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ORIGINAL PAPER

Seismic hazard in mega city Kolkata, India

William K. Mohanty · M. Yanger Walling

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Abstract The damages caused by recent earthquakes in India have been a wake up call for people to take proper mitigation measures, especially the major cities that lie in the high seismic hazard zones. Kolkata City, with thick sediment deposit (~ 12 km), one of the earliest cities of India, is an area of great concern as it lies over the Bengal Basin and lies at the boundary of the seismic zones III and IV of the zonation map of India. Kolkata has been affected by the 1897 Shillong earthquake, the 1906 Calcutta earthquake, and the 1964 Calcutta earthquake. An analysis on the maximum magnitude and *b*-value for Kolkata City region is carried out after the preparation of earthquake catalog from various sources. Based on the tectonic set-up and seismicity of the region, five seismic zones are delineated, which can pose a threat to Kolkata in the event of an earthquake. They are broadly classified as Zone 1: Arakan-Yoma Zone (AYZ), Zone 2: Himalayan Zone (HZ), Zone 3: Shillong Plateau Zone (SPZ), Zone 4: Bay of Bengal Zone (BBZ), and Zone 5: Shield Zone (SZ). The maximum magnitude (m_{max}) for Zones 1, 2, 3, 4, and 5 are 8.30 ± 0.51, 9.09 ± 0.58, 9.20 ± 0.51, 6.62 ± 0.43 and 6.61 ± 0.43, respectively. A probability of 10% exceedance value in 50 years is used for each zone. The probabilities of occurrences of earthquakes of different magnitudes for return periods of 50 and 100 years are computed for the five seismic zones. The Peak Ground Acceleration (PGA) obtained for Kolkata City varies from 0.34 to 0.10 g.

Keywords Seismic microzonation · Seismic hazard · Source zones · m_{max} · PGA

1 Introduction

The occurrence of great earthquakes and their effects in India over the last few years warn us of the need to assess the hazard due to earthquakes and prepare for future calamities.

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The occurrence of seven major damaging earthquakes during the past few decades (1988–2004) is testimony of that. Among the seven earthquakes, three of them occurred in the Peninsular India (1993 Latur Earthquake; 1997 Jabalpur Earthquake; and 2001 Bhuj Earthquake), the other three in the Himalayan region (1988 Bihar-Nepal Earthquake; 1991 Uttarkashi Earthquake; and 1999 Chamoli Earthquake), and the other is the most recent 2004 Sumatra Earthquake, which triggered the tsunami and greatly affected the Andaman and Nicobar Islands. The damage pattern due to earthquakes depends upon the earthquake source type, local site condition, and social developments of the region with the most important condition being the intensity of shaking of ground at the time of the earthquakes. The Peninsular India is generally considered to be stable and less prone to the seismic hazard but the recent past earthquakes of the 1993 Latur, 1997 Jabalpur, and 2001 Bhuj earthquakes and the aftermath indicates even the stable Peninsular India is not safe from earthquake activity.

In the wake of the disastrous events of 26 December 2004 Sumatra ($M_w = 9.3$) earthquake followed by the earthquake of 8 October 2005 ($M_w = 7.6$) in Pakistan, there is a need for the mitigation in zones of high risk to seismic hazard. Among all the natural hazards, earthquakes lead the list of natural disasters in terms of damage and human loss, and they affect very large areas, causing death and destruction on a massive scale. Successful earthquake prediction is not feasible and has proved futile in the past.

The Bureau of Indian Standard (BIS) classified India into four seismic zones (zone II to zone V) (IS: 1893 (Part 1) 2002) (Fig. 1). However, these zones are not sufficient to predict the damage pattern within each zone in the event of an earthquake, as the damage will

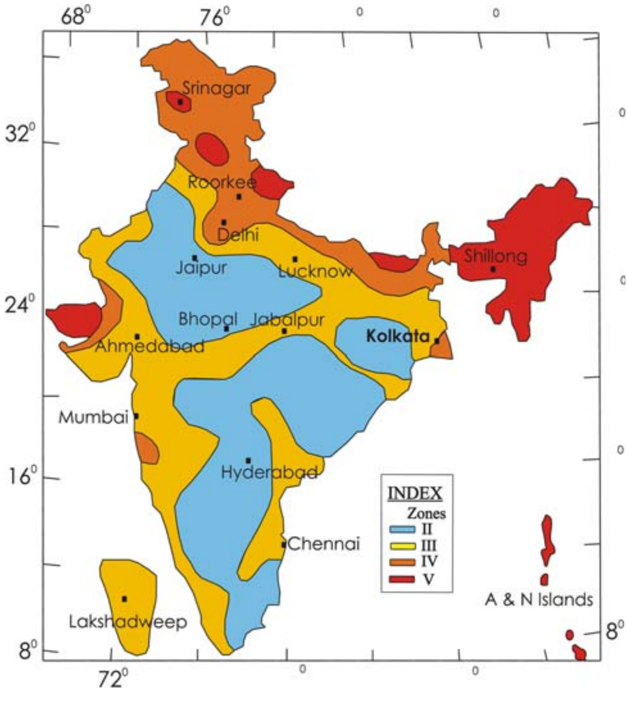

Fig. 1 Map showing the four seismic zones of India (after IS: 1893 (Part 1) 2002). Kolkata City lies on the boundary of seismic zones III and IV

depend on the local geology, vicinity to active faults, geotechnical and geophysical properties of surface and subsurface strata, slope instabilities, and topography. Contrasting seismic response is observed even within a short distance over small changes in the geology of the site. Hence, seismic microzonation over a region is needed to minimize the loss to human life and property.

The strategic areas for the microzonation are urban areas or upcoming urban areas falling within the high-hazard zones (zones IV and V) and high-population density zones. Rapid urbanization due to population increase leading to the creation of mega cities in potential seismic zones without adequate preparation for possible hazard is the main reason for human loss and property damage. Seismic microzonation works are carried out in important Indian cities such as Delhi (Parvez et al. 2004; Mohanty et al. 2007), Sikkim (Nath 2004), and Jabalpur (Mishra 2004), while the seismic ground motion in large urban areas in other parts of the world has been carried out for Bursa (Topal et al. 2003), Bucharest (Moldoveanu 2004), Algiers (Harbi et al. 2004), Alexandria (El-Sayed et al. 2004), Beijing (Ding et al. 2004), Napoli (Nunziata 2004), Santiago de Cuba (Alvarez et al. 2004), Sofia (Slavov et al. 2004), and Zagreb (Herak et al. 2004).

In this study, a quasi-probabilistic approach looks at the expected ground motion for Kolkata because of the surrounding active seismic tectonic zones.

2 Study area

The Kolkata metropolis (formerly known as Calcutta), the second largest urban agglomeration in India, is bounded by latitudes 22°20′ N–23°00′ N and longitudes 88°04′ E–88°33′ E. Kolkata was previously the capital of British India from 1772 to 1911. It covers an area of about 185 km^2 and has developed primarily along the eastern bank of the River Hooghly during the last more than 300 years. According to the Census report 2001 (http://www.censusindia.gov.in/), the population of Kolkata, in the year 1901, was 0.6 million, which increased to 4.4 million in 1991 and to 13 million in 2001.

It is a major center for business and education for eastern and northeastern India. Most parts of the City comprise many high-rise residential complexes, over bridges, subways, and huge shopping malls to meet the demands of its population. Most of these constructions are without proper town planning and seismic resistance design. However, a planned township near Salt Lake is coming up, but it is located on an artificially filled alluvium, which puts the construction of that area under severe threat. Moreover, Kolkata lies at the boundary of the Indian seismic zones III and IV, which comes under high seismic risk.

3 Geological and tectonic setting

Kolkata is situated over the Bengal Basin, which consists of the fluvio-marine sediments of a precratonic Tertiary basin. The Bengal Basin is formed by the Ganga–Brahmaputra river system and is covered by alluvium. It is also the world's largest delta. The elevation of Kolkata is shown in Fig. 2, which will give an estimate of the soil thickness, i.e., higher the elevation, thicker the soil deposit. The elevation map of Kolkata City is obtained by analyzing the Shuttle Radar Topography Mission (SRTM) data accessed from the Global Land Cover Facility (GLCF) site (http://www.landcover.org). It is evident from Fig. 2 that Kolkata is a low-lying area attaining a maximum elevation of around 12 m above mean sea level. The Bengal Basin is underlain by the Tertiary sedimentary sequence as shown by

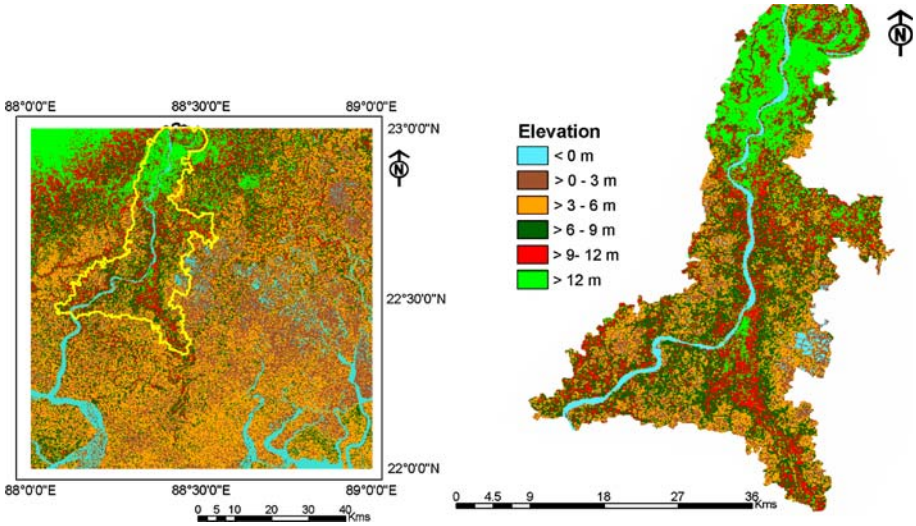

Fig. 2 The map shows the elevation of the Bengal basin. The elevation at various intervals is shown. The region is a low-lying area with most of the area below an elevation of 10 m (*Source:* http://www.landcover.org)

geophysical surveys and deep drilling. The thickness in sediments increases toward the east from 1200 m near the basin margin in the west to about 12,000 m in the deeper part of the Basin in West Bengal (Nandy 2001).

In the shelf zone, the Tertiary sequence dips homoclinally toward the southeast with a sudden flexure along the Eocene Hinge Zone (EHZ). The EHZ, also known as the Calcutta—Mymensing hinge zone, is a NE–SW trending hinge with a width of 25 km and an extension of about 550 km. It is a curvilinear feature and extends from the offshore Mahanadi Basin, across the western part of West Bengal basin through Calcutta–Ranaghat–Pabna–Mymensing, and finally merges into the E-W Dauki fault in the southern boundary of Shillong Plateau.

The EHZ marks a zone of differential thickening and subsidence rate of the overlying Oligocene and Miocene section (Salt et al. 1986). In West Bengal, the hinge zone is traversed by numerous en-echelon faults and also by moderate flexures. Across the EHZ, there is an abrupt change in facies and pressure regimes in the upper paleogene to neogene sections in the seismic records (Ganguly 1997). The hinge zone is a regional feature that demarcates the seaward extent of the Mahanadi pull-apart basin. It also supposedly delineates the continent–ocean transition beneath the Bengal Fan. Beyond the EHZ, toward the east, there is a sharp increase in sediment thickness up to 15 km. The EHZ subdivides the Bengal Basin, tectonically, into two major subdivisions—shelf and geosynclinal area.

The sediment thickness increases further into Bangladesh, reaching more than 20 km. The Bengal Basin has three structural domains: the western scarp zone (architecture by basin marginal faults), middle shelf zone and eastern deeper basin part. The western scarp zone is defined by a series of N-S trending subsurface faults previously identified through deep drilling and gravity modeling, and recently corroborated and refined by deep seismic profiling (GSI 2000). A series of buried basement ridges marks the western margin of the Bengal Basin. To the east of these ridges, there are rows of basin margin en-echelon faults

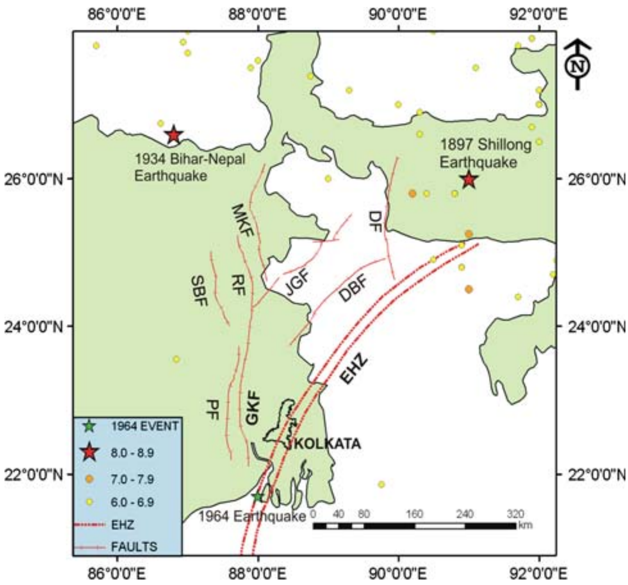

Fig. 3 The tectonic set up of the Bengal Basin and its surroundings. MKF: Malda-Kishanganj Fault, DF: Dhubri Fault, JGF: Jangipur-Gaibandha Fault, RF: Rajmahal Fault, SBF: Sainthia Bahmani Fault, GKF: Garhmoyna-Khandaghosh Fault, DBF: Debagram-Bogra, PF: Pingla Fault, EHZ: Eocene Hinge Zone (Modified after GSI 2000)

and scarps. The western part of the Bengal Basin is bounded by the Basin margin fault zone to the west and northwest and by the Eocene Hinge Zone to the east and southeast and constitutes a broad shelf zone.

The major fault systems of this region are Garhmoyna-Khandaghosh Fault (GKF), Jangipur-Gaibandha Fault (JGF), Pingla fault, Eocene Hinge Zone (EHZ), and Debagram Bogra Fault (DBF) (Fig. 3). The GKF extends along the basin margin that joins the Rajmahal Fault in the north. The NE trending JGF bifurcates from the GKF that separates the Rangpur–Malda saddle (a subsurface structural high joining the Indian Shield and the Shillong Plateau) from the Bogra Shelf. The shelf is limited to the southeast by the DBF. A similar section is present below the West Bengal part of the basin between GKF and the fault passing through Barrackpur and Krishnanagar (GSI 2000). Along the Calcutta–Krishnaga line, the basement depth varies between 7 and 10 km.

4 Seismicity of Kolkata

Kolkata has suffered damages from both far and near source earthquakes in the past. From the available past records of last 350 years, it has been observed that Kolkata and its surrounding region underwent 30 strongly felt earthquakes. The majority of the epicenters of these earthquakes were from 'far sources' and only a few from the 'near sources.' Epicenters for all moderate-large earthquakes are located south of Kolkata near the Ganges delta mouth. The earthquake of 29 September 1906 and 15 April 1964 Calcutta earthquake are the two major near sources that caused considerable damage to Kolkata City. Based on the Rossi-Forel scale (Middlemiss 1908), a maximum intensity of VI–VII was felt in and around Kolkata and caused major cracks to a number of buildings during the September 1906 earthquake. The Calcutta earthquake of 15 April 1964, occurring south of Kolkata induced more damage, in terms of development of severe cracks and falling of plaster in both old and new buildings. An intensity of VI on the Mercalli scale was assigned at Kolkata (Jhingran et al. 1969) and the earthquake was felt over an area of 67,000 km^2. The earthquake was located over the EHZ (GSI 2000).

Some of the large distant earthquakes that shook Kolkata include the 1 September 1803; 26 August 1833; and the 31 December 1881. The great 1897 Shillong Earthquake caused considerable damage in Kolkata to the extent of partial collapse of buildings, though the epicenter was at a distance of about 470 km toward N35E from Kolkata. During the Shillong Earthquake, the intensity felt at Kolkata was of isoseist 3 on the Oldham scale (Oldham 1899), which is equal to intensity VII in Medvedev–Spoonheuer–Karnik (MSK) scale. The Srimangal Earthquake of 8 July 1918, which was also located about 350 km away from Kolkata, caused cracks in many old and new buildings. The Dubhri Earthquake of 3 July 1930, whose epicenter was located 360 km away, also caused similar damage to Kolkata. The Bihar–Nepal Earthquake of 15 January 1934, which was about 480 km away, also caused substantial damage to the buildings. An intensity of VI on the Mercalli scale was assigned to Kolkata because it showed similar damage as that due to the near source Kolkata earthquake of 1964 (Dunn et al. 1939).

5 Source zoning

The earthquake catalog provides the essential input parameters for seismic hazard analysis. For over a hundred years, Earth catalogs have been prepared using different sources such as the United States Geological Survey (USGS), International Seismological Centre (ISC) (2001), Harvard Seismology (Dziewonski et al. 1981; Ekström et. al., 2005), Indian Meteorological department (IMD), Chandra (1992) and Bapat et al. (1983).

The seismic source zone for the region is classified by considering the historical earthquakes and the tectonic set up of the region. Great earthquakes such as the 1897 Shillong earthquake, 1934 Bihar earthquake, and the 1950 Assam earthquake give an overview of the seismicity of the region. The possible earthquake sources that can cause damage to Kolkata are also taken into consideration. The sources from Himalayan frontier and the Arakan-Yoma ranges are the past earthquakes that have rocked Kolkata and caused much damage.

For the present study, the region from 20° N to 31° N and 80° E to 97° E is divided into five seismic zones as shown in Fig. 4. The high seismic activity of the region is very clearly seen from the plots of the epicenters. These zones are the likely nearby seismic source zones that can affect Kolkata. The five zones classified are given below:

Zone 1: Arakan-Yoma Zone (AYZ)
Zone 2: Himalayan Zone (HZ)
Zone 3: Shillong Plateau Zone (SPZ)
Zone 4: Bay of Bengal Zone (BBZ)
Zone 5: Shield Zone (SZ)

Zone 1 comprises the Arakan-Yoma Range, which is characterized by a subduction zone, and represents the junction of the Indian Plate and the Eurasian Plate. The zone shows a dense clustering of earthquake events and the major earthquake of this zone is the 1908 eastern boundary earthquake. The major tectonic features of this zone are the Eastern

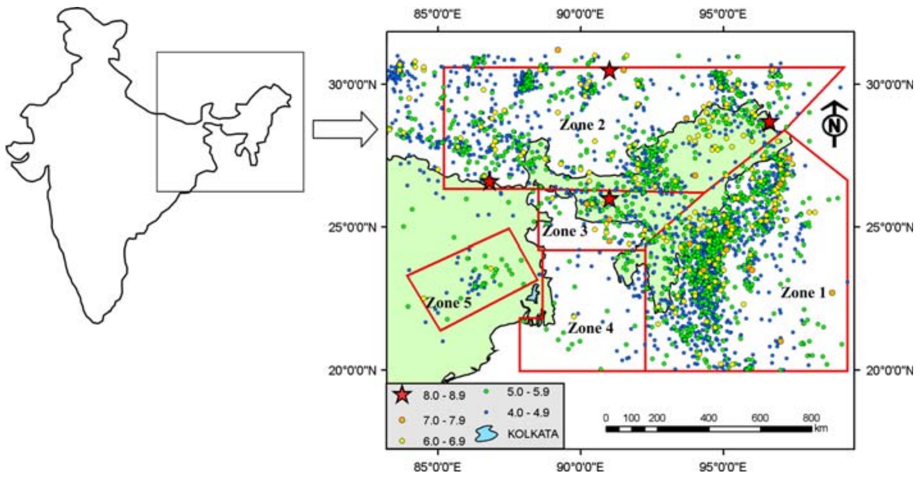

Fig. 4 The five source zones that were taken into consideration. The source zones show intense earthquake activity. The dots and the star represent the epicenters with its respective magnitudes (M_w) as shown in the legend

Boundary Thrust Zone, Naga Thrust, Disang Thrust, Mat Fault (GSI 2000), Kadi Fault, Tapu Thrust, Changrang Zungki Thrust, and Namya Fault (Das Gupta and Biswas 2000). The regional trend of the features is in the NW–SE direction.

Zone 2 covers the Himalayan tectonic zone, representing the subduction zone, and the Assam syntaxis. This zone covers the two major tectonic features of the Himalayan region: Main Central Thrust (MCT) and the Main Boundary Thrust (MBT). Some of the other tectonic features of this zone are the Mishmi Thrust, Lohit Thrust, Tista Fault, and Dhubri Fault. The major earthquakes of this zone are the 1950 Assam earthquake, 1934 Bihar earthquake, and the 1951 Upper Himalayan earthquake all with $M_w > 8$ (Seeber and Armbruster 1981).

Zone 3 is the Shillong Plateau area where the 1897 Shillong earthquake occurred and covers prominent tectonic features such as the Dauki fault (Chen and Molnar 1990), Dudhoni Fault, and Kulsi Fault. The Jangipur-Gaibandha Fault, Debagram Bogra Fault, and Dhubri Fault also are in this zone.

Zone 4 is the Bay of Bengal area and an earthquake of $M_w > 6$ has been recorded offshore. The tectonic features of this zone are the Padma Fault and Syhlet Fault. The 15 April 1964 Calcutta earthquake occurred in this zone where an intensity of VII–VIII, on the Modified Mercalli intensity scale, was felt over the Kolkata region affecting an area of 67,000 km^2. Most of the earthquakes in this zone occur offshore (GSI 2000).

Zone 5 is the Shield area and earthquakes of $M_w > 6$ have been recorded (Fig. 4). The Garhmoyna-Khandaghosh Fault and the Pingla Fault are in this zone. The tectonic features of this zone are the Brahmini Fault, Singhbhum Shear Zone, North Purulia Shear Zone, and South Purulia Shear Zone (GSI 2000).

Malik et al. (2006) have estimated the spectral strong ground motion for the north-eastern region using PSHA, where the region was divided into 10 zones. The seismic source zones considered by Malik et al. (2006) are different from the present study. For the present study, broad seismo-tectonic units are identified which are a threat to Kolkata region. Various authors have also carried out the seismic hazard analysis for the

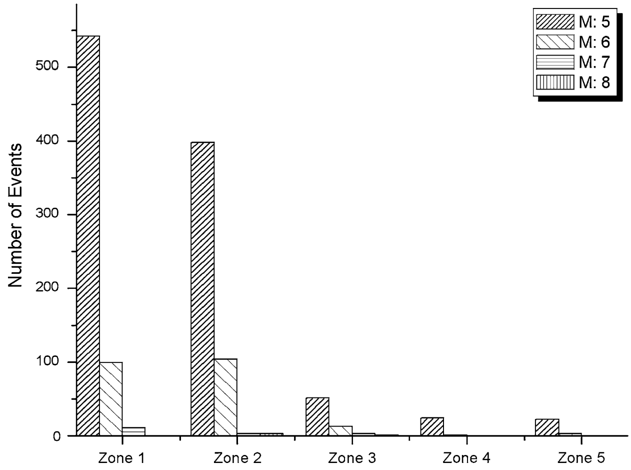

Fig. 5 Histograms of earthquake distribution of different magnitudes for the five source zones

northeastern India (Kaila et al. 1972; Rao and Rao 1979; Gupta and Srivastava 1990; Shanker and Sharma 1998; Arora and Sharma 1998, Bhatia et al. 1999; Sharma and Shanker 2001).

The earthquake distribution of different magnitudes for the five source zones is shown in Fig. 5. There is extensive seismic activity in source zones 1 and 2.

6 Methodology for seismic hazard assessment

A quasi-probabilistic approach is carried out to determine the expected maximum magnitude ($m_{\max}$) and the expected PGA for Kolkata. Probabilistic Seismic Hazard Assessment (PSHA) depends on the completeness of the catalog and Gutenberg–Richter relation fails if the catalog is not complete while the Deterministic Seismic Hazard Assessment (DSHA) takes care of any lack in the completeness of the catalog. For the present work, the $m_{\max}$ is computed through the probabilistic method and the $m_{\max}$ obtained is further used to calculate the PGA through the deterministic approach for all the source zones. Table 1 shows the major earthquake for all the five source zones.

To take care of the incompleteness in the data set of the catalog, a threshold magnitude or the level of completeness of magnitudes (M_c) is considered, for which the magnitude is assumed to be complete. The M_c, which is defined as the minimum magnitude of complete reporting, is determined for each source zone. The M_c is obtained from the frequency–magnitude distribution (FMD) graph as the value from where the FMD graph departs from the straight-line plot (Ameer et al. 2005). Figure 6 illustrates the plot for the M_c for the source zone 5. The M_c of each zone is shown in Table 2.

The M_c is used further for seismic hazard analysis. The method developed by Kijko and Sellevoll (1989, 1992), using both information on strong events contained in the macroseismic part of the catalog and the complete catalog that contains complete data above a certain magnitude threshold, is followed for the estimation of the hazard parameters for the five source zones. The relation known as the Kijko–Sellevoll–Bayes estimator of $m_{\max}$ (Kijko 2004) is used for the computation. In this method, the seismic parameters are treated

Table 1 Major seismic events of the five source zones

	Year	Mo	D	Long	Lat	M	Source
Zone 1	1908	12	12	97	26.5	7.5	USGS
	1912	5	23	97	21	7.9	ISC
	1923	6	22	98.8	22.7	7.3	ISC
	1931	1	27	96.8	25.6	7.6	ISC
	1938	8	16	94.3	23.5	7.2	ISC
	1946	9	12	96.2	23.9	7.8	ISC
	1954	3	21	95.1	24.2	7.25	USGS
	1957	7	1	93.8	24.4	7.25	USGS
	1988	8	6	94.89	25.19	7.2	Harvard
	1991	1	5	95.9	23.61	7.3	USGS
Zone 2	1934	1	15	86.5	26.5	8.3	ISC
	1943	10	23	94	26.8	7.2	ISC
	1947	7	29	94.0	28.5	7.7	ISC
	1950	8	15	96.5	28.5	8.6	ISC
	1951	11	18	91.0	30.5	8	ISC
	1952	8	17	91.5	30.5	7.5	ISC
Zone 3	1897	6	12	91	26	8.7	Bapat et al. (1983)
	1918	7	8	91	24.5	7.6	ISC
	1923	9	9	91	25.25	7.1	ISC
	1930	7	2	90.2	25.8	7.1	ISC
Zone 4	1989	6	12	89.76	21.86	6.1	USGS
Zone 5	1963	5	8	84.5	22.5	6.1	USGS
	2005	2	6	86.84	23.55	6.0	ISC

USGS: United States Geological Survey, ISC: International Seismological Centre

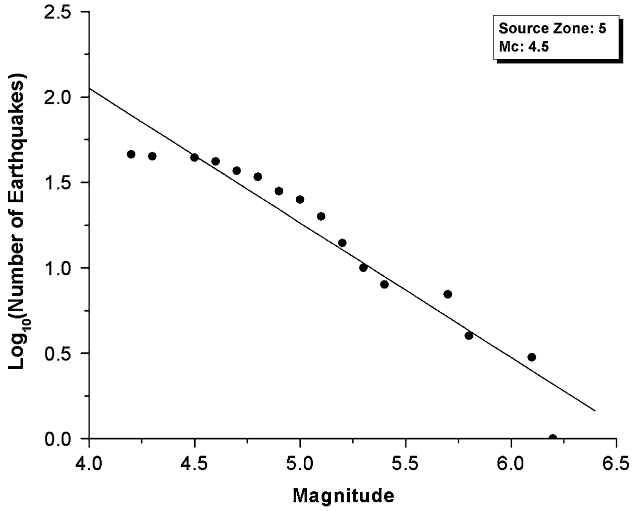

Fig. 6 The plot for the determination of the M_c for the seismic zone 5

Table 2 The input data for the five seismic zones of Kolkata and surrounding areas

Seismic zone	Zone name	M_c	Number of events	Standard deviation	Maximum observed magnitude
1	Arakan-Yoma zone	4.3	1,460	0.52	7.9
2	Himalayan zone	4.0	1,076	0.60	8.6
3	Shillong Plateau zone	4.3	140	0.66	8.7
4	Bay of Bengal zone	4.4	52	0.46	6.1
5	Shield zone	4.5	46	0.47	6.1

as random variables and a Bayesian-based equation is derived for the assessment of the maximum earthquake magnitude in which the uncertainty of the Gutenberg–Richter parameter b is taken into account. The equation for the estimation of the $m_{\max}$ is as follows:

$$m_{\max} = m_{\max}^{\text{obs}} + \frac{\delta^{1/q} \exp[n.r^q/(1-r^q)]}{\beta} [\Gamma(-1/q, \delta.r^q) - \Gamma(-1/q, \delta)]$$

where,

$m_{\max}^{\text{obs}}$ = maximum observed magnitude; $\beta = b \ln(10)$; $\delta = nC_\beta$; n = number of recorded magnitudes; C_β = normalizing co-efficient of β, which is equal to $\{1 - [p/(p + m_{\max} - m_{\min})]^q\}^{-1}$

$$q = \left(\overline{\beta}/\sigma_\beta\right)^2$$

σ_β = standard deviation of parameter β describing its uncertainty;

$$r = p/(p + m_{\max} - m_{\min});$$

$$p = \overline{\beta}/\left(\sigma_\beta\right)^2$$

$\overline{\beta}$ = mean value of parameter β; $\Gamma(.,.)$ = the Complementary Incomplete Gamma function.

Using the model, the $m_{\max}$ is calculated for all five source zones. Table 3 summarizes the seismic hazard variables obtained for the five source zones. The b-value is the lowest for zone 2, as compared with the other zones. The maximum expected magnitude is computed for zone 3. Figure 7 shows the comparison of the observed and predicted maximum magnitude and the b-value for all five source zones.

For most of the engineering analysis, the estimated lifetime is generally taken to be between 50 and 100 years. Therefore, the probability of exceedance of 10% for 50 years is computed for the five zones. The earthquake magnitudes corresponding to this exceedance value are found to be 8.3, 9.0, 8.7, 6.6, and 6.5 for the seismic zones 1, 2, 3, 4, and 5, respectively. The return period R of the earthquakes with a magnitude equal or greater than M_c is a useful parameter in seismic hazard determination. Therefore, the values of R for several values of magnitude $\geq M_c$ is calculated (Table 3) and plotted (Fig. 8). The return period for zone 2 (Fig. 8) is lower than the other zones, indicating that strong events

Table 3 Seismic hazard parameters for the five source zones

Seismic zone	λ	β	m_{max}	b	$R_{6.0}$	$Pr(M_{6.0})$ ($T = 100$)
1	14.91 ± 0.39	1.40 ± 0.04	8.30 ± 0.51	0.61 ± 0.2	0.7	1.0
2	12.09 ± 0.17	0.98 ± 0.02	9.09 ± 0.58	0.42 ± .01	0.6	1.0
3	1.45 ± 0.06	1.04 ± 0.05	9.20 ± 0.51	0.71 ± .05	7.2	1.0
4	0.55 ± 0.08	1.98 ± 0.14	6.62 ± 0.43	0.86 ± 0.06	56.7	0.83
5	0.92 ± 0.14	1.97 ± 0.15	6.61 ± 0.43	0.86 ± 0.06	27.4	0.94

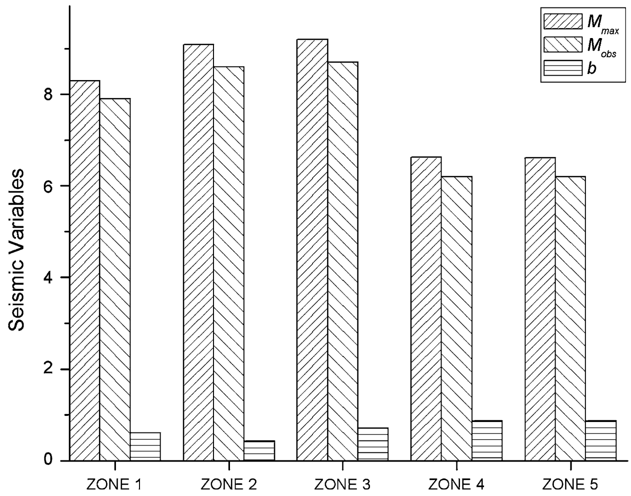

Fig. 7 Histogram showing the variation in the b-values, maximum observed magnitude and m_{max} for the five source zones

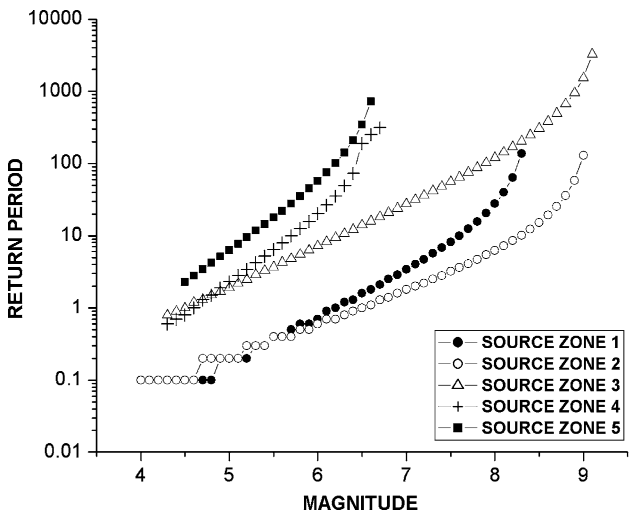

Fig. 8 The plots of return periods for the five seismic source zones

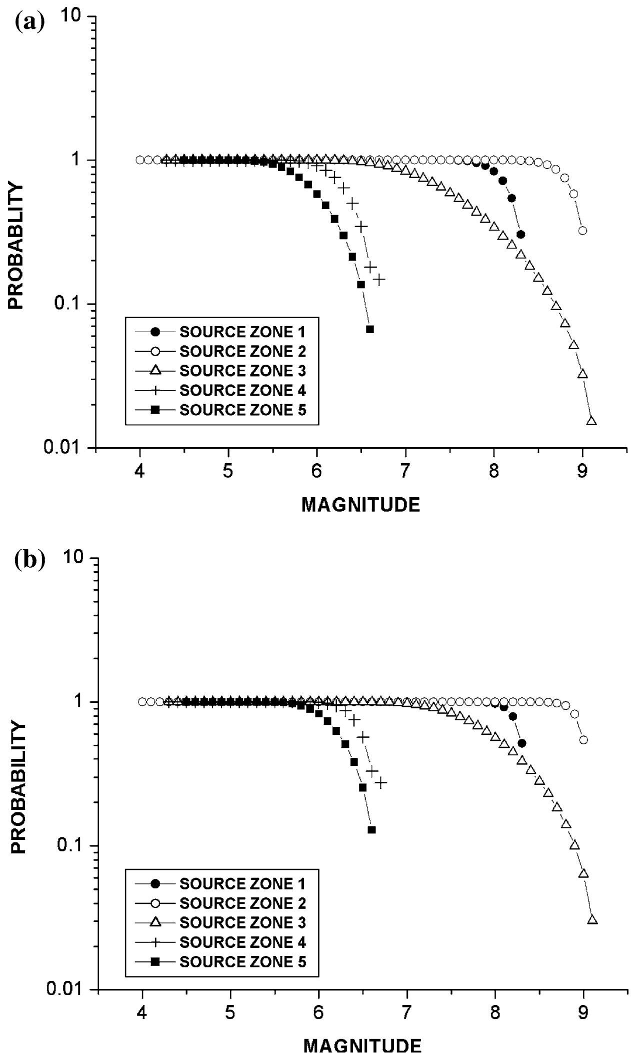

Fig. 9 The probability for occurrence of different magnitudes in the five seismic source zones for return periods of (**a**) 50 years and (**b**) 100 years

($M_w \geq 6$) occur more frequently as compared to the other zones. An earthquake of $M_w \geq 6$ can generate enough ground motion that can be considered hazardous and the hence, return period of $M_w \geq 6$ for the five zones is calculated and listed in Table 3. The plots of the probability of occurrence of earthquakes of different magnitudes, for 50-year and 100-year return periods, are shown in Fig. 9a and b respectively.

7 Peak ground acceleration

The expected ground motion is an important parameter for the seismic design of engineering structures. The Global Seismic Hazard Assessment Program (Giardini et al. 1999)

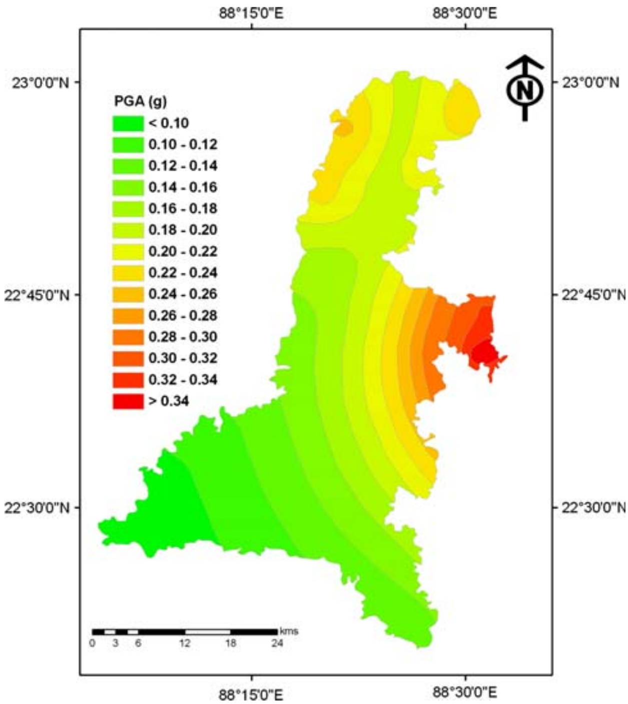

Fig. 10 The maximum PGA distribution over Kolkata due to the combined effect of all the five source zones

estimates a Peak Ground Acceleration (PGA) of 0.08–0.13g for Kolkata City with 10% probability of exceedance in 50 years. Das et al. (2005, 2006) have carried out the seismic hazard analysis for northeast India, where they took into consideration the pseudo-spectral acceleration (PSA) to describe the hazard levels at different natural periods.

Several attenuation relationships have been developed to calculate the PGA depending on the tectonic regime and seismicity of the area. The ground motion for the present study is calculated after examining some of the well-established attenuation relationships: Boore et al. (1997), Atkinson and Boore (1995, 1997), Toro et al. (1997), and Campbell and Bozorgnia (2003). The attenuation relationship of Toro et al. (1997) has been used because this relationship is derived for a coastal region having attenuation characteristics similar to the area under study. The PGA obtained by the Toro et al. (1997) relationship varies from 0.34 g along the eastern part of Kolkata to 0.10 g toward the southeastern Kolkata. Though an $m_{\max}$ of $M_w = 9.2$ is expected from the source zone 3, the major contribution of PGA for Kolkata City is observed from source zones 4 and 5 as Kolkata is very close in its vicinity. The PGA value is plotted taking into consideration the combined effects of all five source zones (Fig. 10).

8 Results and discussions

Though Kolkata has not had any great earthquakes in its vicinity, it can be affected by far away seismic sources. During the 1897 Shillong earthquake ($M_w = 8.7$), an intensity of

VIII was felt on the Bengal Basin (Seeber and Armbruster 1981). The return periods of the five seismic zones show that occurrence of $M_w \geq 6$ is frequent in zone 2 as compared to the other five zones. The probability of occurrences of earthquakes of different magnitudes for 50-year and 100-year return periods is also obtained. In the seismic zonation map, Kolkata lies on the boundary of zone III and IV (which suggest the PGA value of 0.2 and 0.25*g*, respectively). As per the GSHAP (Bhatia et al. 1999), the PGA values for Kolkata range from 0.08 to 0.13*g*, which is an underestimation of the hazard parameter. In the present study, the PGA value range from 0.1 to 0.34*g*. However, the major part of Kolkata City can experience PGA value above 0.25*g*, which suggests that Kolkata is in seismic zone IV. With the present day situation, because of its human growth in population and industrial structures, an earthquake generating a PGA of 0.34*g* can take a heavy toll on the economy and human life.

The alluvium could increase the seismic hazard above that predicted by the present method, because it will amplify the seismic energies. The Bhuj earthquake in 2000, earthquakes of Mexico City in 1985, and the San Francisco Bay area in 1989 are examples of local site effects, where much damage was caused because of local soil conditions. The January 26 2001 Bhuj earthquake caused extensive damage in Ahmedabad, a city that is at a distance of 250 km from the epicenter (Thakur and Wesnousky 2002). The September 19 1985 Mexico earthquake caused moderated damage in the vicinity of its epicenter but caused extensive damages some 350 km away. The soil structure resonance in Old Lake bed zone, underlain by 38 to 50 m of soft soil, was a major factor for the damage (Stone et al. 1987). The October 19 1989 earthquake occurred 100 km south of San Francisco, but the intensities were higher (MMI IX) in portions of San Francisco and Oakland than in the epicentral region (MMI VIII) (Kramer 1996).

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