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Seismic microzonation of Kolkata

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Abstract. This paper presents the probabilistic seismic microzonation of densely populated Kolkata city, situated on the world's largest delta island with very soft alluvial soil deposit. At first probabilistic seismic hazard analysis of Kolkata city was carried out at bedrock level and then ground motion amplification due to sedimentary deposit was computed using one dimensional (1D) wave propagation analysis SHAKE2000. Different maps like fundamental frequency, amplification at fundamental frequency, peak ground acceleration (*PGA*), peak ground velocity (*PGV*), peak ground displacement (*PGD*), maximum response spectral acceleration at different time period bands are developed for variety of end users, structural and geotechnical engineers, land use planners, emergency managers and awareness of general public. The probabilistically predicted *PGA* at bedrock level is 0.12 g for 50% exceedance in 50 years and maximum *PGA* at surface level it varies from 0.095 g to 0.18 g for same probability of exceedance. The scenario of simulated ground motion revealed that Kolkata city is very much prone to damage during earthquake.

Keywords: seismic microzonation of Kolkata city; probabilistic seismic hazard; ground motion amplification; response spectra

1. Introduction

Earthquake is a natural hazard which may adversely affect human activity. So earthquake protection is needed to be taken in advance. But excessive protection may render it uneconomical, unaffordable. Seismic microzonation means subdividing a region into small regions or microzones having different potentials for hazardous earthquake effects like ground motion amplification, liquefaction, and slope failure etc. The results of seismic microzonation may be used for earthquake resistant design of structures, land use planning for further urban development, demarcation of unsuitable areas, selecting ideal heights and types of buildings, retrofitting of critical buildings, providing guidance to general population on earthquake, earthquake insurance and emergency response planning.

The Kolkata city and adjoining region, situated on the largest delta island- Bengal Basin, have undergone several past and recent earthquakes. Parts of the Kolkata have been affected during the Shillong earthquake of 1897 ($M_s = 8.7$), Kolkata earthquake of April 15, 1964 ($M_b = 5.2$), Srimangal

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earthquake of 1918 (M_s = 7.6), Dubhri earthquake of 1930 (M_s = 7.2), Bihar Nepal earthquake of 1934 (M_s = 8.3) (Jhingran *et al*. 1969, Seeber and Armbruster 1981, G.S.I. 2000), September 18, 2011 Sikkim earthquake (M_w = 6.9), April 11, 2012 Indonesia earthquake (M_w = 8.6), November 12, 2012 Myanmar earthquake (M_w = 6.8) (NDTV News). These earthquakes have raised the question of safety of Kolkata city and hence the need of seismic microzonation. The level of seismic threat in Kolkata if further enhanced because of presence of thick soft alluvial soil cover over basement and illegal filling of low marshy land for housing purposes (Nandy 2007).

According to seismic zonation of India (IS – 1893 2002), the city lies in boundary of zone III and zone IV (Mohanty and Walling 2008). Here local site effects like effect of soft sediment deposit, basement topography effects etc are totally neglected. Seismic hazards and site response studies for Kolkata city were carried out by several researchers. Probabilistic seismic hazard analysis at bedrock level was carried out by Mohanty and Walling (2008). Site response studies also have been carried out by Roy and Sahu (2012) and maximum *PGA* was obtained at surface level is 0.42g. The site specific modeling of SH and P-SV waves along metro rail profile was carried by Vaccari *et al*. (2011). Deterministic seismic hazard at bedrock level and amplification variation due to soil at surface level was evaluated by two dimensional (2D) fourth order finite difference method by Shiuly and Narayan (2012) for upper 700 m soil. In the analysis at surface level *PGA* varies from 0.12 g to 0.60 g. Site-specific earthquake response study for hazard assessment in Kolkata city was carried out by Govidaraju and Bhatyacharya (2012). Variation of shear wave velocity and soil site classification in Kolkata has been conducted by regression and sensitivity analysis taking sixty three bore hole locations around city by Chatterjee and Choudhury (2013). Scenario of ground motion amplification in Kolkata megacity was computed using 2D 4rth order finite difference algorithm by Shiuly (2014a). Liquefaction Potential for Kolkata City was computed by Jakka *et al*. (2013). Variations of shear modulus of Kolkata city was presented by Shiuly (2013). Effect of Soil on Ground Motion Amplification of Kolkata was performed by 1D seismic wave propagation technique SHAKE2000 by Shiuly *et al*. (2014b). Performance of a RC building using site specific ground motion parameter of Salt Lake Sector-V region, Kolkata was performed by Shiuly *et al*. (2015).

In this study, probabilistic seismic hazard analysis of Kolkata has been carried out at bedrock level. To incorporate local site effect in ground motion parameter, effect of thick soft sediment soil has been simulated by 1D wave propagation technique using SHAKE-2000. Different types of contour maps like fundamental frequency, amplification of fundamental frequency, *PGA*, *PGV*, *PGD*, maximum response spectral acceleration in different time period band have been generated by Arc GIS 9.2 (2006) for variety of end users. Fig. 1 shows the position of Kolkata in South-East Asia and the study area.

2. Seismotectonic setup of Bengal basin

Kolkata is situated over world's largest delta Bengal Basin. The basin is formed by Ganga, Brahmaputra and Barrack River. The basin consist thick soft alluvial soil. The elevation of Kolkata is about 10 m from mean sea level. At the western area of the basin sediment thickness is 1.2 km, which increases in West Bengal border to 12 km and in Bangladesh it attains 20 km (Nandy 2007, Banerjee *et al*. 2014).

The Bengal basin is divided by western scrap zone, middle shelf zone and eastern deeper basin part (Mohanty and Walling 2008). The western part of the Bengal basin is bounded by basin

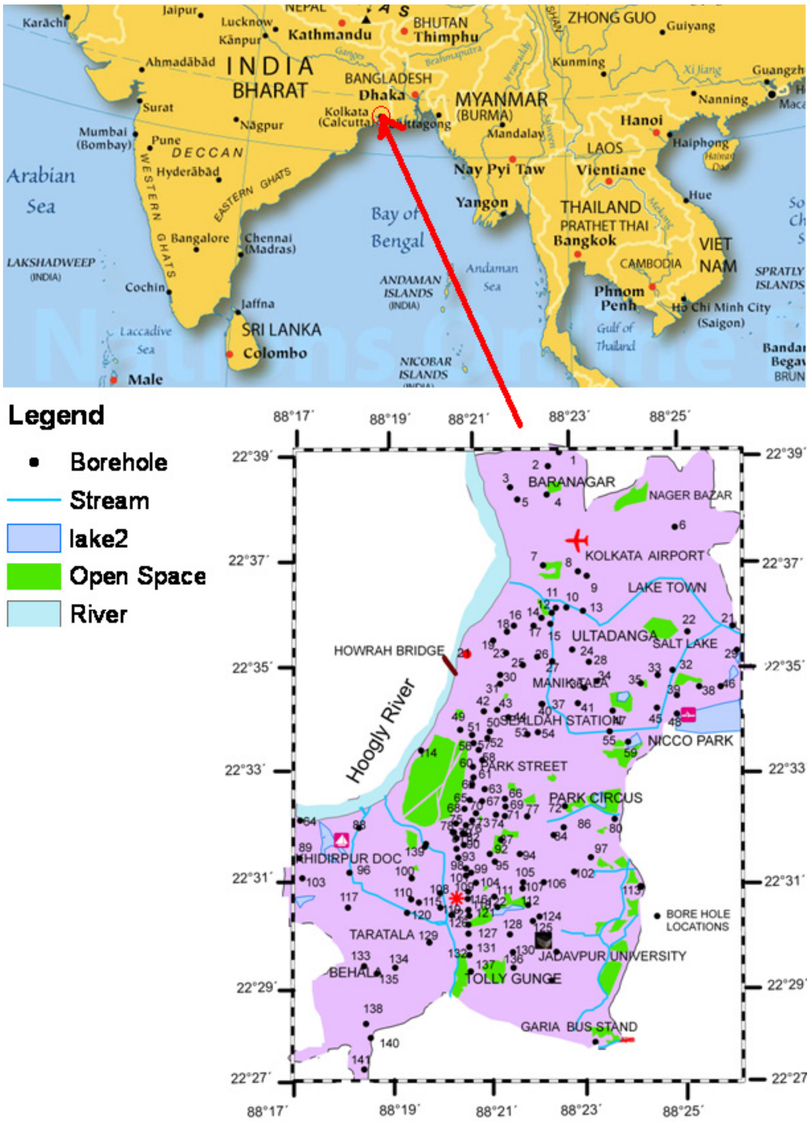


Fig. 1 The position of Kolkata city, position of Kolkata in east Asia (www.nationsonline.org) and important features, places and 144 bore log locations in Kolkata city

margin fault zone to the west and North West and by Eocene Hinge Zone (EHZ). Almost entire Kolkata is situated on this EHZ which is also known as Calcutta-Mymansing hinge zone. The EHZ marks a zone of differential thickening and subsidence rate of Oligocene and Miocene section (Salt *et al*. 1986). The basement of Bengal basin penetrates from 4 to 10 km across EHZ. This EHZ extend more than 500 km from north Dauki fault to South Bay of Bengal. The width varies 110 km north to 25 km south. Other major fault system surrounding Kolkata are Garhomoyana-Khandaghosh Fault (GKF), Jangipur-Gaibandha Fault (GGF), Pingla Fault, Eocene Hinge Zone (EHZ), Debagram Bogra Fault (DBF), Rajmahal Fault (RF) and Dhubri Fault (DF) (Shiuly and Narayan 2012).

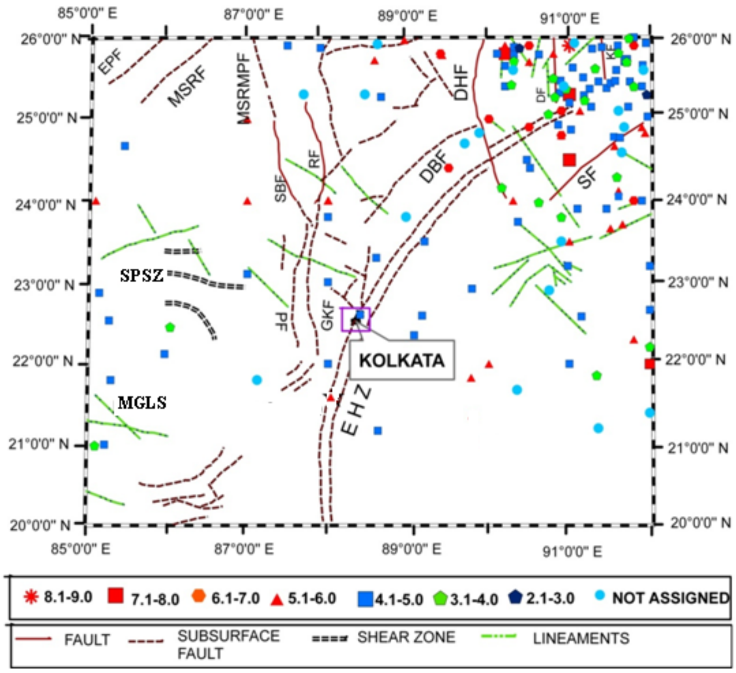


Fig. 2 The seismo-tectonic map around Kolkata city (After IMD, G.S.I. 2000)

3. Seismicity of Kolkata

In past Kolkata city has experienced the shaking due to local and distant earthquakes (Shiuly *et al*. 2014a). During the 1897 Shillong earthquake ($M_s = 8.7$), the city had undergone considerable damage. Several cracks were observed in the houses, tomb of church was broken and some buildings were partially collapsed. Though the epicenter was far away from Kolkata, intensity was III in Oldham scale which is equivalent to VII in MSK scale (Oldham 1899). The September 29, 1906 Calcutta earthquake of ($M_b = 5.0$) caused major cracks in large number of buildings in Kolkata city and intensity of the order of VI-VII was assigned on Rossi-Forel scale. The epicenter was within the Kolkata city (Middlemiss 1908). The intensity of shaking in Kolkata during April 15, 1964 Calcutta earthquake ($M_b = 5.2$) was of the order of VII on MMI scale. The epicenter was near Sagar Island, 106 km south of Kolkata City (Jhingran *et al*. 1969, G.S.I. 2000). The Bihar-Nepal earthquake of January 15, 1934 ($M_s = 8.3$) caused considerable damage to the buildings and developed intensity of the order of VI on MMI scale. The epicentral distance was 480 km from North west of Kolkata (Dunn *et al*. 1939). Srimangal earthquake of July 8, 1918 ($M_s = 7.6$) caused cracks in many building in Kolkata city. The epicenter of this earthquake was 350 km in northeast. The other earthquakes which were felt and caused damage in Kolkata city include Dhubri earthquake of July 3, 1930 and earthquakes of September 1, 1803, August 26, 1833 and December 31, 1881 (Jhingran *et al*. 1969, G.S.I. 2000)

Recently, Kolkata city has felt shaking due to several distant earthquakes. On 18th September, 2011 at about 6:10 PM Sikkim earthquake ($M_w = 6.9$) was felt in Kolkata. The epicenter of this earthquake was 572 km north of Kolkata. The quake caused panic in whole Kolkata city, cracks were oberved at the Ultadanga police quarters and many houses in Burrabazar (NDTV, India).

Fresh tremor were felt in Kolkata around 4:15 PM on April 11, 2012 due to Indonesian earthquake (M_w = 8.9; epicenter = 615 km south). During this time, panic among the citizens was widespread; Kolkata Metro has resumed services after temporary shutdown. Some cracks were also seen in some old houses (Yahoo! India News).

4. Probabilistic Seismic Hazard Analysis (PSHA) of Kolkata

Probabilistic Seismic Hazard Analysis (PSHA) has been carried out in order to find out the Design Basis Earthquake (DBE), which is to be used for determination of bedrock motion for seismic microzonation of Kolkata city. Fig. 2 shows the seismotectonic map of Kolkata and surrounding region. The magnitude scale is not mentioned in IMD data. So, it is assumed that if the magnitude is less than 6, it is either Richter magnitude or body wave magnitude and if magnitude greater than 6, it is surface wave magnitude. These magnitudes are converted to M_w using the magnitude conversion relations given by Das *et al*. (2011).

4.1 Data completeness analysis

The earthquake data in the IMD catalog is incomplete. The incompleteness of data can be determined by means of rate of occurrence, $\lambda = \frac{N}{year}$. Here it havebeen adopted Stepp's method (1972) to check the completeness of earthquake data around the Kolkata region. Analysis has been carried out by grouping the data into four magnitude classes (3-3.9, 4-4.9, 5-5.9, 6-6.9) and each of these classes is modeled as a point process in time. In this process variance of earthquake occurrence is computed. It is assumed that earthquake sequence follows Poison distribution. From that sample mean and variance can be computed. If m_1, m_2, m_3,... m_n are the numbers of earthquake per unit time interval, then an unbiased estimate of mean rate per unit time interval of the sample $\chi = \frac{1}{n}\sum_{j=1}^{n} m_j$ and its variance is $\sigma_\chi^2 = \frac{\chi}{n}$ where n is the number of unit time intervals. Taking the

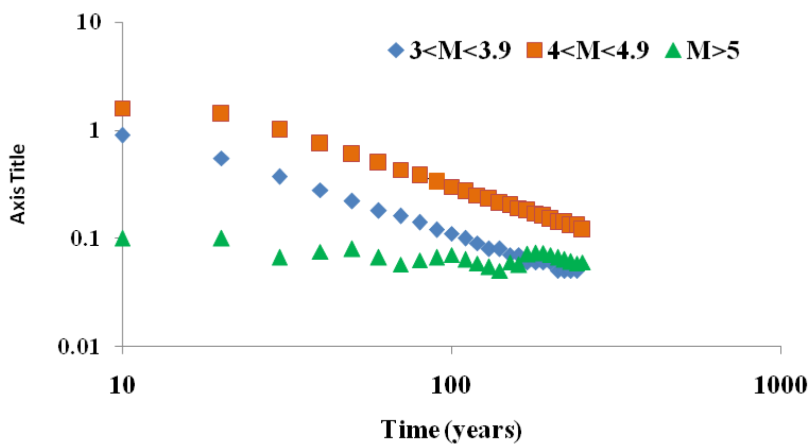


Fig. 3 Variance of seismicity rate for different magnitude intervals and different lengths of moving time window

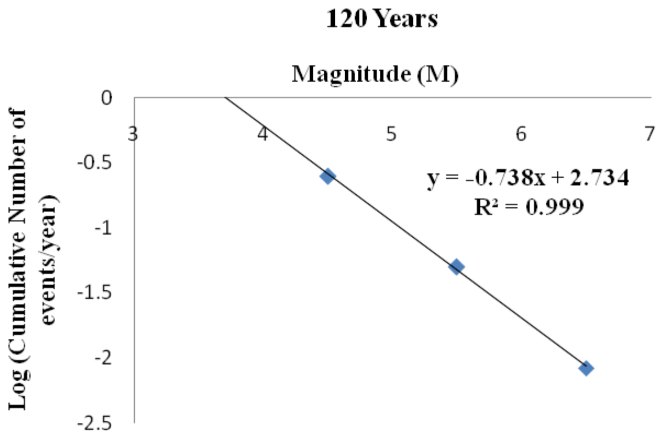


Fig. 4 Frequency magnitude relation for study area

unit time interval to be one year gives standard deviation as

$$\sigma_\chi = \frac{\sqrt{\chi}}{\sqrt{T}} \tag{1}$$

in which T is the sample length. σ_χ behaves as $\frac{1}{\sqrt{T}}$ in the subintervals, in which the mean rate of occurrences is constant. Fig. 3 shows the pictorial representation of present process. Data set of all magnitude intervals seems to be complete in the last 120 years. Fig. 4 reveals the logarithmic of cumulative earthquakes per year for M, where M is the magnitude of the particular interval.

4.2 G-R relationship

To determine G-R relationship available earthquake data catalog should be complete and homogenous (Stepp 1972). Computation of b value has been carried out by grouping the data with interval of 0.5 year for last 120 year data. The G-R relationship assumes an exponential distribution of large and small magnitude events and is given by

$$\log_{10} N = a - bM_w \tag{2}$$

In the relationship N describe the cumulative number of earthquake,
"*a*" describes the seismic activity and "*b*" describes the relative abundance of large and smaller earthquake. From the above equation a seismic hazard parameter "*a*" and "*b*" have been obtained as 2.734 and 0.738 respectively with a correlation coefficient 0.999.

4.3 Hazard analysis

The probability distribution is defined in terms of the annual rate of exceedance of the ground motion y at a particular site $v(y)$, due to all possible pairs (M_w, R) of the magnitude and distance of the earthquake event expected around the site (Cornel 1969). The probability of ground motion parameter at a particular site, Y, will exceed a specified level, y, during a specified time, T and it is represented by

$$P(Y > y) = 1 - e^{-v(y)T} \le v(y)T \tag{3}$$

The uncertainty of time, size and location of future earthquakes and uncertainty of level of grundmotion is incorporated in the function $v(y)$ and is as follows

$$v(y) = \sum_{n=1}^{N} N_n(m) \int_{m=m^L}^{m^U} f_n(m) \left[\int_{r=0}^{\infty} f_n(r/m) P(Y > y/m, r) dr \right] dm \tag{4}$$

$N_n(m_L)$ is the frequency of earthquakes on seismic source n above a minimum magnitude m^L. In this study m^L value is taken as 4. $f_n(m)$ is the probability density function for minimum magnitude m^L and maximum magnitude m^U. $f_n(r/m)$ is the conditional probability density function. $P(Y > y/m, r)$ is the probability that a given magnitude m earthquake distance r from the particular site where ground motion exceed y. The above continuous equation can be given by discrete equation as follows

$$v(y) = \sum_{n=1}^{N} \int_{m_i=m^L}^{m_i=m^U} \lambda_n(m_i) \left[\int_{r_j=r_{\min}}^{r_j=r_{\max}} P_n(R = r_j / m_i) P(Y > y/m, r) \right] \tag{5}$$

Where $\lambda_n(m_i)$ is the frequency of events of magnitude m_i on source n, obtained by discretizing the earthquake recurrence relationship. The uncertainty of magnitude distance and ground motion parameter is discussed below.

4.3.1 Regional recurrence model

The frequency of seismic activity of various sizes per year can be determined from magnitude recurrence model for a seismogenic source. The recurrence relation of each seismogenic source capable of producing earthquake magnitude between m^L to m^U is calculated using Cornell and Vanmark (1969) recurrence relation

$$N(m) = N_n(m) \frac{\beta e^{-\beta(m-m^L)}}{1 - e^{-\beta(m^U - m^L)}} \quad \text{for} \quad m^L \le m \le m^U \tag{6}$$

where $\beta = bln(10)$ and $N_n(m)$ proposed weightage factor for particular source based on deagrregation.

4.3.2 Deagrregation

In order to find out the weightage factor for each source, based on the length (α) and number of earthquake (χ) for a source, the deaggregation procedure followed by Iyengar and Ghosh (2004), Raghuknath and Iyengar (2006), Anbazhagan *et al.* (2009) has been used in the study. The length weighting factor for nth seismogenic source is $\alpha_n = \frac{L_n}{\sum_1^n L_n}$ and earthquake event weighting factor $\chi_n = \frac{\text{Number of earthquake close to the source}}{\text{Total number of earthquakes in the region}}$, where L_n is the length of nth fault. The recurrence relation for nth seismogenic source is given by expression

$$N(m) = \frac{(\alpha_n + \chi_n)}{2} \tag{7}$$

The conditional probability distribution function of hypocentral distance R, for an earthquake magnitude $M = m$ for a fault segment is given by Kiureghian and Ang (1977) is given by

$$P(R < r / M = m) = 0 \quad \text{for} \quad R < (D^2 + L_0^2)^{\frac{1}{2}} \tag{8}$$

$$P(R < r / M = m) = \frac{(r^2 - d^2)^2 - L_0}{L - X(m)} \quad \text{for} \quad \left[(D^2 + L_0^2) \le R < [D^2 + \{L + L_0 - X(m)\}^2\right]^{\frac{1}{2}} \tag{9}$$

$$P(R < r / M = m) = 1 \quad \text{for} \quad R > \left[(D^2 + \{L + L_0 - X(m)\}^2\right]^{\frac{1}{2}} \tag{10}$$

where $X(m)$ is the fault length in kilometer for the event of magnitude m, is determined using Wells and Coppersmith (1994) equation which is given

$$X(m) = \min\left\{10^{(-2.44+0.59(m_j))},\ L_n\right\} \tag{11}$$

The Fig. 5 reveals the notation used in the Eqs. (5), (6) and (7).

4.4 Attenuation relationship

Ground motion attenuation relationship (Eq. (9)) proposed by Raghukanth (2005) for Indian region has been used in this study. There is no seismological observation lab in Kolkata or surrounding Kolkata. It is very difficult to propose attenuatiation relationship for Kolkata region. However attenuation relationship proposed by RaghuKanth (2005) based on synthetic seismogram record for western central India is very much appropriate for Kolkata region, as Kolkata lies in this region. In previous study Roy and Sahu (2012) also used same relationship for estimating MCE at

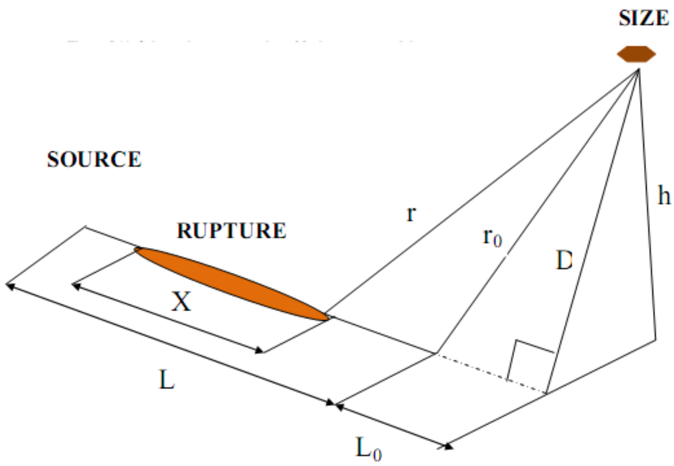


Fig. 5 The schematic representation of fault rupture model

bedrock level.

$$\ln(y) = c_1 + c_2(M_w - 6) + c_3(M_w - 6)^2 - \ln R - c_4 R + \ln(\epsilon) \tag{12}$$

where x, M_w, R and ϵ refer to PGA or spectral acceleration (g), moment magnitude, hypocentral distance and error associated with regression. c_1, c_2, c_3, c_4 are constants. Uncertainty involved in this equation can be obtained by computing the probability of exceedance of a particular value by the attenuation equation. The normal cumulative distribution function given in terms of standard normal variable (z). This can be calculated using the transformation given by Krammer (1996)

$$z = \frac{\ln(PGA) - \overline{\ln(PGA)}}{\sigma_{\ln} PGA} \tag{13}$$

where $\ln(PGA)$ is the various peak acceleration levels that will be exceeded, $\overline{\ln(PGA)}$ is the acceleration calculated using attenuation relationship and $\sigma_{\ln}PGA$ is uncertainity involved in the attenuation relation.

5. Hazard curves

Nine seismogenic sources around Kolkata region have been considered in this study. Nine seismogenic sources are Rajmahal Fault (RMF), Rajmahal Fault (RMF), Malda Kishanganj Fault (MKF), Sainthia Bahmani Fault (SBF), Garhmayna Khanda Ghosh Fault (GKGF), Pingla Fault (PF), Eocene Hinge Zone (EHZ), Debagram Bogra Fault (DF), South Purulia Shear Zone (SPSZ), Malay Giri Lineaments (MGLS).The whole process has been carried out using EXCEL program. Fig. 6 depicts hazard curves in terms of PGA vs. mean annual rate of exceedance (reciprocal of return period) at the center of the Kolkata city at bed rock level for all individual nine sources and cumulative of all sources. PGA vs. return period graph is shown in Fig. 7. The cumulative hazard curve depicts that at 72 years return period PGA can be 0.118g. According to GSHAP report PGA

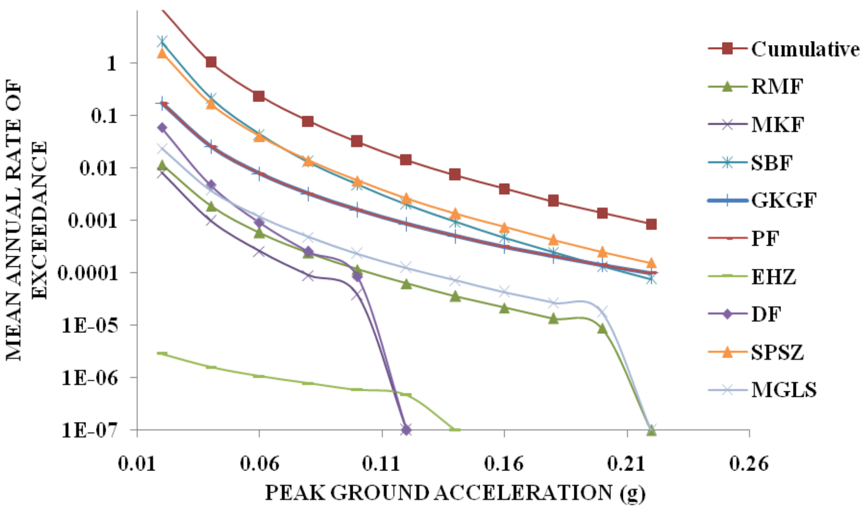


Fig. 6 Hazard curves in terms of *PGA* of Kolkata city at bed rock level respectively

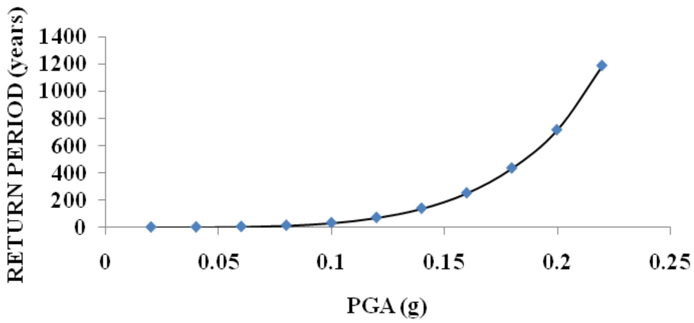
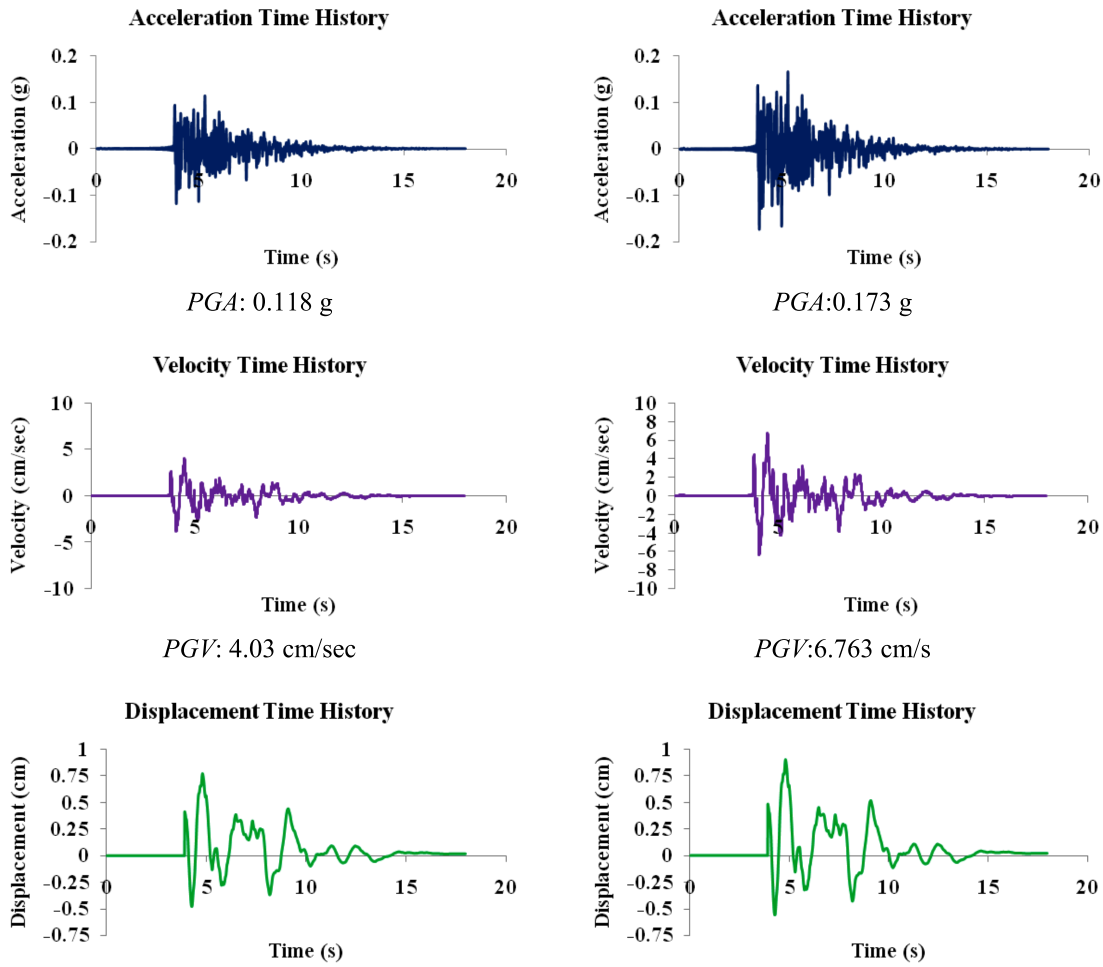


Fig. 7 The plot of *PGA* vs return period



PGA: 0.118 g | *PGA*:0.173 g

PGV: 4.03 cm/sec | *PGV*:6.763 cm/s

PGD: 0.77 cm | *PGD*: 0.903 cm

Fig. 8 (a) shows the acceleration time history, velocity time history and displacement time history at bedrock level respectively; (b) shows the acceleration time history, velocity time history and displacement time history at surface level of BL-137 respectively can be 0.08 g for 50 years returned period. According to IS-1893(I)-2002 Kolkata is situated in between zone III and zone IV. So its estimated *PGA* value is 0.08 g (= 0.16/2) to 0.12 g (= 0.24/2). According to this study the *PGA* value lies in between them.

6. Computation of ground motion parameter at bedrock level

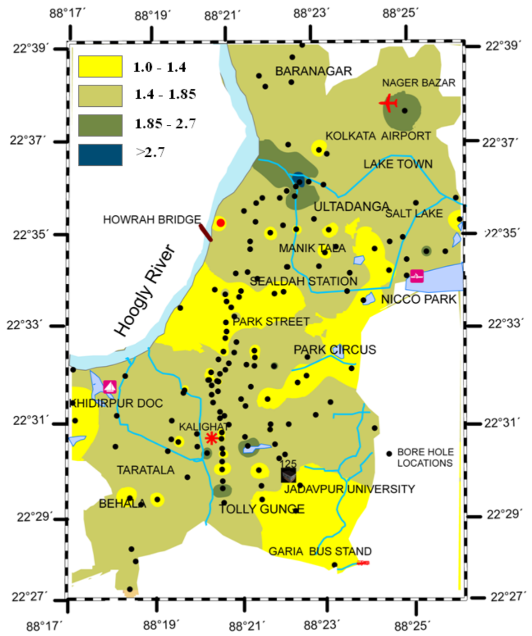
At bed rock, *PGA* has been computed as 0.118 g for seventy two years return period. It can be assumed that *PGA* is equal to zero period acceleration (ZPA). By using IS-1893(I)-2002, response spectra have been computed at bedrock level. From the response spectra it has been computed acceleration time history. It has been windowed the time history by multiplying a windowed function (Boore 2003). Here windowed function is used to shape the synthetic accelerogram into real accelerogram. The shaping window has been applied to the Gaussian noise. Window function may be either a box window or exponential window. However in present study exponential window has been used as stated by Boore (2003). The exponential window is very much useful than box window for deriving various ground motion parameter (Boore 2003). The whole computation were carried out with using excel programming (Kumar 2006, Earthquake Engineering Studies 2008). After windowing the time history is filtered and base line correction has been made. The filtering and base line correction procedure has been carried out with using Seismo-Soft. The modified acceleration, velocity and displacement time history at bed rock level are shown in Fig. 8(a). The *PGA*, *PGV* and *PGD* values are obtained at bed rock level are 0.118 g, 40.27 mm/sec and 7.696 mm, respectively.

7. Computation of soil effect

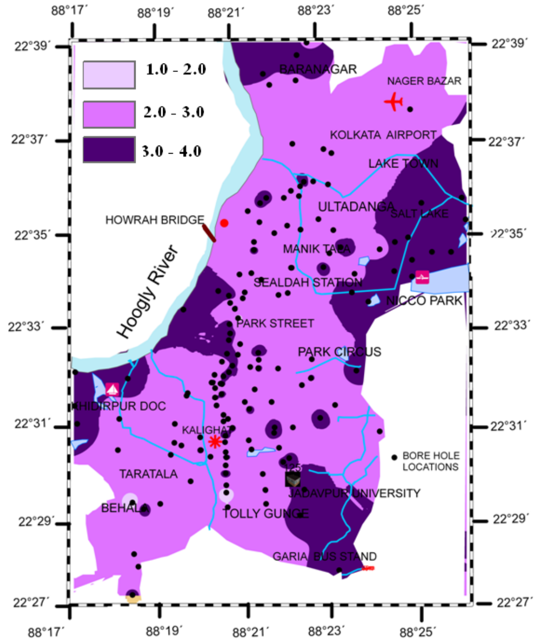
The Bengal basin has been filled up by sediments washed down by Ganga, Brahmaputra and Barak rivers. The study area is situated beside Hoogly River, a branch of a Ganga river. 144 bore logs (Fig. 1) were used for carrying out this study keeping in view that the borelogs (BL) are complete and widely distributed. Several correction factors like overburden correction, finer content corrections, hammer energy correction, rod length correction, bore hole diameter correction, sampling method correction etc are applied on N values (Idriss and Boulenger, 2004). These corrected N values have been used for obtaining the shear wave velocity in different layers using formula $V_S = 51.5N^{0.516}$ (Iyisan 1996).The empirical formula is very much useful for alluvial soil. The same relationship was used by Shiuly and Narayan (2012) for carrying out deterministic seismic hazard analysis of Kolkata city. The deepest information from these borehole data in the study area is up to 50 m. Below 50 m depth the shear wave velocity of soil is greater than 700 m/s. The engineering bed rock is considered at 50 m depth from surface level. Figs. 8(a), (b) and (c) shows the acceleration time history, velocity time history and displacement time history at bed rock level and surface level of BL-137 respectively.

8. Computation of fundamental frequency and soil amplification factor

The variation of fundamental frequency and amplification at fundamental frequency of soil column in Kolkata city are shown in Figs. 9(a) and (b) respectively. The smallest value of fundamental frequency has been obtained in BL-127, Tollygungue area (1 Hz). Low fundamental

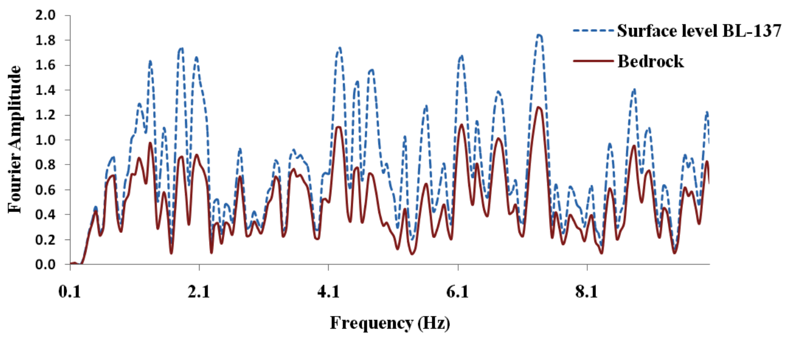


(a) Fundamental frequency

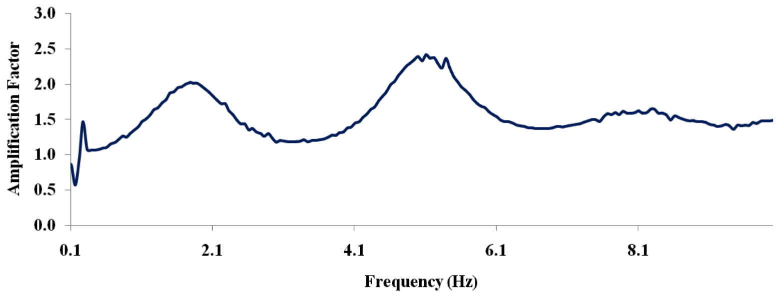


(b) Amplification at fundamental frequency

Fig. 9 Maps of fundamental frequency (Hz) and amplification at fundamental frequency of sedimentary deposit in Kolkata city



(a) Spectral amplitude



(b) Amplification factor

Fig. 10 The spectral amplitude with and without soil (BL-137) and amplification factor of BL-137 respectively frequency of soil deposit (less than 1.3) has been also obtained at southern part of study area-Baghajatin (BL-143), Garia (BL-144). Large fundamental frequencies in order of greater than 2.5 have been obtained in Paresnath Mandir (BL-11), Southern Avenue (BL-122), Childrens Park (BL-123), Bangur Hospital (BL-132). Large fundamental frequency has been obtained due to thin surficial soil layer. At all the remaining BL locations, fundamental frequency has been obtained between 1.2 to 1.9 Hz. In small patches of very high spectral amplification (greater than 2) at fundamental frequency are also observed at Hestings Sarani (BL-114), Salt Lake Area (BL-39, BL-45), Jatindra Mohan Park (BL-23), Benarasi Ghosh Road (BL-58), Southern Avenue (BL-122). This is due to the presence of thick low velocity soil layer at some depth with considerable impedance contrast at both upper and lower interfaces. In rest of the study area spectral amplification at fundamental frequency is found between 2 to 3.5. A typical Fourier spectrum and spectral amplification of BL-137 are shown in Figs. 10(a) and (b) respectively. If fundamental frequency of building match with the fundamental frequency of the soil layer then resonance will occur causing high damage and destruction. This phenomenon was observed in 1994 Northridge earthquake. The high amplification factor at fundamental frequency reveals that city may suffer severe damage even during moderate earthquakes.

9. Computation of Peak Ground Acceleration (*PGA*), Peak Ground Velocity (*PGV*) and Peak Ground Displacement (*PGD*)

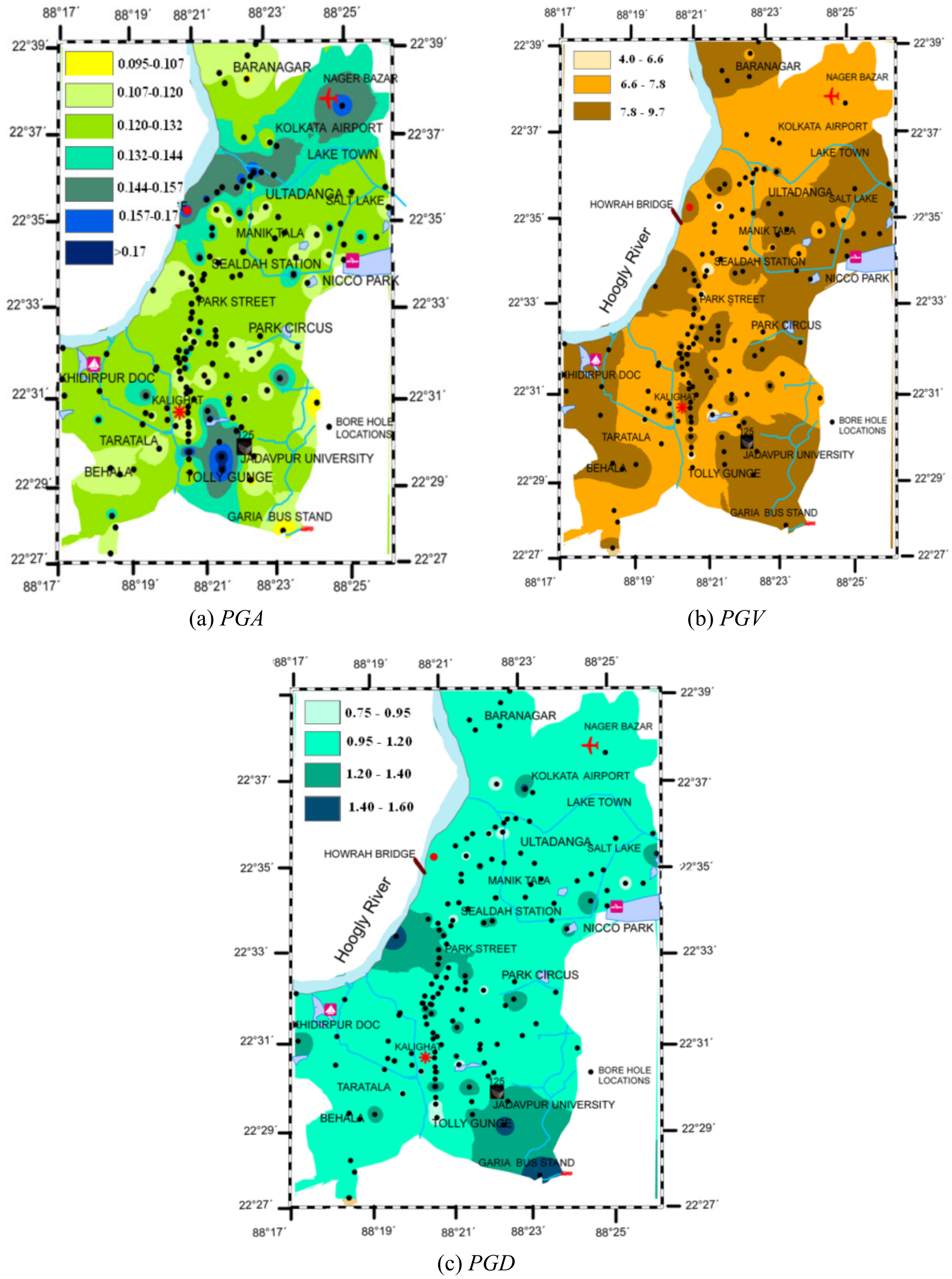
Current Indian seismic code (IS − 1893 2002) contains a discussion about force based design. In this method of design, building is designed against some lateral force which is obtained by multiplying seismic mass and spectral acceleration. But in this procedure the performance of building during earthquake is neglected. In displacement based design, displacement or drift is one of the performance criteria of structure of structural and nonstructural system. Therefore, *PGA*, *PGV* and *PGD* values were computed at free surface level from their time history. Contours of these three parameters have been drawn with the help of Arc GIS (2006) packages.

9.1 Peak Ground Acceleration (*PGA*)

The variation of *PGA* at surface level of Kolkata city also is shown in Fig. 11(a). High *PGA* values has been obtained at DumDum (BL-6), Mall Road (BL-9), Parasnath Mandir (BL-11), Belgachia (BL-14), N.K. Deb Park (BL-19), Bhowanipore (BL-98), Tollygungue (BL-126 and BL-137), Prince Anwar Saha Road (BL-131), and Bangur Hospital (BL-132) locations. In these regions, larger amplification in high frequency band is responsible for generating high *PGA*. Most of these locations were formed due to the siltation Hoogly River and its tributaries canals like Keshtopur canal, Adiganga or Tollynala canal. Lower values of *PGA* have been obtained at Baranagar (BL-3), Ultadanga (BL-15), Jatindra Mohan Park (BL-23), Narkeldanga (BL-37), Tiljala road (BL-87), Mizoram House (BL-94), Ritche Road (BL-95), Hestings Sarani (BL-119), Gobindopur Road (BL-19), and some regions of Tollygunge (BL-130, BL-136). In these locations low amplifications have been obtained at high frequency zone.

9.2 Peak Ground Velocity (*PGV*)

The computed free surface *PGV* at different BL locations are given in Fig. 11(b). Higher values



(a) *PGA* (b) *PGV*

(c) *PGD*

Fig. 11 The peak ground acceleration (g), peak ground velocity (cm/s) and peak ground displacement map (cm) of Kolkata of *PGV* have been obtained at those areas where there is large amplification in the middle of considered frequency range. On an average *PGV* is obtained in the range 7-9 cm/sec except at very few locations like Counsil House Street (BL-49), Garden Reach (BL-103) etc. Lower values of *PGV* have been observed at Ultadanga (BL-45), Benarasi Ghosh Road (BL-58), and Tolly Gungue Tram Depot (BL-137) etc.

9.3 Peak Ground Displacement (PGD)

Fig. 11(c) shows the obtained free surface *PGD* at different BL locations. Large *PGD* has been obtained at those locations where there is a large spectral amplification in low frequency range. Higher values of *PGD* have been observed at Beer Para (BL-8), New Town (BL-29), Salt Lake (BL-45), Victoria House (BL-56), Museum (BL-60), Mayo Road (BL-61), Russel Street (BL-62), E.M. Bypass (BL-81), Khidirpore (BL-86 1nd BL_103), Hestings Sarani (BL-114), Opposite Southern Market (BL-121), some regions of Tollygunge (BL-127, BL-134), Jadavpur (BL-142), Baghajatin (BL-143), and Garia Area (BL-144). In these locations, there is more possibility of damage of high rise building. On an average, the *PGD* variation is 6.5 to 8.0 cm. Lower values of *PGD* (< 0.9 cm) have been obtained in Jatindra Mohan Park (BL-8), Southern Avenue (BL-122), Childrens park (BL-123), New CIT Road (B:-50), Park Street (BL-77) etc. In these regions high rise buildings will be relatively on the safer side as compared to other locations in the city.

10. Spectral accelerations in different time period bands

For each of the 144 locations response spectra has been computed. Fig. 12 shows some site specific response spectra and IS 1893 Zone III and Zone IV response spectra. The response spectra in different time period bands are also presented in the form of contour maps so that it can be used for design of cost effective structures.

10.1 Response spectral acceleration between time period bands of 0.01-0.5 sec

Fig. 13(a) depicts the maximum spectral acceleration in time period band of 0.01 sec to 0.5 sec.

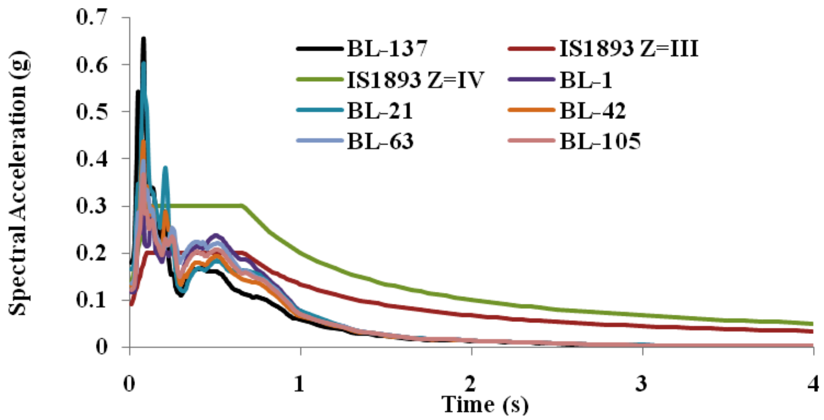
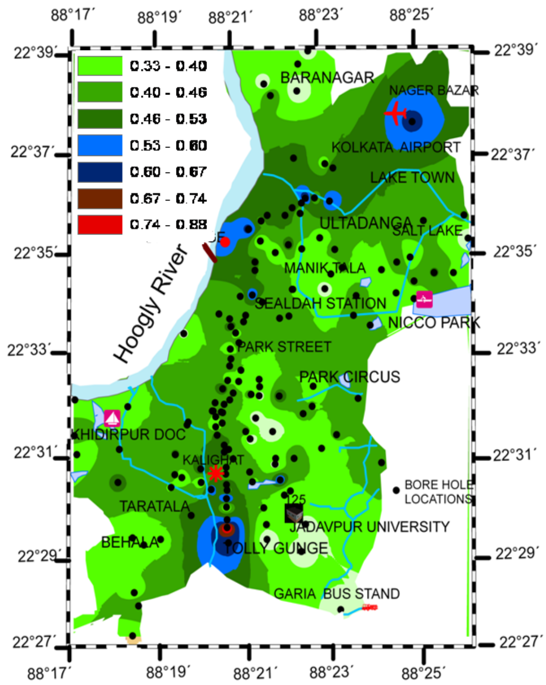
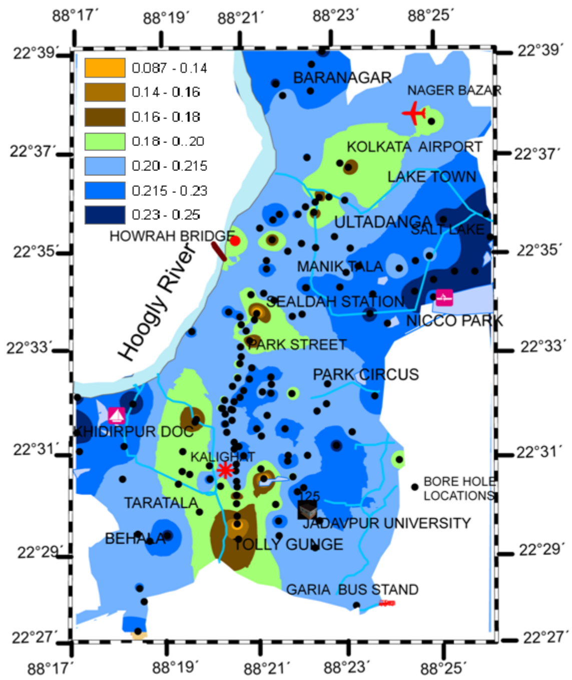


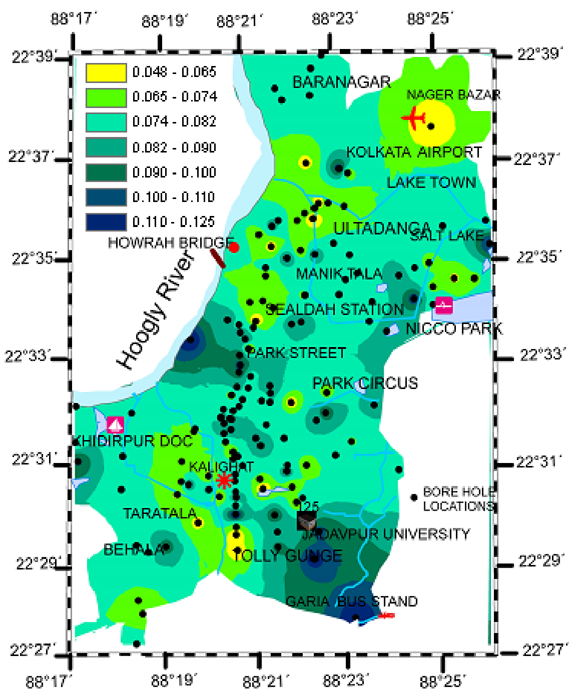
Fig. 12 Some site specific response spectra and IS 1893 zone III and zone IV response spectra



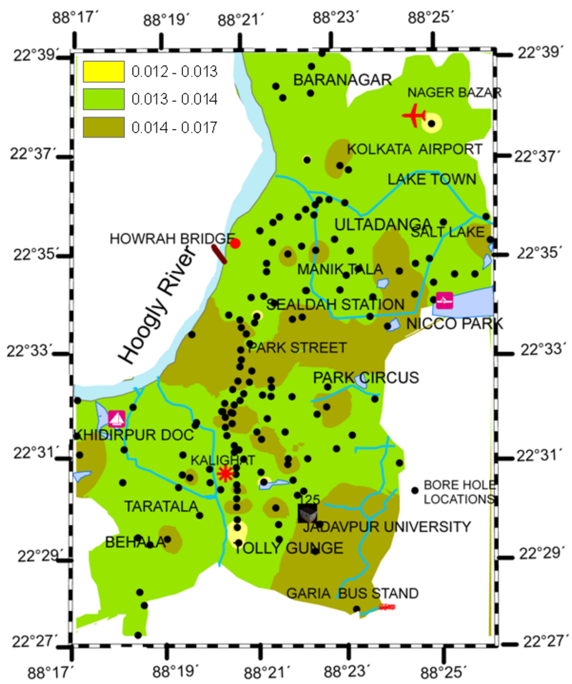
(a) Time period band 0.01 to 0.5 seconds



(b) Time period band 0.5 to 1 seconds



(c) Time period band 1 to 2 seconds



(d) Time period band 2 to 4 seconds

Fig. 13 The maximum response spectral acceleration (g) between different time period bands

Time period for low rise building having storey 1-5 will fall in this time period band. The maximum spectral acceleration values vary 0.33 g to 0.88 g. High spectral amplification has been observed in DumDum (BL-6), Parasnath Mandir area (BL-11), Nimtala (BL-21), Medical college area (BL-43), Haris Park (BL-93), Hindusthan Park (112), and Bangur Hospital area (BL-132). This may be due to soft soil deposit in surficial soil layer. Spectral accelerations of order 0.3g to 0.5 g were observed at most borehole locations.

10.2 Response spectral acceleration in time period band of 0.5 to 1 second

Fig. 13(b) reveals the maximum spectral acceleration varies 0.087 g to 0.25 g. Time period of 5-10 storey buildings lies in range 0.5 sec to 1 sec. High maximum spectral accelerations in order of greater than 0.24 g have been observed at IB Salt Lake (BL-45), Ballygunge circular road (BL-88), Garden reach road (BL-89), Bediadanga (BL-102) etc. In these regions, earthquake force will be high for 5-10 storey building during earthquake. So during design of structure, horizontal seismic coefficient should be taken higher values for these locations. Low maximum spectral accelerations (less than 0.12 g) were observed in CIT Road (BL- 30), British India Street (BL-50), Alipore Road (BL-86), Southern Avenue (BL-122).

10.3 Response spectral acceleration in time period band 1-2 sec

Fig. 13(c) depicts the response spectral acceleration in time period band 1-2 sec varies 0.048 g to 0.125 g. Higher values of maximum response spectral acceleration values in order of greater than 0.1 g have been obtained at Beerpara (BL-8, Newtown (BL-45), Mayo Road (BL-106), Russel Street (BL-62), Hestings Sarani (BL-114), Tollygaungue Area (BL-127), Jadavpur (BL-142), Baghajatin (BL-143), Garia (BL-144) etc. The time period band (1-2 sec) is central range of acceleration response spectra. So where higher values of *PGD* have been obtained, there maximum spectral acceleration in the time band will be high and 10-20 storey building will be subjected higher damage during earthquake.

10.4 Response spectral acceleration in time period band 2-4 sec

The time period of high rise buildings (> 20 storey) falls in this time period band. Fig. 13(d) clearly shows the spectral acceleration is on an average is 0.014 g except at very few locations like Mayo Road (BL-61), Hestings Sarani (BL-114), Tally Gunge area (BL-127), Bagha Jatin Area (BL-143), and Garia Region (BL-144). In these locations, *PGA* is high and the time period of high rise buildings fall in displacement control region. So construction of high rise buildings should be avoided in these locations.

11. Conclusions

The results of present analysis reveal that Kolkata is very much prone to severe damage even during moderate earthquakes due to the presence of soft thick soil layers. Kolkata have already felt unexpected intensity during past earthquakes like 1964 Calcutta earthquake (Intensity VII), and 1897 Shillong earthquake (Intensity VIII). The scenario is similiar to high damages observed at other places including Ahmedabad City during 2001- Bhuj earthquake, Mexico City during 1985, Mexico earthquake, 1994 Northridge earthquake (Shiuly and Narayan 2010, Govindaraju and Bhattacharya 2012).

The probabilistically predicted ground motion at the bedrock level with 50% probability of exceedence is obtained as 0.118 g. This is almost similar to codal value (0.12 g for zone IV-IS 1893(I)-2002). On the basis of present analysis the scenario of variation of *PGA*, *PGV* and *PGD* has been obtained. The range of *PGA* variation obtained at surface level is 0.096 g to 0.206 g. Large *PGA* is obtained at DumDum (BL-6), Mall Road (BL-9), Parasnath Mandir (BL-11), Belgachia (BL-14), N.K. Deb Park (BL-19), Bhowanipore (BL-98), Tollygungue (BL-126 and BL-137), Prince Anwar Saha Road (BL-131), and Bangur Hospital (BL-132) locations. Large *PGA* is also reported by Mohanty and Walling (2008). High *PGD* were obtained at Beer Para (BL-8), New Town (BL-29), Salt Lake (BL-45), Victoria house (BL-56), Museum (BL-60), Mayo Road (BL-61), Russel Street (BL-62), E.M. Bypass(BL-81), Khidirpore (BL-86 1nd BL_103), Hestings Sarani (BL-114), Opposite Southern Market (BL-121), some regions of Tollygunge (BL-127, BL-134) Jadavpur (BL-142), Baghajatin (BL-143), and Garia Area (BL-144). South east Kolkata region is safer with earthquake point of view since *PGA*, *PGV* and *PGD* obtained is low and response spectral acceleration in all time bands is also low. This may be due to the presence of thick low velocity soil layer at high depth with considerable impedance contrast of its upper and lower interface. *PGA* is mainly controlled by larger amplification in high frequency range. In this range of time period the spectral amplification is also large. On the other hand, *PGD* is controlled by larger amplification in low frequency range. In between *PGV* is controlled by amplification at middle frequency zone. Naturally it is clear that larger *PGA* is obtained at most of BL locations due to soft thick soil and high amplification at high frequency range. In these locations high response spectral acceleration is obtained in low time period zone (acceleration control regions of response spectra). In some locations *PGA* obtained is low and *PGD* is high due to larger amplification in low frequency zone. Larger amplification in low frequency range of the city is also reported by Vaccari *et al*. (2011). In those locations response spectral accelerations at larger time period is more (displacement control range of response spectra). In these locations high rise buildings will be affected. High rise buildings in these regions must be designed taking high spectral acceleration values in considerations compared to other locations.

On the basis of the present analysis it can be concluded that Kolkata, being socio-political and economic nerve center of Eastern India demands much more attention by planners, engineers and decision makers from the point of view of earthquake safety. The prepared maps of fundamental frequency, amplification at fundamental frequency, *PGA*, *PGV*, *PGD*, maximum response spectral acceleration different time period bands can be used for variety of end users of communities including structural engineers, land use planners, private business establishments, emergency managers and general public.

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