M_w=8.0 Mandi Earthquake Disaster Scenario for Disaster Risk Management

Earthquake Disaster Scenario for Disaster Risk Management Strategy and Action Plans

Report Number 2

Submitted to

National Disaster Management Authority,
Government of India

Ravi Sinha, CVR Murty, Alok Goyal,
Chaitanya Krishna and Paresh Vishnoi
Indian Institutes of Technology at Bombay & Madras

May 14, 2012

Table of Contents

M_W=8.0 Mandi Earthquake Disaster Scenario for Disaster Risk Management

1. Background

The NDMA has initiated a project to develop a multi-state earthquake disaster scenario for a hypothetical earthquake of magnitude 8 with its epicentre in Himachal Pradesh. The Himalayas have experienced several earthquakes of similar magnitude in the past. The last major earthquake close to the epicentre was the Mw=8.0 Kangra earthquake of 1905. The epicentre of the hypothetical earthquake is located in a "seismic gap" in western Himalaya and several scientists expect this region to experience a large earthquake in the future. The main objectives of the project are:

1. To understand the extent of affected areas due to the earthquake. Amongst various issues, the importance of critical factors such as fault rupture, distance of epicentre and ground shaking will be better understood by the various participating stakeholders.
2. To understand the direct and indirect consequences of the earthquake in the affected area. The consequences include damage to buildings, critical facilities, lifelines (such as transportation, communications, power, water supply etc.), industrial facilities, etc. Other consequences such as the potential of landslides induced by earthquake shaking and their secondary impact can also be estimated.
3. To understand the impact of the earthquake on the functioning and responsibilities of various stakeholders.
4. To understand the impact of the earthquake on family and community of various stakeholder personnel.

5. To facilitate participating state governments in their preparation of community disaster management plans, district disaster management plans and state disaster management plans considering realistic earthquake scenario and its consequences.
6. To facilitate participating stakeholders in their preparation of action plans on the basis of realistic understanding of the consequences of the earthquake.
7. To facilitate participating stakeholders in their preparation of action plans to implement the community, district and state disaster management plans.
8. To facilitate participating stakeholders in their evaluation of effectiveness of actions plans of various agencies and identification of their gaps.
9. To facilitate evaluation of intra-agency coordination capability and identification of their gaps.
10. To facilitate evaluation of inter-agency coordination capability and identification of their gaps.
11. To facilitate evaluation of impact on defence establishments and defence preparedness, and identification of their gaps.
12. To facilitate participating stakeholders in their psychological preparedness for such events (in the scenario region or elsewhere).
13. To facilitate systemic preparedness for such events (in the scenario region or elsewhere).
14. To provide a template for development of damage scenarios for other hazards in the scenario region.
15. To provide a template for development of damage scenarios for earthquakes and other hazards in other parts of the country.

An important activity that will be carried out during the project is to develop an earthquake scenario in terms of ground shaking due to the hypothetical scenario earthquake. The development of earthquake damage scenario is invaluable for advocacy of seismic safety and for disaster risk management. The disaster scenario information can be used to sensitize the various stakeholders regarding the risk and the potential consequences of earthquakes. The information can thus greatly overcome some of the limitations due to the absence of earthquake disaster memory in society. The disaster scenario can also help to identify the most vulnerable areas and population groups that will require special attention in the aftermath of the scenario earthquake. The impact of governance system can also be assessed so that they can be sufficiently strengthened before the next earthquake disaster. 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 losses over time.

It has also been observed during past earthquake disasters in our country and elsewhere that the response to earthquake disasters often results in suboptimal prioritisation and consequent underutilisation of resources to the detriment of the affected people and the society at large. However, disaster management plans that are prepared based on rigorous risk assessment and scenario development are able to take advantage of this information for optimal prioritisation of resources. The use of risk assessment and disaster scenarios also provide tools to assess changes in risk profile of a region and are invaluable for monitoring long-term risk reduction.

2. Scenario Development Team

The earthquake scenario development team is being led by the NDMA and consists of scientific experts in the field of earthquake engineering (from IIT Bombay and IIT Madras) and is expected to include representatives of Himachal Pradesh, Haryana, Punjab, Uttarakhand and Jammu & Kashmir state governments, some of whom are already on board. Representatives from Chandigarh administration are also included in the team. The team is also expected to include representatives of organisations involved in earthquake monitoring, hazard assessment, and managing major infrastructure or facilities in the affected region such as India Meteorological Department, Geological Survey of India, Border Roads Organisation, Central Water Commission, Bhakra-Beas Management Board, etc. Some of these are also already on board. The team also includes a Coordination Agency to facilitate the coordination between the various stakeholders, particularly at the state level. The team has been diligently working to jointly develop the consequences of the scenario earthquake.

3. Summary of Project Review Workshop on March 13, 2012

A workshop to discuss the project details was held in the NDMA on March 13, 2012. The workshop was chaired by Shri M. Sashidhar Reddy, Hon'ble Vice Chairman NDMA, and the other dignitaries included Prof. Harsh K. Gupta, Hon'ble Member, NDMA, Prof. Sutanu Behuria, Secretary, NDMA and Shri PP Srivastava, Member, North-East Council. The workshop was attended by a large number of other participants from IIT Bombay, IIT Madras, GeoHazards Society India, and representatives of participating states and agencies and Central Government Departments.

During the meeting, the technical details of the simulation of earthquake shaking were discussed. Based on the discussions during the workshop and later over email, the following points emerged:

1. Selection of epicentre for the simulation: There was considerable discussion on this issue. Since Kalka is located in Seismic Zone IV, it was felt that considering a Mw=8.0 earthquake at Kalka may result in shaking intensity exceeding the design intensity considered in IS:1893-2002 (Part-1). It was felt that this may result in needless controversy. Since large parts of the Himalaya have been assigned higher intensity by the IS code, it was agreed that the epicentre may be shifted along the MBT to another location situated in Seismic Zone V. Accordingly, the results in this simulation are

based on epicentre located close to Kalka at Mandi, but situated in Seismic Zone V.

2. Selection of Ground Motion Prediction Equations (GMPEs): There was also considerable discussion on this issue. Some GMPEs have been developed using the Himalaya earthquake data and have been included in Report Number 1; however, these are based on relatively low-magnitude earthquakes. As a result, it was felt the prediction of ground motion parameters based on these earthquakes may not be realistic. This was further confirmed by considering the large historical earthquakes, where it was seen that the maximum intensity and isoseismals were not matching with the actual observations when these GMPEs were used. Several GMPEs relevant to the tectonic domain and developed from global earthquake data were also considered. Some of these GMPEs are included in Report Number 1. It was further seen that most of these GMPEs also predict maximum damage intensity that does not match with the observations during large historical earthquakes. Based on all such assessments, it was finally decided that Boore and Atkinson (2008), which is a New Generation Attenuation relationship applicable to the tectonic domain should be used for further simulations.

4. Scenario Simulation Results

4.1 Simulation Background

As stated earlier, the epicenter is taken to be on the surface of Main Boundary Thrust within Seismic Zone V, whose coordinates are at 31°33′00″N and 76°52′48″E. The epicenter is near Sundarnagar town in Mandi district of Himachal Pradesh state. The extent of strong shaking has been predicted in the states of Jammu and Kashmir, Himachal Pradesh, Haryana, Punjab, Uttaranchal, Uttar Pradesh and Chandigarh Province.

The details of the region are shown in Figure 1, where the thick blue line represents the fault rupture:

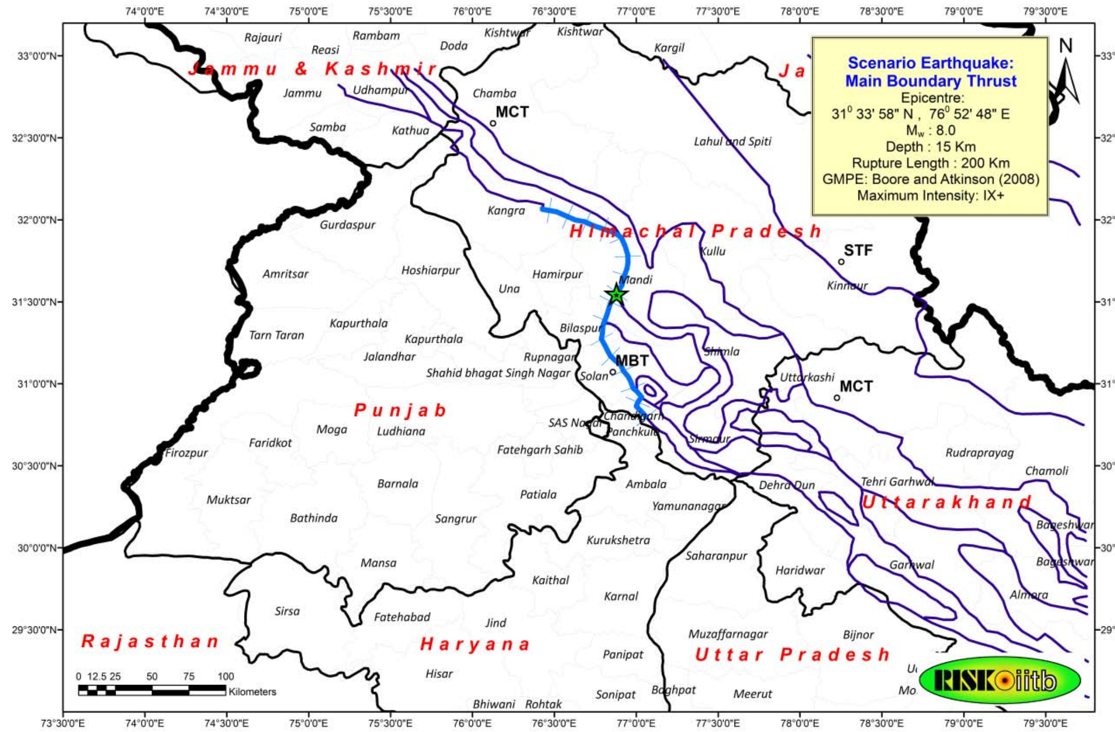

Figure 1. State and district map of the region of interest, along with the major Himalaya tectonic features.

4.2 Seismotectonics of the Region

This region is one of the seismically active regions of the world and has experienced earthquakes since times immemorial. The region has also experienced tectonic movements. This is evident from the several thrusts and faults present around the region. The major tectonic features which have earthquake potential are Main Boundary Thrust (MBT) and Main Crustal Thrust (MCT). In fact, these tectonic features are present all along the entire Himalayan tectonic belt. The seismotectonics of the region had been well studied and the cartographical representation of past earthquakes and seismotectonics of the region is shown in Figure 2 (courtesy Wadia Institute of Himalayan Geology).

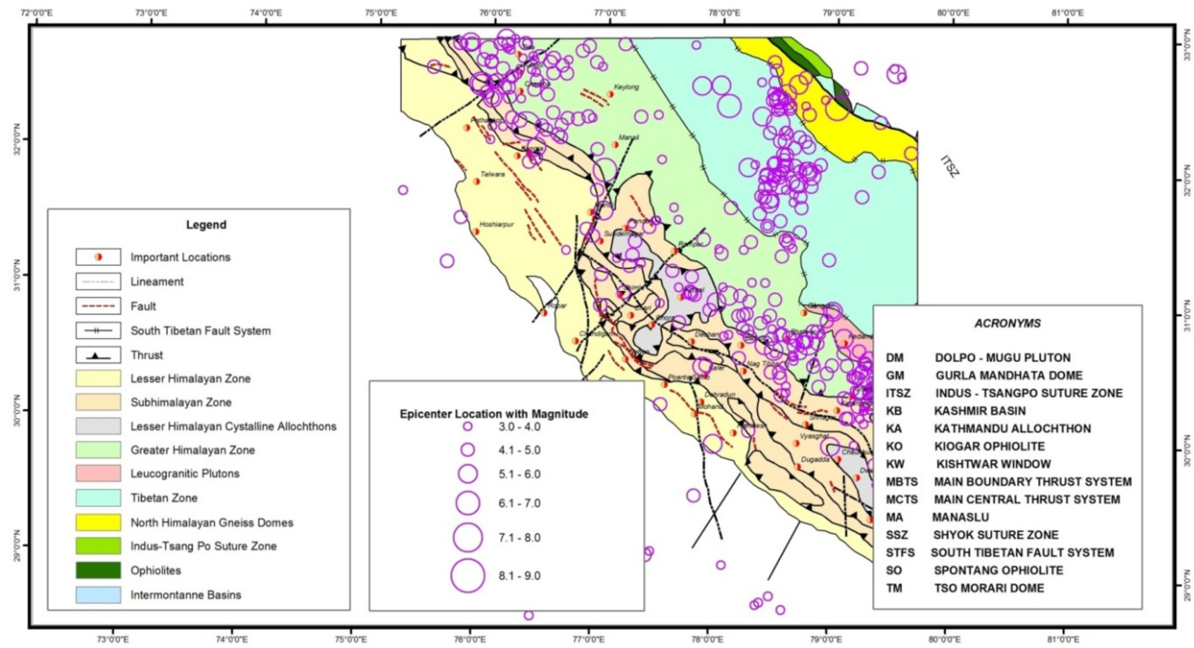

Figure 2. Major tectonic features in the Himalaya near the region of interest (GIS data courtesy of Dr. AK Mahajan, Wadia Institute of Himalayan Geology).

4.3 Past Earthquakes

Several earthquakes, medium to large, have occurred in this region, as per data based on instrumental records. A few significant earthquakes that occurred in this region are given in Table 1.

Table 1. List of significant earthquakes in northern Himalaya in recent past.

Location	Date	Magnitude
Kangra, HP	1905 Apr 04	8.0
Kinnaur, HP	1975 Jan 19	6.2
Uttarkashi, UP Hills	1991 Oct 20	6.6
Chamoli District, UP	1999 Mar 29	6.8
Kashmir	2005 Oct 08	7.6

Source: India Meteorological Department

4.4 Earthquake Scenario

The hypothetical scenario is prepared on the basis of the data presented in Table 2.

Table 2. Parameters used for earthquake simulation.

<table>
<tr><td>Earthquake</td><td colspan="2">Multi-State Earthquake Scenario</td></tr>
<tr><td>Region</td><td colspan="2">Mandi District</td></tr>
<tr><td>M_w</td><td colspan="2">8.0</td></tr>
<tr><td>Depth</td><td colspan="2">15 km</td></tr>
<tr><td rowspan="3">Epicenter</td><td colspan="2">Mandi District, HP</td></tr>
<tr><td>Latitude</td><td>31°33′00″ N</td></tr>
<tr><td>Longitude</td><td>76°52′48″ E</td></tr>
<tr><td colspan="3">Parameters</td></tr>
<tr><td>Fault</td><td colspan="2">Main Boundary Thrust (MBT)</td></tr>
<tr><td>GMPE</td><td colspan="2">Boore and Atkinson (AB08, NGA)</td></tr>
<tr><td>Source</td><td colspan="2">Line Source</td></tr>
<tr><td>Rupture Model</td><td colspan="2">WC84-All</td></tr>
<tr><td>Rupture Length</td><td colspan="2">200 km</td></tr>
<tr><td>Maximum MSK Intensity</td><td colspan="2">9.53 (between IX and X)</td></tr>
<tr><td>Grid Size for Analysis</td><td colspan="2">0.5 km × 0.5 km</td></tr>
</table>

The earthquake scenario considers earthquake of moment magnitude of 8.0. The earthquake has been considered to be on the Main Boundary Thrust at a depth 15 km. The epicentre lies near Sundarnagar town in Mandi district of Himachal Pradesh. A line source has been considered at present and the distance is taken from the site to the nearest point over the surface rupture considering the geodetic surface of the earth.

The simulations for the earthquake have been carried out using RISK.iitb v3.0, developed at IIT Bombay as a tool for integrated seismic hazard, vulnerability and risk assessment (Sinha et al., 2008).

The MSK Intensity map using the Boore and Atkinson (2008) GMPE is shown in Figure 3. It is seen that the maximum intensity obtained due to this earthquake is 9.53 which is observed at the rupture surface. The intensity scale is further described in Appendix-A. It is also seen that the MBT fault is ruptured to a length of 200 km over the districts starting from the middle of Kangra, passing through Mandi, Bilaspur and Solan.

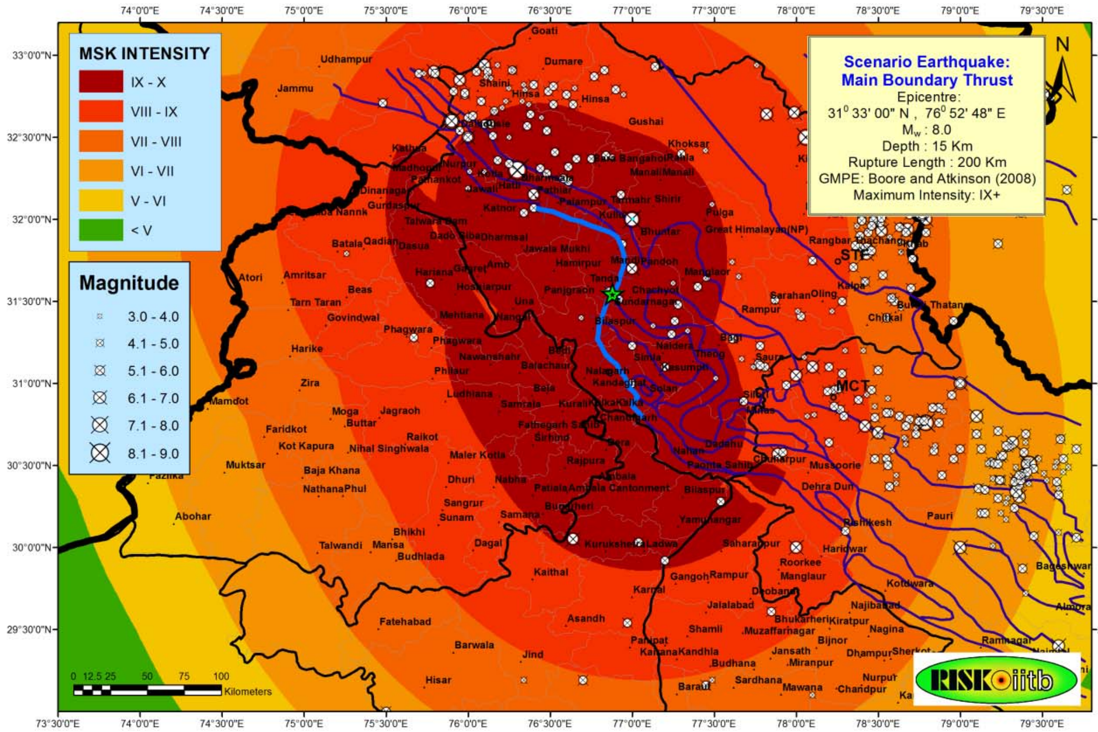

Figure 3. Map showing predicted shaking intensity due to scenario earthquake. The circles show past earthquakes in the region.

The salient points of the simulation results are:

- Intensity IX and above is felt over most parts of Himachal Pradesh, Punjab and in some parts of Haryana, Uttarakhand and Uttar Pradesh.

- The extents of Intensity VI are observed in five states, namely, Jammu and Kashmir, Himachal Pradesh, Haryana, Uttaranchal and

Uttar Pradesh. It may be further noted that the Intensity VI region in the map is truncated, and only the area included in the map are considered for this project.

- The ground motion parameters have been amplified in the south west of the rupture, which is due to the presence of Indo-Gangetic plain in the region.

The important cities that experience strong shaking due to the scenario earthquake are given in Table 3. In Himachal Pradesh, due to low population, the list includes small cities of Class III, IV or V; while only the Class I cities have been included in the other states.

Table 3. List of major cities located in regions with high earthquake intensity.

Intensity	State	Population Class	Cities/Towns
IX - X	Chandigarh	Class I	Chandigarh
	Haryana	Class I	Ambala, Yamunanagar
	Himachal Pradesh	Class I	Shimla
		Class III	Chamba, Mandi, Nahan, Solan
		Class IV	Bilaspur, Dharmsala, Hamirpur, Kullu, Una
	Punjab	Class I	Hoshiarpur, Pathankot, Patiala,
			Talwara Dam (Dam)
VIII - IX	Haryana	Class I	Kaithal, Karnal, Panipat
	Himachal Pradesh	Class V	Rampur
	Punjab	Class I	Batala, Jalandhar, Ludhiana
	Uttarakhand	Class I	Dehradun, Hardwar, Roorkee

Intensity	State	Population Class	Cities/Towns
VII - VIII	Haryana	Class I	Hisar, Jind
	Jammu and Kashmir	Class I	Jammu, Udhampur
	Punjab	Class I	Amritsar, Barnala
	Uttarakhand	Class I	Pauri, Rishikesh

* Population size-class: Class I: 100,000 and above; Class II: 50,000 to 99,999; Class III: 20,000 to 49,999; Class IV: 10,000 to 19,999; Class V: 5,000 to 9,999 and Class VI: Less than 5,000 persons.

The extent of different damage intensities covered over areas have been represented in Table 4 and their corresponding districts are shown in Table 5.

Table 4. Area under different earthquake intensity.

Intensity	Area (in km^2)
IX - X	56167
VIII - IX	87015
VII - VIII	86424
VI - VII	71852*

* Isoseismals incomplete for Intensity less than VII.

Table 5. List of districts located in regions with high earthquake intensity.

Intensity	State	Districts
IX - X	Chandigarh	Chandigarh
	Haryana	Ambala, Karnal, Kurukshetra Yamunanagar
	Himachal Pradesh	Bilaspur, Chamba, Hamirpur, Kangra, Kullu, Lahul and Spiti Mandi, Shimla, Sirmaur, Solan, Una

Intensity	State	Districts
	Jammu and Kashmir	Kathua
	Punjab	Fatehgarh Sahib, Gurudaspur, Hoshiarpur, Jalandhar, Ludhiana, Patiala, Rupnagar SAS Nagar, SBS Nagar
	Uttarakhand	Dehradun
VIII - IX	Haryana	Kaithal, Karnal, Jind, Panipat
	Himachal Pradesh	Kinnaur,
	Jammu and Kashmir	Doda, Jammu, Kargil, Kishtwar, Ladakh(Leh), Rambam, Samba, Udhampur
	Punjab	Amritsar, Bhatinda, Faridkot, Kapurtala, Faridkot, Tarn Taran
	Uttarakhand	Uttarkashi, Tehri Garhwal
VII - VIII	Haryana	Bhiwani, Hisar, Jhajjar, Rohtak, Sonipat
	Jammu and Kashmir	Kulgam, Rajauri, Reasi
	Punjab	Muktsar
	Uttarakhand	Garhwal, Rudraprayag

**District having two or more MSK Intensity regions has been listed in the highest intensity group.*

The total population exposed to different damage intensities (as per 2011 census data) have been represented in Table 6.

Table 6. Population exposure under different earthquake intensity.

Intensity	Population (in lakhs)
IX - X	231.8
VIII - IX	323.6
VII - VIII	251.6
VI - VII	136.3*

* Isoseismals incomplete for Intensity less than VII.

Appendix-A

MSK Intensity Scale

The Medvedev-Sponheuer-Karnik scale, also known as the MSK or MSK-64 scale, is a macroseismic intensity scale used to evaluate the severity of ground shaking on the basis of observed effects in an area of the earthquake occurrence. The definition of the scale adopted in IS:1893-2002 is given in Table A.1.

The intensity scale is based on the people's perception of ground shaking, impact on structures and effect on landscape. The scale considers the following types of structures:

- Type A – Buildings in field-stone, rural structures, unburnt-brick houses, clay houses.
- Type B – Ordinary brick buildings, buildings of large block and prefabricated type, half-timber structures, buildings in natural hewn stone.
- Type C – Reinforced buildings, well built timber structures.

The definition of quantity adopted for intensity scale is:

- Single, few — About 5 percent
- Many — About 50 percent
- Most — About 75 percent

The building damage have been defined in five grades as given below:

- Grade 1 – Slight damage: Fine cracks in plaster; fall of small pieces of plaster.
- Grade 2 – Moderate damage: Small cracks in plaster; fall of fairly large pieces of plaster; pantiles slip off; cracks in chimneys; parts of chimney fall down.
- Grade 3 – Heavy damage: Large and deep cracks in plaster; fall of chimneys.

- Grade 4 – Destruction: Gaps in walls; parts of buildings may collapse; separate parts of the building lose their cohesion; inner walls collapse.
- Grade 5 – Total damage: Total collapse of buildings.

Table A.1. Definition of MSK64 Intensity adopted by IS:1893-2002.

XII. Landscape changes	a) Practically all structures above and below ground are greatly damaged or destroyed b) The surface of the ground is radically changed. Considerable ground cracks with extensive vertical and horizontal movements are observed. Falls of rock and slumping of river banks over wide areas, lakes are dammed; waterfalls appear, and rivers are deflected. The intensity of the earthquake requires to be investigated specially.
XI. Destruction	a) Severe damage even to well built buildings, bridges, water dams and railway lines; highways become useless; underground pipes destroyed b) Ground considerably distorted by broad cracks and fissures, as well as by movement in horizontal and vertical directions; numerous landslips and falls of rock. The intensity of the earthquake requires to be investigated specially
X. General destruction of buildings	a) Many buildings of Type C suffer damage of Grade 4, and a few of Grade 5. Many buildings of Type B show damage of Grade 5; most of Type A have destruction of Grade 5; critical damage to dams and dykes and severe damage to bridges. Railway lines are bent slightly. Underground pipes are broken or bent. Road paving and asphalt show waves b) In ground, cracks up to widths of several centimeters, sometimes up to 1 metre. Parallel to water courses occur broad fissures. Lose ground slides from steep slopes. From river banks and steep coasts, considerable landslides are possible. In coastal areas, displacement of sand and mud; change of water level in wells; water from canals, lakes, rivers, etc, thrown on land. New lakes occur
IX. General damage to buildings	a) General panic; considerable damage to furniture. Animals run to and fro in confusion and cry b) Many buildings of Type C suffer damage of Grade 3, and a few of Grade 4. Many buildings of Type B show damage of Grade 4, and a few of Grade 5. Many buildings of Type A suffer damage of Grade 5. Monuments and columns fall. Considerable damage to reservoirs; underground pipes partly broken. In individual cases railway lines are bent and roadway damaged c) On flat land overflow of water, sand and mud is often observed. Ground cracks to widths of up to 10 cm, on slopes and river banks more than 10 cm; furthermore a large number of slight cracks in ground; falls of rock, many landslides and earth flows; large waves in water. Dry wells renew their flow and existing wells dry up

VIII. Destruction of buildings	a) Fright and panic; also persons driving motor cars are disturbed. Here and there branches of trees break off. Even heavy furniture moves and partly overturns. Hanging lamps are damaged in part b) Most buildings of Type C suffer damage of Grade 2, and few of Grade 3. Most buildings of Type B suffer damage of Grade 3, and most buildings of Type A suffer damage of Grade 4. Many buildings of Type C suffer damage of Grade 4. Occasional breaking of pipe seams. Memorials and monuments move and twist. Tombstones overturn. Stone walls collapse. c) Small landslips in hollows and on banked roads on steep slopes; cracks in ground up to widths of several centimeters. Water in lakes becomes turbid. New reservoirs come into existence. Dry wells refill and existing wells becomes dry. In many cases change in flow and level of water is observed,
VII. Damage of building	a) Most people are frightened and run outdoors. Many find it difficult to stand. The vibration is noticed by persons driving motor cars. Large bells ring. b) In many buildings of Type C damage of Grade 1 is caused; in many buildings of Type B damage is of Grade 2. Most buildings of Type A suffer damage of Grade 3, few of Grade 4. In single instances landslips of roadway on steep slopes; cracks in roads; seams of pipelines damaged; cracks in stone walls
VI. Frightening	a) Felt by most indoors and outdoors. Many people in buildings are frightened and run outdoors. A few persons lose their balance. Domestic animals run out of their stalls. In few instances dishes and glassware may break, books fall down. Heavy furniture may possibly move and small steeple bells may ring b) Damage of Grade 1 is sustained in single buildings of Type B and in many of Type A. Damage in few buildings of Type A is of Grade 2. c) In few cases cracks up to widths of I cm possible in wet ground; in mountains occasional landslips; change in flow of springs and in level of well water are observed
V. Awakening	a) The earthquake is felt indoors by all, outdoors by many, many sleeping people awake. A few run outdoors. Animals become uneasy. Buildings tremble throughout. Hanging objects swing considerably. Pictures knock against walls or swing out of place. Occasionally pendulum clocks stop. Unstable objects may be overturned or shifted. Open doors and windows are thrust open and slam back again. Liquids spill in small amounts from well-filled open containers. The sensation of vibration is like that due to heavy object falling inside the buildings b) Slight damages in buildings of Type A are possible c) Sometimes change in flow of springs
IV. Largely observed	The earthquake is felt indoors by many people, outdoors by few. Here and there people awake, but no one is frightened. The vibration is like that due to the passing of a heavily loaded truck. Windows, doors and dishes rattle. Floors and walls crack. Furniture begins to shake. Hanging objects swing slightly, Liquids in open vessels are slightly disturbed. In standing motor cars the shock is noticeable

III. Weak, partially observed only	The earthquake is felt indoors by a few people, outdoors only in favourable circumstances. The vibration is like that due to the passing of a light truck. Attentive observers notice a slight swinging of hanging objects, somewhat more heavily on upper floors
II. Scarcely noticeable (very slight)	Vibration is felt only by individual people at rest in houses, especially on upper floors of buildings
I. Not noticeable	The intensity of the vibration is below the limit of sensibility; the tremor is detected and recorded by seismographs only

Appendix-B

Fault Rupture Model

The fault rupture model for calculating the surface rupture length, WC84 (All) is given as (Wells and Coppersmith, 1994)

$$\mathrm{Log(SRL)} = \mathrm{a} + \mathrm{b} \ * \mathrm{M} \quad (1)$$

SRL is the surface rupture length in km, M is the moment magnitude and a, b are regression constants given as -3.22 and 0.69

Ground Motion Prediction Equation (GMPE)

The GMPE used is Boore and Atkinson, 2008 expression. The equation for predicting ground motion is as follows:

$$ln\, Y = F_M(M) + F_D(R_{JB}, M) + F_S(V_{S30}, R_{JB}, M) + \varepsilon\sigma_\tau \quad (2)$$

In this equation, F_M, FD and FS represent the magnitude scaling, distance function, and site amplification, respectively. M is moment magnitude, RJB is the Joyner-Boore distance (defined as the closest distance to the surface projection of the fault, which is approximately equal to the epicentral distance for events of M<6), and the velocity V_{S30} is the inverse of the average shear-wave slowness from the surface to a depth of 30 m.

The predictive variables are M, R_{JB}, and V_{S30}. ε is the fractional number of standard deviations of a single predicted value of ln Y away from the mean value of ln Y. All terms, including the coefficient σ_T, are period dependent. σ_T is computed using the equation

$$\sigma_T = \sqrt{\sigma^2 + \tau^2} \quad (3)$$

Where σ is the intra event aleatory uncertainty and τ is the inter event aleatory uncertainty.

The distance function is given by:

$$F_D(R_{JB,}M) = [c_1 + c_2(M - M_{ref})]\, ln\left(\frac{R}{R_{ref}}\right) + c_3(R - R_{ref}) \quad (4)$$

$$R = \sqrt{{R_{JB}}^2 + h^2} \quad (5)$$

And c_1, c_2, c_3, M_{ref}, R_{ref} and h are the coefficients; and are given as follows

c_1	c_2	c_3	M_{ref}	R_{ref}	h
-0.66220	-0.1970	-0.01151	4.5	1	1.35

The magnitude scaling is given by:

a. $M \leq M_h$

$$F_M(M) = e_1U + e_2SS + e_3NS + e_4RS + e_5(M - M_h) + e_6(M - M_h)^2 \quad (6)$$

b. $M > M_h$

$$F_M(M) = e_1U + e_2SS + e_3NS + e_4RS + e_7(M - M_h) \quad (7)$$

where U, SS, NS and RS are dummy variables used to denote unspecified, strike-slip, normal-slip, and reverse slip fault type respectively as given in the table given below:

Fault Types	U	SS	NS	RS
Unspecified	1	0	0	0
Strike-Slip	0	1	0	0
Normal	0	0	1	0
Thrust/Reverse	0	0	0	1

where M_h is the "hinge magnitude" for the shape of the magnitude scaling, and is a coefficient to be set during the analysis.

e_1, e_2, e_3, e_4, e_5, e_6 and e_7 are the regression constants given as:

e_1	e_2	e_3	e_4	e_5	e_6	e_7	M_h
-0.53804	-0.5035	0.75472	-0.5097	-0.28805	-0.10164	0	6.75

The site amplification function is given as:

$$F_S = F_{LIN} + F_{NL} \tag{8}$$

F_{LIN} and F_{NL} are the non linear terms respectively.

The linear term is given by:

$$F_{LIN} = b_{lin} \ln\left(\frac{V_{S30}}{V_{ref}}\right) \tag{9}$$

where b_{lin} is a period dependent coefficient, and V_{ref} is the specified reference velocity.

The non linear term is given as:

a. pga4nl ≤ a_1

$$F_{NL} = b_{nl}\, ln\left(\frac{pga_{low}}{0.1}\right) \tag{10}$$

b. a_1 < Pga4nl ≤ a_2

$$F_{NL} = b_{nl} \ln(pga\_low/0.1) + c[\ln(pga4nl/\mathrm{a}_1)]^2 + dc\left[\ln\left(\frac{pga4nl}{\mathrm{a}_1}\right)\right]^3 \tag{11}$$

c. a_2 < Pga4nl

$$F_{NL} = b_{nl} \ln(pga4nl/0.1) \tag{12}$$

where a1 (=0.03 g) and a2 (=0.09 g) are assigned threshold levels for linear and non-linear amplification, respectively, pga_low (=0.06 g) is a variable assigned to transition between linear and nonlinear behaviors, and pga4nl is the predicted PGA in g for Vref=760 m/ s, as given by Equation 1 with FS =0 and ε=0. The three above equations for the non-linear portion of the soil response are required for two reasons: 1) to prevent the nonlinear amplification from increasing indefinitely as pga4nl decreases and 2) to smooth the transition from linear to non-linear behavior. The coefficients c and d as:

$$c = \frac{(3\Delta y - b_{nl}\Delta x)}{\Delta x^2} \tag{13}$$

$$d = -\frac{(2\Delta y - b_{nl}\Delta x)}{\Delta x^3} \tag{14}$$

$$\Delta x = \ln\frac{a_2}{a_1} \tag{15}$$

$$\Delta y = \ln\frac{a_2}{pga\_low} \tag{16}$$

The nonlinear slope b_{nl} is a function of both period and V_{S30} as given by:

a. $V_{S30} \leq V_1$

$$b_{nl} = b_1 \tag{17}$$

b. $V_1 < V_{S30} \leq V_2$

$$b_{nl} = (b_1 - b_2)\frac{\ln\left(\frac{V_{S30}}{V_2}\right)}{\ln\left(\frac{V_1}{V_2}\right)} + b_2 \tag{18}$$

c. $V_1 < V_{S30} \leq V_{ref}$

$$b_{nl} = b_2\frac{\ln\left(\frac{V_{S30}}{V_{ref}}\right)}{\ln\left(\frac{V_1}{V_2}\right)} \tag{19}$$

d. $V_{ref} \le V_{S30}$

$$b_{nl} = 0 \qquad (20)$$

where V_1 =180 m/ s, V_2 =300 m/ s, and b_1 and b_2 are period-dependent coefficients (and consequently, b_{nl} is a function of period as well as $V_{S3}0$).

The constants b_{lin}, b_1, b_2 are as follows:

b_{lin}	b_1	b_2
-0.360	-0.640	-0.14

Aleatory uncertainties (σ: intra-event uncertainty; τ: inter-event uncertainty; σ_T: combined uncertainty; subscripts U, M for fault type unspecified and specified, respectively)

σ	τ_U	σ_{TU}	τ_M	σ_{TM}
0.502	0.265	0.566	0.260	0.564

PGA to MSK Intensity Conversion

The conversion of PGA to MSK Intensity (Wald et al., 1999) is according to the following equation, assuming equivalence of MSK Intensity and Modified Mercalli Intensity:

$For\ I \ \geq V,$

$$I = 3.66\ \log_{10} PGA - 1.66 \qquad (21)$$

$For\ I \ < V,$

$$I = 2.2\ \log_{10} PGA + 1 \qquad (22)$$

where I is the Damage Intensity and PGA is the peak ground acceleration in cm/sec^2.

References

Boore, D. M. and Atkinson, G. M. (2008). "Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s", *Earthquake Spectra*, **24**, 99-138.

BIS (2002). *Indian Standard Criteria for Earthquake Resistant Design of Structures*, IS : 1893 - 1984, Bureau of Indian Standards, New Delhi.

Sinha, R., Aditya, K. S. P., Gupta, A. (2008). "GIS based urban seismic risk assessment using RISK.iitb", *ISET Journal of Earthquake Technology,* **45**, pp. 41–63.

Wald, D. J., Quitoriano, V., Heaton, T. H., and Kanamori, H. (1999). "Relationships between peak ground acceleration, peak ground velocity, and Modified Mercalli Intensity in California", *Earthquake Spectra*, **15**, pp. 557–564.

Wells, D. L. and Coppersmith, K. J. (1994). " New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement", *Bulletin of Seismological Society of America*, **84**, pp. 974 - 1002.