

# Seismic Hazard Assessment in India

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## SUMMARY:

The current zoning maps in the Indian seismic code are prepared based on earthquake information available up to 1993 and has not been updated since 2002. It is considered that the hazard zoning needs to be re-examined and that the boundaries of zoning areas revised. The code design peak ground acceleration (PGA) for the Maximum Considered Earthquake (MCE) is 0.36 g and the Design Basis Earthquake (DBE) is 0.18 g for service life of structure, for the highest area, Zone V. However, some Indian regions are located in the high seismicity areas of the active Himalayan plate boundary but are indicated to be Zone IV which has an MCE of 0.24 g. These Himalayan regions have experienced several instances of severe to moderate ground shaking and building damage within last 100 years. Consequently it is feared that the design PGA of the Indian code for DBE event is too optimistic and may underestimate the seismic loading in such a high seismicity region.

A preliminary site-specific probabilistic seismic hazard assessment (PSHA) has been carried out to review the potential risk of seismic source zones and the latest earthquake information. The PSHA method combines the knowledge of seismic source zones and their associated earthquake recurrence with appropriate attenuation relationships to produce hazard curves in terms of level of ground motion and an associated annual probability of being exceeded. Design response spectra have been calculated for sites in the Himalayan region and for other major cities in India. The results are compared to those implied by the current Indian seismic code and those from the recent study carried out by the Indian National Disaster Management Authority (NDMA).

*Keywords: India, Seismic Hazard Assessment, Code Based Design, Re-zoning, Near Source Factor*

## 1. INTRODUCTION

The Indian subcontinent is a region that is prone to earthquakes. Between 1990 to 2006, more than 23,000 lives were lost due to six major earthquakes in India. The most notable being the 2001 Bhuj earthquake and the 2005 Kashmir earthquake. Recent newspaper reports and technical papers have highlighted that there is a link between high stress accumulation in the Himalayan region and the global clustering in time of high magnitude tremors since the devastating 2004 quake off the Sumatra coast. In the event of a major earthquake in the Himalayan region, the most affected areas would be one of the most populated areas of the world.

The current zoning maps in the Indian seismic code were prepared based on earthquake information available up to 1993 and has not been updated since 2002. It is thus considered that the hazard zoning needs to be re-examined and that the boundaries of zoning areas revised. This paper presents a site-specific probabilistic seismic hazard assessment (PSHA) carried out to review the potential risk of seismic source zones based on the latest earthquake information. The PSHA method combines the knowledge of seismic source zones and their associated earthquake recurrence with appropriate attenuation relationships to produce hazard curves in terms of level of ground motion and an associated annual probability of being exceeded. Design response spectra have been calculated for sites in the Himalayan region and for other major cities in India. The results are compared to those implied by the current Indian seismic code and those from the recent study carried out by the Indian National Disaster Management Authority (NDMA, 2011).

## 1.1 Indian Seismic Code

The first formal seismic code in India, (IS 1893, Part 1), was published in 1962 and subsequently it has been revised five times and the current version is IS-1893 (Part I), 2002, Indian Standard Criteria for Earthquake Resistant Design of Structures (5th Revision). The major provisions of the code are based on the Uniform Building Code (1997) which is now outdated and has been replaced by International Building Code (2009). The intent of the Indian design code, as with most seismic codes, is to protect life under a rare seismic event, by preventing collapse of the structure or its parts and maintaining structural integrity and residual load capacity.

According to this code the country is divided into four seismic zones – Zones II (MSK intensity VI), Zone III (MSK intensity VII), Zone IV (MSK VIII) and Zone V (MSK intensity IX or more) each associated with a seismic zoning factor ( $Z$ , effective peak ground acceleration) based on anticipated intensity of shaking as shown in Table 1. The zoning map is based on expected maximum seismic intensity on the Modified Mercalli scale.

**Table 1.** Zone factors based on Intensity of shaking (IS-1893, 2002)

Zone II	Zone III	Zone IV	Zone V
0.10 g	0.16 g	0.24 g	0.36 g

## 1.2 General Comments about the Code

The national Seismic Zone map presents a large scale view of the seismic zones in the country ([http://www.nicee.org/IITK-GSDMA\\_Codes.php](http://www.nicee.org/IITK-GSDMA_Codes.php)). The values of the Zone factor ( $Z$ ) specified in the code were arrived at empirically based on engineering judgement and no explicit calculations were done to relate the values to the design life of the structure. Therefore, for important projects, such as a major dam or a nuclear power plant, the seismic hazard is evaluated specifically for that site by performing a probabilistic seismic hazard study.

### 1.2.1 Some specific issues

The provisions of IS 1893:2002 have been critically reviewed by several academics and the key inconsistencies in the use of terminology can be found in [http://www.nicee.org/IITK-GSDMA\\_Codes.php](http://www.nicee.org/IITK-GSDMA_Codes.php). A draft version of the suggested changes to IS 1893:2002 can be seen in the NICEE website. However this has not been approved yet. Some of the key issues are highlighted here.

- The seismic hazard map is not based on probabilistic seismic hazard analysis and thus it is impossible to deduce the probability of occurrence of a certain level of shaking in a given zone based on this code. This map, however, only indicates areas with low, moderate and high seismic hazards based on past earthquake occurrences.
- The code uses two terms which are confusing as they are described in the code. The MCE (Maximum Credible Earthquake) is the most severe earthquake effects considered by this standard. The DBE (Design Basic Earthquake) is the earthquake effects which can reasonably be expected to occur at least once during the design life of the structure. The design approach adopted in this standard is to ensure that structures resist the DBE without significant structural damage though some non-structural damage may occur, and aims that structures withstand a major earthquake (MCE) without collapse. The DBE is taken as half of the MCE values. However, the code does not give a definition on the risk level (the return period) associated with the MCE.
- Some international codes include provisions for sites located in the vicinity of active fault through the inclusion of Near-Source Factors  $N_a$  and  $N_v$ . The value of these factors depends on the Seismic Source Type of the faults in the vicinity of the site. The Indian seismic code completely ignores this aspect and it may be critical for those areas which are in close proximity to faults.

## 2. RECENT PSHA AND MICROZONATION STUDIES BY OTHERS

The National Disaster Management Assessment (NDMA) report: Development of Probabilistic Seismic Hazard Map of India (NDMA, 2011, <http://ndma.gov.in/ndma/eqinformation.html>) has recently been the major government sponsored study to determine the seismic hazard map for India. It is however noted that the NDMA (2011) publication code does not have the status of a building code document. Additionally, for the purposes of urban planning, some metropolitan areas are being microzoned to account for local variations in geology, local soil profile for many cities of the nation where major Infrastructure projects are being envisaged.

## 3. SEISMIC HAZARD ASSESSMENT

There are two basic methods for assessing the seismic ground motion hazard in a particular region or at a specific site, namely deterministic methods and probabilistic methods. A full description of these methods is given in Reiter (1990). A Probabilistic Seismic Hazard Assessment (PSHA) combines seismic source zoning, earthquake recurrence and the ground motion attenuation to produce “hazard curves” in terms of level of ground motion and an associated annual frequency of being exceeded. The elements used to carry out the PSHA in this study are as follows:

- A definition of the seismotectonic source zones that define the geographical variation of earthquake activity.
- A model of earthquake recurrence with respect to earthquake magnitude. There are generally more small (low-magnitude) earthquakes than large (high-magnitude) earthquakes.
- A ground-motion prediction equation (GMPE), or attenuation relationship, is required, which defines what ground motion should be expected at location A due to an earthquake of known magnitude at location B.

The basic methodology adopted is based on that originally proposed by Cornell (1968), that includes integration over the aleatory variability of the ground-motion prediction equations. The probabilistic seismic hazard calculations were carried out using the Arup in-house program *Oasys SISMIC*.

### 3.1 Earthquake Catalogue

The earthquake catalogue in the NDMA report has been used as the catalogue has already compiled many historical and instrumental earthquake sources in India and the overseas (NDMA, 2011). The catalogue dates from BC2474 to AD2008 with  $M_w \geq 4.0$  (Figure 1). Aftershocks were removed by using the Gardner & Knopoff (1974) procedure. As the magnitude provided in NDMA report is already presented in  $M_w$ , magnitude conversion is not required.

The USGS catalogue from AD1973 to AD2008 with  $M_w \geq 4.0$  is also used for independent checking. The magnitude scales conversion is based on the relationships from Johnston (1995) to determine moment magnitude:

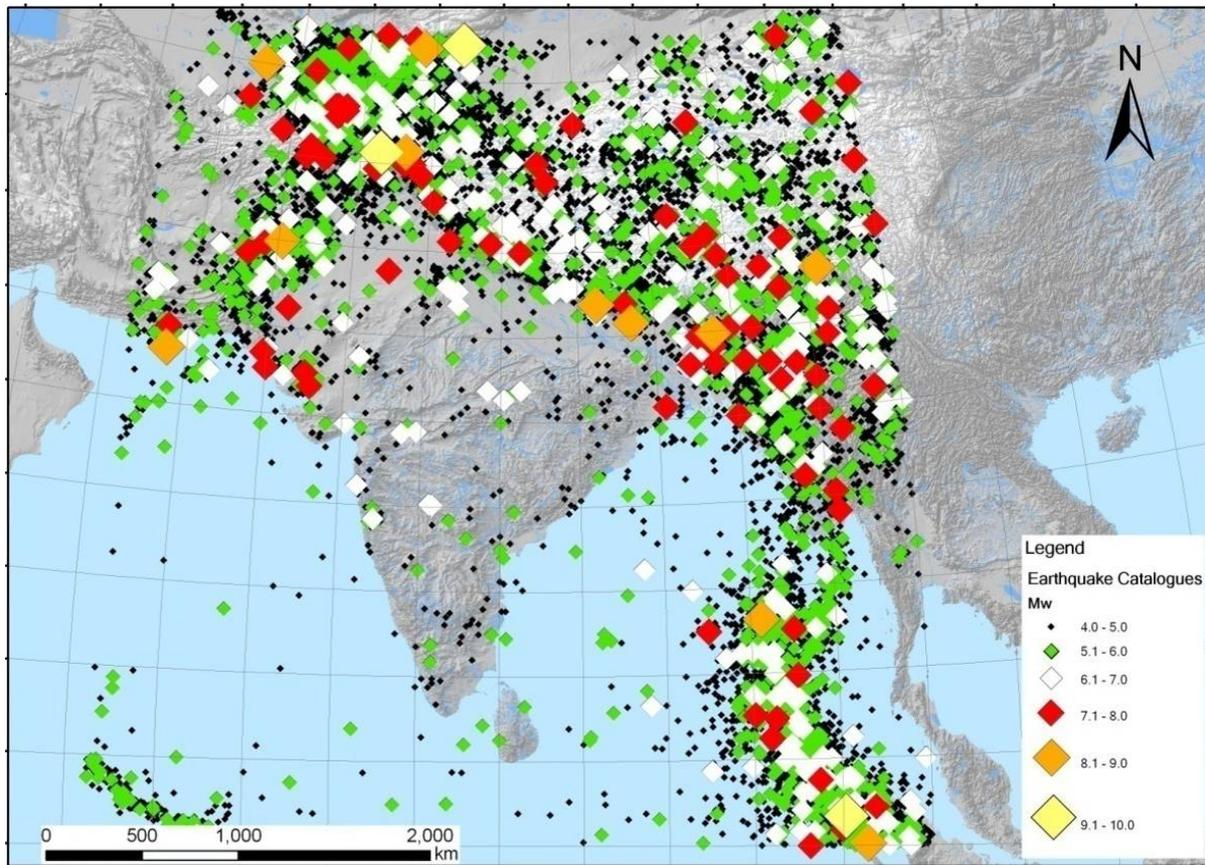
$$\begin{aligned}\log(M_o) &= 18.75 + 0.496(m_b) + 0.094(m_b)^2 \\ \log(M_o) &= 24.67 - 1.077(M_s) + 0.190(M_s)^2\end{aligned}$$

where  $M_o$  is the seismic moment which is related to moment magnitude,  $M_w$ , by the following correlation relationship (Kanamori, 1977):

$$M_w = 2/3 \log(M_o) - 10.7.$$

### 3.2 Tectonic Map

Two tectonic maps extracted from the NDMA report (2011) were used as reference in the Arup work. The first tectonic map includes the Neotectonic faults within the India region and the second one does not specifically consider the Neotectonic activity of the faults but covers a larger region.



**Figure 1.** Earthquake catalogue from NDMA from BC2474 to AD2008 with  $M_w \geq 4.0$  (aftershocks removed)

The earthquake catalogue has been put into a 3D GIS (Geographical Information System) to analyse the earthquake distribution against depth and it was seen that no clear subduction is evident along the Himalaya region.

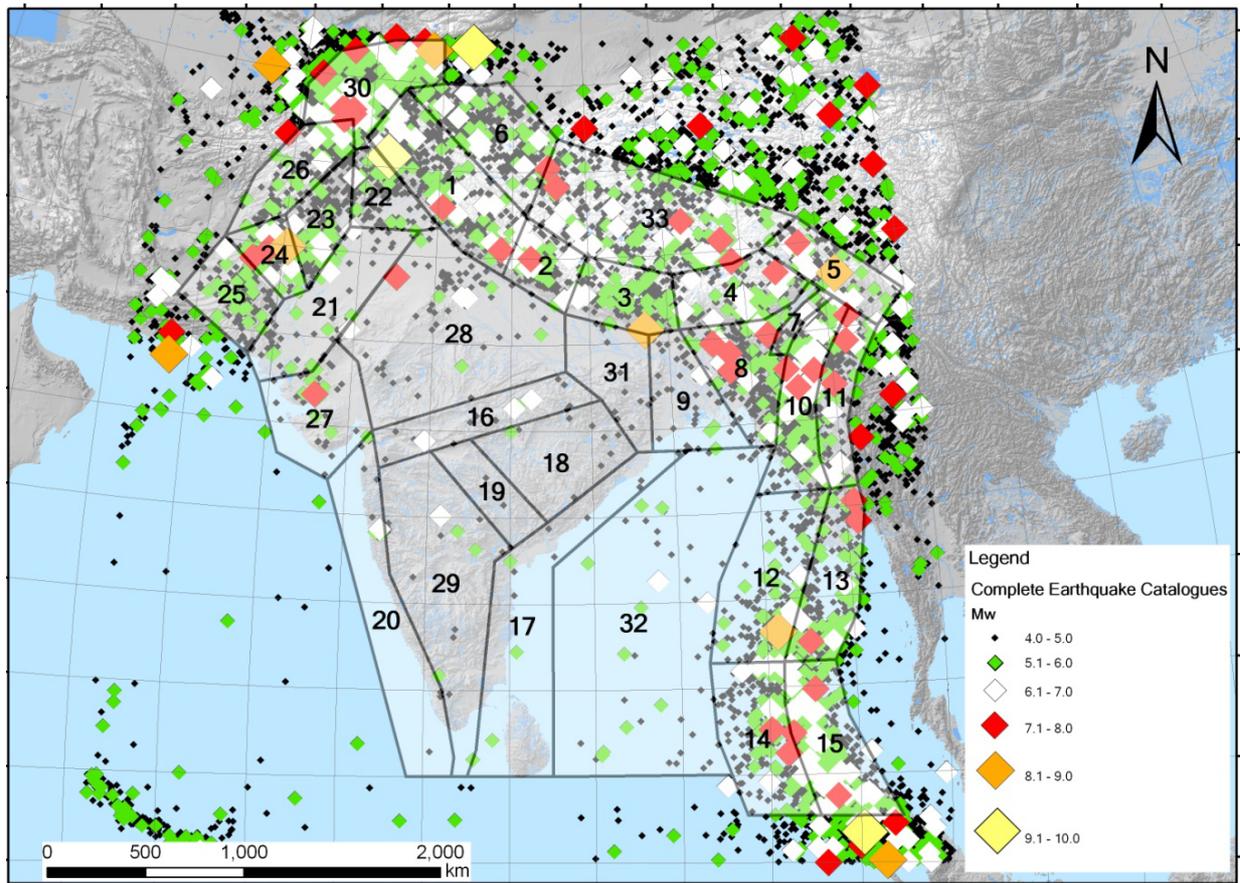
### 3.3 Catalogue Completeness

The statistical completeness of the NDMA catalogue has been assessed by the method proposed by Weichert (1980) in which magnitude-recurrence plots are compared for different time periods. This method is used to identify the time periods for which different magnitude ranges have been well recorded. The following magnitude and time ranges are considered to be complete in the earthquake catalogue.

- 1900 to 2008 for  $M_w \geq 5.5$
- 1970 to 2008 for  $M_w \geq 4.0$

### 3.4 Source Zones

As the Indian plate collides with the Eurasian plate without obvious subduction as mentioned previously, the seismic sources have been modelled as area sources for simplicity. The source zones follow the 32 source zones defined by NDMA report (2011) with an additional source zone (33) to the north of the Indian Himalayas. There are also some changes of the boundaries of Source Zones 8 and 9 based on the seismicity. The boundary of these 33 source zones have also been checked with the spatial distribution of seismicity and the regional tectonic structures and are shown in Figure 2.



**Figure 2.** Seismic source zones with earthquake complete catalogue and regional tectonic structures

### 3.5 Focal Depth Distributions

The focal depth is the depth from ground level to the hypocentre of an earthquake. The depth distributions used for the probabilistic seismic hazard assessment has been determined based upon the focal depth data compiled for the earthquake catalogue and are listed in Table 2.

**Table 2.** The focal depth distribution for each source zone

Depth Distribution	Shallow	Intermediate	Deep
Depth in km (and Weight in %)	0-10 (30)	0-20 (35)	0-25 (10)
	11-20 (15)	21-40 (35)	26-50 (20)
	21-30 (20)	41-60 (20)	51-75 (15)
	31-40 (20)	61-80 (5)	76-100 (15)
	41-50 (15)	81-100 (5)	101-125 (10)
			126-150 (5)
			150-200 (10)
			200-300 (15)
Source zone	7, 8, 9, 16, 17, 18, 19, 20, 21, 27, 28, 29, 31, 32	1, 2, 3, 4, 5, 6, 11, 12, 13, 14, 22, 23, 24, 25, 26, 33	10, 15, 30

### 3.6 Recurrence Curves

The recurrence curves of each source zone were analysed. The methodology proposed by Weichert (1980) is firstly used to get the recurrence values (a and b) for each source zone and the best estimate of a and b values (Gutenberg & Richter, 1954, earthquake recurrence relationship) were refined to fit the observed seismicity of each zones. The recurrence curves from the NDMA (2011) report were also compared. The best fit values were generally consistent with those in the NDMA report.

In total the 33 zones were grouped into two types of tectonic conditions for comparing the observed recurrence curve with the best estimate in this study; they are “Plate Boundary” and “Intraplate”. In addition the “Zones 1 to 4 (Close to Himalayan)”, a subset of the “Plate Boundary” region was studied. The best fit recurrence curves for the zones within each group were summed and compared with the total observed seismicity of each group. The results are comparable (see Figure 3 as an example). The Best Estimate is derived by considering the catalogue completeness.

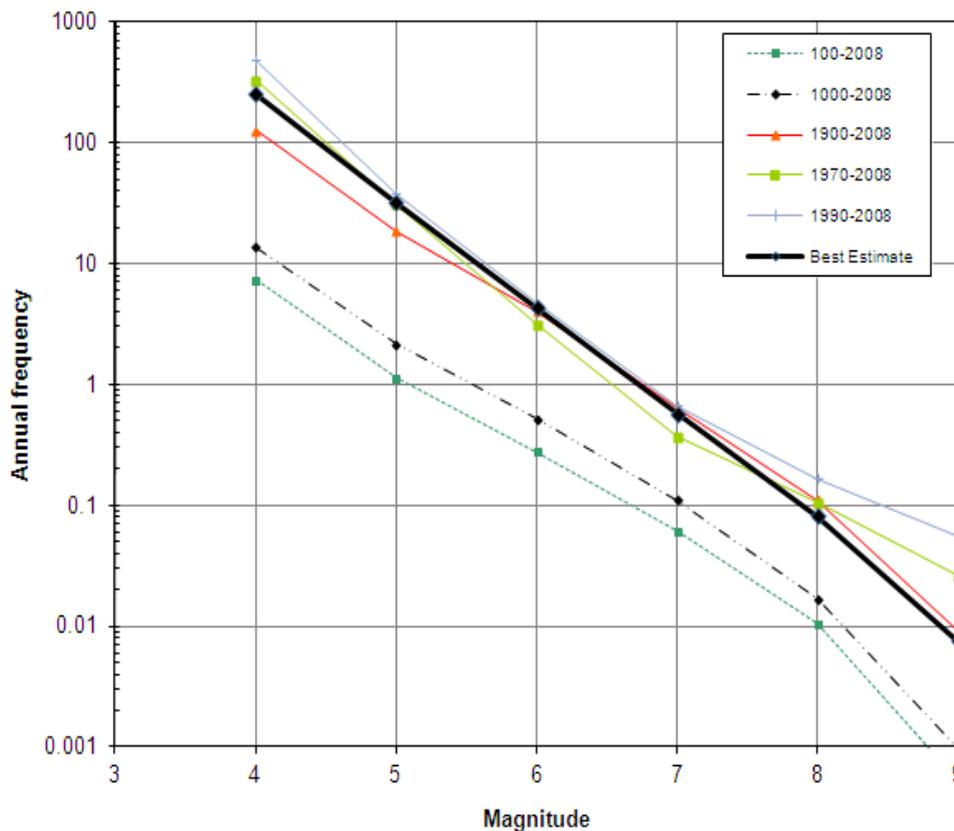


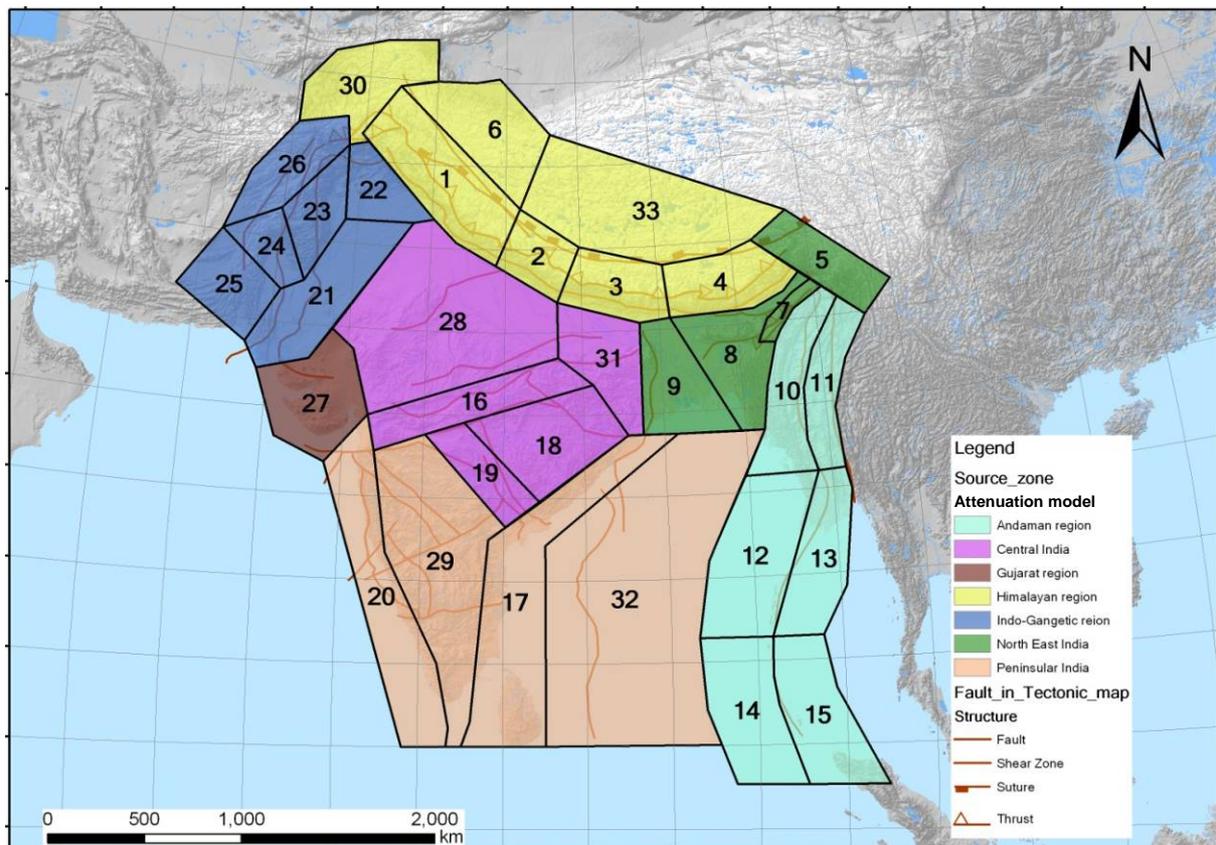
Figure 3. Recurrence plot for Plate Boundary region

### 3.7 Maximum Magnitudes

The maximum earthquake magnitudes were based on the maximum magnitude proposed by NDMA (2011) report by adding an extra magnitude of 0.5 to cater for the maximum considered earthquake. In general, the plate boundary regions have a maximum moment magnitude between magnitudes 8.0 and 9.0, while the intraplate part varies between regions and has maximum magnitudes of 6.5 to 7.0. The maximum magnitude for each source zone has been checked against the observed seismicity to ensure they are not lower than the observed seismicity.

### 3.8 Attenuation Models

Seven attenuation models were extracted from the NDMA report and incorporated into the Arup seismic hazard assessment model. These attenuation models were developed for different locations in India and the source zones were assigned with different attenuation models based on their location (Figure 4). In the PSHA, the attenuation models of the NDMA report (Andaman region, North east India, Himalayan region and Indo-Gangetic region) were weighted with 50% and the other 50% of the weighting was given to the New Generation of Attenuation (NGA) models (Abrahamson & Silva, 2007; Boore & Atkinson, 2007; Campbell & Bozorgnia, 2007) developed for the western north America on shallow crustal conditions were used. For stable crust, 50% intra-plate attenuation models in the NDMA report and 50% of Atkinson & Boore (2006), developed for the continental crust of eastern North America, were used.



**Figure 4.** Attenuation models adopted for different source zones in the NDMA report

## 4. RESULTS

The PSHA was carried out using the Arup in house program *Oasys SISMIC*. Several locations were selected to be analysed in this study. Peak ground accelerations and response spectra have been compared with the results of the NDMA (2011) study and this study for seismic ground motions having 10% & 2% probabilities of being exceeded in the next 50 years.

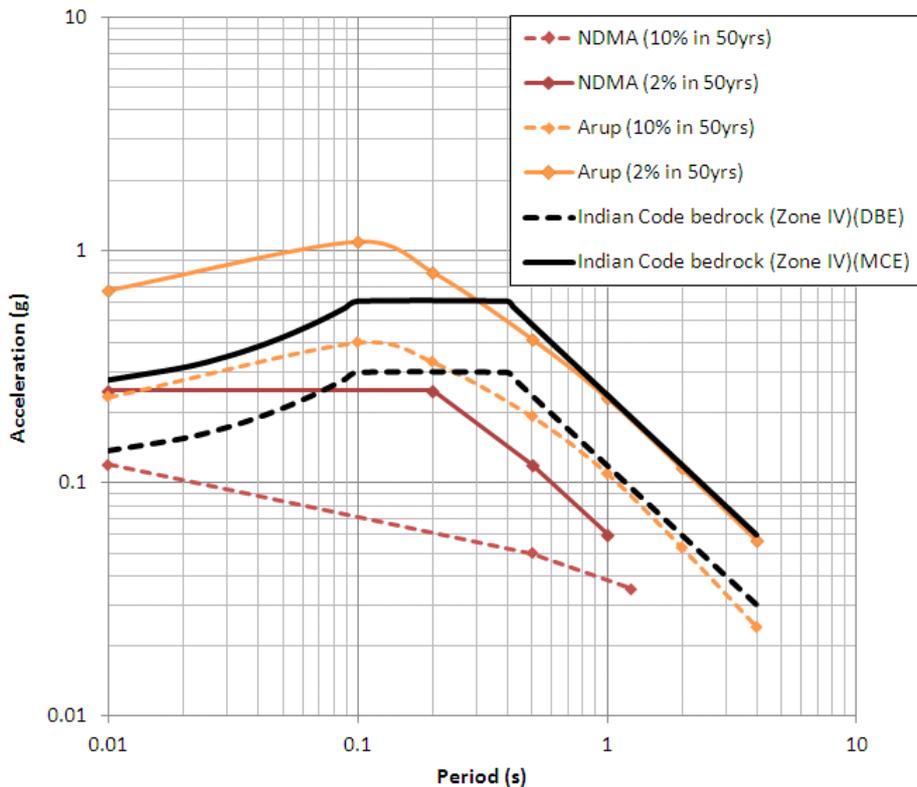
The PGA's having a 10% probability of being exceeded in the next 50 years calculated in this study are compared with those of the NDMA (2011) study in Table 3. The results from the NDMA (2011) report are generally lower than the results in this study except for Mumbai where their results are somewhat higher. The values are also compared with the recommended code values and it can be seen that the code is conservative for most of the country, except for the areas close to the Himalayas.

**Table 3.** Comparison of Peak Ground Accelerations (PGA's) from different studies for major cities in India

Location	IS 1893 Zone	Zone factor based on IS 1893 -2002 for MCE	(PGA's) having a 10% probability of being exceeded in the next 50 years based on this Arup Study	NDMA (2011) PGA's having a 10% probability of being exceeded in the next 50 years	Comment
Delhi	IV	0.24 g	0.065 g	0.08 g	The Zone factor provided by IS – 1893 (2002) is for MCE. The DBE is taken as half of that value
Patna	IV	0.24 g	0.062 g	0.04 g	
Sikkim	IV	0.24 g	0.325 g	0.18 g	
Kolkatta	III	0.16 g	0.135 g	0.09 g	
Mumbai	III	0.16 g	0.047 g	0.09 g	
Bangalore	II	0.10 g	0.033 g	0.02 g	

The response spectra calculated by this Arup study have also been compared with those of the NDMA (2011) study as illustrated in Figure 5 to 7. The results of the NDMA (2011) study only presented limited periods in their spectral acceleration contour plots.

The Indo-Norwegian Programme of Institutional Cooperation on Earthquake Risk Reduction project which is a joint Norwegian and Indian project has recently conducted research on ‘Seismic Risk Reduction in the Himalayas’. The results of their project are presented in Sharma & Lindholm (2010) and have also been compared to the results in this study. As can be seen in Figure 6, the comparison at Dehradun for the 10% and 2% in the next 50 years response spectra agree quite well, especially at periods of 1 and 2 seconds.



**Figure 5.** Response Spectra for Baddi

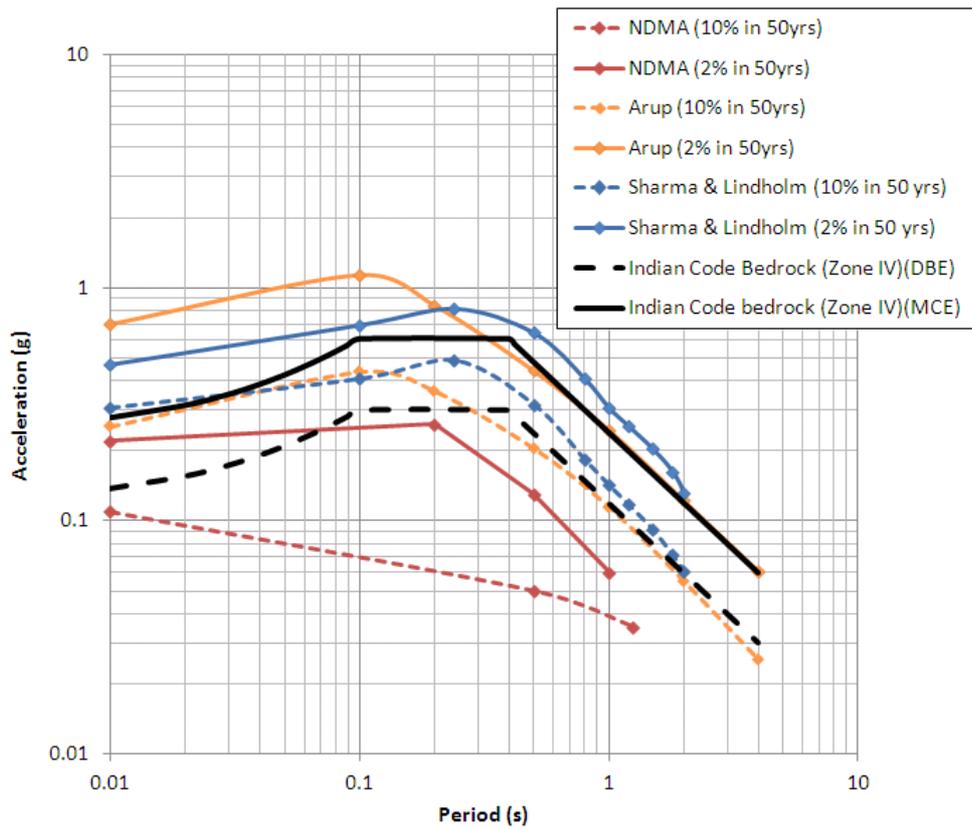


Figure 6. Response Spectra for Dehradun

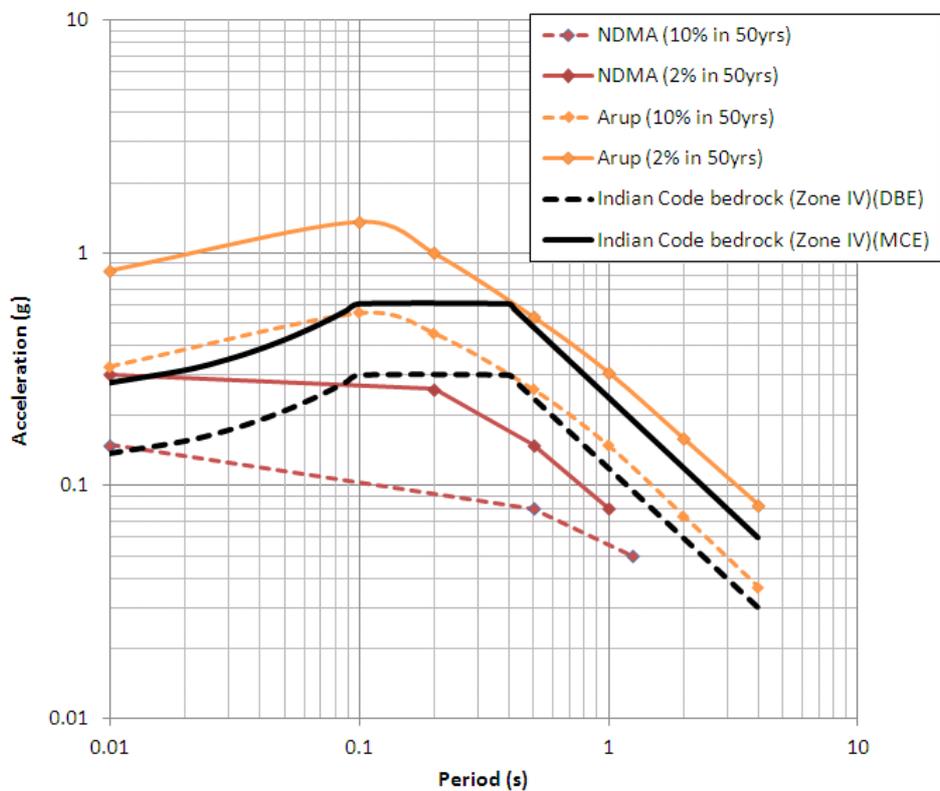


Figure 7. Response Spectra for Sikkim

## 5. SUMMARY & CONCLUSIONS

A site-specific probabilistic seismic hazard assessment (PSHA) has been carried out to review the potential risk of seismic source zones and the latest earthquake information for India. The PSHA method combined the knowledge of seismic source zones and their associated earthquake recurrence with appropriate attenuation relationships to produce hazard curves in terms of level of ground motion and an associated annual probability of being exceeded. Elastic response spectra, with 5% damping, have been calculated for sites in the Himalayan region and for other major cities in India. The results are compared to those specified by the current Indian seismic code and those from the recent study carried out by the Indian National Disaster Management Authority (NDMA).

The Indian seismic code defined peak ground acceleration (PGA) for the Maximum Considered Earthquake (MCE) is 0.36 g and the Design Basis Earthquake (DBE) is 0.18 g for service life of structure, for the highest seismicity area, Zone V. However, some Indian regions are located in the high seismicity areas of the active Himalayan plate boundary but are classified to be in Zone IV which has a PGA of 0.24 g for the MCE event.

This work indicates that the DBE level seismic hazard is underestimated in these regions. This finding is particularly important for the prevalent low-rise construction typically found in India. It is our opinion that further collaborative research is needed to update the seismic hazard map in the India earthquake code.

## REFERENCES

- Abrahamson, N. & Silva, W. (2007). Abrahamson & Silva New Generation Attenuation (NGA) Ground Motion Relations for the Geometric Mean Horizontal Component of Peak and Spectral Ground Motion Parameters. Pacific Earthquake Engineering Research Center, USA.
- Atkinson, G.M. & Boore, D.M. (2006). Earthquake Ground-Motion Prediction Equations for Eastern North America. *Bulletin of the Seismological Society of America* **96**:6,2181- 2205.
- Boore, D.M. & Atkinson, G.M. (2007). Boore-Atkinson New Generation Attenuation (NGA) Ground Motion Relations for the Geometric Mean Horizontal Component of Peak and Spectral Ground Motion Parameters. Pacific Earthquake Engineering Research Center, USA.
- Campbell, K.W. & Bozorgnia, Y. (2007). Campbell-Bozorgnia New Generation Attenuation (NGA) Ground Motion Relations for the Geometric Mean Horizontal Component of Peak and Spectral Ground Motion Parameters. Pacific Earthquake Engineering Research Center, USA.
- Gardener, J.K. & Knopoff, L. (1974). Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian? *Bulletin of the Seismological Society of America* **64**:5,1363-1367.
- Gutenberg, B. & Richter, C.F. (1954). Seismicity of the Earth and Associated Phenomena (Second Edition). Princeton University Press, New Jersey, 310p.
- International Code Council (2009) International Building Code IBC-2009, USA.
- Johnston, A.C. (1995a). Moment magnitude assessment of stable continental earthquakes, Part 1: Instrumental Seismicity. *Geophysical Jn. Int.*
- Johnston, A.C. (1995b). Moment magnitude assessment of stable continental earthquakes, Part 2: Historical Seismicity. *Geophysical Jn. Int.*
- Kanamori, H. (1977). Quantification of earthquake. *Nature* **271**,411-414.
- National Disaster Management Authority (NDMA) (2011), Development of Probabilistic Seismic Hazard Map of India. Govt. of India.
- Reiter, L. (1990). Earthquake Hazard Analysis: Issues and Insights, Columbia University Press, USA.
- Sharma, M. & Lindholm, L. (2010). Use of Characteristic Earthquake Recurrence Modelling for Himalaya Frontal Fault (HFF) in Estimating the Earthquake Hazard Assessment for Dehradun, Uttarakhand, India. *14SEE*.
- Weichert, D.H. (1980). Estimation of the earthquake recurrence parameters for unequal observation periods for different magnitudes. *Bulletin of the Seismological Society of America* **70**:4,1337-1346.