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ORIGINAL PAPER

Seismic hazard analysis of Lucknow considering local and active seismic gaps

Abhishek Kumar · P. Anbazhagan · T. G. Sitharam

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Abstract The Himalayas are one of very active seismic regions in the world where devastating earthquakes of 1803 Bihar–Nepal, 1897 Shillong, 1905 Kangra, 1934 Bihar–Nepal, 1950 Assam and 2011 Sikkim were reported. Several researchers highlighted central seismic gap based on the stress accumulation in central part of Himalaya and the non-occurrence of earthquake between 1905 Kangra and 1934 Bihar–Nepal. The region has potential of producing great seismic event in the near future. As a result of this seismic gap, all regions which fall adjacent to the active Himalayan region are under high possible seismic hazard due to future earthquakes in the Himalayan region. In this study, the study area of the Lucknow urban centre which lies within 350 km from the central seismic gap has been considered for detailed assessment of seismic hazard. The city of Lucknow also lies close to Lucknow–Faizabad fault having a seismic gap of 350 years. Considering the possible seismic gap in the Himalayan region and also the seismic gap in Lucknow–Faizabad fault, the seismic hazard of Lucknow has been studied based on deterministic and the probabilistic seismic hazard analysis. Results obtained show that the northern and western parts of Lucknow are found to have a peak ground acceleration of 0.11–0.13 g, which is 1.6- to 2.0-fold higher than the seismic hazard compared to the other parts of Lucknow.

Keywords Himalayan belt · Central seismic gap · Indo-Gangetic basin · PGA

1 Introduction

Earthquake is the most vulnerable natural hazard and it can be evidenced from the past earthquake events that almost every part of the land is exposed to the earthquake effects directly or indirectly. The amounts of damages caused during such events are very large.

A. Kumar · P. Anbazhagan (✉) · T. G. Sitharam
Department of Civil Engineering, Indian Institute of Science, Bangalore 560 012, Karnataka, India
e-mail: anbazhagan@civil.iisc.ernet.in; anbazhagan2005@gmail.com
URL: http://civil.iisc.ernet.in/~anbazhagan/

Earthquakes, such as 2001 Bhuj in India killing 20,000 lives with an estimated loss of over $5 billion (Wallace et al. 2006), 2004 Sumatra earthquake in Indonesia that took more than 225,000 lives with an insured loss of over $10 billion (RMS 2005), 2010 Haiti which took more than 316,000 lives with an insured catastrophes of $80 billion (Wikipedia 2010; Haiti Earthquake and RMS 2010) and 2011 Sendai in Japan where more than 16,000 were reported dead with a insured loss of over $34 billion in Japan (RMS 2011), are in the continuation. Even though a large improvement in the design codes has been made in the recent years of earthquake-resistant design of structures, the above figures show that still there is a need to improve our present knowledge and the construction practices. Predicting the seismic hazards values can help to design buildings and infrastructures to minimise earthquake hazards. Such studies are more effective in highly active seismic regions of the world where the occurrence of earthquakes is more frequent and magnitudes of such events are relatively large. Subduction zones have been the source of many great events in the history including 1905 Kangra, 1934 Bihar–Nepal, 1960 Chilean, 1985 Mexico, 1989 Loma Prieta, 2004 Sumatra and 2011 Sendai earthquakes. Possibility of seismic gap in the subduction zones makes the scenario worse. Some of the well-known seismic gaps around the world include seismic gaps on San Andreas fault (namely the Loma Prieta gap, San Francisco gap and the Park field gap), the Guerrero seismic gap in Mexico (Kostoglodov et al. 2003), central seismic gap in Himalayan region (Khattri 1987) and Kurile seismic gap in Russia (Natalia et al. 2007; Fedotov 1968). The San Andreas fault and the Himalayan subduction zone are the two most seismically active regions in the world. Much of the work on estimation of seismic activity parameters, seismic microzonation and NEHRP site classification work have been done based on earthquake records on San Andreas fault (Seed and Idriss 1970; Sun et al. 1988; Schnabel et al. 1972; BSSC 2003). Much of these findings have been incorporated in the seismic design codes in the USA. However, similar comprehensive studies are very much demanding for the Himalayan region and its environs due to rapid development, population density and the increasing seismicity. In its present form, the Indian Standard (IS 1893 2002) code has many limitations including delineation of vulnerable seismic sources, active sources study and region-specific seismic design parameters. Seismic hazard estimation at bedrock is the first step to determine the seismic activity parameters for any region and the level of ground shaking due to possible future earthquakes. Namely, two methods including the deterministic seismic hazard analysis (DSHA) and probabilistic seismic hazard analysis (PSHA) are followed for seismic hazard analyses. Numerous researchers have produced seismic hazard maps for various parts of Indian subcontinent. PCRSMJUA (2005) presented the DSHA-based seismic map for Jabalpur city. Iyenger and Ghosh (2004) studied DSHA of Delhi region. Similarly, Raghukanth and Iyengar (2006) produced the seismic hazard map for Mumbai city based on PSHA. Sitharam and Anbazhagan (2009) produced the seismic hazard map for Bangalore considering both DSHA and PSHA. Nath (2006) produced the seismic hazard and the seismic microzonation of Sikkim and Guwahati (Nath 2007). Suganthi and Boominathan (2006) developed the seismic hazard map for the Chennai city. Similarly, many studies can be found on seismic hazard throughout the world. Recently, National Disaster Management Authority (NDMA 2010) developed the probabilistic seismic hazard map for the entire India. Most of the earlier published seismic hazard maps were at macro-level, and PGA values were arrived based on old GMPEs (ground motion prediction equations). One of the controlling parameters for seismic hazard estimation is the GMPE. In this work, seismic hazard analysis of Lucknow has been attempted by DSHA and PSHA using representative GMPEs for the region.

2 Study area and seismicity

The Indo-Gangetic basin (IGB) covers an area about 250,000 km^2. It extends between the latitude 24°–30°N and longitude 77°–88°E. Approximately 200 million people live in the basin which defines it as one of the most densely populated regions of India. The Ganga is the main river of the basin that flows from the Himalayas in the north to the Bay of Bengal in the north-west.

The origin of IGB is related with the collision between Eurasian and Indian plate, which has been causing the rise in the Himalayas since the Cenozoic era till date. At the same time when this collision started, the weathering by the River Ganga during its course of flow also took place. Further, these sediments underwent gradual deposition in the lower courses. Although a major part of the sediment was deposited in Ganga Delta, a considerable amount of sediments had also been deposited in the Indo-Gangetic basin (IGB). This gradual deposition continued for a long period, which had resulted in a large thick fluvial deposition. This deposit consists of different layers of sediments with an overall thickness of up to several kilometres in many parts of IGB (Sinha et al. 2005; Anbazhagan et al. 2012a). Many important urban centres are located in various parts of IGB such as Lucknow, Meerut, Agra, Aligarh, Allahabad, Gorakhpur, Ghaziabad and Jhansi. Since the IGB lies close to the seismically active Himalayan belt, most of the urban centres of IGB are vulnerable to great earthquakes in the Himalayan belt. In addition to the seismicity of Himalayan region, IGB itself consists of many active tectonic features such as Delhi–Haridwar ridge from Delhi to Gharwal Himalayas, Delhi–Muzaffarabad ridge running from Delhi to Kathgodam, Faizabad ridge from Allahabad continuing towards Kanpur, Lucknow ending in Nepal and Monghy–Saharsa ridge. Some of the earthquakes which have occurred in the IGB includes 1833 Bihar, 1934 Bihar–Nepal, 1988 Bihar and 2011 Delhi. The above discussion has clearly highlighted that urban centres in IGB are at great seismic risk. Such a risk is not only because of the seismic scenario in Himalayan region but also due to regional seismic activity in the IGB as well.

The study area of 'Lucknow' lies in the central part of IGB. Lucknow, the capital of Uttar Pradesh, also known as the 'City of Nawabs', is located in the historical region of Awadh. It is a multicultural city, famous for beautiful gardens, music and architectural styles. The study region of Lucknow city covers an area of about 370 km^2 and with its centre point at Vidhan Sabha having latitude 26°51.6′N and longitude 80°54.6′E. Figure 1 shows the study area of Lucknow with Himalayan belt and IGB. The elevation difference in the entire study area is about 29 m from its highest elevation of 129 m in the area of the Sarda canal and its lowest elevation of 100 m on the south-eastern Dilkusha garden. The River Gomati flows from the middle of Lucknow in north-west–south-east (Husainabad–Dilkusha garden). The study area of Lucknow lies in the Seismic zone III in current Seismic zonation map of India (IS 1893 2002) with an average design acceleration coefficient of 0.08 for design basis earthquake.

The study area of Lucknow is surrounded by several ridges and deep soil terrains of IGB. The southward expansion of IGB in the middle Pleistocene caused variable deposition over the earlier deposited sediment layers. As a result, a number of ridges have been formed under the IGB. These include Delhi–Hardwar ridge, Faizabad ridge, Monghy–Saharsa ridge and Mirzapur–Ghazipur ridge (Singh 2012). Two important depressions that lie in IGB are the Gandak Deep and the Sarda Deep (Sinha et al. 2005). The Lucknow–Faizabad fault connects the Sarda deep in the north-west to Faizabad ridge in the central part of IGB (Sinha et al. 2005). The Disaster Risk Management Program of the Ministry of Home Affairs in association with the United Nations Development Program (UNDP 2008)

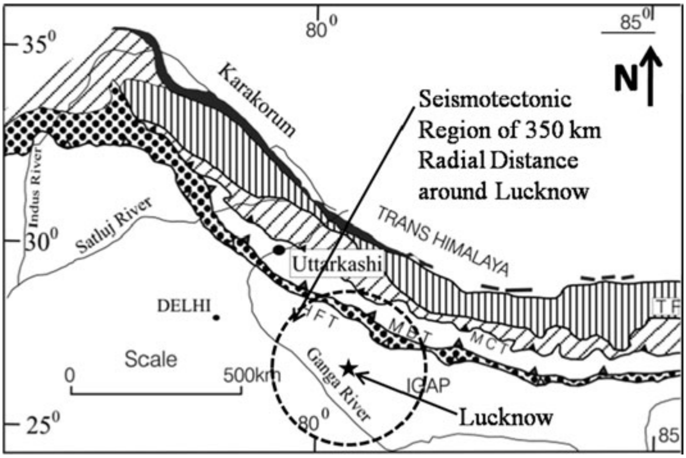


Fig. 1 Study area of Lucknow along with the radial extent of seismotectonic region used for this study (modified after Dubey 2010)

has highlighted that Lucknow city lies within of the Lucknow–Faizabad fault (Nadeshda 2004). This fault lies in a curved fashion running east to west from Allahabad to Kanpur and then bend towards the north-east towards Lucknow continues towards the Himalayas in Nepal. As per the above study, this fault has been inactive for 350 years (Nadeshda 2004). Researchers have highlighted that this fault has been under heavy stress for a long time and has the potential to cause a great earthquake in the future. With the Himalayas rise due to the subduction of the Indian plate under Eurasian plate, a movement of the Indian plate by 5.25 m could cause an earthquake as high as magnitude 8 on the Richter scale on Faizabad fault as per Earthquake Mitigation Department, Government of Uttar Pradesh (Nadeshda 2004). This fault passes through the Lucknow district. Other faults that lie under the state of Uttar Pradesh include Delhi–Hardwar ridge running from New Delhi towards Garwal Himalayas. Delhi Muzaffarnagar ridge is trending in east–west running from New Delhi to Nepal. Muradabad fault running north-east to south-west is an extension of great boundary fault between the Aravalli and Vindhyas (Encyclopedia 1997) and Bhairwan fault passing in close proximity to Allahabad about 180 km from Lucknow. Past seismic study in and around Lucknow highlights no recorded earthquakes with epicentre in Lucknow, but many events have occurred in close vicinity of Lucknow. These include 1925 Sultanpur earthquake ($M_L = 6.0$), 1961 Kheri earthquake ($M_L = 6.0$) and 1965 Gorakhpur earthquake ($M_L = 5.7$). All these earthquakes have occurred within 250 km radius of Lucknow (ASC 2010).

Apart from the local seismic activity around Lucknow, the area also lies within a radial distance of 350 km from Main Boundary Thrust (MBT) and the Main Central Thrust (MCT), where many devastating earthquakes have been reported. Historical evidences show severe damages during 1803 Nepal earthquake which caused damage to Imambada and Roumi Darwaza in Lucknow (Bilham et al. 2001). Similarly, 1833 Kathmandu earthquake caused MMI of VII in Lucknow, which was located at a distance of more than 500 km from the epicentre (Bilham et al. 1995). Based on geological similarities between Ahmedabad and Lucknow (UEVRS 2004), the area can undergo massive destruction due to any future earthquake in Himalayan region similar to catastrophic failure which has been observed at Ahmedabad during the 2001 Bhuj earthquake. Considering the above seismic aspects of areas in and around Lucknow, Lucknow urban centre can be considered under a high potential for seismic hazard due to any future earthquake. Thus, there is a need to establish representative seismic hazard map considering updated seismic data and recent GMPEs for the Lucknow.

3 Seismotectonic map

In order to conduct the seismic hazard analysis of any urban centre, information about active seismic features such as faults, lineaments and shear zones with all the earthquakes occurred close by are required to be compiled in the form of a map. Such a map is called the 'Seismotectonic map' for the study area. The radial extent of seismotectonic area for seismic hazard analysis is generally 300 km from the centre of the study area (Gupta 2002). However, in case of more seismically active and geologically weaker regions, earthquake damages were experienced beyond 500 km from epicentre (Anbazhagan et al. 2012b). Since, the study area of Lucknow comes within 350 km from the Main Boundary Thrust (MBT), the radial extent of seismotectonic area for Lucknow has been considered as 350 km for the present work.

Geological Survey of India (GSI) produced the seismotectonic atlas of India showing significant earthquakes and isoseismal maps along with the tectonic features for entire country at a scale of 1:1,000,000 SEISAT (2000). Forty-three sheets with each sheet covering an area of 3° × 4° were developed. For the present work, 9 out of 43 sheets have been digitised showing all the linear features within 350 km radial distance around Lucknow and a source map has been developed. Since well distribution of linear sources in the seismotectonic province is available, no aerial source has been considered in this study. Main Boundary Thrust (MBT) and Main central Thrust (MCT) demarcate the northern boundary of the study area. Since the names of all faults were not available in the literature, these have been nomenclature in the present work for further discussion.

All the past event data within 350 km around Lucknow have been collected from different resources such as the Indian Meteorological Department (IMD), United State Geological Survey (USGS), Northern California Earthquake Data Centre (NCEDC), National Earthquake Information Centre (NEIC) and Geological Survey of India. A total of 1831 events have been collected; the collected data consisted of epicentre coordinates, focal depth, date, month, year and magnitude in different magnitude scale. These data were in different magnitude scales such as local magnitude or Richter magnitude (M_L), body wave magnitude (m_b) and surface wave magnitude (M_s). In order to achieve homogeneity in the database, all the collected events have been converted to moment magnitude (M_w). Numerous researchers have developed correlations between different magnitudes (Stromeyer et al. 2004; Castellaro et al. 2006; Scordilis 2006; Bormann et al. 2007; Thingbaijam et al. 2008; Sreevalsa et al. 2011). In the present work, Scordilis (2006) worldwide correlation has been used.

Declustering of earthquake data is required in order to filter main events from foreshocks and aftershocks. The phenomenon of earthquake is modelled based on Poisson's distribution, which implies that earthquake occurs randomly with no memory of time, size and location. Thus, all the foreshocks and aftershocks need to be removed before performing any seismic hazard analysis. In the present work, all the 1831 events have been declustered using static window method (Reasenberg 1985). As per this method, all the events that are falling within 30 km distance and within a time gap of ±30 days will be grouped as one category. The maximum magnitude event in that category will be called as the main shock, while other events in that category will be treated as foreshocks or aftershocks. This approach has been applied for the whole data set to filter independent events. A total of 496 events have been obtained after declustering the 1831 events. For further analysis, only those events with $M_w \geq 4$ were considered since lesser magnitudes are not strong enough to produce significant ground motions for building damage. Superimposing the declustered data on the source map, a seismotectonic map has been developed. Figure 2 shows the seismotectonic map of Lucknow showing all the active faults along with the event data. It can be observed from Fig. 2 that in areas near to MBT and MCT, events are more densely located when compared to other areas. Based on event distribution, the whole seismotectonic area has been divided into two regions separated by a rectangle as shown in Fig. 2. Region I belongs to events inside the rectangle covering MBT and MCT, while Region II represents event outside the rectangle. For further study, both the regions have been analysed separately.

4 Data completeness and the recurrence relation

The seismic hazard analysis for any region is solely governed by its past seismicity. Thus, in order to forecast the ground motion due to future earthquake, it is mandatory to estimate the magnitude frequency relation, that is the seismicity pattern of the region based on past data. The seismic recurrence rate can be estimated accurately if the collected data set is complete. Hence, the collected earthquake data have to be analysed for both the regions separately for its completeness. Stepp (1972) proposed a method to determine the duration of completeness by dividing the homogenised data into small bins considering the variance of each bin as the same. In order to estimate an efficient variance for over all the data, the occurrence of earthquakes can be modelled as Poisson's distribution. Detailed procedure for completeness analysis as per Stepp (1972) can be found in Anbazhagan et al. (2009). Stepp (1972) method has been applied for the completeness analysis of earthquake data of

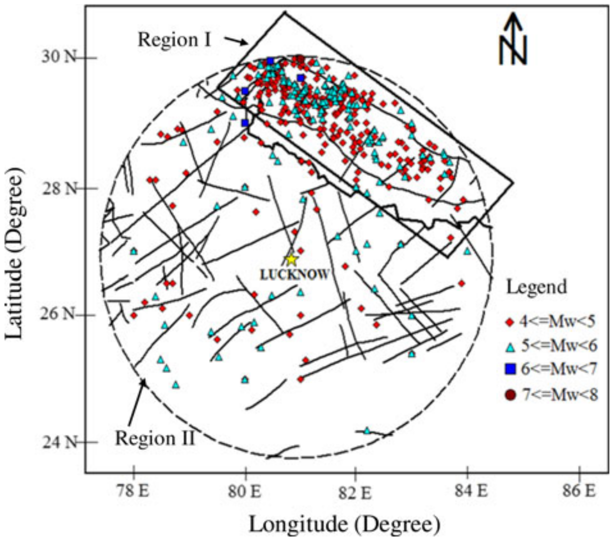


Fig. 2 Seismotectonic map of Lucknow urban centre

both Region I and Region II. The total data available for Region I cover a time period from 1840 to 2010 (or 170 years) as given in the Table 1, while the data for Region II cover a time period from 1830 to 2010 (or 180 years) as given in the Table 2. Both the databases have been analysed separately to check for the data completeness of each region. Figures 3 and 4 show the variation of the standard deviation with respect to different magnitude class for Region I and Region II, respectively. It can be observed from Fig. 3 that the on-standard variation plots are found to be approximately parallel to $1/\sqrt{T}$ line for the last 80 years (1930–2010), which resembles that the earthquake <5 is complete for the last 80 years and higher magnitudes are completed for 130 years. Similarly, Fig. 4 also shows that for Region II also, the data are complete for the last 80 years (1930–2010).

Maximum magnitude and the frequency of occurrence of various magnitude events can be estimated once the recurrence relation for the region is known. Gutenberg and Richter (1956) proposed the following form of the recurrence relation considering the exponential distribution of event size of each fault.

$$\log(N) = a - bM \tag{1}$$

where N resembles the number of earthquakes of magnitude M, 'a' and 'b' are positive real constants in which 'a' denotes the seismic activity (log number of events with $M = 0$) and 'b' describe the relative abundance of large to small shocks (Gutenberg and Richter 1956). Once the earthquake catalogues have been checked for the completeness, the complete portions of data are analysed to determine the 'a' and 'b' parameters for both the regions. The number of earthquakes in each magnitude class from the complete data set in the last 80 years will give the frequency of exceedence of that magnitude class. Once the frequency of exceedence versus the magnitude value is known, it can be used to determine the

Table 1 Data used for completeness analysis of Region I

Starting year	Ending year	Time interval (years)	Number of event of various magnitude range			
			$4 \leq M_w \leq 4.9$	$5 \leq M_w \leq 5.9$	$6 \leq M_w \leq 6.9$	$7 \leq M_w \leq 7.9$
2010	2000	10	108	20	0	0
2010	1990	20	186	50	0	0
2010	1980	30	235	75	1	0
2010	1970	40	242	90	1	0
2010	1960	50	244	106	3	0
2010	1950	60	244	106	4	0
2010	1940	70	244	106	4	0
2010	1930	80	244	107	4	1
2010	1920	90	244	107	4	1
2010	1910	100	244	107	4	1
2010	1900	110	244	107	4	1
2010	1890	120	244	107	4	1
2010	1880	130	245	107	4	1
2010	1870	140	245	107	4	1
2010	1860	150	245	107	4	1
2010	1850	160	245	107	4	1
2010	1840	170	245	108	4	1

Table 2 Data used for completeness analysis of Region II

Starting year	Ending year	Time interval (years)	Number of event of various magnitude range			
			$4 \leq M_w \leq 4.9$	$5 \leq M_w \leq 5.9$	$6 \leq M_w \leq 6.9$	$7 \leq M_w \leq 7.9$
2010	2000	10	17	11	0	0
2010	1990	20	52	31	1	0
2010	1980	30	64	40	1	0
2010	1970	40	66	40	1	0
2010	1960	50	66	41	1	0
2010	1950	60	66	41	1	0
2010	1940	70	66	41	1	0
2010	1930	80	66	41	1	0
2010	1920	90	66	41	1	0
2010	1910	100	66	41	1	0
2010	1900	110	66	41	1	0
2010	1890	120	66	41	1	0
2010	1880	130	66	42	1	0
2010	1870	140	66	42	1	0
2010	1860	150	67	44	1	0
2010	1850	160	67	47	1	0
2010	1840	170	67	50	1	0
2010	1830	180	67	52	1	0

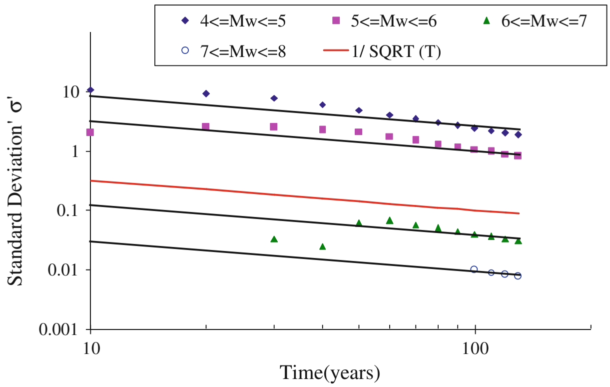


Fig. 3 Variation of standard deviation with respect to magnitude classes and time window for Region I

Gutenberg–Richter (G–R) recurrence law for that zone. Figures 5 and 6 show the G–R recurrence law for Region I and Region II with correlation coefficients of 0.95 and 0.73, respectively. The '*b*' values for Region I and Region II are 0.86 and 0.80, respectively. It can be observed from Fig. 6 with magnitude interval of 0.5 that the data are slightly scattered which may be because of the fact that not many events of higher magnitude events ($M_w > 6$) are available for Region II.

A comparison of '*b*' parameter for both the regions found in the present study with earlier studies has been given in Table 3. These values are found comparable with macro-zone study by NDMA (2010), Nath and Thingbaijam (2011) and Sreevalsa et al. (2011).

Fig. 4 Variation of standard deviation with respect to magnitude classes and time window for Region II

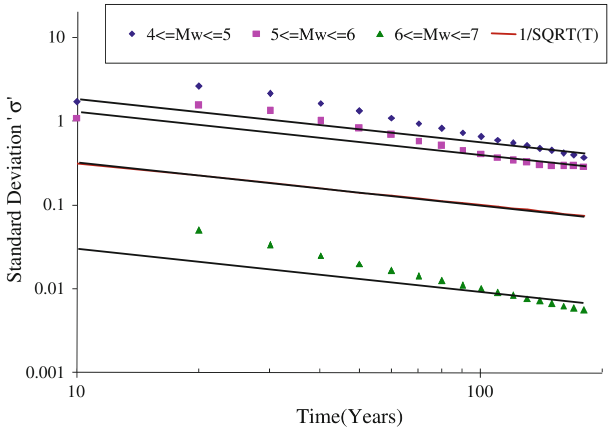
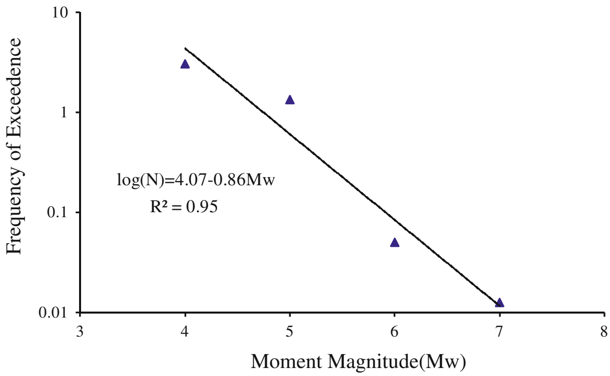


Fig. 5 Gutenberg–Richter relation for the Region I



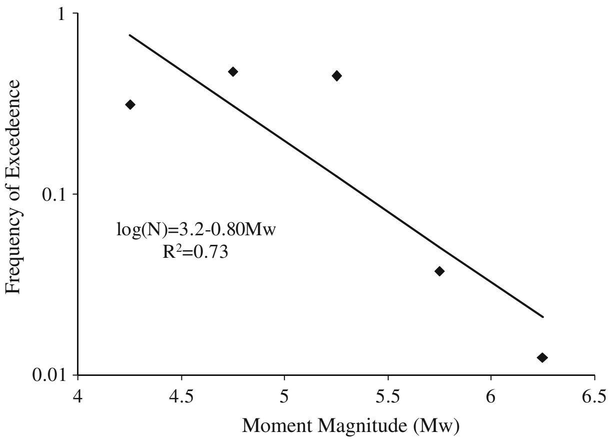


Fig. 6 Gutenberg–Richter relation for the Region II

NDMA (2010) gave the '*b*' value for Region I as 0.73. Mahajan et al. (2010) gave the '*b*' value for Region I as 0.80. For Region II, NDMA (2010) gave the '*b*' value as 0.81 for 28 seismicity source zones. Similarly, based on declustered data by Sreevalsa et al. (2011), the

b values for Region I and Region II were given as 1.0 and 0.85, respectively. Thus, from the literature, it can be observed that there is a wide variation in the 'b' value obtained. NDMA (2010) presented the value of 'a' for Region I and Region II as 3.15 and 1.16 in comparison with the value of 'a' in the present work as 4.07 and 3.2. These values were given by NDMA (2010) based on a bigger area compared to the seismotectonic map considered in the present study.

5 Maximum magnitude estimation (M_{max})

The complete earthquake catalogue for any region represents a very small portion of its total seismic activity. Thus, based on complete catalogue, it is very difficult to understand the complete potential of any region or source for future seismicity. The maximum magnitude (M_{max}) is defined as the upper limit of the magnitude or the largest possible earthquake in any region or seismic source. The maximum observed magnitudes on each fault may not represent the full potential of that fault, since the earthquake catalogue has been found complete only for the last 80 years. Thus, M_{max} for each fault has to be been estimated in this work considering two methods given below;

1. Kijko and Sellevoll (1989) have given method to estimate maximum magnitude considering doubly truncated Gutenberg–Richter relation as given below. This method is only valid when β for the region is known (CASE I; Kijko and Sellevoll 1989).

$$M_{max} = m_{max}^{obs} + \frac{E_1(n_2) - E_1(n_1)}{\beta \exp(-n_2)} + m_{min} \exp(-n) \quad (2)$$

where M_{max} is the largest possible earthquake magnitude, m_{max}^{obs} is the maximum observed magnitude on each fault, and n is the total earthquakes above m_{min} (in the present study, minimum magnitude 'm_{min}' for the region of interest has been considered as 4), $n_1 = {}^{n}/\{1 - \exp[-\beta(m_{max} - m_{min})]\}$, $n_2 = n_1\{\exp[-\beta(m_{max} - m_{min})]\}$, $E_1(\cdot)$denotes an exponential integration function which can be estimated as $E_1(z) = \frac{z^2 + a_1 z + a_2}{z(z^2 + b_1 z + b_2)} \exp(-z)$, where $a_1 = 2.334733$, $a_2 = 0.250621$, $b_1 = -3.330657$ and $b_2 = -1.681534$ (Abramowitz and Stegun 1970). The above approach for the estimation of maximum expected magnitude as per Kijko and Sellevoll (1989) has been used in many of the seismic hazard studies worldwide as well as in India. In the absence of any regional values of the coefficients given in Eq. 2 for the study area, values as per Kijko and Sellevoll (1989) have been used in this work.

Table 3 Comparison of seismic parameters 'b' obtained in this study with previous published values

Region I	Region II
0.86 (present work)	0.80 (present work)
0.73 (NDMA 2010)	0.81 (NDMA 2010)
1.0 (Sreevalsa et al. 2011)	0.85 (Sreevalsa et al. 2011)
0.80 (Mahajan et al. 2010)	–
0.65 (Kumar 2012)	–

The value β for Region I (1.98) and Region II (1.85), the number of earthquakes with magnitude >4 (n), m_{max}^{obs} for each fault and m_{min} as 4 and the value of M_{max} have been estimated using the Eq. (2).

2. M_{max} magnitude has also been estimated by adding a constant value of 0.3, if the m_{max}^{obs} is <5 (M_w) and add 0.5 for m_{max}^{obs} >5 to the m_{max}^{obs} value of each fault similar to NDMA (2010).

Table 4 lists the values of M_{max} for each fault obtained from the above two methods. The absolute maximum value of M_{max} between the two approaches has been considered for each fault to estimate hazard values.

6 Seismic hazard analysis

Deterministic seismic hazard analysis (DSHA) and probabilistic seismic hazard analysis (PSHA) are widely used to perform the seismic hazard of any region. Both the above approaches forecast the amount of ground shaking in terms of peak ground acceleration (PGA) and/or spectral acceleration (SA) based on the past seismicity and projected future earthquake magnitude. Detailed steps and procedure for both approaches can be found in Kramer (1996). Using these procedures, separate MATLAB codes have been generated to perform the DSHA and PSHA for the study. These codes were validated with the results of EM-1110 (1999). In order to perform the seismic hazard analyses of Lucknow urban centre, the whole city area has been divided into 225 grids with each grid of size 0.015° × 0.015° along the latitude and the longitude, respectively. Following the procedural steps, the seismic hazard analyses have been performed for each grid. Further the ground motion parameters obtained for all the grids were mapped using Kriging interpolation method.

6.1 Deterministic seismic hazard analysis

Deterministic seismic hazard analysis (DSHA) provides the worst scenario earthquake without considering its likelihood during the design life of the structure. Thus, the results obtained after DSHA are too conservative and thus are not highly economical. Thus, the results from such analyses can be used in preliminary stages while performing seismic hazard analysis and also for very important structures such as nuclear power plants, telecommunication towers, dams, bridges.

In the present work, the DSHA of Lucknow urban centre has been carried out considering earthquake catalogue discussed earlier. In total, 47 earthquake sources have been found which have experienced earthquake magnitude of more than 4 in the past within 350 km radial distance around Lucknow. Since the details of linear tectonic features of the region are available in SEISAT (2000), no aerial sources have been considered for the study (See Fig. 2). One crucial step in any seismic hazard program is the appropriateness of the GMPE selected. For the present work, three GMPEs have been selected. The first GMPE given by Kanno et al. (2006) was highlighted as the best suitable GMPE for the Himalayan region by Nath and Thingbaijam (2011). Secondly, NDMA (2010) proposed GMPE for Himalayan region which was later used for the probabilistic seismic hazard analysis for the entire country. The third GMPE was developed by the authors for the microzonation of Lucknow based on the combined earthquake data set of recorded and

Table 4 Seismic sources used in the study and M_{max} based on two methods

Fault name	Fault coordinates				M_{max} observed	M_{max} estimation		M_{max} considered
	Lat 1 (°)	Long 1 (°)	Lat 2 (°)	Long 2 (°)		Kijko and Sellevoll (1989)	By incremental value	
F1	28.66	78.15	28.68	78.52	5.8	5.8	6.1	6.1
F113	29	78.83	28.05	79.24	5.8	5.8	6.1	6.1
F114	28.99	79.72	27.84	79.19	5.2	5.2	5.5	5.5
F115	27.12	77.64	28.95	80.07	4.9	4.9	5.2	5.2
F116	28.09	79.16	27.78	80.44	5.2	5.2	5.5	5.5
F117	28.17	80.42	26.97	80.89	4.8	4.8	5.1	5.1
F118	28.05	81.51	27.89	81.01	5.3	5.3	5.6	5.6
F119	27.84	81.11	26.77	80.67	4.6	4.6	4.9	4.9
F121	26.1	81.81	27.83	81.23	4.9	4.9	5.2	5.2
F122	26.83	82.06	27.92	81.68	5.6	5.6	5.9	5.9
F123	27.69	82.38	27.11	81.49	5	5.0	5.3	5.3
F125	26.99	82.69	26.6	82.4	4.9	4.9	5.2	5.2
F127	25.56	83.17	26.69	81.98	5.1	5.1	5.4	5.4
F128	27.14	83.72	26.47	82.8	4.8	4.8	5.1	5.1
F129	26.51	83.98	26.46	82.86	4.6	4.6	4.9	4.9
F131	26.23	83.37	25.92	82.33	4.9	4.9	5.2	5.2
F133	26.11	84.88	27.56	83.71	4.6	4.6	4.9	4.9
F134	25.72	83.91	25.59	83.63	5.1	5.1	5.4	5.4
F152	24.18	82	24.12	82.67	5.3	5.3	5.6	5.6
F154	24.18	82.01	24.1	82.19	5.3	5.3	5.6	5.6
F2	28.64	77.87	27.87	77.99	6.2	6.3	6.5	6.5
F223	25.78	83.65	25.25	82.51	4.7	4.7	5	5
F224	25.95	83.73	25.01	81	4.3	4.3	4.6	4.6
F225	25.56	82.03	25.2	81	4.7	4.7	5	5
F227	26.07	80.09	26.48	80.94	5.6	5.6	5.9	5.9
F228	25.27	79.39	25.88	80.11	5.5	5.5	5.8	5.8
F231	26.47	78.42	27.23	79.33	5.1	4.9	5.2	5.2
F260	25.19	78.04	26.17	79.04	5.5	5.5	5.8	5.8
F261	26.07	77.99	26.41	79.31	5.1	5.1	5.4	5.4
F272	24.52	80.04	24.99	80.77	5.2	5.2	5.5	5.5
F279	23.49	81.02	23.5	81.13	6.5	6.6	6.8	6.8
F299	25.4	80.22	26.25	81.91	4.6	4.6	4.9	4.9
F3	28.39	77.81	27.92	77.9	6.2	6.3	6.5	6.5
F501	28.94	82.32	28.08	81.7	5.7	5.7	6	6
F505	27.92	83.62	28.33	83.8	4.7	4.7	5	5
F508	26.79	78.03	27.84	79.86	5.2	5.2	5.5	5.5
F90	29.86	79.22	29.85	79.33	5.4	5.4	5.7	5.7
F92	30.43	80.68	29.39	79.27	6.4	6.5	6.9	6.9
F97	29.42	80	29.02	80.02	4.8	4.8	5.3	5.3
F98	29.94	80.57	29.42	80.02	4.9	4.9	5.4	5.4

Table 4 continued

Fault name	Fault coordinates				M_{max} observed	M_{max} estimation		M_{max} considered
	Lat 1 (°)	Long 1 (°)	Lat 2 (°)	Long 2 (°)		Kijko and Sellevoll (1989)	By incremental value	
FA1	28.45	83.04	28.03	82.4	5.3	5.3	5.8	5.8
MBT	27.55	84.9296	29.96	78.34	5.6	5.6	6.1	6.1
MCT	30.49	79.17	28.218	84.75	7	7.2	7.5	7.5
F226	25.72	80.69	26.6	79.85	4.6	4.6	5.1	5.1
F509	26.51	77.99	26.38	77.67	4.8	4.8	5.3	5.3
F127	26.68	81.97	25.56	83.16	5.1	5.1	5.6	5.6
F132	26.1	83.66	26	82.19	4.6	4.6	5.1	5.1

simulated ground motions for the Himalayan region. Detailed discussion about recorded ground motion data and simulated ground motions with new GMPE can be found in Anbazhagan et al. (2012b). The new GMPE proposed by the authors will be called as AGMPE from here onwards in this manuscript. It has to be noted here that all the three GMPEs used here provide the value of ground motion parameter for Site Class A ($V_s^{30} > 1.5$ km/s). GMPE proposed by Kanno et al. (2006) is applicable for hypocentral distance of 200 km, while the GMPE proposed by NDMA (2010) is applicable up to hypocentral distance of 500 km. Similarly, the AGMPE can be used up to 300 km. The comparison of the three GMPEs has been given in Fig. 7. Comparisons between the GMPEs show that up to a hypocentral distance of 50 km, all the three GMPEs are giving identical results. However, beyond 50 km, NDMA (2010) is giving lesser values compared to other two GMPEs. The three GMPEs have been assigned weightage factors of 0.4 (AGMPE), 0.3 (Kanno et al. 2006) and 0.3 (NDMA 2010) to arrive at hazard values. Slightly higher weightage factor has been given to the AGMPE since it has been developed for Lucknow microzonation and is based on regional ground motion data in comparison

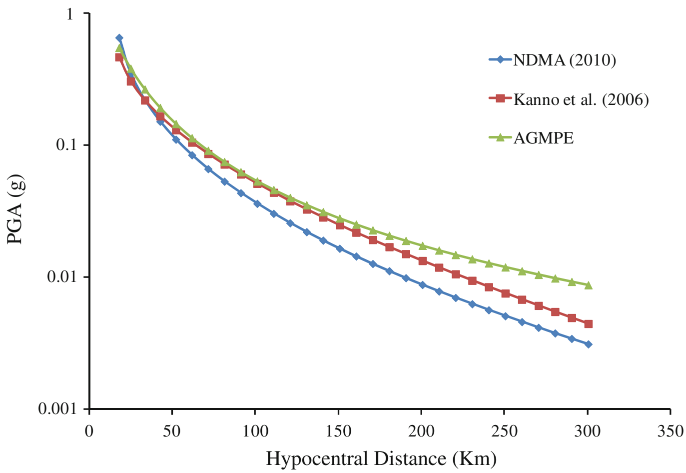
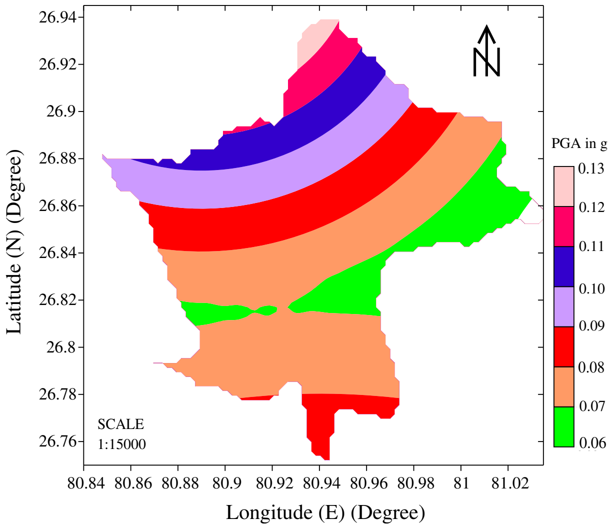


Fig. 7 Comparison between the three GMPEs used for the study

with the other two GMPEs by Kanno et al. (2006) and NDMA (2010) which were developed based on recorded data in Japan and synthetic ground motions for Himalayan region, respectively. Comparison of GMPE by Kanno et al. (2006) with the other two GMPEs beyond 200 km can be seen from the Fig. 7, which shows a very slight variation and hence the GMPE by Kanno et al. (2006) can also be used up to 350 km.

For events with magnitude <7.0 (M_w), the focal depth has been taken as 10 km, and for events >7.0, the focal depth of 15 km has been considered (Parvez et al. 2003). A MATLAB code has been developed for the DSHA which has also been verified with the manual calculation for Lucknow city centre. This code estimates the minimum hypocentral distance from the centre of each grid to each fault. PGA value from each source at each grid has been estimated considering M_{max} and the three GMPEs using suitable weightage factor. The maximum PGA from all the 47 sources will be assigned as the PGA for that grid. The same procedure has been followed for all the 225 grids, and the seismic hazard map of Lucknow city has been developed. Intermediate values have been interpolated using Kriging interpolation technique and mapped. Figure 8 shows the seismic hazard value map of the Lucknow urban centre of DSHA approach. The PGA variation has been found from 0.05 g in the eastern periphery of the city to 0.13 g in the northern part of Lucknow. DSHA shows that north-eastern part of the city is expected to have PGA values of 1.8–2.6 times PGA of south-eastern part of the city. North-western part includes areas like Aliganj, Hasanganj, Butler colony, Indiranagar and surrounding areas which are more prone to earthquake-induced ground shaking. However, areas which fall in south and eastern part of the city such as Vikram Khand, Gomati Nagar, Telibagh, Hudson lines and their nearby areas are less susceptible to earthquake shaking. Based on the three GMPEs used and the associated weightage factors for each GMPE, the response spectra from DSHA have been developed at Lucknow centre. Figure 9 shows the response spectra at Lucknow urban centre obtained from DSHA. It can be observed from the Fig. 9 that spectral acceleration at the city centre is 0.10 g at 0 s which has reached to 0.20 g at 0.05 s. Thus, there has been a twofold increase in the spectral acceleration from zero to 0.05 s change in period of motion. Since the results of DSHA do not provide information about the probability of a particular ground acceleration to occur in a certain interval of time or not, the results

Fig. 8 Deterministic seismic hazard map of Lucknow urban centre



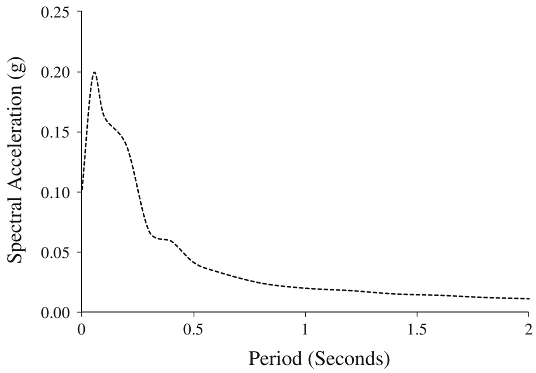


Fig. 9 Response spectra at the Lucknow city centre based on DSHA

involve a high degree of uncertainty. In order to account for the uncertainty involved in the seismic hazard analysis, probabilistic seismic hazard analysis (PSHA) has been carried out as discussed in the next section.

6.2 Probabilistic seismic hazard analysis

Probable ground motions at any site for given probability of exceedence in a particular period can be estimated once the probability of its size, locations and level of ground shaking is known cumulatively. Cornell (1968) developed the probabilistic seismic hazard method to account for various uncertainties which was later improved by Algermissen et al. (1982). PSHA accounts for probability of occurrence of a particular magnitude, probability of hypocentral distance and probability of ground motion exceeding a particular value. Combining all the above probabilities will give the ground motions at a site with a known probability of exceedence in a desired exposure period. The final outcome of a PSHA is a hazard curve, showing the ground motion parameters such as PGA or SA as the function of the frequency of exceedence of that level of ground motion. Individual hazard curve for each seismic source is obtained by considering all possible combinations of magnitudes, hypocentral distances and the level of ground shaking due to these combinations of magnitudes and epicentral distances. Detailed discussion on the methodology of probabilistic seismic hazard analysis can be found in Anbazhagan et al. (2009) in this journal.

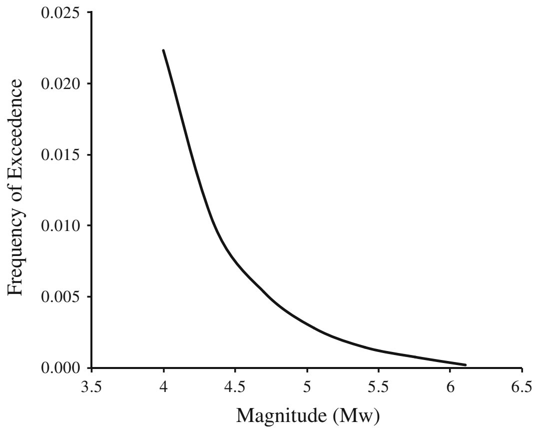


Fig. 10 Frequency of exceedence of various magnitudes for fault F1

The recurrence relation given by Eq. (1) resembles the recurrence law for the whole region; however, individual source recurrence relation is needed to estimate hazard values. Due to lack of slip rate data for individual source, the estimation of recurrence relation for each source is not possible. As an alternate, Iyenger and Ghosh (2004) proposed deaggregation based on the principle of super-position which was successfully used for PSHA by Iyenger and Ghosh (2004), Raghukanth and Iyengar (2006), Anbazhagan et al. (2009); Vipin et al. (2009); and NDMA (2010). The same method has been used for the present work. Figure 10 shows the frequency of occurrence of different magnitude for fault F1. Probability of rupture to occur at various hypocentral distances has been estimated as per Kiureghian and Ang (1977). More details can be found in Anbazhagan et al. (2009) in the same journal.

The entire study area has been divided into 225 grids of 0.015° × 0.015°. Based on the above steps, the conditional probability for various range of hypocentral distances from different faults has been estimated. A typical distribution of conditional probability for hypocentral distance from fault F1 is shown in Fig. 11. It can be seen from the Fig. 11 that the probability density function starts with a value of 0.056 at a hypocentral distance of 332 km which is the minimum distance of this fault from the city centre. Beyond this value, there is a sudden increase in the probability density function from 0.056 at 332 km to 0.075 at 338 km. Once the value reaches 345 km as shown in Fig. 11, the probability density function for this fault achieves a constant value of 0.078.

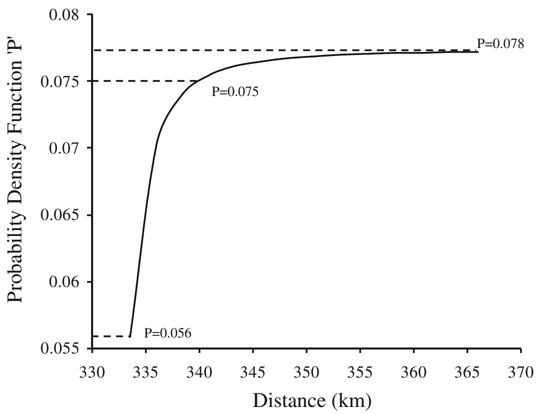
The condition probability of exceedence for GMPEs is estimated using a lognormal distribution as given below (EM-1110 1999)

$$P(Y > z|m_i, r_j) = 1.0 - F'\left\{\frac{\ln(z) - E[\ln(Z)]}{S[\ln(z)]}\right\}, \tag{3}$$

where $E[\ln(z)]$ is the log of mean ground motion estimated from the GMPE used, $S[\ln(z)]$ is the log of standard error term obtained from the GMPE used, $\ln(z)$ is the specified ground motion with respect to which the probability of exceedence has to be calculated. The specified ground motions 'z' used in the present study have been given at a constant interval of 0.025 g in the range of 0.025–1.0 g for each of the seismic source.

Once the frequency of exceedence of a particular magnitude 'm_i' occurring at a distance of 'R' with a known probability of exceedence with respect to 'z' is known, the combined frequency of exceedence of that particular ground motion can be estimated by merging all

Fig. 11 Hypocentral distance probability density function for fault F1 for M_w 4



types of uncertainties for each source. Hazard curve defines the frequency of exceedence of various levels of ground motions (z). Plot of ten most contributing sources for the Lucknow city centre has been given in Fig. 12. It can be seen from Fig. 12 that F117 is the most vulnerable source located at a hypocentral distance of 15.11 km with maximum magnitude of 5.1 (M_w). Other sources, which have been found vulnerable for Lucknow, are also shown in the Figure as F119, F227, F123, F122, F118, F116, F121, F228 and F127. In order to understand the hazard contribution from various combinations of magnitude and hypocentral distance, deaggregation plot is a useful tool. Hence, the deaggregation plot for the most contributing source at the Lucknow centre is shown in Fig. 13 for 2 % probability in 50 years. It can be observed from Fig. 13 that the maximum contribution of 17.2 % from source F117 is corresponding to hypocentral distance of 15.11 km and magnitude of 4.55 (M_w). Also, the major hazard contributions are corresponding to hypocentral distance of 15.11 km. In another exercise comparison of individual hazard curves in the northern and western parts of Lucknow was carried out, source F117 has been found as the vulnerable source for these regions as well. Figures 14 and 15 show the deaggregation plot for northern and western parts of Lucknow, respectively, for source F117. It can be observed from Fig. 14 that the maximum hazard contribution of 14.32 % is corresponding to magnitude of 4.37 (M_w) at a hypocentral distance of 11.91 km followed by 4.55 (M_w) occurring at 11.91 km. Similarly, Fig. 15 explains the maximum hazard of 15.58 % corresponding to a magnitude of 4.55 (M_w) at a hypocentral distance of 14.83 km followed by a hazard of 14.54 % due to an event of 4.55 (M_w) occurring at a distance of 14.83 km.

The cumulative hazard curve at any site can be obtained by the summation of all the hazard curves obtained from all the sources. Figure 16 shows the cumulative hazard curve obtained at the Lucknow city centre for 0, 0.05, 0.2, 0.4 and 0.8 s. Hazard curve corresponding to different periods provides the spectral acceleration values for a known probability of exceedence in a given time period. In can be observed from the Fig. 16 that the frequency of exceedence for 0.025 g at 0 s is 0.00671 (value of y-axis) which will give the return period 149 years (return period is the inverse of the frequency of exceedence).

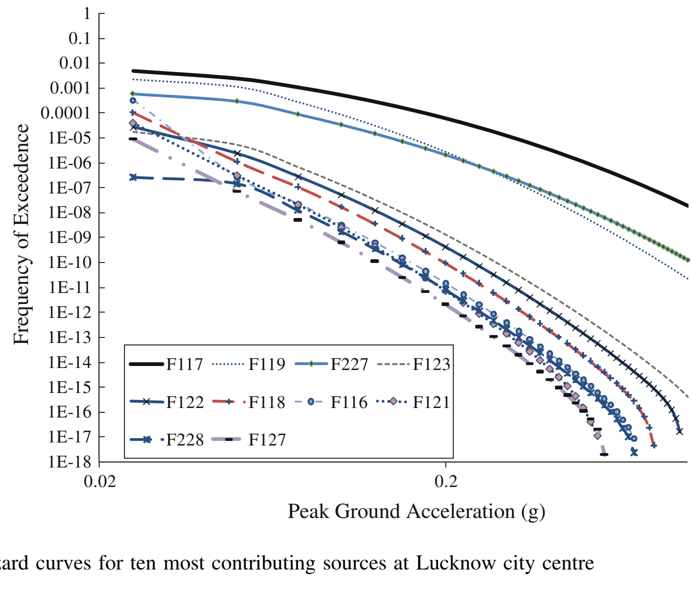


Fig. 12 Hazard curves for ten most contributing sources at Lucknow city centre

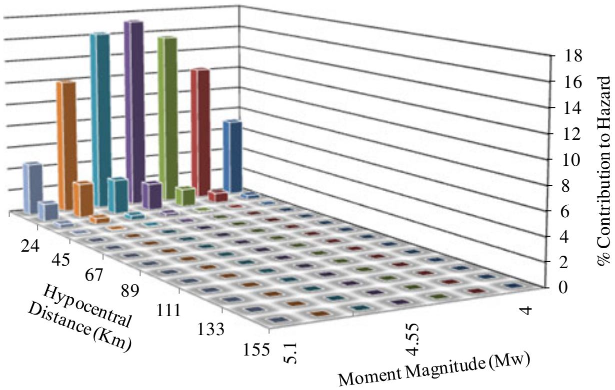


Fig. 13 Deaggregation plot for source F117 at Lucknow city centre

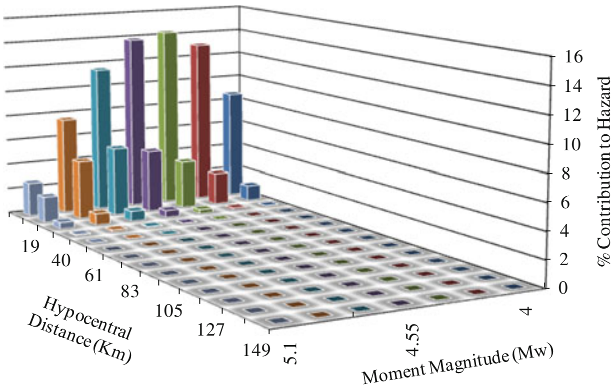
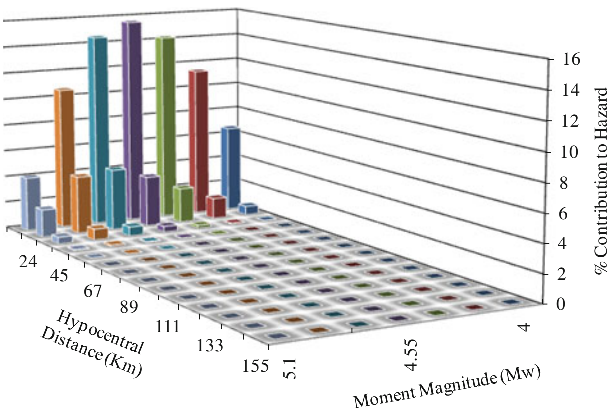


Fig. 14 Deaggregation plot for source F117 in the northern part of Lucknow

Fig. 15 Deaggregation plot for source F117 in the western part of Lucknow



This indicates that PGA of 0.025 g has a 28.93 % probability of exceedence in 50 years at the Lucknow city centre. Once the hazard curve is available, for a known probability of exceedence ($P(Y > z)$) during a specified time 'T', the frequency of exceedence '$v(z)$' can

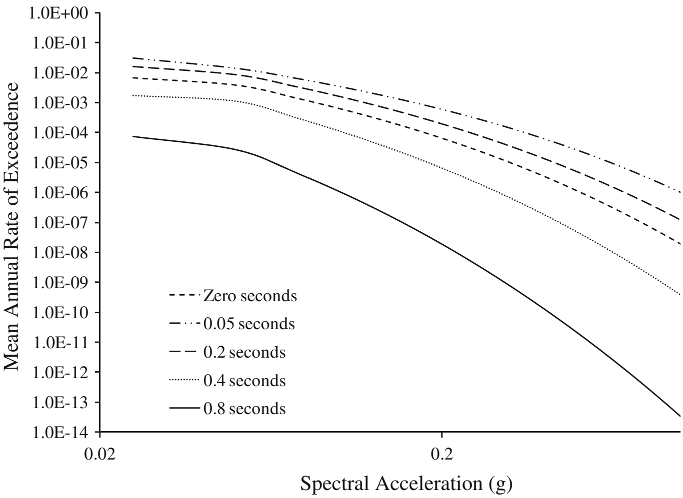
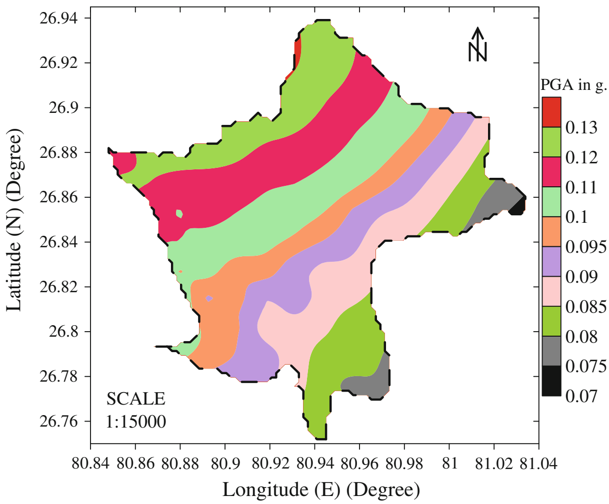


Fig. 16 Hazard curve at Lucknow city centre for different periods

be estimated using Eq. (3). The level of ground motion for this frequency of exceedence 'v(z)' can be read from the hazard curve also. For 2 % probability of exceedence within 50 years, the value of '$v(z)$' as estimated from equation 10 is 0.004. Level of ground motion for this '$v(z)$' as can be read from Fig. 16 for zero period hazard curve is 0.11 g. Thus, this will be the PGA value at the Lucknow urban centre.

Hazard curves were generated at the centre of each grid. The levels of ground motions have been evaluated from the zero period hazard curves of each grid for 2 and 10 % probabilities of exceedence in 50 years. Figures 17 and 18 are the PSHA maps for Lucknow urban centre for 2 and 10 % probabilities of exceedence in 50 years, respectively. It can be observed from Fig. 18 that PGA varies from 0.07 g in the eastern periphery to 0.13 g towards the north, while the southern part of the city encounters PGA of 0.08 g. Similar to the observation made in DSHA, the north-western part has been found

Fig. 17 PSHA map for Lucknow urban centre for 2 % probability of exceedence in 50 years



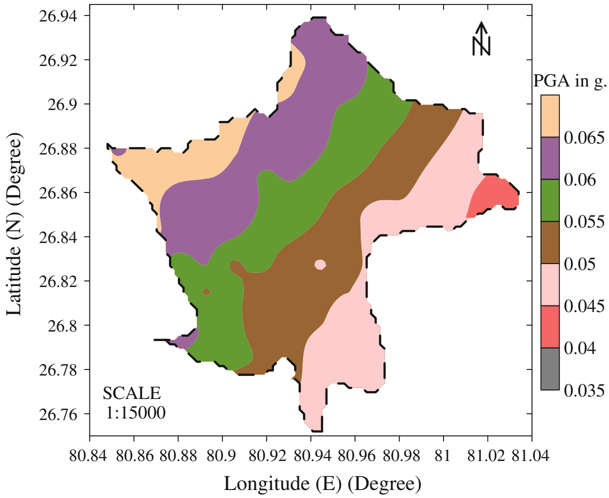


Fig. 18 PSHA map for Lucknow urban centre for 10 % probability of exceedence in 50 years

more vulnerable compared to the south-eastern part of the city. Aliganj, Hasanganj, Butler colony, Indiranagar and surrounding areas are more prone to earthquake-induced ground shaking. However, areas which fall in southern and eastern parts of the city such as Vikram Khand, Gomati Nagar, Telibagh, Hudson lines and their nearby areas are less susceptible to earthquake shaking when compared to northern–western part. Since these levels of ground shaking are evaluated at bedrock level, no changes in PGA along the alignment of River Gomati can be seen here. Further, Fig. 18 shows the PSHA map for Lucknow for 10 % probability of exceedence in 50 years. There is a large variation in the PGA across the city from 0.035 g in the southern part to 0.07 g in the north and north-eastern part of the city. In this case also, the areas which come in north and north-east part of the Lucknow urban centre are susceptible to higher levels of ground motions compared to the eastern and the southern parts of the city. Vulnerable source which is producing the maximum level of ground motion observed from DSHA and PSHA is same.

Uniform hazard spectra (UHS) are a spectral curve from PSHA and show the variation in spectral acceleration at different period for the same probabilities of exceedence. In the present work, UHS at Lucknow urban centre for 2 and 10 % probabilities of exceedence in

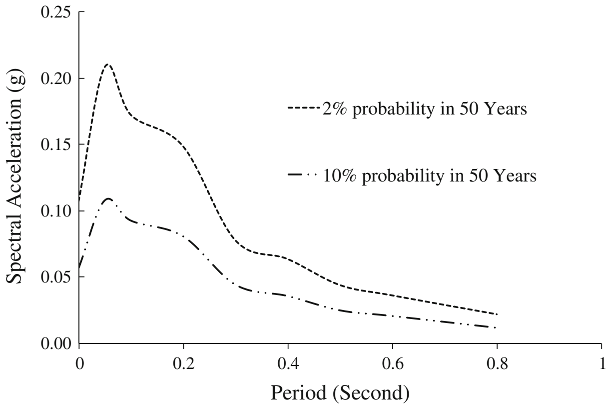


Fig. 19 Uniform hazard spectra (UHS) at Lucknow city centre

Table 5 Comparison of PGA obtained from present study with earlier published work

S. no.	References	Methodology	PGA (g)
1	Present work	DSHA	0.05–0.13
2	Parvez et al. (2003)	DSHA	0.15
3	Present work	PSHA (10 % probability of exceedence in 50 years)	0.04–0.07
4	Khattri et al. (1984)	PSHA (10 % probability of exceedence in 50 years)	0.05
5	GSHAP (Bhatia et al. 1999)	PSHA (10 % probability of exceedence in 50 years)	0.08
6	NDMA (2010)	PSHA (10 % probability of exceedence in 50 years)	0.07
7	Present work	PSHA (2 % probability of exceedence in 50 years)	0.07–0.13
8	NDMA (2010)	PSHA (2 % probability of exceedence in 50 years)	0.13

the 50 years have been drawn in Fig. 19. It can be observed from Fig. 19 that UHS are similar for 2 and 10 % probability and hazard values increase for 2 % probability exceedence in the same return period. The spectral acceleration at 0 s is called as zero spectral acceleration or PGA for Lucknow.

7 Results and discussion

DSHA of the Lucknow urban centre showed that the northern part of the urban centre is more prone to earthquake-induced ground shaking when compared to the southern part. The maximum PGA obtained from DSHA of Lucknow was 0.13 g. Parvez et al. (2003) conducted the DSHA of the entire Indian subcontinent and found PGA of 0.15 g for western Uttar Pradesh (the state where Lucknow lies). Khattri et al. (1984) presented the PSHA for the Himalayan region and its adjoining areas. As per the Khattri et al. (1984), the PGA for Lucknow considering 10 % probability of exceedence in 50 years was 0.05 g. However, in the present study, the 10 % probability of exceedence map of Lucknow shows the maximum PGA of 0.07 g. Bhatia et al. (1999) developed PSHA of whole India based on a computer program FRISK88. The attenuation relation developed by Joyner and Boore (1981) based on California earthquakes was used. Bhatia et al. (1999) predicted PGA value at Lucknow considering a 10 % probability of exceedence in 50 years in the range of 0.05–0.1 g in Global Seismic Hazard Assessing Programme (GSHAP). These values are comparable with the results obtained in present work. NDMA (2010) developed the PSHA for whole India by dividing the whole country into 32 sources zones based on historical seismicity, tectonic features and geology. As per NDMA (2010), the PGA at Lucknow for 10 and 2 % probabilities of exceedence in 50 years were determined as 0.04 and 0.08 g, respectively. Table 5 shows comparison of PGA values obtained from this study with previously published values. The estimated PGA values from this study are comparable and slightly higher than those from the other published values, which may be attributed by updated seismicity and GMPEs used in this study.

8 Conclusions

In the present work, the seismic hazard of Lucknow urban centre was presented considering the seismotectonic province of 350 km radial distance around the city centre. Past events in the seismotectonic region have been collected and analysed for declustering and homogeneity. Later, a seismotectonic map for Lucknow has been developed during this work considering the available information on linear sources within the seismotectonic province. Based on the study, the following observations have been drawn from this study:

1. The earthquake catalogue for Region I and Region II has been found complete for the last 80 years.
2. The '*b*' parameters estimated using G–R recurrence relations have been found as 0.86 and 0.91 for Region I and region II, respectively.
3. Based on DSHA, the variation in PGA was found between 0.05 and 0.13 g. The northern and western part of the city is more vulnerable to earthquake shaking compared to south-eastern part.
4. In order to account for uncertainties with respect to the magnitude, location and size of earthquake, probabilistic seismic hazard analysis of the study area has also been performed in the study.
5. Hazard curves for periods of 0, 0.05, 0.2, 0.4 and 0.8 s at the Lucknow city centre are generated.
6. PSHA for 2 % probability shows the variation in PGA from 0.07 to 0.13 g, and 10 % probability shows PGA variation from 0.035 to 0.07 g.
7. Based on hazard analysis, the northern part of the city such as Aliganj, Hasanganj, Butler colony, Indiranagar and the surrounding areas are suffering 1.6–2.6 times more level of ground motions compared to other areas like Vikram Khand, Gomati Nagar, Telibagh, Hudson lines and their nearby areas.

Seismic hazard values given in this paper are at hard rock condition with $V_s^{30} > 1{,}500$ m/s. These values may alter when site effects based on site-specific soil properties are considered.

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References

Abramowitz M, Stegun IA (1970) Handbook of mathematical functions, 9th edn. Dover Publication, New York

ASC (Amateur Seismic Centre) (2010) Seismicity of Uttar Pradesh. http://asc-india.org/seismi/seis-uttar-pradesh.htm, last visited on 02 Jan 2013

Algermissen ST, Perkins DM, Thenhaus PC, Hanson SL, Bender BL (1982) Probabilistic estimates of maximum acceleration and velocity in rock in the contiguous United States, Open File Report 82–1033. USGS, Washington, DC 99

Anbazhagan P, Vinod JS, Sitharam TG (2009) Probabilistic seismic hazard analysis for Bangalore. Nat Hazards 48:145–166

Anbazhagan P, Kumar A, Sitharam TG (2012a) Seismic site classification and correlation between standard penetration test N value and shear wave velocity for Lucknow City in Indo-Gangetic Basin. Pure Appl Geophys. doi:10.1007/s00024-012-0525-1

Anbazhagan P, Kumar A, Sitharam TG (2012b) Ground motion prediction equation based on combined dataset of recorded and simulated ground motions. Soil Dyn Earthq Eng (under review)

Bhatia SC, Ravi MK, Gupta HK (1999) A probabilistic seismic hazard map of India and adjoining regions. Ann Geofis 42:1153–1164

Bilham R, Bodin P, Jackson M (1995) Entertaining a great earthquake in western Nepal: historical inactivity and geodetic tests for the present state of strain. J Nepal Geol Soc 11(1):73–78

Bilham R, Gaur VK, Molnar P (2001) Himalayan seismic hazard. Science 293:1442–1444

Bormann P, Liu R, Ren X, Gutdeutch R, Kaiser D, Castellaro S (2007) Chinese national network magnitudes, their relation to NEIC magnitudes and recommendations for new IASPEI magnitude standard. Bull Seismol Soc Am 95:58–74

BSSC (2003) NEHRP recommended provision for seismic regulation for new buildings and other structures (FEMA 450), part 1: provisions, building safety seismic council for the federal Emergency Management Agency. Washington, DC, USA

Castellaro S, Mulargia F, Kagan YY (2006) Regression problems for magnitudes. Geophys J Int 165:913–930

Cornell CA (1968) Engineering seismic rick analysis. Bull Seismol Soc Am 58:1583–1606

Dubey AK (2010) Role of inversion tectonics in structural development of the Himalaya. J Asian Earth Sci 39(6):627–634

EM-1110 (1999) Engineer manual 1110-2-6050. Department of Army, U.S. Army corps of Engineers, Washington DC-20314-1000

Encyclopedia (1997) Encyclopedia of European and Asian regional geology. http://books.google.co.in/books?id=tFqp-3oVccC&printsec=frontcover&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false, last visited on 01/01/2013

Fedotov SA (1968) Seismic cycle, seismic zoning, and long-term seismic forecast), in Seismic Zoning, Institute of Physics of Earth. USSR Academy of Sciences, Nauka, Moscow, pp 121–150 (in Russian)

Gupta ID (2002) The state of the art in seismic hazard analysis, ISET. J Earthq Technol 39(4):311–346

Gutenberg B, Richter CF (1956) Magnitude and energy of earthquakes. Ann Geofis 9:1–15

IS 1893 (2002) Indian standard criteria for earthquake resistant design of structures, part 1—general provisions and buildings. Bureau of Indian Standards, New Delhi

Iyenger RN, Ghosh S (2004) Microzonation of earthquake hazard in Greater Delhi area. Curr Sci 87(9):1193–1202

Joyner WB, Boore DM (1981) Peak horizontal acceleration and velocity from strong motion records including records from the 1979 Imperial Valley California earthquake. Bull Seismol Soc Am 71:2011–2038

Kanno T, Narita A, Morikawa N, Fujiwara H, Fukushima Y (2006) A new attenuation relation for strong ground motion in Japan based on recorded data. Bull Seismol Soc Am 96:879–897

Khattri KN (1987) Great earthquakes, seismicity gaps and potential for earthquakes along the Himalayan plate boundary. Tectonophysics 38:79–92

Khattri KN, Rogers AM, Perkins DM, Algermissen ST (1984) A seismic hazard map of India and adjacent areas. Tectonophysics 108:93–134

Kijko A, Sellevoll MA (1989) Estimation of earthquake hazard parameters from incomplete data files. Part I, Utilization of extreme and complete catalogues with different threshold magnitudes. Bull Seismol Soc Am 79:645–654

Kiureghian DA, Ang AH-S (1977) A fault rupture model for seismic risk analysis. Bull Seismol Soc Am 67:1173–1194

Kostoglodov V, Singh SK, Santiago JA, Franco SI, Larson KM, Lowry AR, Bilham R (2003) A large silent earthquake in the Guerrero seismic gap, Mexico. Geophy Res Lett 30(15), SDE 9 (1–4)

Kumar S (2012) Seismicity in the NW Himalaya India: fractal dimension, b-value mapping and temporal variation for hazard evaluation. Geosci Res 3(1):83–87

Mahajan AK, Thakur VC, Sharma ML, Chauhan M (2010) Probabilistic seismic hazard map of NW Himalaya and its adjoining area, India. Nat Hazards 53:443–457

Nadeshda TNN (2004) "Lucknow is on earthquake list". Published online, Times of India. http://timesofindia.indiatimes.com/city/lucknow/Lucknow-is-on-earthquakelist/articleshow/679471.cms, last accessed on 11/1/2011

Natalia AR, Jonathan ML, Natalia PK (2007) Seismicity, earthquakes and structure along the Alaska-Aleutian and Kamchatka-Kurile subduction zones: a review, volcanism and subduction: the Kamchatka region geophysical monograph series 172. Am Geophys Union. doi:10.1029/172GM12

Nath SK (2006) Seismic hazard and microzonation atlas of the Sikkim Himalaya. Department of Science and Technology, Government of India, New Delhi, India

Nath SK (2007) Seismic microzonation atlas of Guwahati region. Department of Science & Technology, Government of India, New Delhi

Nath SK, Thingbaijam KKS (2011) Peak ground motion predictions in India: an appraisal for rock sites. J Seismolog 15:295–315

NDMA (2010) Development of probabilistic seismic hazard map of India. Technical report by National Disaster Management Authority, Government of India

Parvez IA, Vaccari F, Panza GF (2003) A deterministic seismic hazard map of India and adjacent areas. Geophys J Int 155:489–508

PCRSMJUA (2005) Project completion report of seismic microzonation of Jabalpur Urban Area, vol 2. Department of Science and Technology, Government of India, India
Raghukanth STG, Iyengar RN (2006) Seismic hazard estimation for Mumbai city. Curr Sci 9:1486–1494
Reasenberg PA (1985) Second order moment of central California seismicity, 1969–1982. J Geophys Res 90:5479–5495
RMS (2005) Estimating losses from the 2004 Southeast Asia earthquake and tsunami. Risk Manag Solut (special report)
RMS (2010) 2010 Haiti earthquake and Caribbean earthquake risk. Risk Manag Solut
RMS (2011) Estimating insured losses from the 2011 Tohoku, Japan earthquake and Tsunami. Risk Manag Solut (special report)
Schnabel B, Lysmer J, Seed HB (1972) SHAKE—a computer program for earthquake response analysis of horizontally layered sites. Report EERC, University of California, Berkeley, 72/12: 102
Scordilis EM (2006) Empirical global relations converting MS and mb to moment magnitude. J Seismol 10:225–236
Seed HB, Idriss IM (1970) Soil moduli and damping factors for dynamic response analysis. Report No EERC 70-10, University of California, Berkeley
SEISAT (2000) Seismotectonic Atlas of India and its environs. Geological Survey of India, India
Singh IB (2012) Inception, sedimentation and deformation of Ganga foreland basin. Himal Geol. http://www.himgeology.com/himgeol/volume(29)3/abstract80.htm, last visited on 20 Dec 2012
Sinha R, Tandon SK, Gibling MR, Bhattarcharjee PS, Dasgupta AS (2005) Late Quaternary geology and alluvial stratigraphy of the Ganga basin. Himal Geol 26(1):223–340
Sitharam TG, Anbazhagan P (2009) Report on seismic microzonation of Bangalore Urban Centre, Seismology Division-Main Volume, Ministry of Earth Sciences, Government of India, Printed in Bangalore, India, p 174
Sreevalsa K, Sitharam TG, Vipin KS (2011) Spatial variation of seismicity parameters across India and adjoining area. Nat Hazards. doi:10.1007/s11069-011-9898-1
Stepp JC (1972) Analysis of completeness of the earthquake sample in the Puget sound area and its effect on statistical estimates of earthquake hazard. In: Proceeding of the International conference on microzonation, vol 2. Seattle, USA, pp 897–910
Stromeyer D, Grunthal G, Wahlstrom R (2004) Chi square regression for seismic strength parameter relations, and their uncertainty with application to an Mw based earthquake catalogue for central, northern and north-western Europe. J Seismol 8:143–153
Suganthi A, Boominathan A (2006) Seismic response study of Chennai city using geotechnical borelog data and GIS. In: Proceedings on the Indian geotechnical conference 2006, 14–16 December, Chennai, India, pp 831–832
Sun JI, Golesorkhi R, Seed HB (1988) Dynamic moduli and damping ratios for cohesive soils. Report No. EERC 88-15, University of California, Berkeley
Thingbaijam KKS, Nath SK, Yadav A, Raj A, Walling MY, Mohanty WK (2008) Recent seismicity in Northeast India and its adjoining region. J Seismol 12:107–123
UEVRS (2004) Proceedings report: Lucknow City consultation on urban earthquake vulnerability reduction strategy, Organized by Lucknow Development Authority, Government of Uttar Pradesh. http://awas.up.nic.in/linkfile/Disaster/Proceedings%20Report%20Final.pdf, last accessed on 18/04/2012
UNDP (United Nations Development Programme) (2008) Lucknow vulnerable to earthquakes. Express India. http://www.expressindia.com/latest-news/lucknowvulnerable-to-earthquake/311524/, last visited on 24 Oct 2009
Vipin KS, Anbazhagan P, Sitharam TG (2009) Estimation of peak ground acceleration and spectral acceleration for South India with local site effects: probabilistic approach. Nat Hazard Earth Syst Sci 9:865–878
Wallace K, Bilham R, Blume F, Gaur VK, Gahalaut V (2006) Geodetic constraints on the Bhuj 2001 earthquake and surface deformation in the Kachchh Rift Basin. Geophys Res Lett 33:L10301. doi:10.1029/2006GL025775
Wikipedia (2010) Haiti earthquake. http://en.wikipedia.org/wiki/2010_Haiti_earthquake, last visited on 17 July 2012