Influence of epicentral distance on local seismic response in Kolkata City, India

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The influence of source and epicentral distance on the local seismic response in the Kolkata city is investigated by computing the seismic ground motion along 2-D geological cross-sections in the Kolkata city for the earthquake that occurred on 12 June 1897 ($M_w = 8.1$; focal mechanism: dip = 57°, strike = 110° and rake = 76°; focal depth = 9 km) in Shillong plateau. For the estimation of ground motion parameters, a hybrid technique is used, which is the combination of modal summation and finite difference method. This technique allows the estimation of site specific ground motion for various events located at different distances from Kolkata city, taking into account simultaneously the position and geometry of the seismic source, the mechanical properties of the propagation medium and the geotechnical properties of the site. The epicenter of the Shillong earthquake is about 460 km away from Kolkata. The estimated peak ground acceleration (PGA) varies in the range of 0.11–0.18 g and this range corresponds to the intensity of IX to X on the Mercalli-Cancani-Sieberg (MCS) scale and VIII on the Modified Mercalli (MM) scale. The maximum amplification in terms of response spectral ratio (RSR) varies from 10 to 12 in the frequency range 1.0–1.5 Hz. These amplifications occur in correspondence to low-velocity shallow, loose soil deposit. The comparison of these results with earlier ones obtained considering the Calcutta earthquake that occurred on 15 April 1964 ($M_w = 6.5$; focal mechanism: dip = 32°, strike = 232° and rake = 56°; focal depth = 36 km) shows that the source parameters (magnitude and focal mechanism) and epicentral distance play an important role on site response but the variation in the frequency of the peak values (RSR) is negligible. The obtained results match with observed reported intensities in Kolkata region.

1. Introduction

Kolkata, the capital of West Bengal state, is one of the oldest industrial cities in India and it has attained the population of about 13 million (Census 2001, http://www.censusindia.gov.in/). The rapid increase in population density and industrial developments across the city has increased the seismic risk, and therefore it is important to assess the seismic hazard of the city for civil engineers and city planner to construct new and retrofit the old buildings. This metropolitan city lies between latitude 22°20′N to 23°00′N and longitude 88°04′E to 88°33′E in the eastern part of India. Kolkata is very close to the plate boundary zone (northeast and Indo–Burma ranges) of India, which is

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one of the seismically most active regions of the world. As per the Seismic Zonation Map of India, Kolkata lies at the boundary of Indian seismic zones III and IV. The expected ground motion for these zones ranges 0.20–0.25 g (IS: 1893 (Part 1): 2002). A recent study by Mohanty and Walling (2008a) suggests that most of Kolkata lies in zone IV. The city and its environ have been and will be affected by near as well as far earthquakes from Assam Seismic Gap, Shillong Plateau, Indo–Burma ranges, Andaman–Nicobar Island and the whole NE Himalayan. The distant earthquakes that shook Kolkata include the 1 September 1803; 26 August 1833; 31 December 1881; 12 June 1897; 15 January 1934 and the 15 August 1950 Assam earthquake. Two near events that have been strongly felt in Kolkata are the 29 September 1906 and 15 April 1964 earthquakes. Earthquakes have shaken most of the megacities in India, such as Delhi, Kolkata, Mumbai, Bangalore and Chennai, numerous times in the past 200 years. Among these, Delhi and Kolkata have experienced maximum shaking as cumulative number of events per year (Martin and Szeliga 2010). Kolkata and Delhi show the shortest interval between shaking at a given intensity due to their tectonic setting. In these cities, the intensity V (MSK-64/EMS-98 scale) occurs every 15 years approximately (Martin and Szeliga 2010). Any macroseismic intensity scale by its nature is a discrete sequence of integer values and half-integer epicentral intensity values formally do not belong to any intensity scale. Therefore, to be conservative, we rounded off by excess the non-integer values given in the literature.

Along the Kolkata–Krishnanagar line, the basement depth varies from 7 to 10 km. For a given earthquake magnitude, the ground response varies in different locations of Kolkata. Alluvial deposits (alternating layers of sand and clay) of Gangetic Delta form the upper soil in Kolkata. Usually the younger softer soils amplify the ground motion relative to older more competent soils or bedrock at particular frequencies due to the higher acoustic impedance contrast with the underlying hard deposits. Thick Holocene alluvium plays a great role in the amplification of ground motion as well as earthquake related failure like liquefaction, large ground deformation and lateral spreading.

The site response is the local ground response; it includes basin effects and the influence of surface topography. ‘Local ground response’ represents essentially the influence of relatively shallow geology on the propagating waves and these effects can be satisfactorily modelled using 2-D geological profiles. Several site response studies with special attention towards microzonation have already been carried out for metropolitan cities in India like Delhi (Parvez *et al.* 2004, 2006; Mohanty *et al.* 2007), Sikkim (Nath 2004), Jabalpur (Mishra 2004), Haldia (Mohanty and Walling 2008b), Talchir (Mohanty *et al.* 2009; Walling and Mohanty 2009), and all show that the response of a given site is not invariant with respect to changes in the earthquake source properties and its epicentral distance, as clearly proven by straightforward application of basic theory (e.g., Field *et al.* 2000; Panza *et al.* 2001). These variations depend upon many factors such as source mechanism (SM), epicentral distance (ED), focal depth (FD), geological condition (GC) or variation along energy transmission path, magnitude (M), soil condition (SC) at the vicinity of the site, damping ratio (DR) and period (T). Thus, according to Clough and Pension (1993), the response spectra for earthquake ground motion is a multispace non-linear function with the form:

$$\mathrm{S} = \mathrm{S}\,(\mathrm{SM}, \mathrm{ED}, \mathrm{FD}, \mathrm{GC}, \mathrm{M}, \mathrm{SC}, \mathrm{DR}, \mathrm{T})$$

The effects of ED, FD, M and SC on response spectra are usually taken into consideration while specifying the intensity levels of the design response spectra. But the effects of SM and GC on the response spectra are not well understood; therefore, such effects cannot be quantified when defining response spectra for design purposes. The separation of the effects of magnitude, distance, style of the faulting, tectonic feature and site conditions on the ground response is an important task and should be considered in the seismic hazard analysis at a given site, although the boundaries between source, path and site related factors are not always clear, due to the non-linearity of the relation between them. The ground motion variability could be reduced by eliminating the event-specific or site-specific contribution to the ground motion amplitudes (Strasser and Bommer 2009a), but very often, this is ‘mission impossible’ (Panza *et al.* 2011). The empirical data are unlikely to capture the full variability of source parameter combinations, even in the case of a single source. On the other side, realistic numerical simulations permit a physically sound analysis of the influence of source parameter variability on ground motion and allow the control of site locations, and thus ground motions can be computed on a properly dense grid. Nowadays the perception of the maximum physically possible ground motion may gradually become more influenced by prediction of well-constrained theoretical models than by empirical models, since there is still no guarantee on the variability associated with observed ground motion (Strasser and Bommer 2009b). The acceleration varies from component to component and it has also been reported that the high value of the vertical component is due to large objects being thrown in the air during earthquakes (e.g., Brune 1970; Hanks and Johnson 1976). A study by Oldham (1899) interprets the high value of vertical acceleration in excess of gravity in which the large boulders were thrown out of their sockets without disturbing the surrounding soil during the 1897 Shillong earthquake. It has also been shown that PGA is not a good indicator of the overall level of shaking and related damage (Uang and Bertero 1990; Decanini and Mollaioli 1998; Panza *et al.* 2001, 2003; Bommer *et al.* 2002). Mohraz (1978) describes the influence of earthquake magnitude on response amplification for alluvium. The study showed larger amplification of acceleration for records with magnitudes between 6 and 7 than for those with magnitudes between 5 and 6. While the study used a limited number of records and no specific recommendation was made, it shows that earthquake magnitude can influence spectral shapes in a nonlinear way, and this fact may need to be considered when developing design spectra for a specific site, particularly for critical structures.

The argument to study seismic response in Kolkata city due to far distant earthquakes (1897, Shillong earthquake in this study) is very essential for looking at the effects of distant earthquakes in the recent times. In this context, a recent study by Bhattacharya *et al.* (2011) supports the present objective where it has been reported that Katno (Tokyo) area in Japan was strongly affected by an earthquake occurred at a distance of ∼450 km. In this study, we simulate the seismic ground motion along a 2-D geological cross-section in Kolkata city for a seismic source in Shillong plateau (i.e., Shillong earthquake of 1897 located at ∼460 km from Kolkata). Ground motion parameter are estimated using a hybrid technique (Fäh *et al.* 1993, 1994; Panza *et al.* 2001), which is the combination of modal summation (Panza 1985; Florsch *et al.* 1991; Panza *et al.* 2001) and finite difference method (Alterman and Karal 1968; Boore 1972; Kelly *et al.* 1976; Virieux 1984, 1986; Levander 1988). This technique takes into account simultaneously the position and geometry of the seismic source, the mechanical properties of the propagation medium and the geotechnical properties of the site. In the computation, we consider the earthquake of 12 June 1897, Shillong earthquake, $M_w = 8.1$; focal mechanism: dip = 57°, strike = 110° and rake = 76°; focal depth = 9 km (Bilham and England 2001), located at a distance of about 460 km from Kolkata. Then, comparative analysis is made of the results obtained in this computation with earlier ones (Vaccari *et al.* 2011) obtained considering the Calcutta earthquake that occurred on 15 April 1964, $M_w = 6.5$; focal mechanism: dip = 32°, strike = 232° and rake = 56°; focal depth = 36 km (GSI 2000; Chandra 1977). In this paper the local seismic response in Kolkata city is analysed for two earthquake scenarios with different source mechanisms, one located near to Bay of Bengal and the other in the Shillong plateau. Further, the effect of epicentral distance is analysed keeping source parameters fixed and equal to those of the Shillong earthquake. The adopted method is innovative and at the same time a well-established one and has been employed in several site response studies worldwide (e.g., Fäh *et al.* 1994; Fäh and Panza 1994; Panza *et al.* 2002; Ding *et al.* 2004; Parvez *et al.* 2003, 2006; Zuccolo *et al.* 2008).

2. Geology and seismo-tectonic setting of the study area

Kolkata lies over the Bengal basin (figure 1). Thick alluvial deposits of the Gangetic Delta – the world's largest delta – comprising alternate layers of sand and clay, form the soil over which the study region lies (Gobindraju and Bhattacharya 2012). The thickness of the sediments increases towards south and east to more than 16 km, i.e., the deepest part in the West Bengal basin (Curray and Moore 1971; Murphy 1988), and finally attains the thickness of 20 km underneath Bangladesh (Nandy 2001). The Mesozoic and Tertiary rocks are exposed in the folded flank of Bengal basin and the Permo–Carboniferous Gondwana coals are the oldest Phanerozoic sediments at the holes drilled into the Precambrian Indian platform tectonic zone in northwest Bengal basin. These intracratonic, fault-bounded Gondwana coal deposits are exposed at the western fringe of the Bengal basin, in Bihar state of India (Khan and Muminullah 1980).

Kolkata lies over a sedimentary deposit about 7 km thick, above the crystalline basement (Murty *et al.* 2008). In the depositional sequence the top 0.35–0.45 km is Quaternary followed by 4.5–5.5 km of Tertiary sediments, 0.5–0.7 km of Cretaceous Trap and 0.6–0.8 km of Permo–carboniferous Gondwana rocks. There is a huge impedance contrast (i.e., very sharp increase in S-wave velocity) at very shallow depth (at the boundary between 2-D and 1-D structural model in this study), which agrees closely with the model given by Mitra *et al.* (2008) (see figures 2 and 3).

Tectonically, the Bengal basin can be grossly subdivided as follows: (1) the western 'stable shelf' region (also named 'Indian platform'), underlain by Precambrian continental crust, (2) the central deep basin, and (3) the eastern Chittagong–Tripura fold belt. The Eocene Hinge Zone (EHZ)

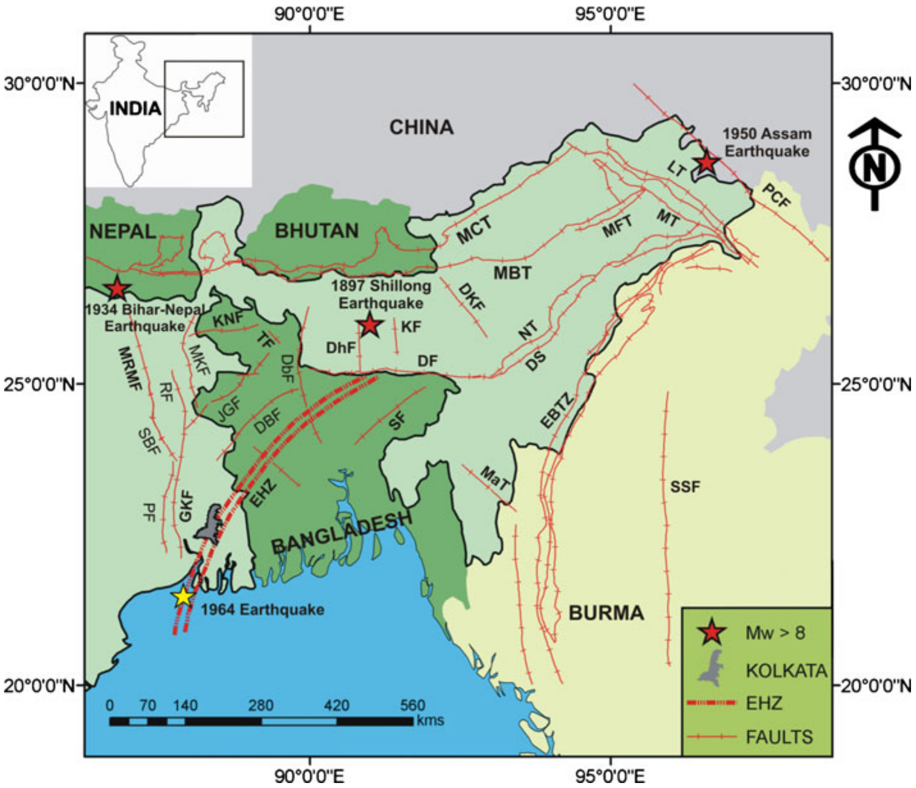

Figure 1. Tectonic setting of Kolkata, Bengal basin and its surroundings. MKF: Malda-Kishanganj Fault; DbF: Dhubri Fault; JGF: Jangipur-Gaibandha Fault; RF: Rajmahal Fault; SBF: Sainthia Bahmani Fault; GKF: Garhmayna-Khandaghosh Fault; DBF: Debagram-Bogra Fault; PF: Pingla Fault; EHZ: Eocene Hinge Zone; MCT: Main Central Thrust; MBT: Main Boundary Thrust; MFT: Main Frontal Thrust; PCF: Po Chu Fault; NT: Naga Thrust; DT: Disang Thrust; DF: Dauki Fault; KF: Kulsi Fault; DhF: Dudhnoi Fault; SF: Sylhet Fault; LT: Lohit Thrust; DKF: Dhansiri Kopili Fault; MT: Mishmi Thrust; KNF: Katihar-Nailphamari Fault; TF: Tista Fault; MaT: Mat Fault; SSF: Shan-Shagaing Fault; EBTZ: Eastern Boundary Thrust Zone; MRMF: Munger-Saharsha Ridge Marginal Fault (modified after GSI 2000; after Vaccari *et al*. 2011). The square box (inset) shows the location of the Bengal basin and its surrounding region in the Indian context.

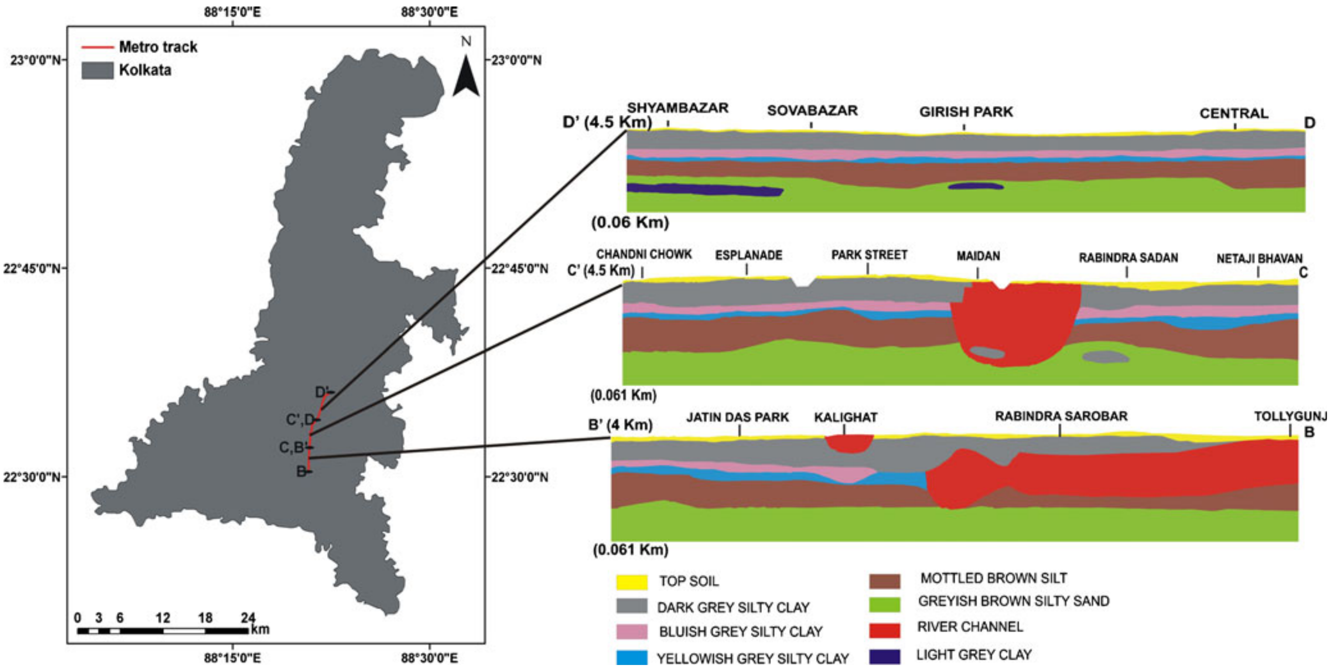

Figure 2. 2-D Geological cross–sections BB′, CC′ and DD′ run from Tollygunj to Shyam Bazar in Kolkata city. The numbers at the left top and bottom are the length and depth of the respective profiles.

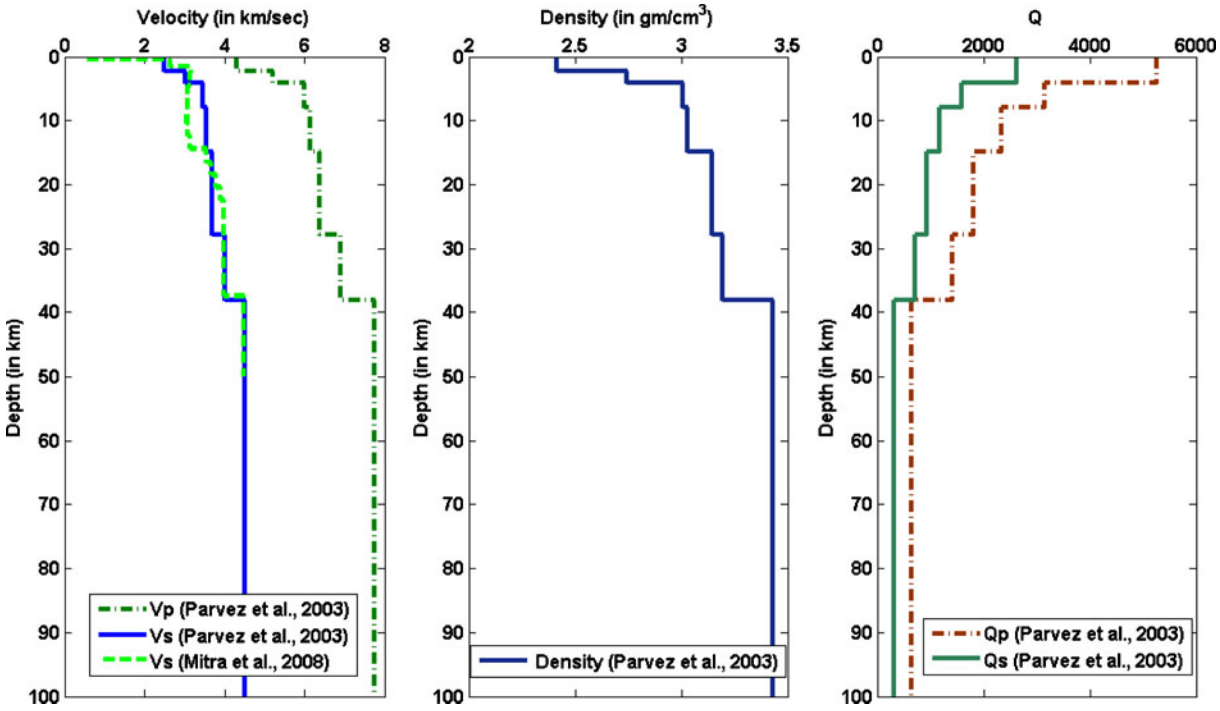

Figure 3. Regional structural reference model for the study area. Variations of seismic velocities (i.e., Vp and Vs), density and Q with depth after Parvez *et al.* (2003).

separates the stable shelf region from the central deep basin (Sengupta 1966). The narrow (25–100 km) EHZ is also known as the 'Calcutta–Mymensingh gravity high' (Sengupta 1966; Khandoker 1989), although more recent data (Khan and Agarwal 1993) suggest that this term is somewhat misleading. The hinge zone runs in a NE–SW direction (figure 1) between the Naga–Haflong–Disang thrust (NT) zone or Dauki fault (DF), at the southern boundary of the Shillong Plateau of Assam in the northeast, to the Indian part of the Bay of Bengal, off the east coast of India to the south (figure 1). The other major fault systems of the basin are the Garhmayna–Khanda Ghosh Fault (GKF), Jangipur–Gaibandha Fault (JGF), Pingla Fault (PF), Sainthia–Bahmani Fault (SBF), Malda–Kishanganj Fault (MKF), Rajmahal Fault (RF) and Debagram–Bogra Fault (DBF) (figure 1). The EHZ is a regional feature that demarcates the continent–ocean transition beneath the Bengal Fan and divides, tectonically, the Bengal basin into two major units: the shelf and the geosynclinal area. The EHZ demarcates a zone of differential thickening and subsidence rate of the overlying Oligocene and Miocene section (Salt *et al.* 1986). In West Bengal, the hinge is cut across by numerous en-echelon faults and by moderate flexures. From the seismic prospecting records, across the EHZ, there is a sharp change in facies and pressure regime in the Upper Paleogene and Neogene sections (Ganguly 1997).

3. Seismicity of the study area

The seismic hazard around Kolkata city is moderate to high, according to the seismic zonation map of India. The region lies in the expected PGA range from 0.2 to 0.25 g that corresponds to the seismic zones III and IV (IS: 1893 (Part 1): 2002). Although Kolkata historical record does not report any destructive earthquake inside the city, it has been strongly affected by near as well as far earthquakes. Two near source events are known to have caused considerable damage to Kolkata: the 29 September 1906 with intensity VI, in Modified Mercalli (MM) scale, VII as per Rossi–Forel scale (Middlemiss 1908) or Mercalli-Cancani-Sieberg (MCS) scale (Decanini *et al.* 1995) at Kolkata and the 15 April 1964 earthquake (source at 100 km south of Kolkata) with reported damage intensity of VI (MCS) surrounding Kolkata (Jhingran *et al.* 1969). The far source earthquakes that have recorded history of damage in Kolkata are the 23 March 1839 (Burma), the 10 January 1869 (Cachar, Assam; Oldham 1883), the 31 December 1881 Nicobar earthquake, the 12 June 1897 Shillong earthquake, the Srimangal earthquake of 8 July 1918 that generated intensity V (isoseismal 5 in Oldham scale, Stuart 1926) and the Bihar–Nepal earthquake (source at 480 km from Kolkata, towards N20°W) of 15 January 1934 (intensity VII (MCS) Dunn *et al.* 1939). Among these, the most notable earthquake is the Shillong earthquake of 12 June 1897, $M_w = 8.1$ (Bilham and England 2001), epicenter at about 470 km towards N35°E from Kolkata, that gave rise to damage of intensity (MSK-64/EMS-98) of VII (isoseismal 3 in Oldham scale, Oldham 1899) and VIII in MM scale (Seeber and Armbruster 1981) at Kolkata. The reported PGA for thick alluvium deposit in Kolkata is 0.08 g (Giardini *et al.* 1999). Martin and Szeliga (2010) estimate shaking intensity VII (MSK-64/EMS-98) in Kolkata with recurrence interval of 30 years, an interval of time comparable to the design

Table 1. *Geotechnical properties of the various soil layers in profiles* BB', CC' *and* DD'.

Formation	ρ (g/cm^3)	V_p (m/s)	V_s (m/s)	Q_p	Q_s
Top soil	1.5	240	140	40	18
Dark grey silty clay	1.8	260	150	45	20
River channel deposit	1.9	460	265	50	23
Bluish grey silty clay with kankar	1.85	325	185	60	27
Yellowish grey silt with clay binders	1.9	415	240	60	27
Mottled brown/grey silty clay	1.9	460	265	60	27
Light grey clay	1.9	485	280	60	27
Dense greyish brown silty sand	1.9	615	355	64	29

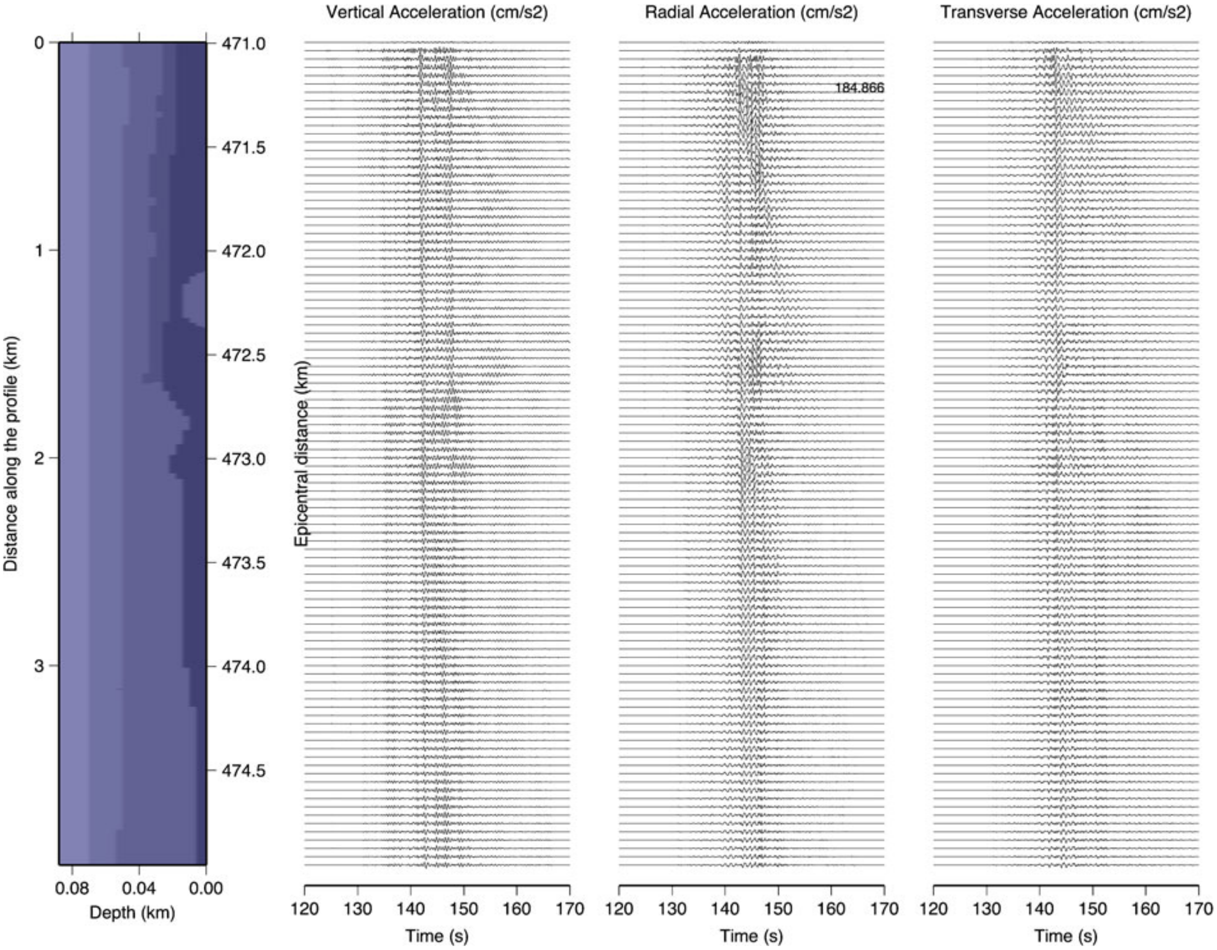

Figure 4. The accelerograms along the geological cross-section B′B for the three components of ground motion, when the source ($M_w = 8.1$) is at 471 km. The maximum amplitude A_{MAX} is indicated in cm/s^2.

life of most structures. A list of significant earthquakes in the West Bengal state has been compiled by Amateur Seismic Centre (ASC) (available at http://asc-india.org/seismi/seis-west-bengal.htm; Gobindraju and Bhattacharya 2012).

4. Methodology

In order to estimate the seismic ground motion at a particular site (Kolkata in this study), we calculate synthetic seismograms with the hybrid method developed by Fäh *et al.* (1994) and Panza *et al.* (2001), which account simultaneously for the contribution of three factors: (1) seismic source: i.e., how the earthquake source controls the radiation of seismic energy from the fault, (2) travel path: i.e., the effect of the earth through which waves propagate from source to site and (3) local soil condition: i.e., the influence of near surface lateral heterogeneities, and topography, at the site of interest. This hybrid method is a deterministic approach based on the theoretical and computational modelling of wave propagation in laterally heterogeneous media. The hybrid method couples the modal summation (MS) technique (Panza 1985; Florsch *et al.* 1991; Panza *et al.* 2001) with the finite difference (FD) method (Alterman and Karal 1968; Boore 1972; Kelly *et al.* 1976; Virieux 1984, 1986; Levander 1988) and optimizes the use of the advantages of both methods. Wave propagation is treated by means of the modal summation technique from the source to the vicinity of the local, heterogeneous structure that we want to model in detail. A laterally homogeneous anelastic structural model is adopted, which represents the average crustal properties of the region. The generated wavefield is then introduced in the mesh that defines the heterogeneous area, and it is propagated according with the finite difference scheme. Source, path and site effects are all taken into

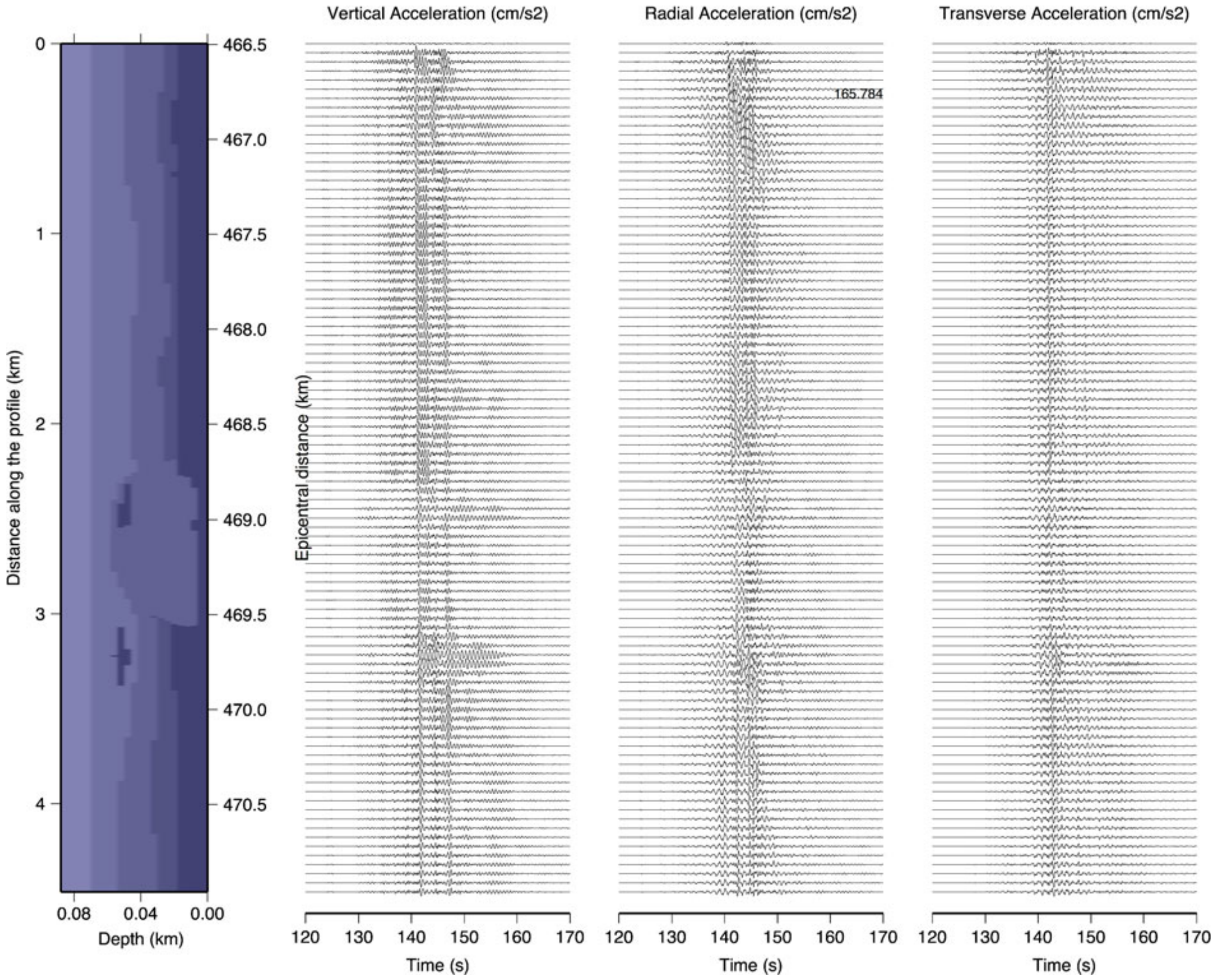

Figure 5. The accelerograms along the geological cross-section C′C for the three components of ground motion when the source ($M_w = 8.1$) is at 466.5 km. The maximum amplitude A_{MAX} is indicated in cm/s^2.

account, and it is therefore possible a detailed study of the wavefield that propagates even at large distances from the epicenter. The procedure is described in some detail by Panza *et al.* (2001, 2002), and it has been employed in several studies worldwide (e.g., Fäh *et al.* 1994; Ding *et al.* 2004; Parvez *et al.* 2003, 2006; Zuccolo *et al.* 2008; Mohanty *et al.* 2009; Vaccari *et al.* 2011). The input parameters to be specified are the seismic source parameters of an earthquake scenario and the structural models through which the seismic waves propagate from the source to the site of interest.

5. Structural models

The regional model (1-D geological bedrock structure), as shown in figure 3, represents the average properties of the various sub-surface lithologies for the study area and has been published by Parvez *et al.* (2003), who compiled the available geological and geophysical information for the uppermost 100 km.

The local heterogeneous model (2-D geological cross-section) is prepared from different sources (Ghosh and Gupta 1972; Som 1999; C.E. Testing Company Pvt. Ltd. 2002; Sengupta 2000; Pal 2006) along the Kolkata metro track that runs from Tollygunj to Shyam Bazar station in the N-S direction (figure 2). The entire cross-section BD′ is about 13 km long and the soil profile is available up to a depth of about 60 m. This cross-section has been divided into three part as BB′ = 4 km, CC′ = 4.5 km and DD′ = 4.5 km (figure 2). The details of the geotechnical properties of different soil types are given in table 1. Further geotechnical properties like SPT-N values for different soil deposits in the study region can be found in Gobindraju and Bhattacharya (2012). The effect of the shallow

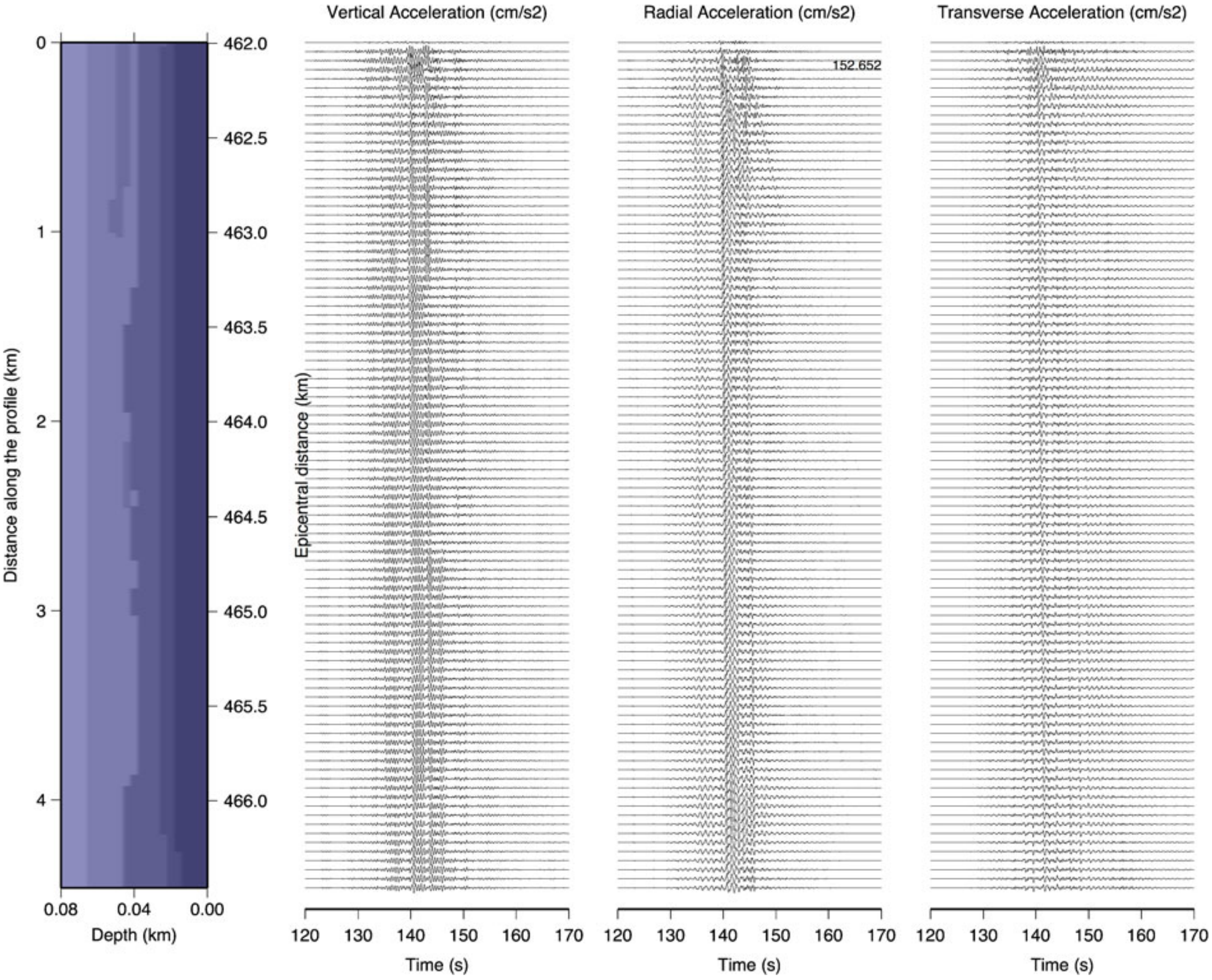

Figure 6. The accelerograms along the geological cross-section D′D for the three components of ground motion when the source ($M_w = 8.1$) is at 462 km. The maximum amplitude A_{MAX} is indicated in cm/s^2.

sedimentary basin can be assessed by the computation of the spectral ratios between the signals obtained for the 2-D model and the corresponding signals obtained for the bedrock (1-D) model. The sharp jump in S-wave velocity between the shallow sediments of the 2-D model and the underlying 1-D bedrock structure mimics the model given by Mitra *et al.* (2008).

6. Earthquake source

In the present study, the Shillong earthquake of 12 June 1897 is considered with epicenter at about 462 km of distance from the Shyam Bazar station (figure 2), i.e., from the nearest site of profile D′B. The source parameters of the 1897 Shillong earthquake used in the computation are dip = 57°, strike = 110° and rake = 76°, focal depth = 9 km, $M_w = 8.1$ (Bilham and England 2001). The epicenter of the event is within the EHZ, about 460 km north of Kolkata (figure 1). A maximum intensity of VIII (MM) (isoseismal 3 in Oldham scale, Oldham 1899) was felt at Kolkata due to this event (GSI 2000).

7. Computation of the synthetic seismograms

The geological profiles run from north to south along the metro track in the Kolkata city and the earthquake source (used in computation) is located in the northern side of Kolkata. The accelerograms are generated along the geological cross-sections B′B, C′C and D′D according to the technique described by Panza *et al.* (2001). The signals were computed analytically (modal summation) along

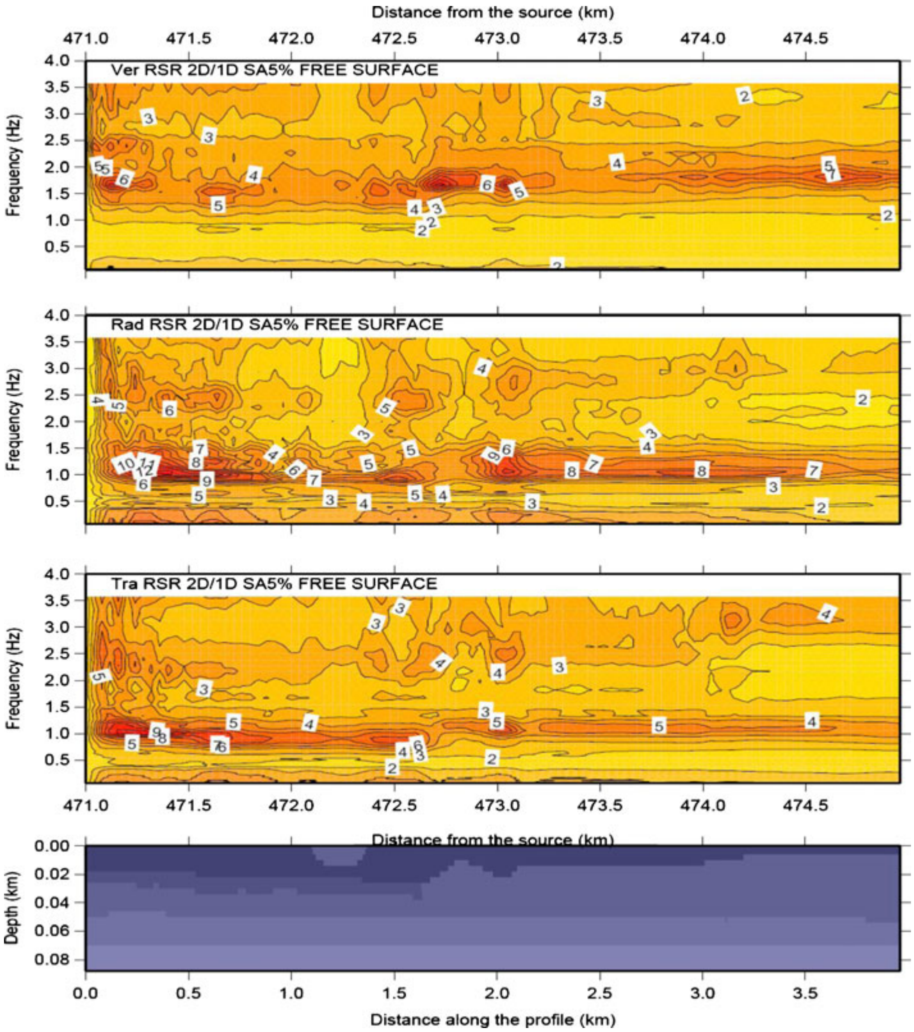

Figure 7. The response spectra ratio (RSR with 5% damping) *versus* frequency and epicentral distance along the geological cross-section B′B.

the path from the source to the site, for frequencies as high as 10 Hz. To account for the epistemic uncertainty about the propagation path, they were subsequently filtered to f $\leq$ 3·5 Hz. These signals are then numerically propagated through the laterally varying local structure by the finite difference method considering a grid step of 0.004 km that obeys the empirical condition that at least 10 points per minimum wavelength are required to assure stability and enough accuracy in the computations. The waveforms are scaled to the desired magnitude in the frequency domain using the scaling law of Gusev (1983) as reported by Aki (1987).

The resulting signals are used for the seismic microzoning via the 'response spectra ratio' (RSR), i.e., the spectral amplification defined by RSR = Sa(2D)/Sa(1D), where Sa(2D) is the response spectrum (at 5% of damping) for the signals calculated in the laterally varying structure, and Sa(1D) is the one calculated for signals at the top of the counterpart bedrock reference model.

8. Results

The synthetic signals (accelerograms) for the profiles B′B, C′C and D′D are shown in figures 4, 5 and 6, respectively. The peak ground acceleration (PGA) estimated in the study ranges from 0.11 to 0.54 g.

8.1 *B′B profile*

The maximum acceleration (A_{MAX}) of 0.19 g is observed in the radial component at the epicentral distance of 471 km, while for the transverse and the

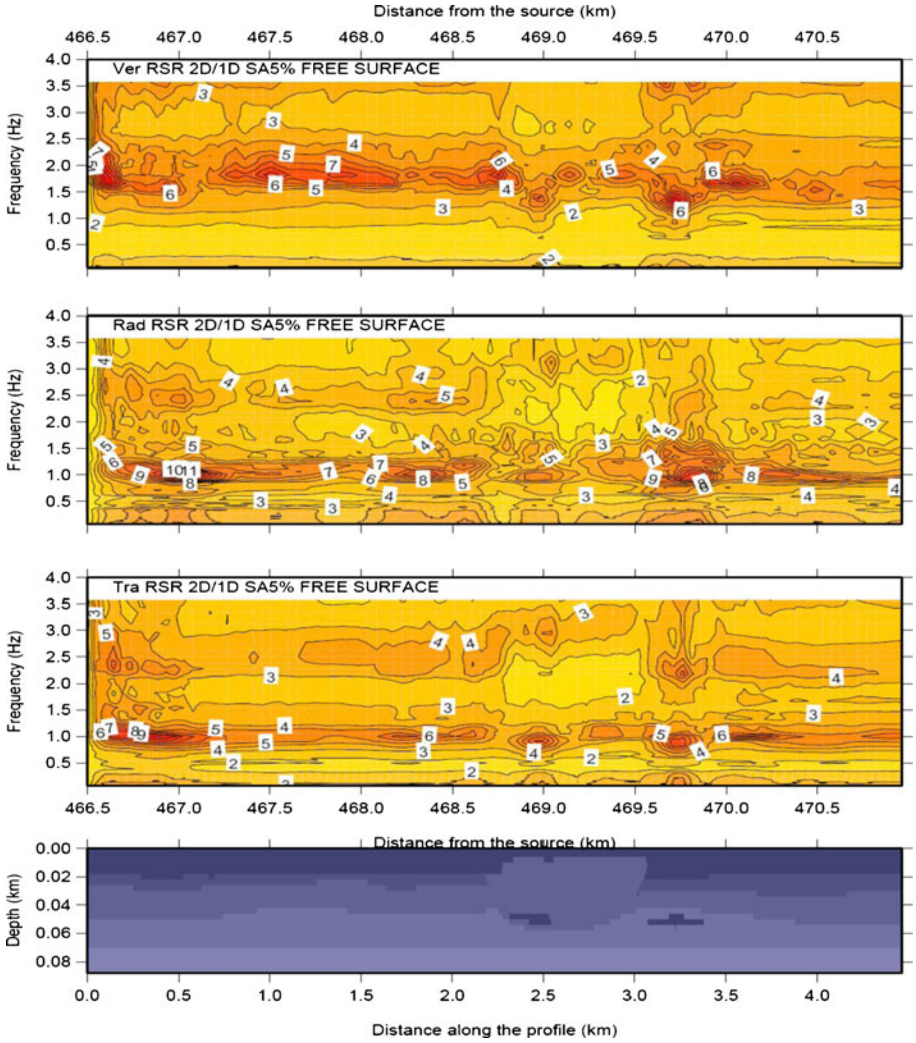

Figure 8. The response spectra ratio (RSR with 5% damping) *versus* frequency and epicentral distance along the geological cross-section C′C.

vertical components, it is 0.14 and 0.13 g, respectively (figure 4). The site amplification is obtained by the distribution of RSR (response spectral ratio with 5%) versus frequency and epicentral distance along the profile (figure 7). The maximum amplification is observed in the radial component and equals 12 in the frequency range from 1.0 to 1.5 Hz. The observed amplification for the vertical component is 9 at the frequency of 1.0 Hz, while in the transverse component the amplification is 7 in the frequency range from 1.0 to 2.0 Hz.

8.2 *C′C profile*

The largest acceleration ($A_{\mathrm{MAX}} = 0.17$ g) is seen in the radial component at 466.7 km from source, while for transverse and vertical components, it is 0.14 and 0.13 g, respectively (figure 5).

The site amplification along profile C′C is shown in figure 8. In this case the absolute maximum amplification is 11 for the radial component at the frequency of 1.0 Hz and epicentral distance of 462.5 km. For the vertical and transverse components the maximum amplifications are 5–7 in the frequency range from 1.5 to 2.5 Hz and 5–9 at 1.0 Hz, respectively.

8.3 *D′D profile*

Peak acceleration ($A_{\mathrm{MAX}} = 0.16$ g) is reached in the radial component rather than in the transverse ($A_{\mathrm{MAX}} = 0.12$ g) and vertical ($A_{\mathrm{MAX}} = 0.15$ g) components (figure 6). These peak values are observed at the distance of 462 km from source.

The RSR versus frequency and epicentral distance plot along the D′D profile is shown in figure 9. Maximum amplification around 8–10

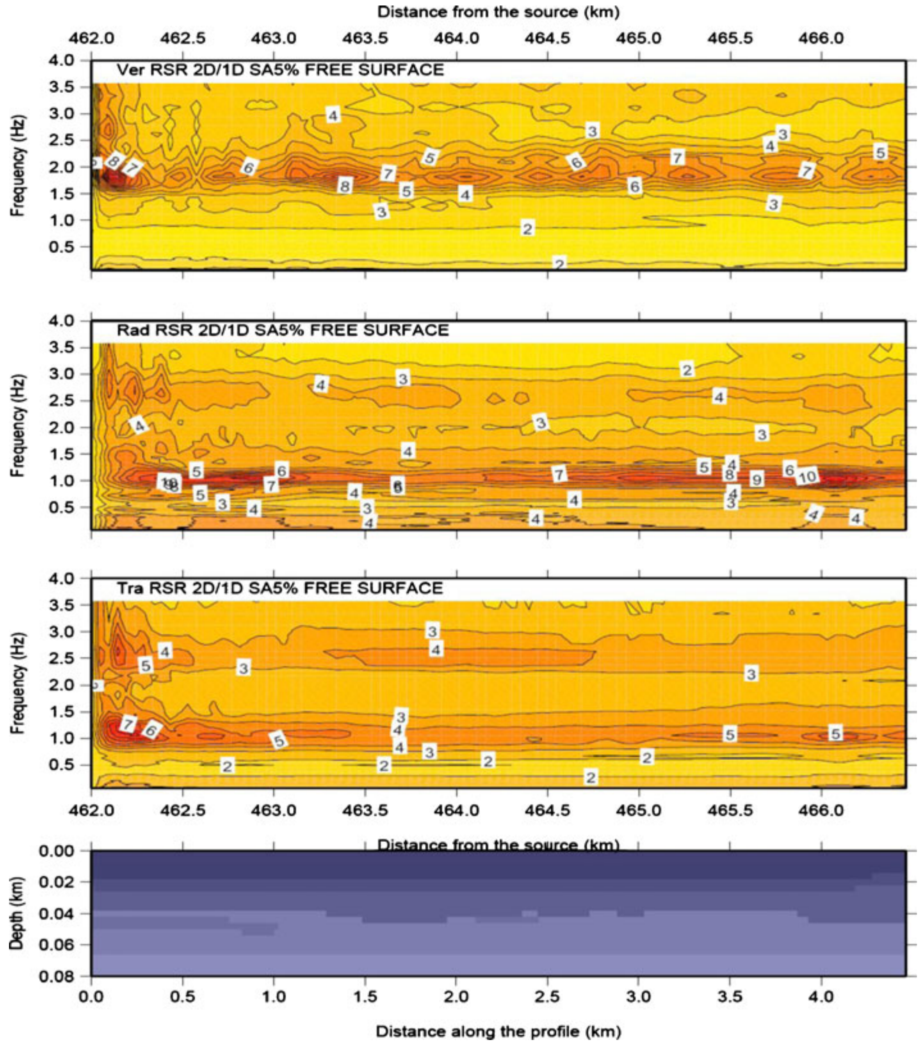

Figure 9. The response spectra ratio (RSR with 5% damping) *versus* frequency and epicentral distance along the geological cross-section D′D.

times is seen at the frequency of 1.0 Hz in the radial component. For the vertical and transverse components the maximum is 8 at 2.0 Hz and 7 at 1.3 Hz, respectively.

To find out the effect of epicentral distance, we performed the computation for the radial component (the most amplified component) for distances of 471, 400 and 300 km and the maximum amplification are 12, 13 and 10, respectively, at a common frequency of 1.0 Hz for section B′B (figure 10). Therefore, the distance dependence of the amplification, in the considered case, can be as high as 30%.

For C′C profile, the amplification value of 11 at 1.2 Hz, 13 at 1.2 Hz and 8 at 1.0 Hz are observed in radial component for epicentral distance 466.5, 400 and 300 km, respectively, as shown in figure 11. This confirms the dependence of the amplification on epicentral distance.

Figure 12 shows the amplification (RSR) for the radial component for D′D profile when the source distances are 300, 400 and 462 km. For a source distance of 300 km the amplification is 10 at the frequency of 1.0 Hz and for an epicentral distance of 400 km it is 6 at 1.2 Hz, however for 462 km source distance the amplification is 10 at the frequency of 1.0 Hz.

The variations, with epicentral distance and source properties, of amplification values and peak's frequency are given in table 2, where the results of Vaccari *et al.* (2011) are reported as well.

9. Discussion and conclusion

The peak ground acceleration (PGA) and response spectral ratio (RSR) in the Kolkata city due to a scenario earthquake in the Shillong plateau varies

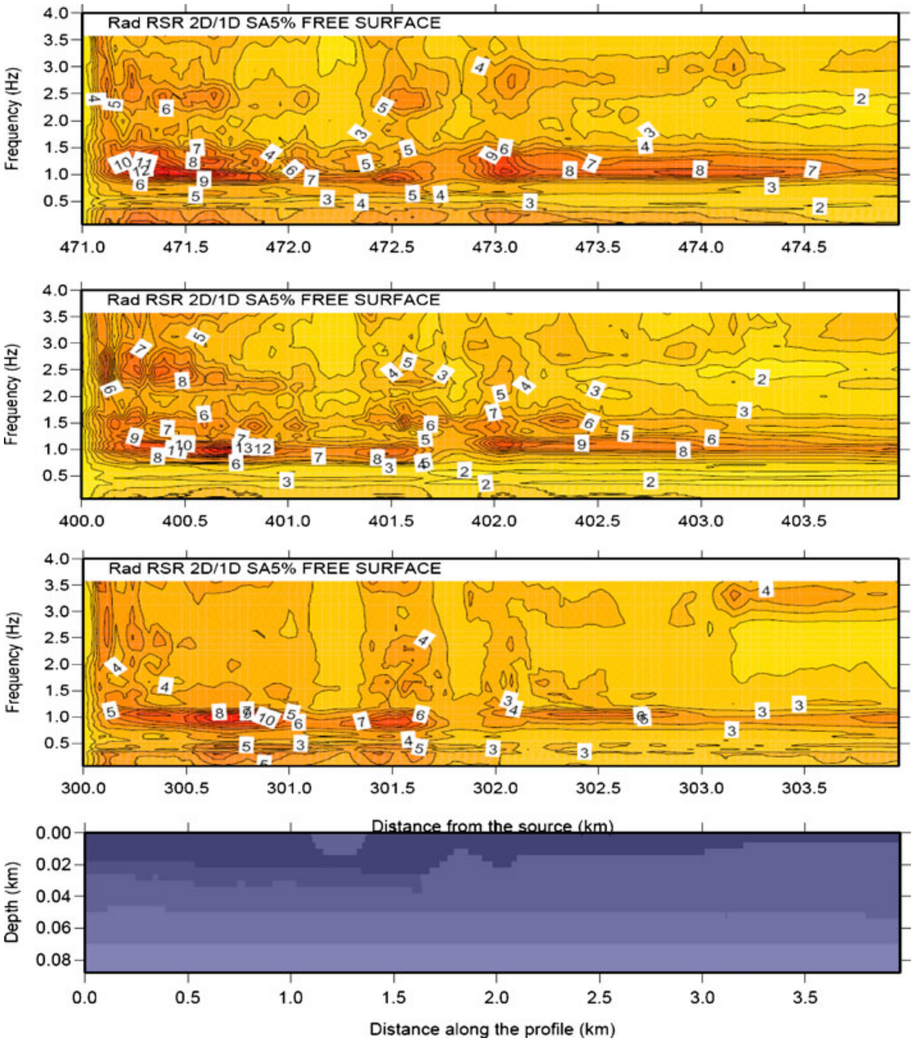

Figure 10. The radial component of response spectra ratio (RSR with 5% damping) *versus* frequency and epicentral distance along the geological cross-section B′B for epicentral distances of 300, 400 and 471 km.

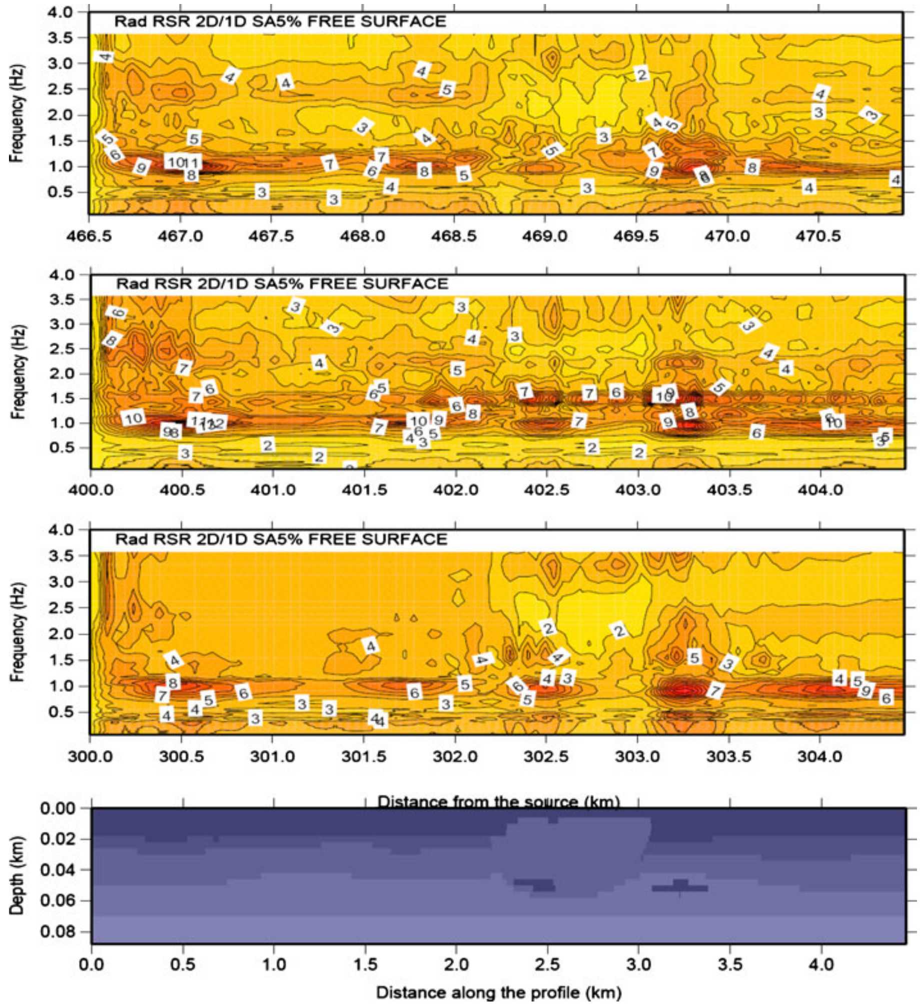

Figure 11. The radial component of response spectra ratio (RSR with 5% damping) *versus* frequency and epicentral distance along the geological cross-section C′C for epicentral distances of 300, 400 and 466.5 km.

from 0.11 to 0.18 g. This acceleration range corresponds to the intensity IX to X on the MCS intensity scale (Panza *et al.* 1997) and VIII on the Modified Mercalli (MM) scale (Bolt 2004). The maximum amplification in terms of RSR (with 5% damping) is observed in the radial components for all profiles and varies from 10 to 12 in the frequency range from 1.0 to 1.5 Hz. These amplifications are observed at sites characterized by shallow, loose, low velocity soil deposits. The area where extreme PGA (or macroseismic intensity) are computed will be, very likely, completely destroyed with great loss of property, at the occurrence of the considered earthquake scenario. The obtained ground motion level in the Kolkata city due to distant earthquake (e.g., 1897 Shillong earthquake, ∼460 km away from Kolkata) is in agreement with the study of Bhattacharya *et al.* (2011), where significant destructions are reported in the Kanto due to the 2011 Tohoku (Japan) earthquake occurred at an epicentral distance of ∼450 km.

To assess the effect of the epicentral distance on ground motion variations in Kolkata, we have computed the seismic ground motion parameters (i.e., PGA and RSR) for different distances (e.g., actual epicentral distance of each profile, and assumed distances of 400 km and 300 km) keeping fixed source mechanism and local properties of sites. Figure 10 shows the amplification pattern for the radial component, along the profile B′B, at 300, 400 and 471 km of epicentral distance. The radial amplification versus source distance for the profiles C′C and D′D is plotted in figures 11 and 12, respectively. The PGA values for epicentral distances of 471 km and 400 km vary in the range from 0.11 to 0.19 g, while for the epicentral distance of 300 km PGA ranges from 0.24 to 0.54 g. The amplification varies slightly for distances 300, 400 and 471 km and the frequency of the peak values varies in a small range (figures 10, 11 sand 12 for profile B′B, C′C and D′D, respectively). Therefore, we can say that, for the cases considered, the relative seismic response

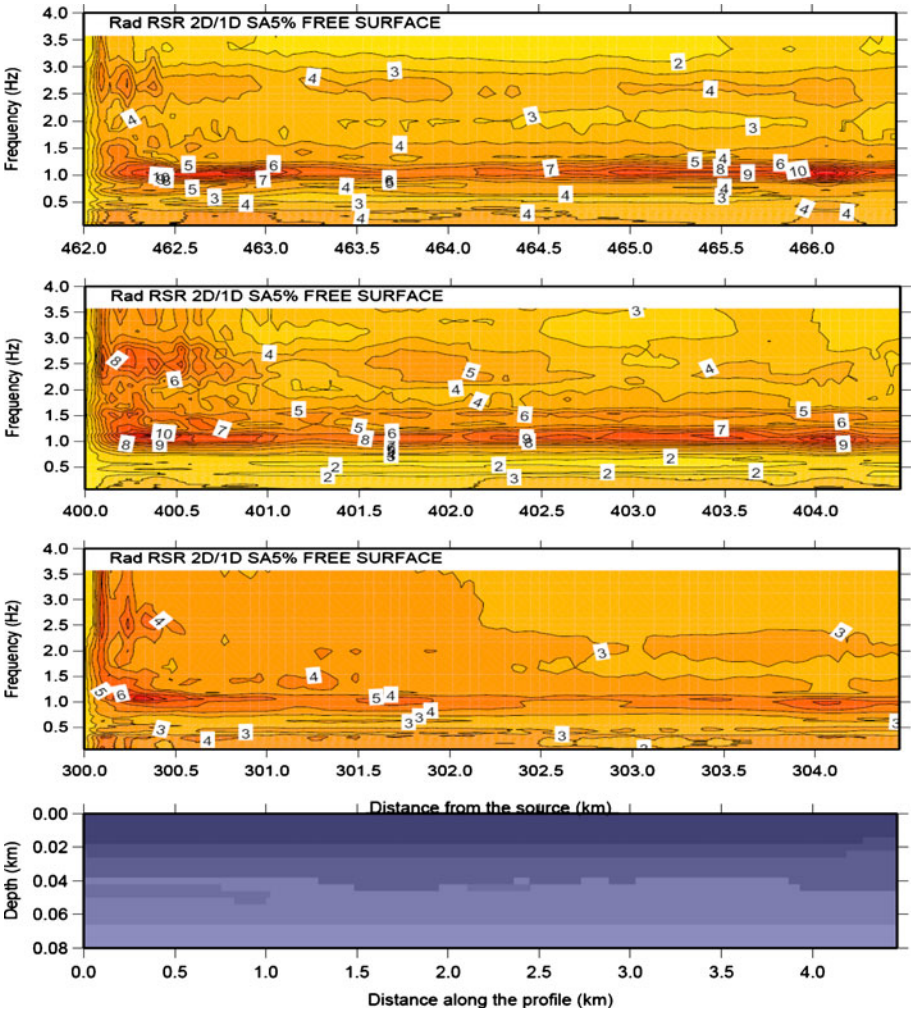

Figure 12. The radial component of response spectra ratio (RSR with 5% damping) *versus* frequency and epicentral distance along the geological cross-section D′D for epicentral distances of 300, 400 and 462 km.

(in terms of RSR) does not vary significantly with changes in epicentral distance.

In addition we compare, for the same sites, our results (i.e., seismic response in Kolkata due to an $M_w = 8.1$ source at an epicentral distance of about 460 km in the Shillong plateau) with the results of Vaccari *et al.* (2011), who considered as scenario the Calcutta earthquake of 15 April 1964 ($M_w = 6.5$) located at about 100 km from Kolkata. The maximum acceleration ($\mathrm{A_{MAX}}$) for the near source (M_w 6.5) is 0.17 g and for the far source (M_w 8.1) it is 0.18 g. The comparative analysis of amplification, performed up to the frequency of 3.5 Hz, shows that the frequency ranges corresponding to peak amplifications are quite similar for near and distant earthquake scenarios, although there is a slight variation in the amplification values. This may be because, for the near source the scenario magnitude considered is $M_w = 6.5$ and for the far source the magnitude is $M_w = 8.1$, and therefore we can say that there is a compensation of the effect of source magnitude with that of distance on site response in Kolkata city.

Although the peak ground acceleration (PGA) varies with varying source parameters (focal mechanism) and epicentral distance, we can conclude that the site response in terms of RSR (i.e., the ratio of response spectra (2-D) to response spectra (1-D), plotted as a function of frequency) at similar site conditions shows similarities in amplification and corresponding frequencies. The major finding from this study suggests that the PGA for 300 km epicentral distance is 0.54 g and for 400 km and 471 km it is in the range from 0.18 to 0.19 g. The frequency that corresponds to peak amplifications does not vary although amplification values vary slightly. This implies that the frequency that corresponds to peak values is a weak function of the location and property of the source. The finding of an almost constant response is not a general property, but it is true for the scenario earthquakes considered in the present study. The obtained PGA

Table 2. *Comparison of estimated maximum amplifications for each ground components along three profiles for two different sources. The amplifications for the Shillong earthquake are computed in this study while those for the 1964 event are taken from the work done by Vaccari et al. (2011).*

Profile name	Source parameters used	Component	Maximum amplification factor	Frequency (Hz)	Distance from the source (km)
BB′	$M_w = 8.1$, dip = 57°,	Vertical	7	1.5–2.0	471.1, 473, 474.5
	strike = 110°, rake = 76°	Radial	12	1.0–1.5	471.2
	and focal depth = 9 km	Transverse	9	1.0	471.3
	(1897, Shillong earthquake)				
	$M_w = 6.5$, dip = 32°,	Vertical	6	1.5–2.3	96.6, 98.2–98.7, 99.5
	strike = 232°, rake = 56°	Radial	8	1.0	97.0, 99.0
	and focal depth = 36 km	Transverse	5	1.0–1.5	96.6
	(1964, Calcutta earthquake)				
CC′	$M_w = 8.1$, dip = 57°,	Vertical	7	1.5–2.3	466.5, 467.3
	strike = 110°, rake = 76°	Radial	11	1.0–1.5	467
	and focal depth = 9 km	Transverse	9	1.0	466.2
	(1897, Shillong earthquake)				
	$M_w = 6.5$, dip = 32°,	Vertical	8	1.5–2.5	102–102.5
	strike = 232°, rake = 56°	Radial	10	1.0	101
	and focal depth = 36 km	Transverse	6	1.0	100.3
	(1964, Calcutta earthquake)				
DD′	$M_w = 8.1$, dip = 57°,	Vertical	8	1.5–2.0	462.2, 663.4
	strike = 110°, rake = 76°	Radial	10	1.0–1.3	462.4, 466
	and focal depth = 9 km	Transverse	7	1.0–1.5	462.3
	(1897, Shillong earthquake)				
	$M_w = 6.5$, dip = 32°,	Vertical	8	1.5–2.0	106.4
	strike = 232°, rake = 56°	Radial	10	1.0	105.5, 108.6
	and focal depth = 36 km	Transverse	7	1.0	105.4
	(1964, Calcutta earthquake)				

Table 3. *PGA for B′B, C′C and D′D profiles with varying source mechanism with fixed magnitude and epicentral distance.*

PGA components	strike = 110°, dip = 57° and rake = 76°; focal depth = 9 km	strike = 232°, dip = 32° and rake = 56°; focal depth = 36 km
B′B		
Transverse	0.135 g	0.037 g
Radial	0.188 g	0.131 g
Vertical	0.130 g	0.089 g
C′C		
Transverse	0.137 g	0.039 g
Radial	0.169 g	0.159 g
Vertical	0.130 g	0.080 g
D′D		
Transverse	0.118 g	0.039 g
Radial	0.155 g	0.136 g
Vertical	0.148 g	0.076 g

Magnitude ($M_w = 8.1$) and distance are the same for each profile (i.e., 471 km for B′B, 466.5 km for C′C and 462 km for D′D profile).

does not follow a clear pattern in terms of their distribution in the magnitude–distance space and this result is consistent with the observation reported by Strasser and Bommer (2009a). Furthermore, the comparison of PGA values, for the same epicentral distance and magnitude, but with different focal mechanism, shows a variation in the PGA values (table 3). Therefore, the ground response may also depend on some other property (e.g., size and orientation of the fault, duration, topographic effect, etc.,) rather than location and property of the source.

Therefore, for Kolkata, as it has been clearly shown in our analysis, the reliable assessment of seismic hazard requires that the ground response should be evaluated for different scenario earthquakes with varying epicentral distances and source parameters.

The ground motion parameters we have computed are well in agreement with the observed intensities in Kolkata reported due to near and far earthquakes. Therefore, in the absence of real strong motion data recorded in Kolkata, the synthetic time series can be used to estimate the expected ground motion, thus leading towards predisaster microzonation without having to wait for an earthquake to occur. The estimated results can be fruitfully used and analyzed by civil engineers for design, urban planning and retrofitting of the existing build environment and therefore can be used as guidelines for the effective mitigation of seismic hazard in Kolkata.

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