

Site specific ground motion simulation and seismic response analysis for microzonation of Kolkata

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Abstract. The spatial variation of ground motion in Kolkata Metropolitan District (KMD) has been estimated by generating synthetic ground motion considering the point source model coupled with site response analysis. The most vulnerable source was identified from regional seismotectonic map for an area of about 350 km radius around Kolkata. The rock level acceleration time histories at 121 borehole locations in Kolkata for the vulnerable source, Eocene Hinge Zone, due to maximum credible earthquake (MCE) moment magnitude 6.2 were generated by synthetic ground motion model. Soil investigation data of 121 boreholes were collected from the report of Soil Data Bank Project, Jadavpur University, Kolkata. Surface level ground motion parameters were determined using SHAKE2000 software. The results are presented in the form of peak ground acceleration (PGA) at rock level and ground surface, amplification factor, and the response spectra at the ground surface for frequency 1.5 Hz, 3 Hz, 5 Hz and 10 Hz and 5% damping ratio. Site response study shows higher PGA in comparison with rock level acceleration. Maximum amplification in some portion in KMD area is found to be as high as 3.0 times compared to rock level.

Keywords: synthetic ground motion; site response; time history; PGA; response spectra; amplification.

1. Introduction

The Kolkata city, formerly known as Calcutta, covers an area of about 185 sq. km with population of about 4.5 million (Census of India 2011). More than 80% of the city has built up areas dotted with high rise residential buildings, congested business district, hospitals and schools, most of these without any proper town planning and are very old. Density of population in some parts of north Kolkata is over 100,000 per square kilometers (Nandy 2007).

Kolkata had suffered damage by both far and near source earthquakes in the past. Notable among them were 1897 Great Assam earthquake, 1906 and 1964 Kolkata earthquake. The Kolkata earthquake of 15 April, 1964 had an intensity VIII (MM scale) was felt over an area of 67,000 Km². The earthquake was located over the Eocene Hinge Zone (SEISSAT 2000).

The Bureau of Indian Standard (IS: 1893, Part 1-2002) classified India into four seismic zones (zone II to zone V) (Fig. 1). Kolkata lies at the boundary of zone III and IV with a triangular zone of IV with its tip from north of Kolkata and spreading towards south covering the area of North and

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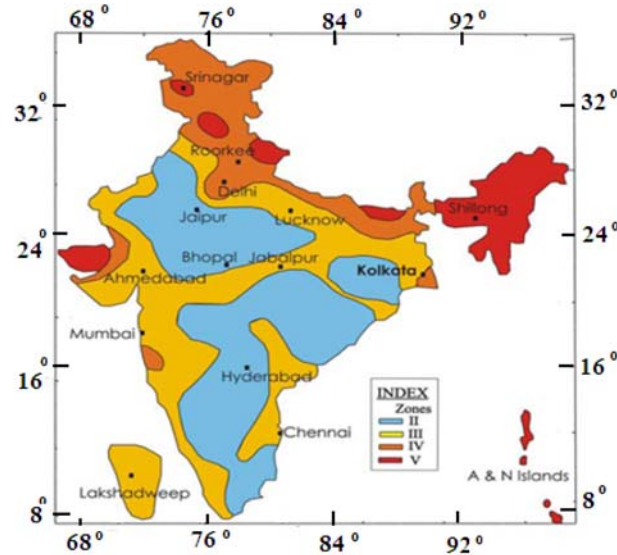


Fig. 1 Seismic zones of India (from IS: 1893, Part 1-2002)

South 24 parganas and eastern part of Purba Medinipur district. However, the zones are not sufficient to predict the damage pattern within each zone in the event of an earthquake, as the damage will depend on the local geology, vicinity to active faults, geotechnical and geophysical properties of surface and subsurface strata, and topography.

Microzonation of Kolkata on the basis of PGA variation was presented by Mohanty and Walling (2008) using a quasi-probabilistic approach considering attenuation relationship of Toro *et al.* (1997). They, however, did not consider local site effects. In this context, it may be noted that Kolkata lying on the alluvial Gangetic deposit has two distinct soil formations, namely, normal Kolkata deposit and river channel deposit. Normal Kolkata deposit consists of a thick soft compressible silty clay/clayey silt down to a depth of about 14.0 m below existing ground surface followed by stiff/very stiff/hard/very hard clayey deposit with intermediate sand layers down to considerable depth of 40-50 m. The river channel deposit existing along the old Adiganga channel consists of medium/dense/very dense sandy deposit down to considerable depth. These soil characteristics along with phenomenal increase in industrial and commercial activities in Kolkata and adjoining areas necessitates microzonation considering local site effects in order to prevent huge loss of life and properties due to earthquake.

In this work, an attempt has been made to generate site specific ground motion and local site effects for Kolkata Metropolitan District area (Fig. 3) which covers an area of 1250 sq. km. The analysis has been done using synthetic ground motion model by Boore (1983, 2003) for determination of rock level time history followed by ground response using SHAKE2000 considering 121 nos. boreholes of depths 30 to 40 m below ground level. Further, it may be noted that most of the site effect studies in earthquake ground motion are based on the geotechnical properties in the upper 30 m (Finn 1991, Boore *et al.* 1993, Anderson *et al.* 1996). According to Borcherdt (1994), the upper 30-m soil column is considered to be responsible for site amplification. Here, the soil at a depth of 30 m below ground level is hard/very hard/very dense, so, rock level was considered to be at 30 m depth for synthetic ground motion generation. Due to unavailability of recorded ground motion data

in this region the method proposed by Boore (1983, 2003) [SMSIM-program] was applied to simulate the artificial ground motion using local seismotectonic parameters. The Boore's model has been successfully used to generate ground motion in all over the world (Junn *et al.* 2002, Ebrahimian *et al.* 2008) as well as in India (Sitharam *et al.* 2006, Raghukanth *et al.* 2009). 1-D ground response analysis has been carried out using SHAKE2000, based on the SHAKE developed by Schnabel *et al.* (1972).

2. Geological and tectonic setting

The Kolkata metropolis 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. Originally Kolkata grew in a north-south direction over the natural levee of the river Bhagirathi for over a length of 50 Km. But due to enormous population pressure it has encroached into the back swamp and marshy land to the east by way of filling up extensive areas, especially in the Salt Lake and subsequently Rajarhat areas as well in many other places in unplanned ways (Nandy 2007).

Kolkata is situated over the Bengal Basin which is a huge pericratonic Tertiary basin with enormous thickness of fluvio-marine sediments. The Bengal Basin can be divided into three structural units: the western most shelf or platform, the central hinge or shelf/slope break, known as Eocene Hinge Zone (EHZ), and deep basinal part in the east and southeast that open in the present Bay of Bengal. Kolkata is located over the western part of hinge zone across which the sediment thickness significantly varies from shelf area in the west to deep basin area in the east. The hinge zone and the shelf area traverse by many faults, some of them seem to be tectonically active at present (Nandy 2007). The EHZ is about 25 Km wide that occurs at a depth of about 45000 m below Kolkata. The total sediment thickness below Kolkata is of the order of 7500 m above the crystalline basement; of these the top 350 to 450 m is Quaternary, followed by 4500-5500 m of Tertiary sediments, 500-700 m trap wash of Cretaceous Trap and 600-800 m Permocarboneous Gondwana rocks.

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). 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 (SEISSAT 2000).

Geological survey of India has compiled all available geological, geophysical and seismological data for entire India and published a seismotectonic map of India in the year 2000. Seismotectonic atlas (SEISSAT 2000) contains 43 maps in 42 sheets of 3° × 4° sizes with scale of 1:1 million, which also describes the tectonic frame work and seismicity. From the seismotectonic atlas, a seismotectonic map of Kolkata covering a circular area of radius 350 Km (Fig. 2) has been prepared on ArcGis-9.2 showing faults, lineaments, shear zones and past earthquake events using seismotectonic atlas (SEISSAT 2000) of India and also earthquake data collected from IMD (Indian Meteorological Department, Delhi). Total 76 nos. of earthquake events have been collected for the period 1764 to 2009. The earthquake data was converted into moment magnitude (M_w) using the relation given by Idriss (1985). The seismotectonic map contains 41 nos. of faults, 19 nos. lineaments, 5 shear zones

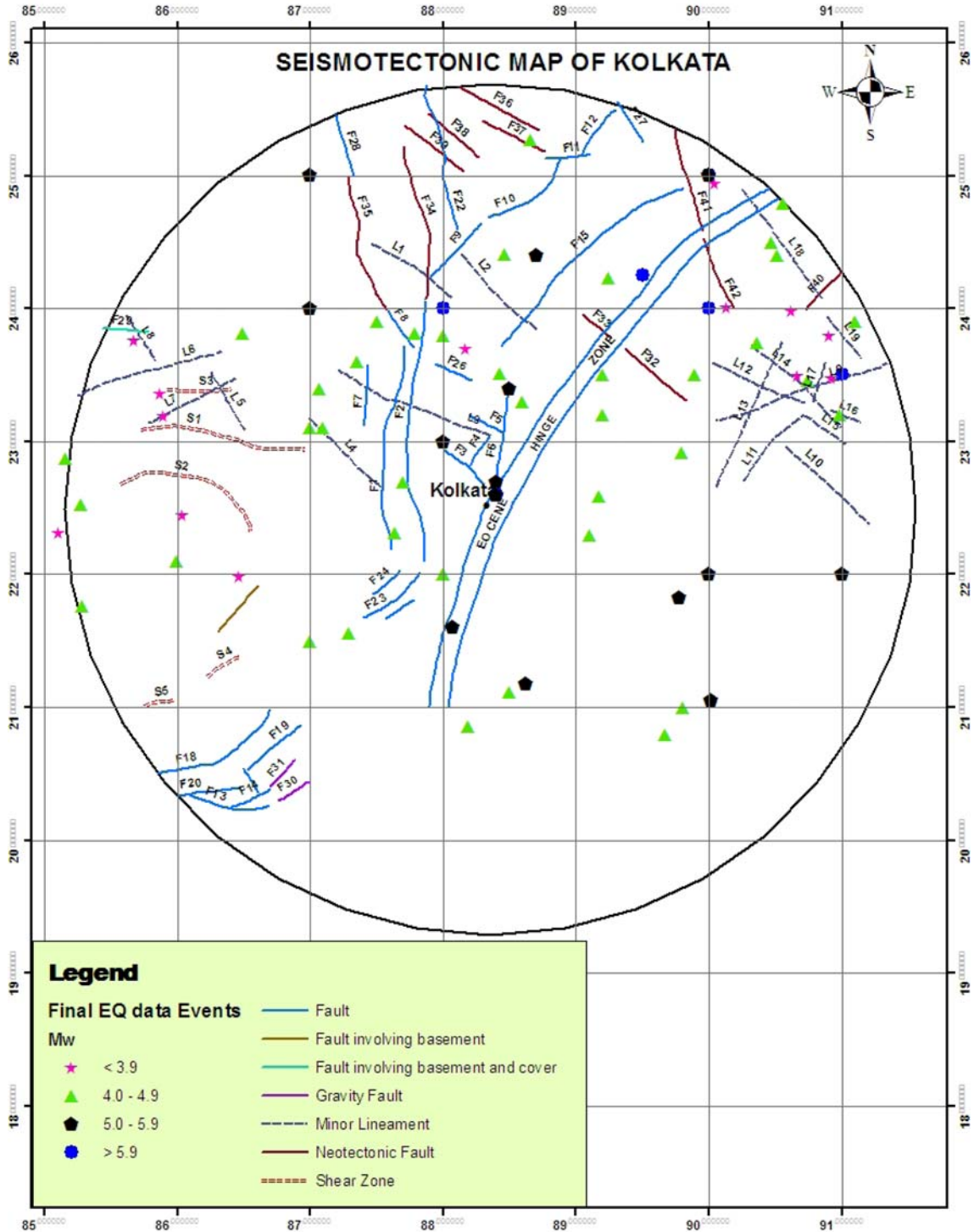


Fig. 2 Seismotectonic map of Kolkata (from SEISSAT 2000)

and one hinge zone (EHZ).

3. Ground motion simulation

3.1 Synthetic ground motion model

Synthetic ground motion model by Boore (1983, 2003) [SMSIM-program] was used for determining rock level PGA and generation of synthetic acceleration-time history (Atkinson and Boore 1995, Hwang and Huo 1997). The Fourier amplitude spectrum of ground motion at a site is expressed in terms of source and wave propagation functions and is given in Eq. (1).

$$\text{Ground motion } (f) = C \times \text{Source } (f) \times \text{Path } (f) \times \text{Site } (f) \times \text{Type } (f) \quad (1)$$

Where, C is the scaling factor and is given by

$$C = R_{\theta\varphi} F H / 4\pi\sigma\beta^3 r \quad (2)$$

Where, $R_{\theta\varphi}$ represents the radiation pattern for a range of azimuths θ and takeoff angles φ . F accounts for the free surface effect. H is the reduction factor that accounts for the partitioning of energy into two horizontal components and r is the hypocentral distance. σ and β are crustal density and shear wave velocity.

The source spectrum, the ω -square model (Brune 1970) used in this study, is given by

$$\text{Source } (f) = M_o / (1 + (f/f_c)^2) \quad (3)$$

Where, M_o and f_c are seismic moment and corner frequency. The value of f_c is obtained from

$$f_c = 4.9 \times 10^6 \beta (\Delta\sigma/M_o)^{1/3} \quad (4)$$

Where, f_c is in Hertz, β is in km/s, $\Delta\sigma$, the stress drop in bars and M_o is dyne-cm.

The Path term is interpreted in terms of the geometrical spreading (GSP) factor and the frequency dependent quality factor $Q(f)$ as given below,

$$\text{Path } (f) = \text{GSP}(r) \exp(-\pi fr / Q(f)\beta) \quad (5)$$

The Site term is given in terms of frequency dependent amplification $A(f)$ and diminution $D(f)$ factors as

$$\text{Site}(f) = A(f) \times D(f) \quad (6)$$

The amplification of waves as they travel upward to the surface through a rock column is given by

$$A(f) = \{\rho \times \beta / \rho(z)_{avg} \times \beta_{avg}(z)\}^{1/2} \quad (7)$$

$\rho(z)_{avg}$ and $\beta_{avg}(z)$ are averages of near-surface density and velocity from the surface to the depth of a quarter wavelength.

The diminution factor $D(f)$ is given by the following equation

$$D(f) = \exp(-\pi k_0 f). \quad (8)$$

Where, k_0 , the distance-independent high frequency attenuation operator (Kappa factor).

Type (f) is a filter used to shape the spectrum correspond to the particular ground motion and is given by

$$\text{Type}(f) = (2\pi f)^s$$

Where, $s = 0$ for acceleration
 $= 1$ for velocity
 $= 2$ for displacement

3.2 Input parameters

Raghukanth and Somala (2009) estimated the stress drop for Bengal Basin-Shillong Plateau earthquakes that occurred in the region to be 156 to 258 bars. In this study a stress drop of 250 bars was used.

In the path properties the whole-path attenuation is governed by the frequency dependent quality factor Q . For the Bengal basin-Shillong plateau region the Q was estimated as $224f^{0.93}$ (Raghukanth and Somala 2009).

Geometrical spreading factor (GSP) is $1/r$ for $r < 100$ km and equal to $1/10 \sqrt{r}$ for $r > 100$ km (Singh *et al.* 1999), where, r is the hypocentral distance.

Distance dependent duration, which is a function of the path as well as the source, is given by

$$T = 1/f_c + br \quad (9)$$

Where, the first part $1/f_c$ is the source duration and the second part is a distance dependent term that accounts for dispersion. The value of b was taken to be 0.05 (Herrmann 1985, Boore and Atkinson 1987, Boore 1996).

The regional velocity model in the Kolkata region for equivalent rock-type sites with density used in this study was taken from Gopali-Port Canning Deep Seismic Sounding (DSS) profile near Kolkata city (Prasad *et al.* 2005) and is given in Table 1. From this data average shear wave velocity was considered to be 870 m/s. Site amplification [$A(f)$] at the assumed engineering rock level was determined using quarter-wavelength method of Boore and Joyner (1997) and is given in Table 2.

Chandler *et al.* (2006) compiled a database of kappa factors estimated for various parts of the world. They proposed an empirical equation for estimating the kappa factors from the average shear wave velocity in the top 30 meters of the soil ($V_{s,30}$) as

Table 1 Regional velocity profile used in this study

Depth (km) below earth surface	Shear wave velocity (km/s)	Density (g/cm ³)
0-0.20	0.87	2.23
0.2-1.20	1.56	2.33
1.2-1.70	2.20	2.44
1.7-5.70	2.60	2.82
5.7-8.70	3.40	2.70
8.7-9.20	3.30	2.66
9.2-21.20	3.60	2.80

Table 2 Site amplification $A(f)$ for the rock layers

Frequency(Hz)	Amplification $A(f)$
0.01	1.03
0.31	1.84
0.62	2.00
0.92	2.21
1.22	2.37
2.13	2.37
5.16	2.37
8.19	2.37
10.30	2.37
12.70	2.37

$$k_0 = \frac{0.057}{V_{s,30}^{0.8}} - 0.02 \quad (10)$$

Taking $V_{s,30}$ as 870 m/s (Table 1), the average kappa factor for the rock site in Kolkata was obtained as 0.04. In the scaling factor, a reduction factor (H) of 0.71 was taken to represent the partitioning of the S-wave energy into two horizontal components (Boore and Boatwright 1984). For radiation pattern ($R_{\theta\phi}$) a value of 0.55 was used (Atkinson and Boore 1998). For free surface amplification a value of 2 was taken (Boore 1996). All the above mentioned input parameters are summarized in Table 3.

Table 3 Input seismic parameter for synthetic model

Source properties:
$\rho = 2.9 \text{ gm/cm}^3$
$V_S = 3.6 \text{ Km/s}$
$\Delta\sigma = 250 \text{ bars.}$
$M = 6.2$
Single corner frequency ω^{-2} spectra.
Path properties:
$Q = 224 f^{0.93}$
Duration = $1 / f_c + 0.05R.$
Geometric spreading:
r^{-1} for $r < 100 \text{ km}$ and $1/(10 \sqrt{r})$ for $r > 100 \text{ km.}$
Site properties:
Reduction factor = 0.71
Radiation pattern = 0.55
Free surface factor = 2.0
$k_o = 0.04$

3.3 PGA at rock level

PGA at rock level considered to be at a depth of 30 m below existing ground level were calculated using synthetic ground motion model for four major sources around Kolkata and is given in Table 4 along with the corresponding source to site distance, hypocentral distance and earthquake magnitude.

Table 4 PGA obtained from the synthetic ground motion model

Fault name	Distance to site (km)	Hypocentral distance (km)	Earthquake magnitude (M _w)	PGA (g)
F2 Garhmoyna-Khandaghosh Fault	55	62	4.6	0.005
F3	17	35	5.0	0.027
F6	22	37	5.3	0.037
Eocene Hinge zone	0.5	30	6.2	0.141

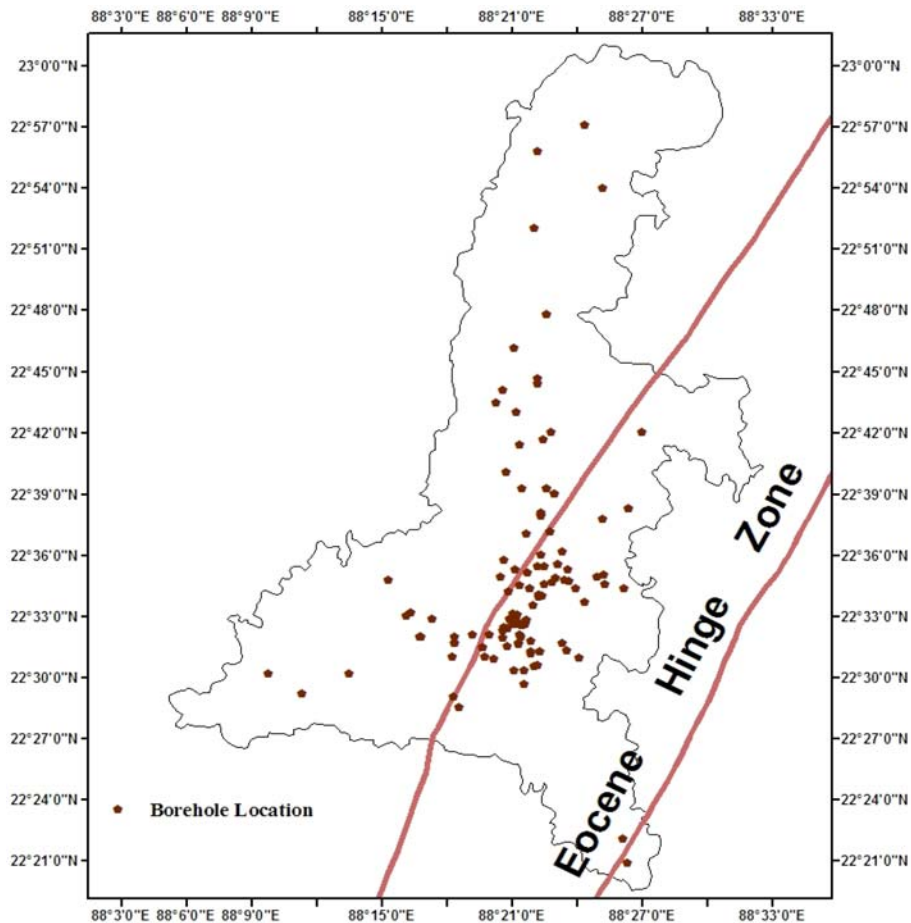


Fig. 3 Borehole locations with most vulnerable source for Kolkata

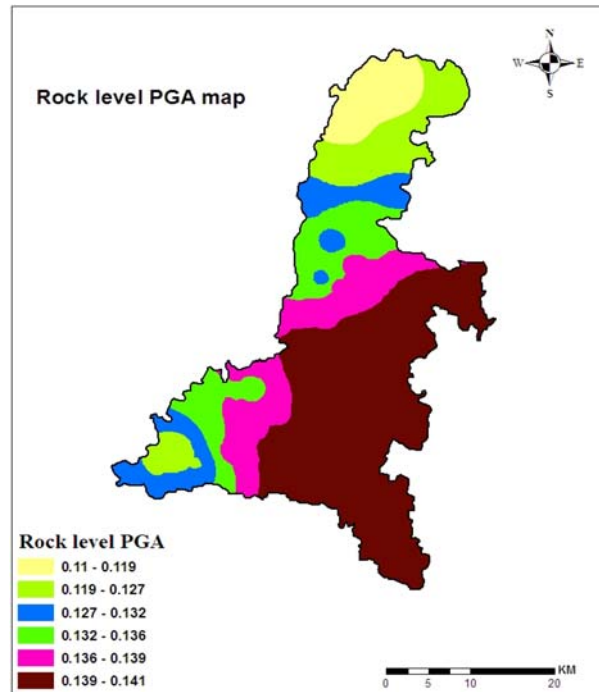


Fig. 4 Rock level PGA contour map for Kolkata

From Table 4 it is seen that Maximum PGA value is 0.141g due to Eocene Hinge with a earthquake magnitude of 6.2 Mw. For other three sources PGA values are 0.005 (F2 Garhmoyna-Khandaghosh Fault), 0.027 (F3) and 0.037 (F6) respectively. So, Eocene Hinge Zone (EHZ) is the most vulnerable source with maximum credible earthquake magnitude of 6.2 Mw for Kolkata. Rock level PGA and time histories was, then, generated at 121 borehole locations in KMD area (Fig. 3) considering EHZ as the vulnerable source. This rock level PGA was used to develop a contour map using Geostatistical Analyst Wizard ArcGis9.2 (Fig. 4).

4. Site specific response

4.1 Local soil condition

In this study, detailed soil investigation data as obtained from the report of Soil Data Bank Project (1986) of 121 boreholes at various locations of Kolkata (Fig. 3) were used for ground response analysis. Typical bore log of normal Kolkata deposit and river channel deposit are shown in Fig. 5 and Fig. 6 respectively. Subsurface profile information including unit weight, ground water level, SPT values etc. at different borehole locations were used for the ground response analysis using SHAKE2000.

4.2 Input parameters

Synthetic ground motions at rock level generated at each borehole location for the source Eocene

Depth	Soil strata	Soil description
1.5		Fill(N value- 2, Unit Wt-17kn/m ³)
3		Soft brownish clayey silt (N - 5, Unit wt. -18.5 kN/m ³ ,LL-53,PL-25)
12.5		Soft dark grey / grey silty clay with decayed vegetation & organic matter (N - 3, Unit wt-17.5kN/m ³ , LL-56, PL-20)
16.5		Stiff bluish grey silty clay with kankar (N value- 12, Unit Wt-20.9 kN/m ³ , LL-62, PL-18)
18.5		Stiff to very stiff molted brown clayey silt with sand (N - 16, Unit wt.- 20.8kN/m ³ , LL- 35, PL- 18)
25.5		Dense to very dense yellowish / brownish silty sand (N value- 47, Unit Wt.- 20kN/m ³)
30		Very stiff to hard molted grey clayey silt to silty clay with sand (N value- 29, Unit Wt.- 20.5kN/m ³ , LL- 50, PL- 29)

Fig. 5 Normal kolkata deposit (22 CIT Road site)

Depth	Soil strata	Soil description
2		Fill (N value- 5, Unit Wt-17kN/m ³)
6		Loose brownish grey sandy silt (N value- 11, Unit Wt-18kN/m ³ ,)
27		Dense to very dense bluish grey silty sand (N value- 42, Unit Wt-19.5kN/m ³)
30		Very dense grey fine to medium Sand (N value- 50, Unit Wt-20.1kN/m ³)

Fig. 6 River channel deposit (22/1 Alipore Road)

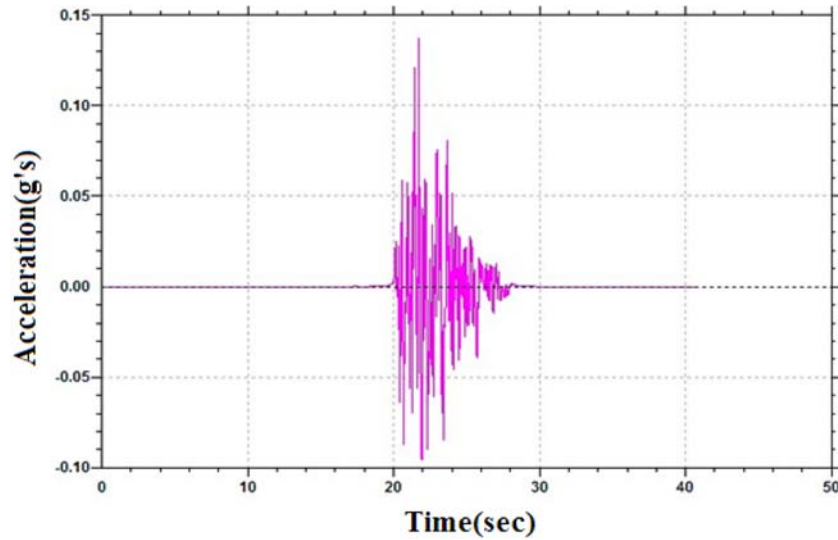


Fig. 7 Typical input Acceleration time history used in SHAKE2000

Hinge Zone with MCE 6.2 Mw were used as input ground motion in SHAKE2000 for evaluating peak acceleration values and acceleration time histories at the top of each sub layer. A typical input motion for the borehole at 22 CIT Road site is shown in Fig. 7. The dynamic properties such as

modulus reduction and damping ratio were taken from the database of material properties provided with SHAKE2000 (Seed and Idriss 1970, Schnabel 1973, Seed *et al.* 1986, Sun *et al.* 1988, Vucetic and Dobry 1991).

4.3 Output of site response analysis

As waves travel through the soil column, the ground motion is generally amplified. The amplification potential of soil depends on soil type, soil thickness, soil stiffness, and impedance contrast with the underlying bed rock. The ground surface acceleration time history were computed

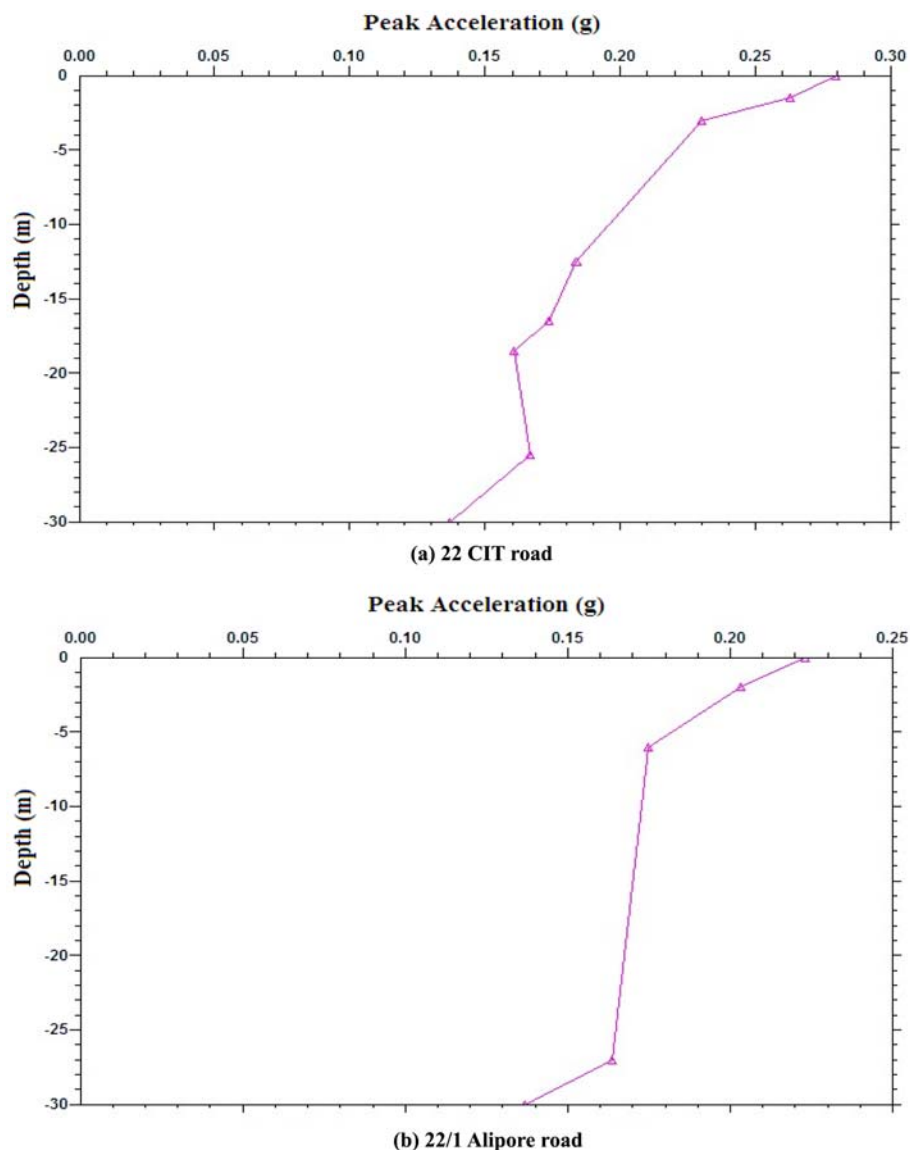


Fig. 8 PGA variation with depth (a) 22 CIT road site (b) 22/1 Alipore road

for all the borehole locations. Fig. 8 shows PGA variation with depth at two typical sites, 22 CIT Road and 22/1 Alipore Road, representing Normal Kolkata Deposit and River Channel Deposit. It is found that the amplitude of the ground surface acceleration time history has increased. PGA at rock level 0.141 g has amplified to 0.278 g at 22 CIT road site and while at 22/1 Alipore Road site PGA at rock level 0.136 g is amplified to 0.223 g. From Fig. 8(a), it may be seen that top three layers amplify the motion most which consist of 1.5 m fill, followed by a 1.5 m of very soft silty clay/clayey silt and 9.5 m of soft dark grey/grey silty clay/clayey silt with decayed vegetation and

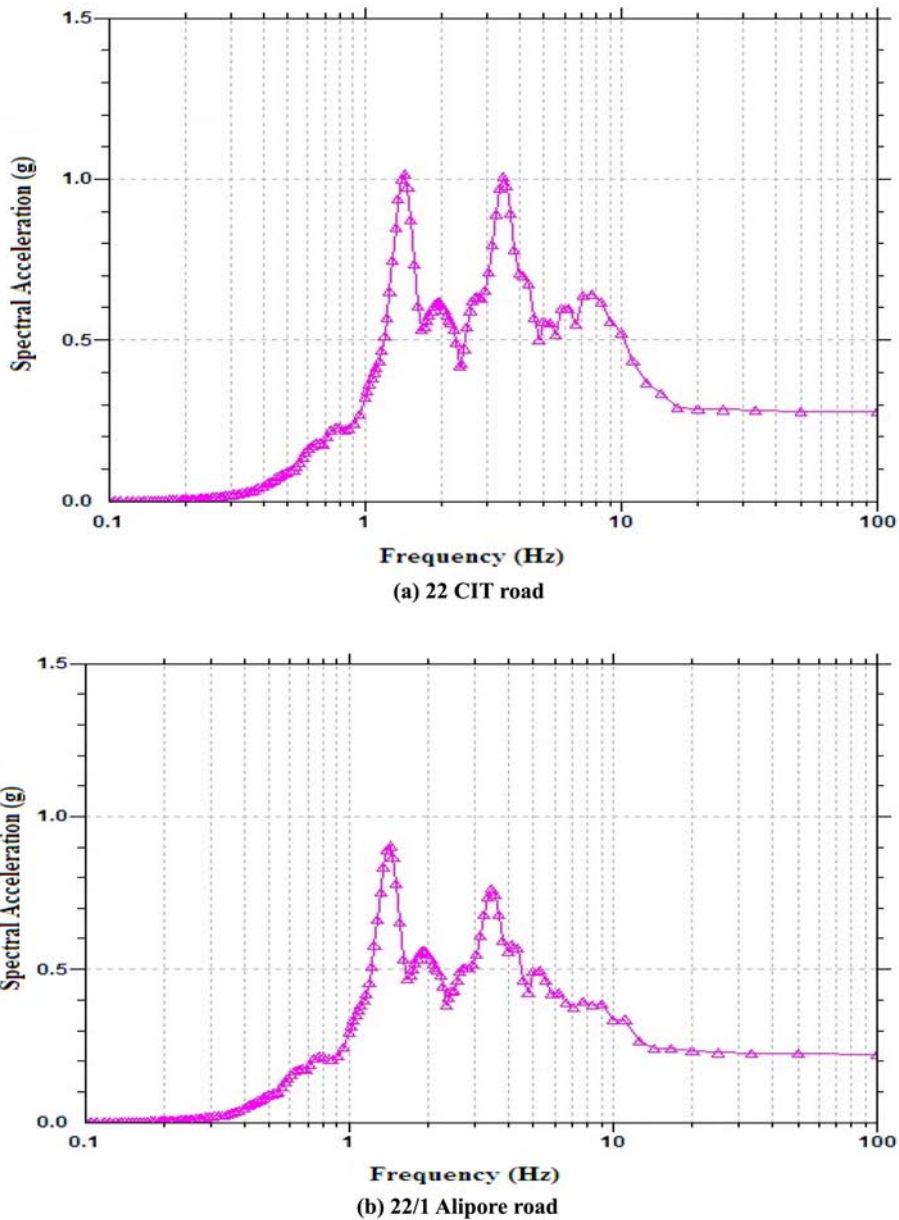


Fig. 9 Response spectra of (a) 22 CIT road site (b) 22/1 Alipore road site at 5% damping

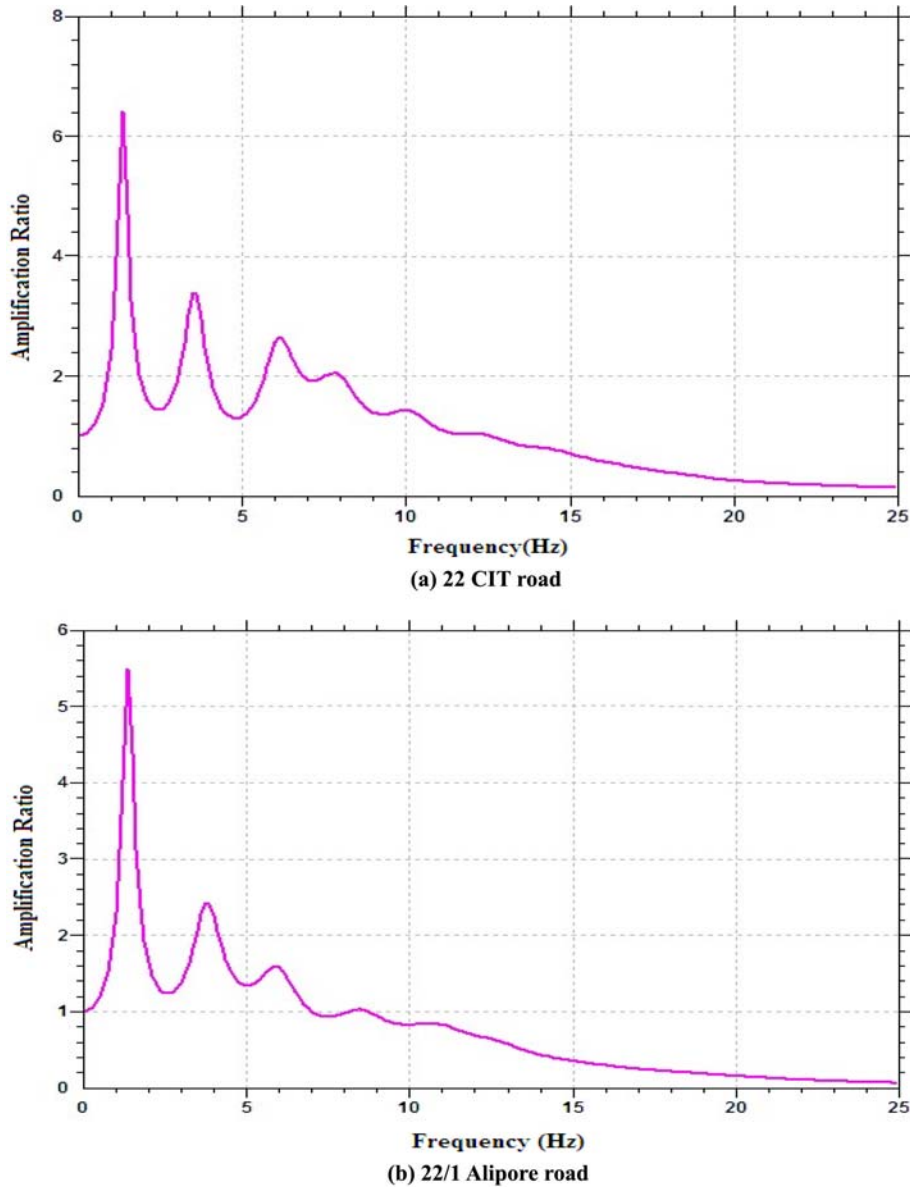


Fig.10 Amplification spectra for (a) 22 CIT road site (b) 22/1 Alipore road site

organic matter. Fig. 8(b) shows top two layers of 2.0 m fill followed by 4.0 m loose sandy silt deposit contribute most of the amplification.

Response spectra at the ground surface and amplification ratio between the first and last layer were also determined for 5% damping. Typical results obtained for borehole location 22 CIT Road site and 22/1 Alipore Road site are shown in Fig. 9 and Fig. 10.

From the response spectrum shown in Fig. 9(a) for 22 CIT Road site it is seen that first peak of 1.01 g occurred at 1.43 Hz and second peak of 1.0 g occurred at 3.45 Hz. From Fig. 9(b) for 22/1 Alipore Road it is seen that two peaks of 0.90 g and 0.76 g occurred at 1.43 Hz and 3.45 Hz

respectively. In amplification spectrum maximum amplification ratio occurred is 6.4 at 1.37 Hz for 22 CIT Road Site (Fig. 10(a)) and 5.5 at 1.37 Hz for 22/1 Alipore Road site (Fig. 10(b)) which are the predominant frequencies of the soil column at those locations.

4.4 Spatial variation of site effects

The parameters obtained from the ground response analysis are presented as maps, which are developed using the software Arcgis9.2 to depict the variation of various parameters in the study area. The maps show the peak ground acceleration at ground surface, amplification factor, and response spectra at the ground surface at frequency 1.5 Hz, 3 Hz, 5 Hz and 10 Hz for 5% damping ratio.

The peak acceleration values at the ground surface obtained from SHAKE have been used to prepare the peak ground acceleration (PGA) map of Kolkata Metropolitan District (Fig. 11). The PGA values are found to range from 0.169 g to 0.414 g. However, major portion of Kolkata has a PGA range 0.23 g to 0.35 g.

The amplification factor is evaluated at all borehole locations using the PGA at bedrock obtained from the synthetic acceleration time history and the peak ground surface acceleration obtained using SHAKE2000. The amplification factor thus calculated ranges from 1.2 to 3. The amplification factor map for KMD area is shown in Fig. 12. Lower amplification values indicate lesser amplification potential and hence lesser seismic hazard. It can be observed that the amplification factor for most of the northern part of the study area is in the range of 2.2-3. This can be considered as significant zone of amplification.

The ground surface response spectra for all the 121 borehole locations were determined from

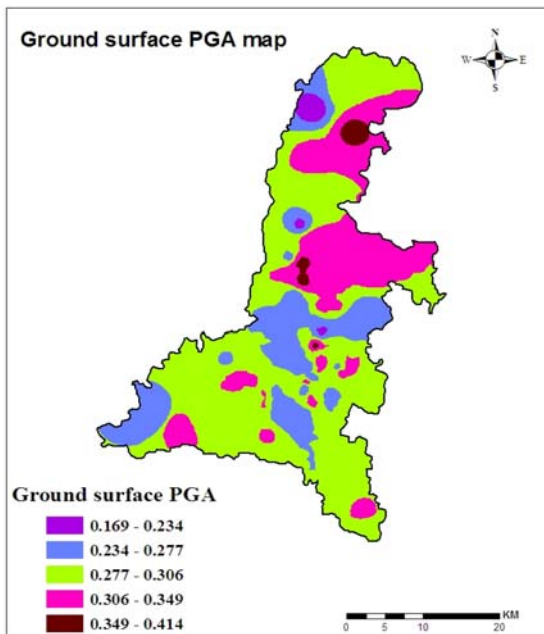


Fig. 11 Ground surface PGA contour for Kolkata

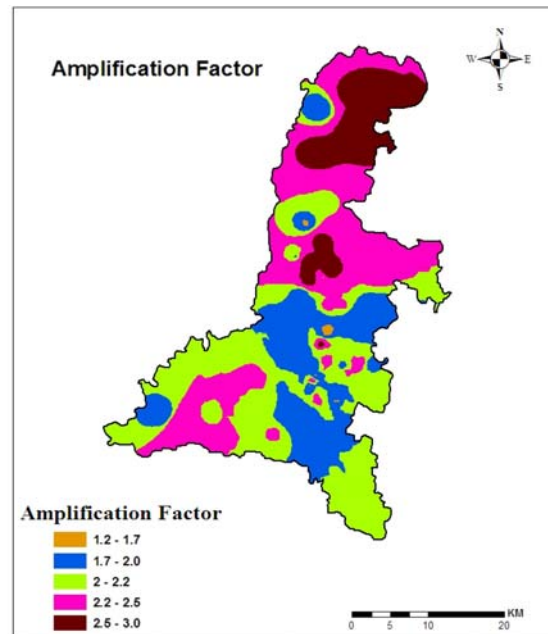


Fig. 12 Amplification factor map for Kolkata

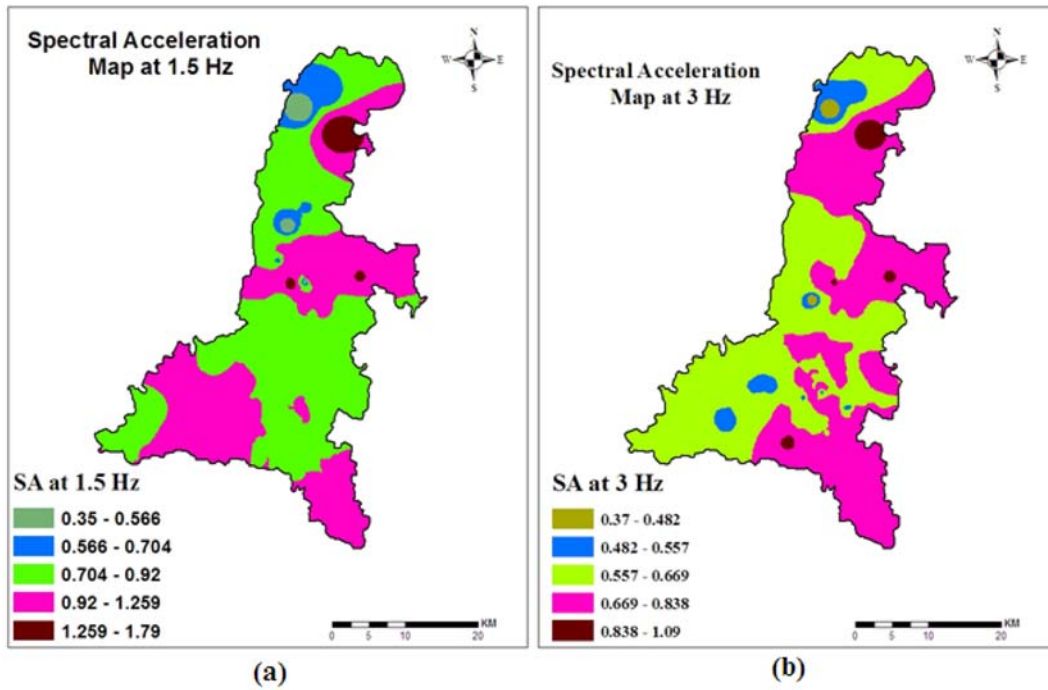


Fig. 13 Spectral acceleration map for 5% damping at 1.5 and 3 Hz frequencies

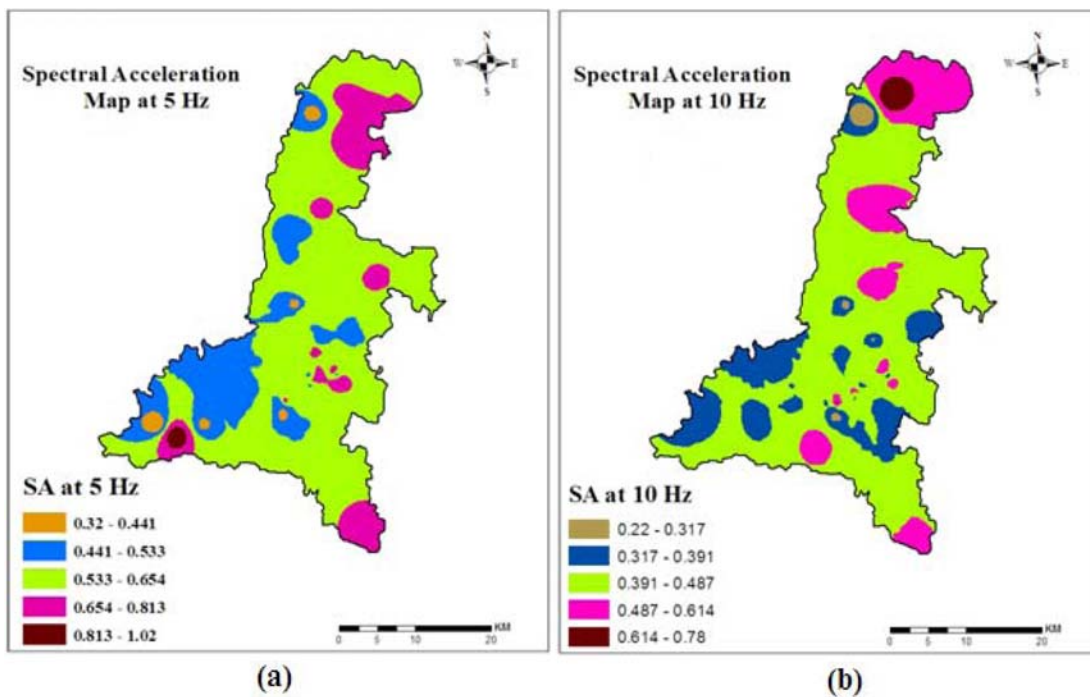


Fig. 14 Spectral acceleration map for 5% damping at 5 and 10 Hz frequency

SHAKE for 5% damping. The spectral acceleration (SA) values for all the locations at 1.5, 3, 5 and 10 Hz are presented as contour maps in Fig. 13 and Fig. 14. From these figures it may be seen that at 1.5, 3, 5 and 10 Hz frequency SA of major portion of Kolkata varies from 0.7 g to 1.26 g, 0.56 g to 0.84 g, 0.44 g to 0.65 g and 0.32 g to 0.5 g respectively. The frequencies from 1.5 Hz to 10 Hz were selected as they represent the range of natural frequencies of tall buildings to single storey buildings.

5. Conclusions

The synthetic ground motion model was used to generate synthetic ground motion considering local seismotectonic parameters at rock level with the goal of determining the seismic responses of Kolkata Metropolitan District. The acceleration time histories thus obtained were used to determine the response of the 30 m soil column to earthquake waves by 1-D ground response analysis using SHAKE2000. The analysis gives the output of amplified peak surface ground acceleration, surface acceleration time-history, response spectra and other ground motion parameters. The acceleration time-histories and response spectra thus determined would help to understand the peak response of the ground surface and the relative frequency content variations of the ground motion.

On the basis the present analysis following conclusions may be drawn:

- From synthetic ground motion model Eocene Hinge Zone was identified as the most vulnerable source with maximum credible earthquake of 6.2 Mw for Kolkata.
- Peak ground acceleration at two typical soil deposits, namely, Normal Kolkata Deposit and River Channel Deposit of Kolkata amplified from 0.141 g to 0.278 g and 0.136 g to 0.223 g due to the presence of soft compressible silty clay/loose sandy silt deposit, which indicates effect of local soil condition on seismic response.
- Peak ground acceleration of Kolkata Metropolitan District varies from 0.169 g to 0.414 g, however, in major portion of the study area it ranges from 0.23 g to 0.35 g.
- Maximum amplification factor is observed in the northern part of Kolkata which ranges from 2.2 to 3.
- Spectral acceleration of the major portion of study area for 1.5, 3, 5 and 10 Hz, which corresponds to natural frequencies of tall buildings to single storey buildings, were found to range from 0.7 g to 1.26 g, 0.56 g to 0.84 g, 0.44 g to 0.65 g and 0.32 g to 0.5 g respectively.

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