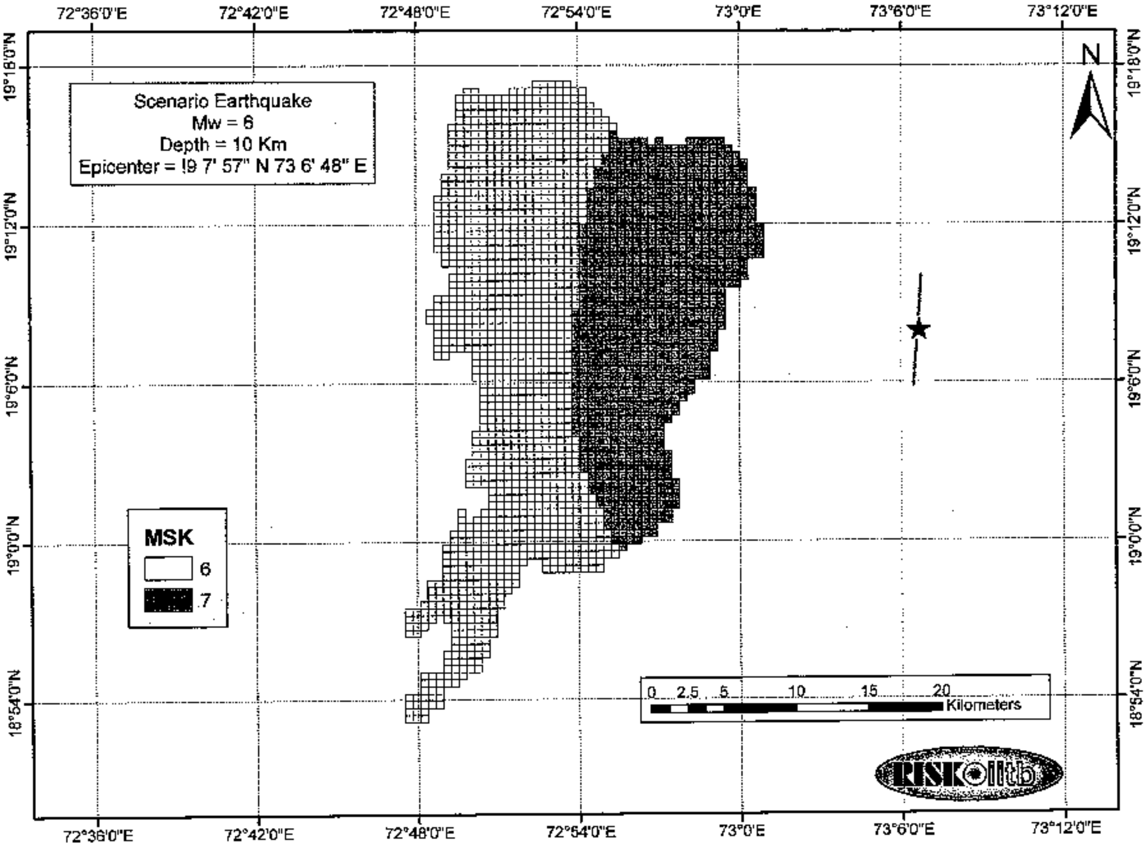

Fig. 12 Damage intensity map of Mumbai with 0.5×0.5 km resolution

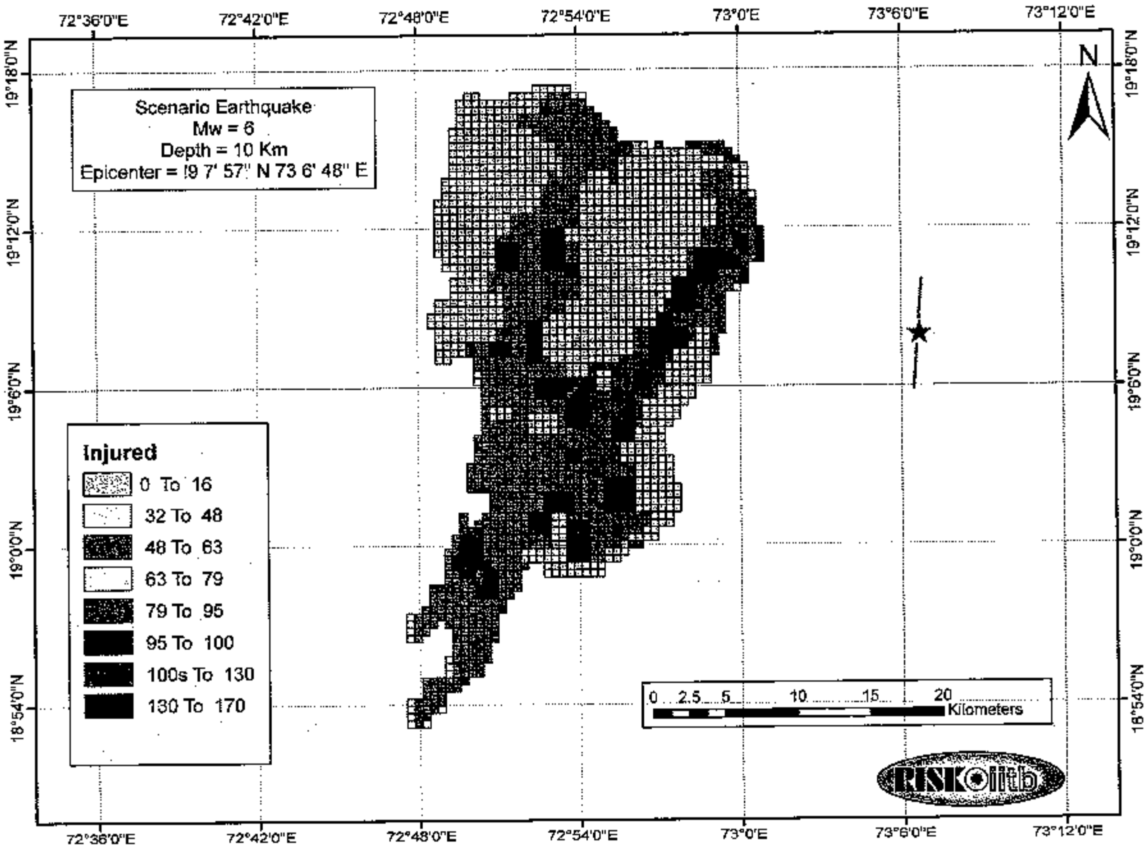

Fig. 13 Injury intensity map of Mumbai with 0.5×0.5 km resolution

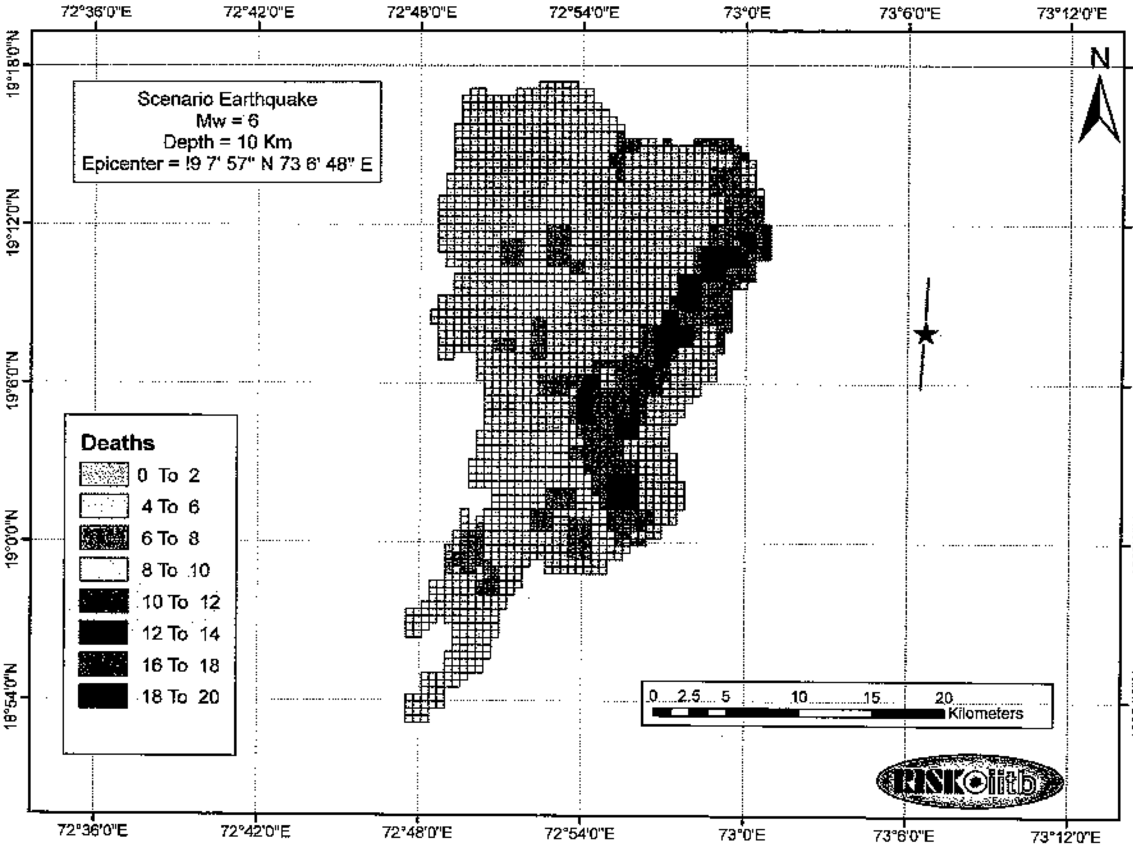

Fig. 14 Fatality intensity map of Mumbai with 0.5×0.5 km resolution

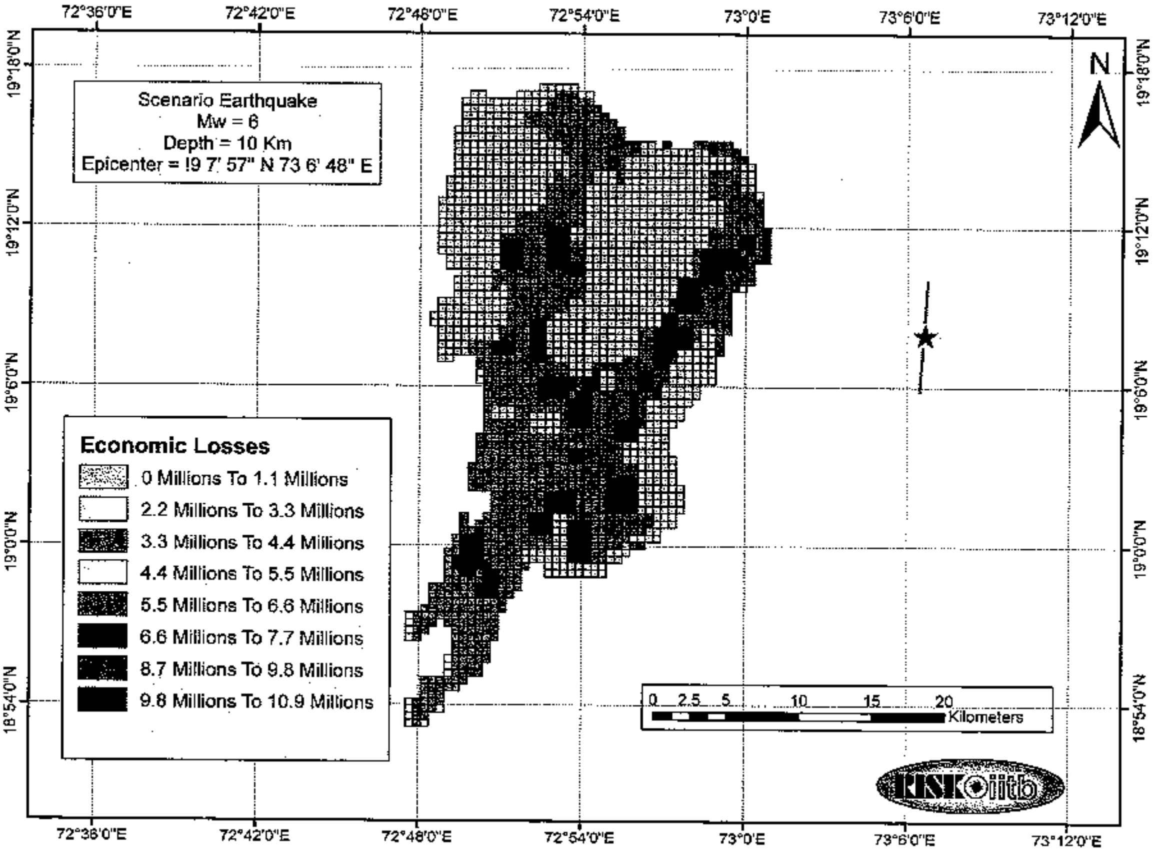

Fig. 15 Economic loss intensity map of Mumbai with 0.5×0.5 km resolution

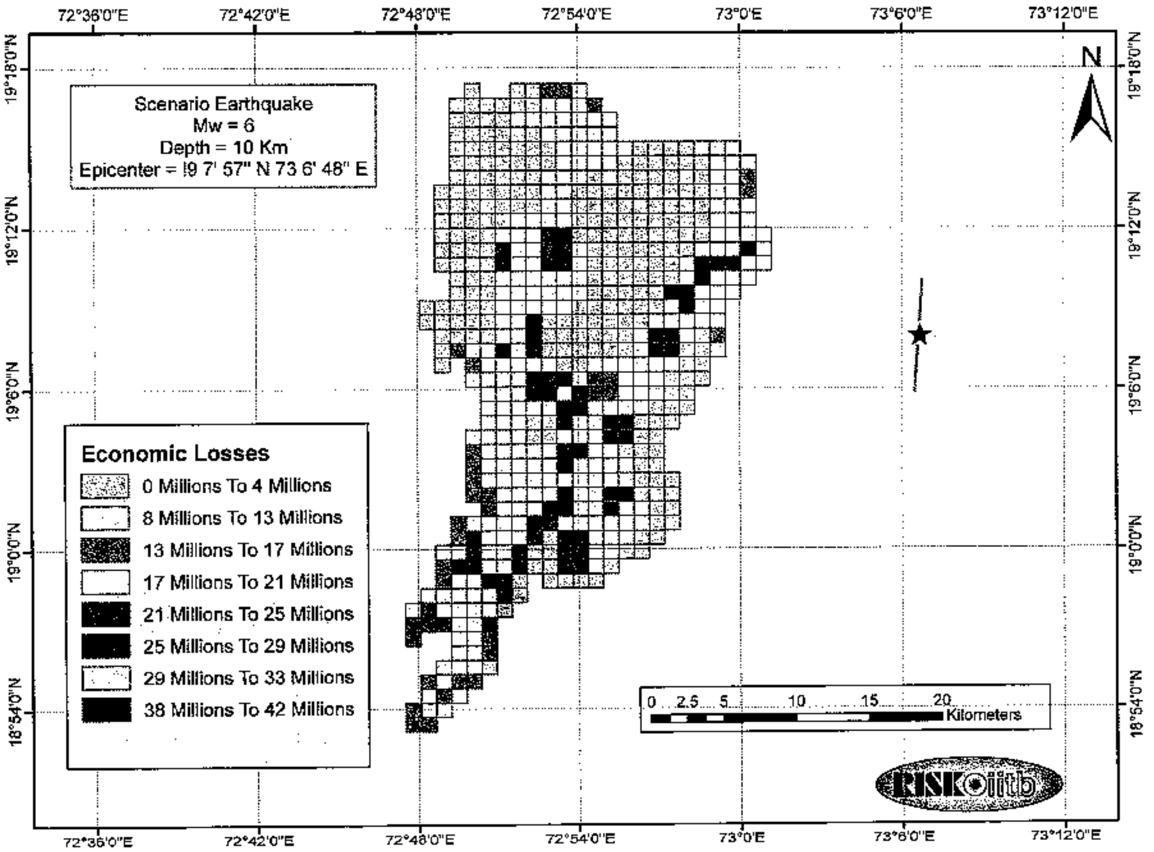

Fig. 16 Economic loss intensity map of Mumbai with 1.0×1.0 km resolution

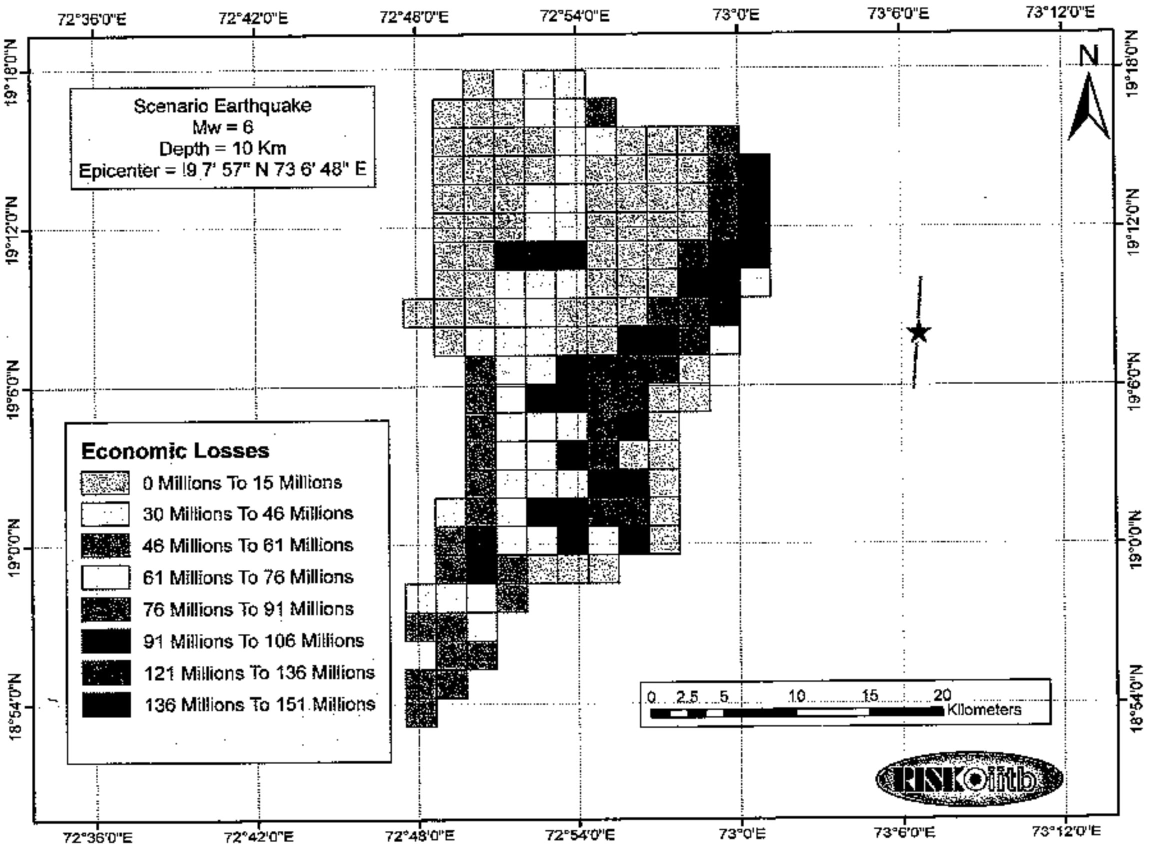

Fig. 17 Economic loss intensity map of Mumbai with 2.0×2.0 km resolution

The results of damage and loss estimation presented in the example assessment above can be considered as preliminary due to the number of assumptions made on account of the non-availability of data. These results can be further refined when such information as the soil classification map for amplification assessment, and more refined building data, becomes available. However, it should be noted that these results are adequately detailed for developing initial disaster management plans for the city of Mumbai, and for assessing the scale of likely losses due to the scenario earthquake disaster. Such results and their presentation through tables and thematic maps are, therefore, invaluable for policy-making and for communicating with the non-technical stakeholders.

SUMMARY AND CONCLUSIONS

This paper presents a methodology for carrying out an assessment of the consequences of future earthquake events in urban areas. The risk assessment procedure needs to be scientifically rigorous, while the results should be easy to understand by the various stakeholders. The use of GIS platform for developing seismic risk assessment tools has provided the opportunity to integrate the two requirements. A GIS-based risk assessment tool, RISK.iitb, has been developed considering the Indian conditions. The tool has the capability to carry out seismic risk assessment considering a large number of options regarding hazard and vulnerability. The results are generated in the form of tables and colour-coded maps for parameters such as injury, fatality, and economic loss in the region of interest. The GIS platform facilitates generation and display of various thematic maps.

RISK.iitb can be used for carrying out the risk assessment of urban areas to sensitize the policy-makers and public of the role of different contributors, such as seismic hazard and vulnerability of different categories of buildings, to the seismic risk. Since the assessment results, such as the extent of damaged buildings and also the number of injuries and casualties, are generated for each grid, those can be used in identifying areas with potentially heavy damage in the case of an earthquake, so that the disaster management plans in those areas can be suitably strengthened.

The results of risk assessment depend on the inventory data available. It is shown that the basic level assessment can be carried out using the urban data already available from a variety of sources. However, a more accurate assessment requires detailed data that is not available or is difficult to compile. Since most major urban areas are expected to update their records on an IT platform in future, and several are also expected to migrate to GIS-based platforms, the development of RISK.iitb provides the opportunity to various urban authorities to compile the most important data for carrying out the seismic risk assessment. This will enable a more accurate seismic risk assessment in a larger number of urban areas and will be invaluable in developing their disaster management plans.

An example seismic risk assessment for the city of Mumbai has been carried out to demonstrate the main features of the system. It is seen that consistent and convergent results are obtained for the grid-size between 2.0 and 0.5 km. It is also seen that there is an insignificant difference between the results obtained for the 2.0×2.0 km and 0.5×0.5 km grid sizes. Based on this example, it can be concluded that a grid resolution of 2.0×2.0 km is adequate for an urban area of the size of Mumbai, and further assessment can be carried out for other earthquake scenarios using a larger grid size. However, the spatial variation of risk has much better resolution when smaller grid sizes are used, and thus provides a basis for choosing the grid density.

RISK.iitb is undergoing continuing improvements to improve its capability and modelling. For example, besides specifying the earthquake hazard in terms of its epicentral parameters, faults can also be specified and the earthquake magnitude estimated from the type of faulting and the rupture length. Several other enhancements are also currently in progress.

It may also be noted that the results presented in the paper can be considered as a postulated scenario and are intended to demonstrate the most useful features of RISK.iitb for communicating the complex issues of seismic risk to the non-technical stakeholders.

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