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Site-Specific Modeling of *SH* and *P-SV* Waves for Microzonation Study of Kolkata Metropolitan City, India

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Abstract—Kolkata, one of the oldest cities of India, is situated over the thick alluvium of the Bengal Basin, where it lies at the boundary of the zone III and zone IV of the seismic zonation map of India. An example of the study of site effects of the metropolitan Kolkata is presented based on theoretical modeling. Full synthetic strong motion waveforms have been computed using a hybrid method that combines the modal summation and finite difference techniques. The 1964 Calcutta earthquake, which was located at the southern part of Kolkata, is taken as the source region, with the focal mechanism parameters of dip = 32°, strike = 232° and rake = 56°. Four profiles are considered for the computation of the synthetic seismograms from which the maximum ground acceleration (A_{MAX}) is obtained. Response spectra ratios (RSR) are then computed using a bedrock reference model to estimate local amplifications effects. The A_{MAX} varies from 0.05 to 0.17 g and the comparison of the A_{MAX} with the different intensity scales (MM, MSK, RF and MCS) shows that the expected intensity is in the range from VII to X (MCS) for an earthquake of magnitude 6.5 at an epicentral distance of about 100 km. This theoretical result matches with the empirical (historical and recent) intensity observations in Kolkata. The RSR, as a function of frequency, reaches the largest values (largest amplification) in the frequency range from 1.0 to 2.0 Hz. The largest site amplification is observed at the top of loose soil.

Key words: Bengal basin, Eocene hinge zone, seismic microzonation, Kolkata megacity, response spectra ratio (RSR), response spectra (RS), synthetic seismogram and A_{MAX}.

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1. Introduction

Earthquakes are among the most devastating of natural phenomena. On average, about 17,000 persons per year were killed in the twentieth century as a consequence of earthquakes (Chen and Scawthorn, 2003). Over the past few decades, India has been adversely affected by seismic events, with the most notable earthquakes being the 1991 Uttarkashi, 1993 Latur, 1997 Jabalpur, 1999 Chamoli, 2001 Bhuj, 2004 Sumatra and 2005 Kashmir. Several megacities, such as Kolkata, Delhi, Ahmedabad, Mumbai and Guwahati, have suffered severe damage due to earthquakes in the past. With the population increasing rapidly in these cities and much construction anticipated, the damage and death tolls could be even higher in future earthquakes.

The Bureau of Indian Standard (BIS) classified India into four broad seismic zones (zone II to zone V) (IS: 1893 (Part 1) 2002). However, these zones are the product of a gross generalization of empirical observations, as it is not possible to sort out effects due to seismic source characteristics, wave propagation and effects of local site conditions, which are known to have considerable influence on amplification of seismic waves in different source-path-site conditions. Hence, the zones are not adequate to predict potential damage on a site-specific basis, as the damage is greatly influenced by the relative position of the earthquake source, on one side, and the local geology (vicinity to active faults, geophysical properties of the surface and subsurface strata, slope instabilities, topography, etc.) on the other. Different soil types respond differently when subjected to ground motion from an earthquake, with the younger softer soils generally amplifying the ground shaking in comparison to the older competent soils or rock. Contrary to the common belief, the earthquake response of a site can vary even for small changes in the relative position of the earthquake source with respect to the local geology of the site of interest. Hence, to effectively minimize the loss to human life and property, a seismic microzonation is needed based on the computation of realistic synthetic seismograms, whenever possible calibrated against observations.

The areas that call for preventive measures to reduce earthquake hazards are the established densely populated urban areas and the developing urban areas that fall within the high hazard zone (zone IV and V) where there is a rapid increase in population. Seismic microzonation studies have been already carried out for several important Indian cities including Delhi (Parvez *et al.*, 2004; Mohanty *et al.*, 2007), Sikkim (Nath, 2004), Jabalpur (Mishra, 2004), Haldia (Mohanty and Walling, 2008a) and Talchir (Mohanty *et al.*, 2009).

The Kolkata megacity (formerly known as Calcutta) is in the state of West Bengal, India. It is one of the oldest cities of India and lies within the co-ordinates 22°27′N–22°40′N and 88°18′E–88°28′E (Fig. 1). The city developed primarily along the eastern bank of the Hoogly River and covers an area of 185 km^2. According to the Census report 2001 (http://www.censusindia.gov.in/), the city has increased in population from 4.4 million in 1991 to 13 million in 2001. With such an increase in population there is a demand for much construction of high-rise residential complexes, huge shopping malls, educational institutions, bridges, subways, hospitals, etc. to meet the needs of the people.

For the present study, a realistic modeling of *P-SV-* and *SH-* wavefields for four profiles of Kolkata (Fig. 2) was carried out. The event of 15th April 1964 (M_b: 5.2) was taken as the source for the computation of the synthetic seismograms. The maximum intensity felt over Kolkata for the 15th April 1964 earthquake was ~VII in the Modified Mercalli (MM) scale (GSI, 2000). Since any macroseismic intensity scale by its nature is a discrete scale of integer values, when in the literature non-integer values for the epicentral intensity are reported, we use the symbol ~followed by an integer, rounded off by excess, to be conservative.

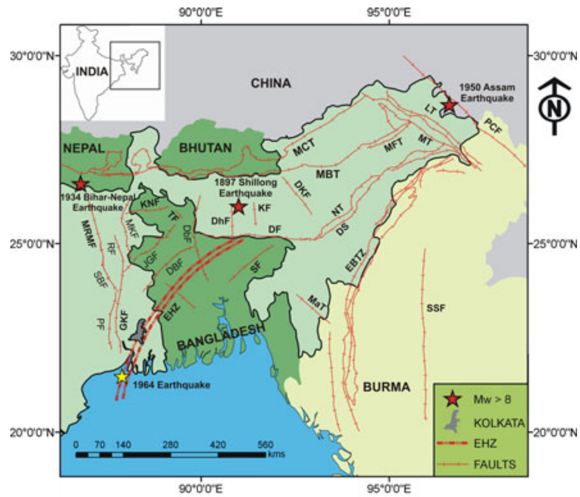

Figure 1
Tectonic scheme of the Bengal Basin and its surroundings. *MKF* Malda-Kishanganj Fault, *DbF* Dhubri Fault, *JGF* Jangipur-Gaibandha Fault, *RF* Rajmahal Fault, *SBF* Sainthia–Bahmani Fault, *GKF* Garhmayna-Khandaghosh Fault, *DBF* Debagram-Bogra Fault, *PF* Pingla Fault, EHZ Eocene Hinge Zone, *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). The *square box* (*inset*) shows the location of the Bengal Basin and its surrounding region in the Indian subcontinent context

2. Regional Geology and Tectonic Settings

Kolkata overlies the Bengal Basin, which is formed by the Ganga–Brahmaputra river system and is also one of the largest deltas in the world. The basin consists of fluvio-marine sediment of a pre-cratonic Tertiary basin. At the western margin of the basin the sediment thickness is 1,200 m, which increases to 12 km towards the deeper parts of the basin in West Bengal and finally attains a thickness of more than 20 km underneath Bangladesh (Nandy, 2001). The surficial geology in and around Kolkata is rather uniform, characterized by the presence of 10–15 m of silty clay, below which occur relatively coarser sediments consisting of either silt/clay with kankar or sand.

The salient tectonic feature of the Bengal Basin is a curvilinear Eocene Hinge Zone (EHZ), also known as the Calcutta–Mymensing hinge zone. The EHZ has

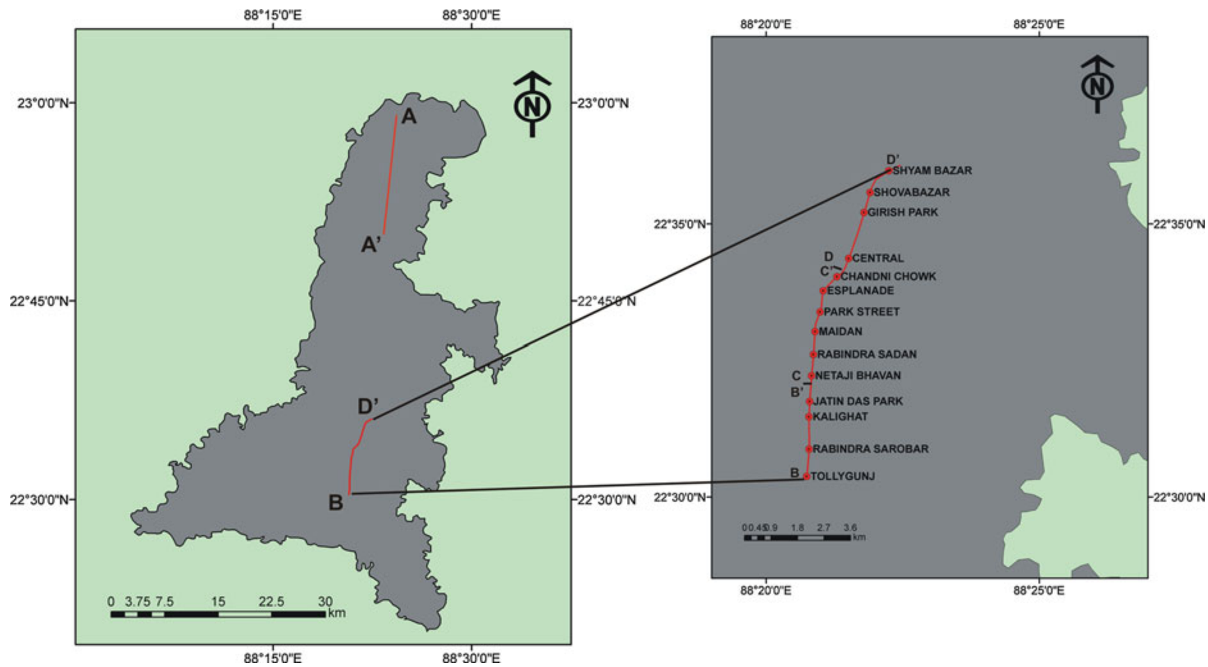

Figure 2
Profiles along which the synthetic seismograms have been generated for Kolkata

a NE–SW trend, a width of 25 km and an extension of 550 km. It terminates at the E–W striking Dauki Fault (DF) at the southern boundary of Shillong Plateau (Fig. 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) (Fig. 1). The EHZ is a regional feature that demarcates the continent-ocean transition beneath the Bengal Fan and also divides, tectonically, the Bengal Basin into two major units: the shelf and the geosynclinal area. The EHZ demarcates a zone of differential thickening and a 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 regimes in the Upper Paleogene and Neogene sections (Ganguly, 1997).

In the Bengal Basin, three structural domains are recognized: the western scarp zone, the middle shelf zone and the eastern deeper basin. The western scarp zone is defined by a series of N–S trending subsurface faults originally identified through deep drilling and gravity modeling, and recently imaged by deep seismic profiling (GSI, 2000). A series of buried basement ridges marks the western margin of the Bengal Basin. To the east of these ridges, there are rows of basin margin en-echelon faults and scarps. The western part of the Bengal Basin constitutes a broad shelf zone bounded by the Basin margin fault zone to the west and northwest and by the Eocene Hinge Zone to the east and southeast.

The total sedimentary thickness below Kolkata, above the crystalline basement, is around 7 km (Murty *et al.*, 2008); of this, the top 0.35–0.45 km is quaternary, which overlies, from top to bottom, 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. Mitra *et al.*, (2008) show, at very shallow depth, the very sharp increase in S-wave velocity that is visible in our section models.

3. Seismic Activity of Kolkata

Kolkata city lies at the boundary of Indian seismic zones III and IV, which comes under high seismic

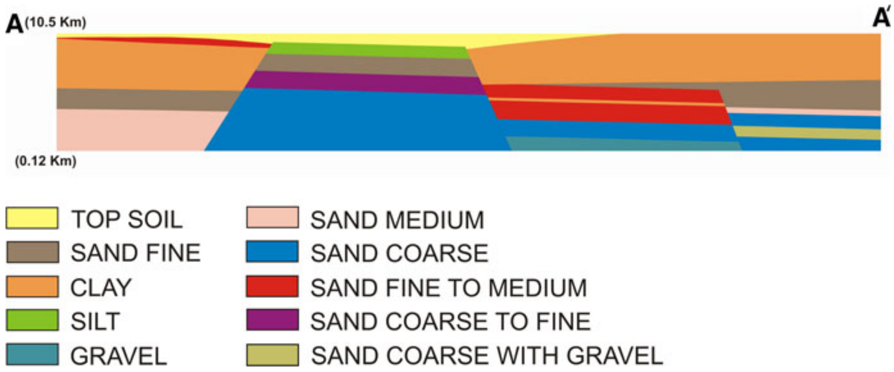

Figure 3
The cross section AA′ with its different geological units. The *colors* represent different layers as shown in the legend. The numbers at the *left top* and *bottom* are the length and depth of the AA′ profile, respectively

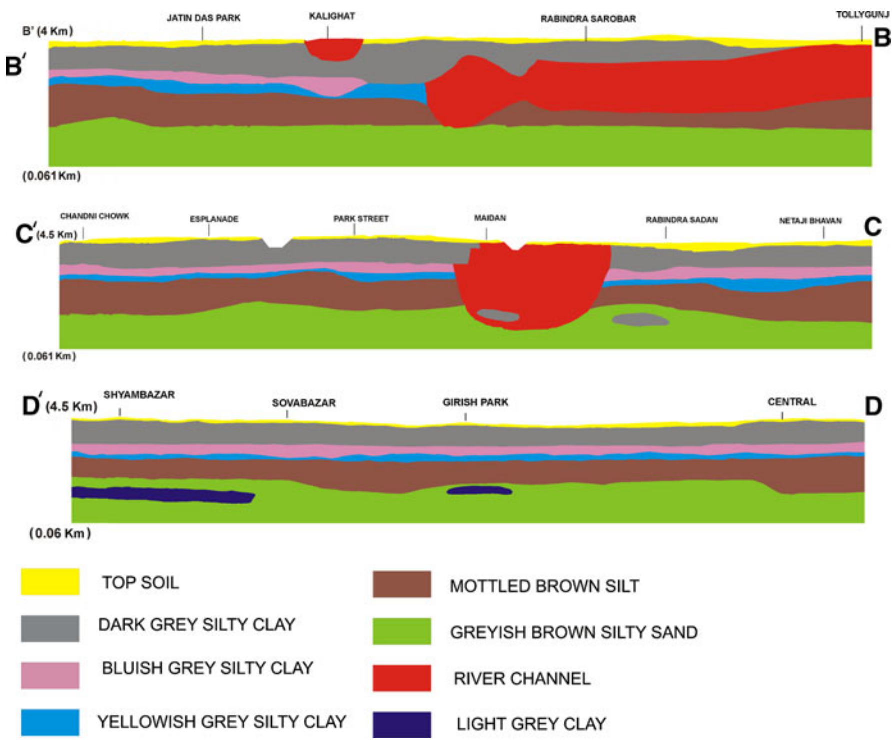

Figure 4
Cross sections BB′, CC′ and DD′ with their different geological units. The *colors* represent different layers as shown in the legend. The numbers at the *left top* and *bottom* are the length and depth of the respective profiles

risk (IS: 1893 (Part 1): 2002). The Global Seismic Hazard Assessment Program (GSHAP, 1999) estimates a PGA of 0.08 g for firm soil site in greater Kolkata.

The area has been affected by distant as well as nearby earthquakes. Near sources include the earthquakes of 29th September 1906 and 15th April 1964 Calcutta earthquake (located south of Kolkata over the EHZ), which were strongly felt in and around Kolkata and caused considerable damage. A maximum intensity of VII, in the Rossi–Forel scale, was felt for the September 1906 earthquake (Middlemiss, 1908) and an intensity of VII, in the Mercalli scale (Jhingran *et al.*, 1969) and ~VII in the Modified

Mercalli (MM) scale for the April 1964 earthquake (GSI, 2000). In other words, the maximum observed intensity is VII in the Mercalli-Cancani-Sieberg (MCS) or VI in the Medvedev–Sponheuer–Karnik (MSK) scales, which roughly corresponds to the acceleration range 0.025–0.05 g (PANZA *et al.*, 1997). Though both earthquakes caused severe cracks in buildings, the April 1964 earthquake was the most damaging event and was felt over an area of 67,000 km^2.

Distant earthquakes that shook Kolkata include those of 1st September 1803, 26th August 1833 and 31st December 1881. The best documented event was the great 1897 Shillong earthquake where a maximum intensity of VIII (MM scale) was felt over the Bengal Basin (SEEBER AND ARMBRUSTER, 1981). The Shillong earthquake was located at an epicentral distance of 470 km from Kolkata but caused considerable damage, to the extent of partial collapse of buildings. OLDHAM (1899) reported an intensity of isoseist 3 on the Oldham scale for the Shillong earthquake, which is equivalent to an intensity of VII in the MSK scale or to VIII on the MCS scale (e.g. DECANINI *et al.*, 1995). The 8th July 1918 Srimangal earthquake, located about 350 km from Kolkata, also caused cracks in many old and new buildings (http://www.gbpihed.gov.in/envis/HTML/vol10_1/rptiwari.htm). Similar damage was observed in Kolkata during the Dubhri earthquake of 3rd July 1930. The Bihar–Nepal earthquake of 15th January 1934, which was about 480 km distant, also caused substantial damage to buildings. An intensity of VI (MM) was assigned to Kolkata since the damage pattern was similar to that observed after the nearby-source Kolkata earthquake of 1964 (DUNN *et al.*, 1939).

4. Methodology

An essential parameter in seismic microzonation is the distribution of strong ground motion within the study area. The strong motion data can be obtained in two ways: (a) by recording earthquakes in real time and (b) by theoretically computing seismic signals. The recorded data are reliable and useful, if the strong earthquakes, possibly with different source mechanisms and locations, are recorded on a dense set of instruments. In the absence of reliable strong motion data or while waiting for the strong earthquakes to occur, the computation of synthetic seismograms, calibrated whenever possible against available observations, is the only way to build a timely microzonation.

In this paper, we use the hybrid method (FÄH, 1992; FÄH *et al.*, 1993; FÄH AND PANZA, 1994; FÄH *et al.*, 1994) based on the modal summation (MS) (PANZA, 1985; FLORSCH *et al.*, 1991; PANZA *et al.*, 2001) and finite difference (FD) methods (VIRIEUX, 1984, 1986; LEVANDER, 1988). The methodology belongs to the Neo-deterministic seismic hazard assessment (NDSHA) procedure, developed and, so far, applied to the realistic modeling of the seismic input in 13 megacities and large urban areas in Europe, Central America, Africa and Asia. The procedure and some results are discussed in detail by

Table 1

Mechanical properties of the various soil layers in profile AA′

Formation	ρ (g/cm^3)	V_p (m/s)	V_s (m/s)	Q_p	Q_s
Top soil	1.5	400	230	40	19
Sand fine	1.6	500	290	44	20
Clay	1.8	550	320	60	25
Silt	1.8	550	320	60	25
Gravel	1.82	600	345	62	26
Sand medium	1.82	700	405	64	28
Sand coarse	1.83	800	460	64	28
Sand fine to medium	1.83	900	520	66	29
Sand fine to coarse	1.83	1000	580	66	29
Sand coarse with gravel	1.85	1100	635	70	30

Table 2

Mechanical 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

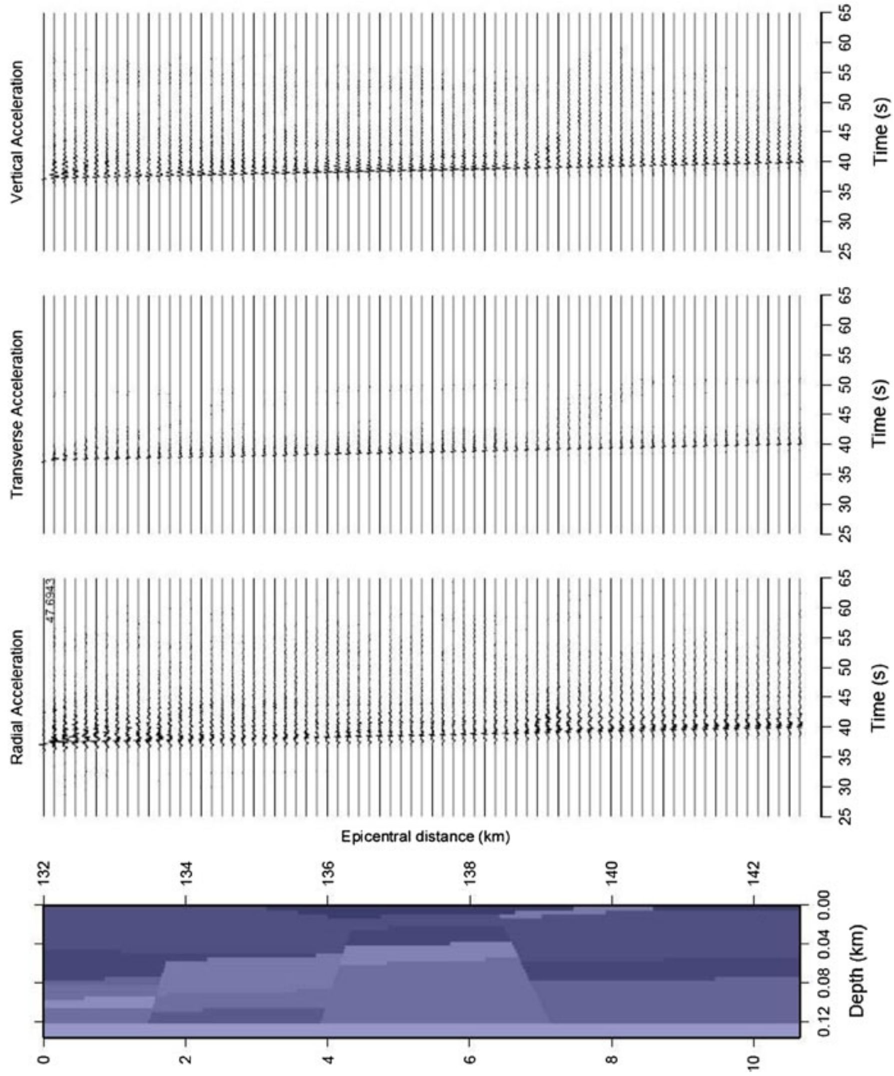

Figure 5
Accelerograms along the AA′ profile for the three components of ground motion. The maximum amplitude A_{MAX} is given in cm/s^2

PANZA *et al*. (2001, 2002), and a recent example of its application is given by ZUCCOLO *et al*. (2008).

The input parameters are the earthquake source and the geological structures through which the seismic waves propagate from the source to the site of interest. The structural model used in the computations consists of two parts: a simple 1D ‘bedrock’ or ‘regional’ structure and a 2D lateral heterogeneous structure. The source is located in the bedrock structure and the calculations are performed in two stages. The seismic wavefield is propagated from the earthquake source to the boundaries of the laterally heterogeneous area applying the MS method. The resulting time series are used to excite the wave propagation in the laterally heterogeneous medium where the seismic wavefield is propagated with the FD technique. The hybrid approach thus allows the calculation of the local seismic wavefield for short (few kilometers) as well as for long (several hundred kilometers) epicentral distances.

The bedrock model is defined as a stack of horizontal layers, each characterized by its thickness, P- and S-wave velocities, density and Q factor, controlling the anelastic attenuation.

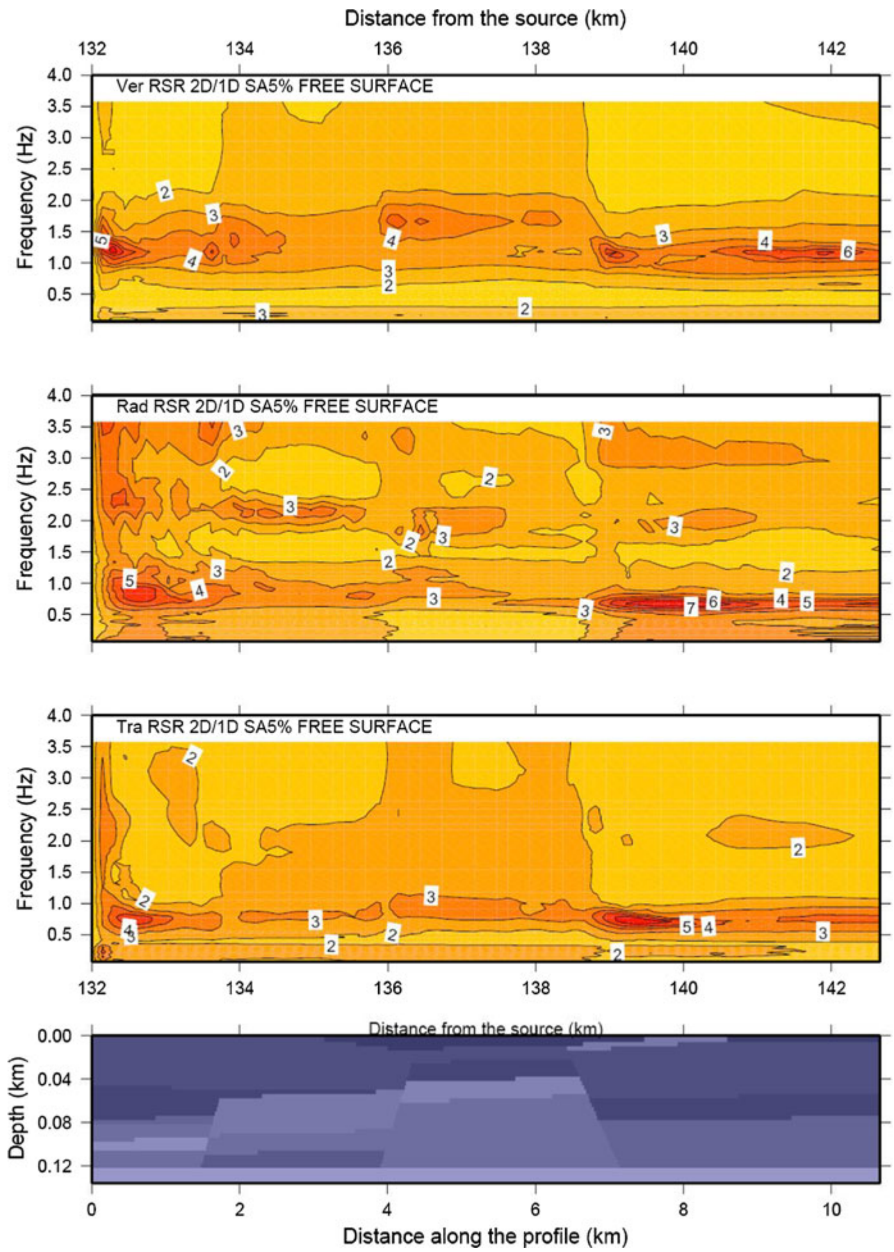

Figure 6
Response spectra ratio (RSR) versus frequency and epicentral distance along the AA′ profile. A 5% damping is assumed

To optimize the setting of relevant parameters in the FD model (optimal model depth, grid step, proper removal of reflections at boundaries), the results obtained from the MS computation are compared with those given by FD for the case of the 1D regional model. When the differences between these two results do not exceed 5%, then a 2D simulation is performed with the obtained optimal values of parameters.

5. Input Data

The input data considered for the earthquake ground motion simulations using the hybrid approach are (a) the earthquake source model, (b) the regional (bedrock) model parameter describing the average properties of the various sub-surface lithologies and (c) the local model parameters.

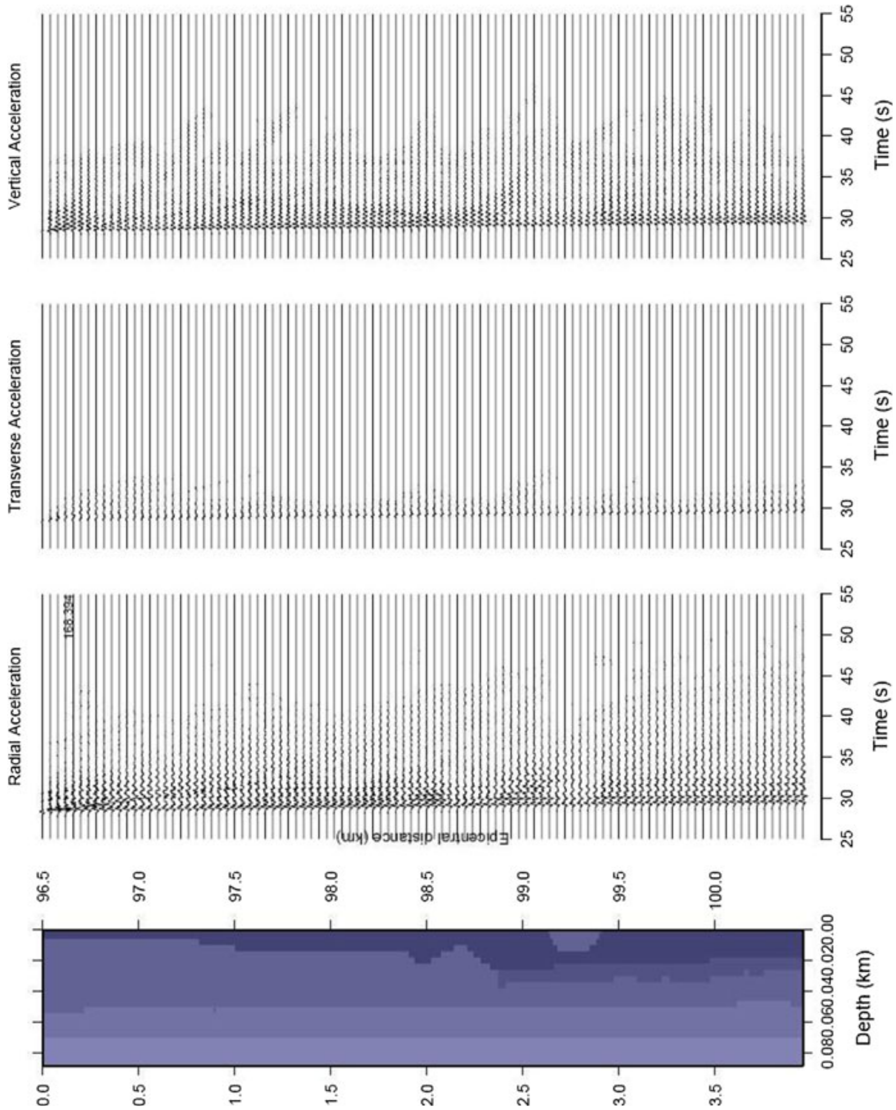

Figure 7
Accelerograms along the BB′ profile for the three components of ground motion. The maximum amplitude A_{MAX} is given in cm/s^2

The 15th April 1964 Calcutta earthquake, along the EHZ,was taken as the source for the computation. The source is at an epicentral distance of 96.5 km from the nearest profile (i.e. BB′). For modeling ground motion, the earthquake hypocenter is placed at 36 km of depth with the focal mechanism parameters dip = 32°, strike = 232° and rake = 56°, as reported for the 15th April 1964 Earthquake (GSI, 2000; Chandra, 1977), but the magnitude is taken as $M_w = 6.5$, that is, the maximum expected magnitude in this region, as suggested by Mohanty and Walling (2008b).

The regional bedrock structure is taken from the comprehensive work of Parvez *et al*., (2003) compiled from the available geological and geophysical information. The Indian subcontinent is divided into 15 regional polygons based on their structural model and *Q*-structure; structural polygon 7 is considered for the present study.

For the 2D local structural model, four N–S trending profiles are considered: AA′, BB′, CC′ and DD′ (Fig. 2). Profile AA′ is obtained from GSI (Chatterjee *et al*., 1964) (Fig. 3) and BB′, CC′ and

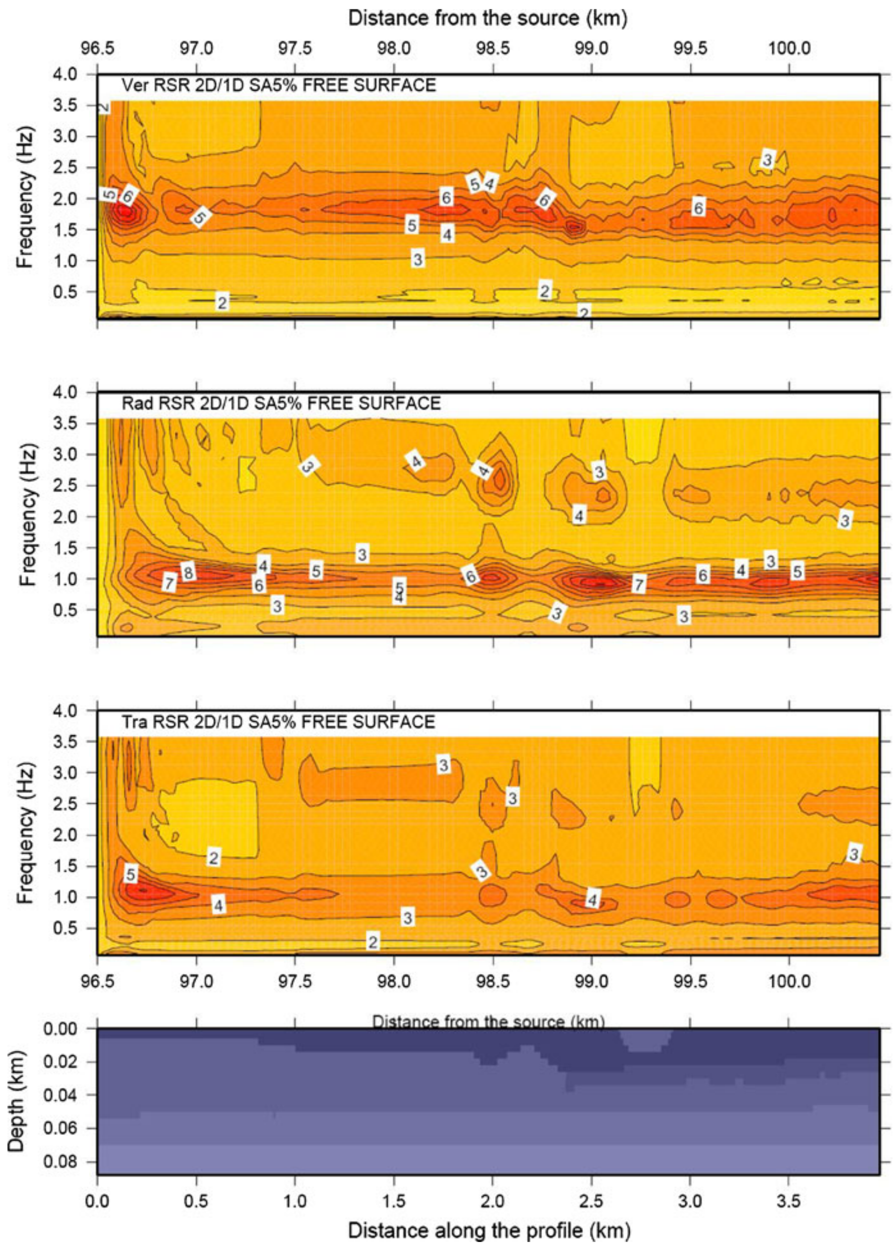

Figure 8

Response spectra ratio (RSR) versus frequency and epicentral distance along the BB′ profile. A 5% damping is assumed

DD′ are compiled from different sources (GHOSH AND GUPTA, 1972; SOM, 1999; C.E. TESTING COMPANY PVT. LTD., 2002; SENGUPTA, 2000 and PAL, 2006) (Fig. 4). The AA′ profile runs from Daulat, Triveni to Children Park, Bhatpara with a length of about 10.5 km and a depth of 120 m. The cross-section profile was prepared using data from 6 boreholes. The BB′ (4 km), CC′ (4.5 km) and DD′ (4.5 km) profiles run through the length of the metro track with a total length of 13 km from the Tollygunj to Shyam Bazar station and reach a depth of 60 m. The mechanical properties of *S*-wave velocity (V_s), density (ρ) and the quality factor (Q_p and Q_s) for the local structural model of various soil layers along each profile are shown in Tables 1 and 2. The 2D structural model used for computation is a realistic model which reflects the

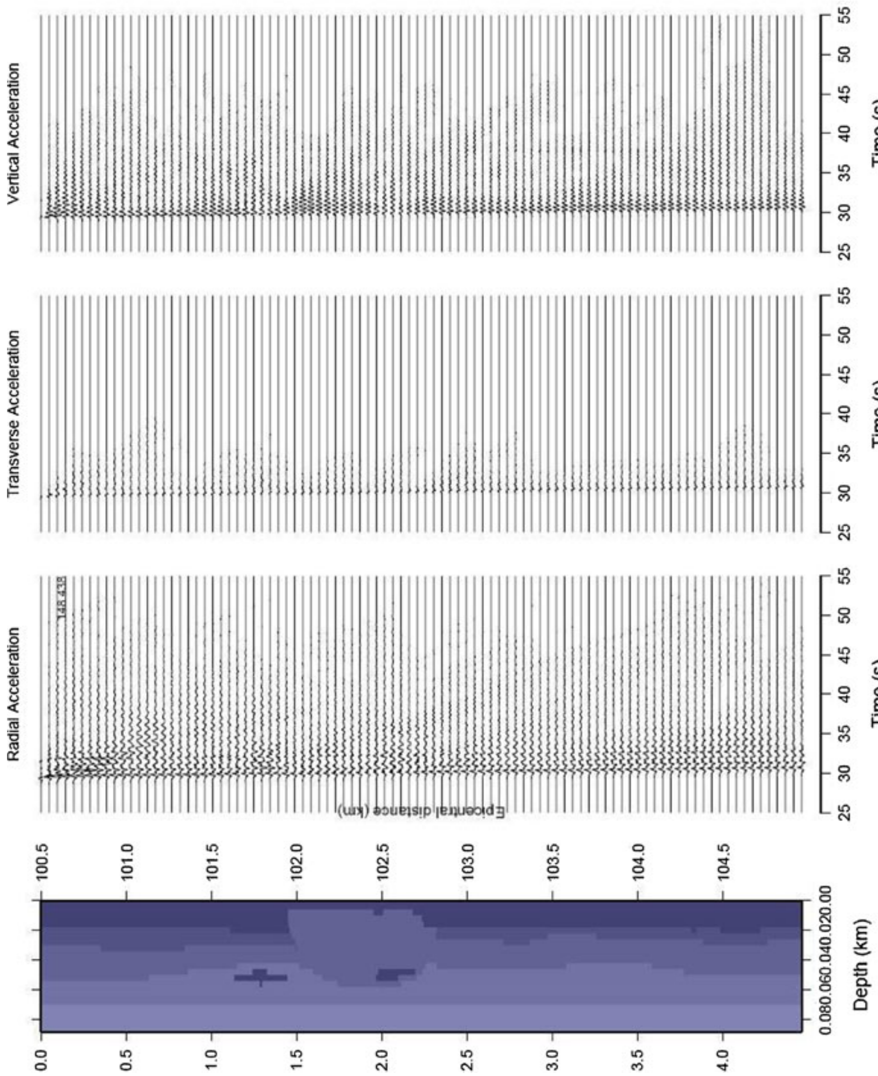

Figure 9
Accelerograms along CC′ profile for the three components of ground motion. The maximum amplitude A_{MAX} is given in cm/s^2

sharp jump in the *S*-wave velocity (V_s) followed by a continuous 1D structure model (MITRA *et al.*, 2008). In the computation for BB′, CC′ and DD′, we have merged the very thin topmost layer with the layer below, to avoid digitization problems. However, this does not influence the results, given the wavelengths involved. The relation between V_p and V_s is considered to be $V_p = 1.73\ V_s$, approximately.

6. *Results*

For the four profiles AA′, BB′, CC′ and DD′, synthetic seismograms were generated with a cutoff frequency of 6 Hz, using the scaled point-source approximation by GUSEV (1983) as reported in AKI (1987). The hazard factor was computed in terms of acceleration and response spectra ratio (RSR). The

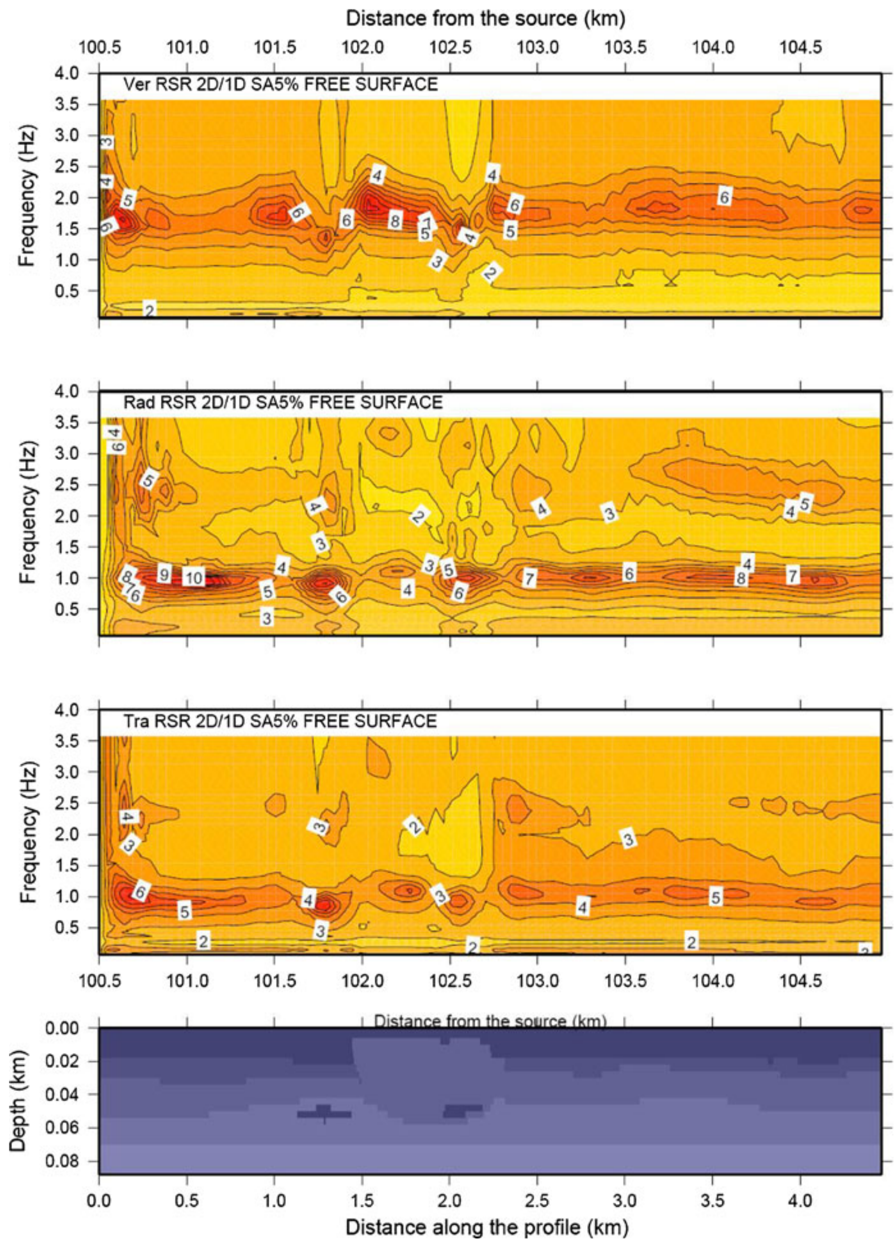

Figure 10

Response spectra ratio (RSR) versus frequency and epicentral distance along the CC′ profile. A 5% damping is assumed

RSR was used as an estimate of the amplification at each site and is expressed as:

$$\mathrm{RSR} = \mathrm{RS(2D)}/\mathrm{RS(1D)}$$

RS (2D) is the response spectrum (at 5% damping) of the signals in the laterally varying local structure and RS (1D) is the response spectrum calculated for the bedrock regional reference model. The site amplification is estimated in terms of RSR as a function of frequency and epicentral distance.

The maximum ground acceleration (A_{MAX}) along the AA′ profile, located at a distance of about 132 km from the source, is observed to be 0.05 g for the radial component (Fig. 5), 0.02 g for the transverse component and 0.025 g for the vertical component. A maximum amplification of 7 is observed for the

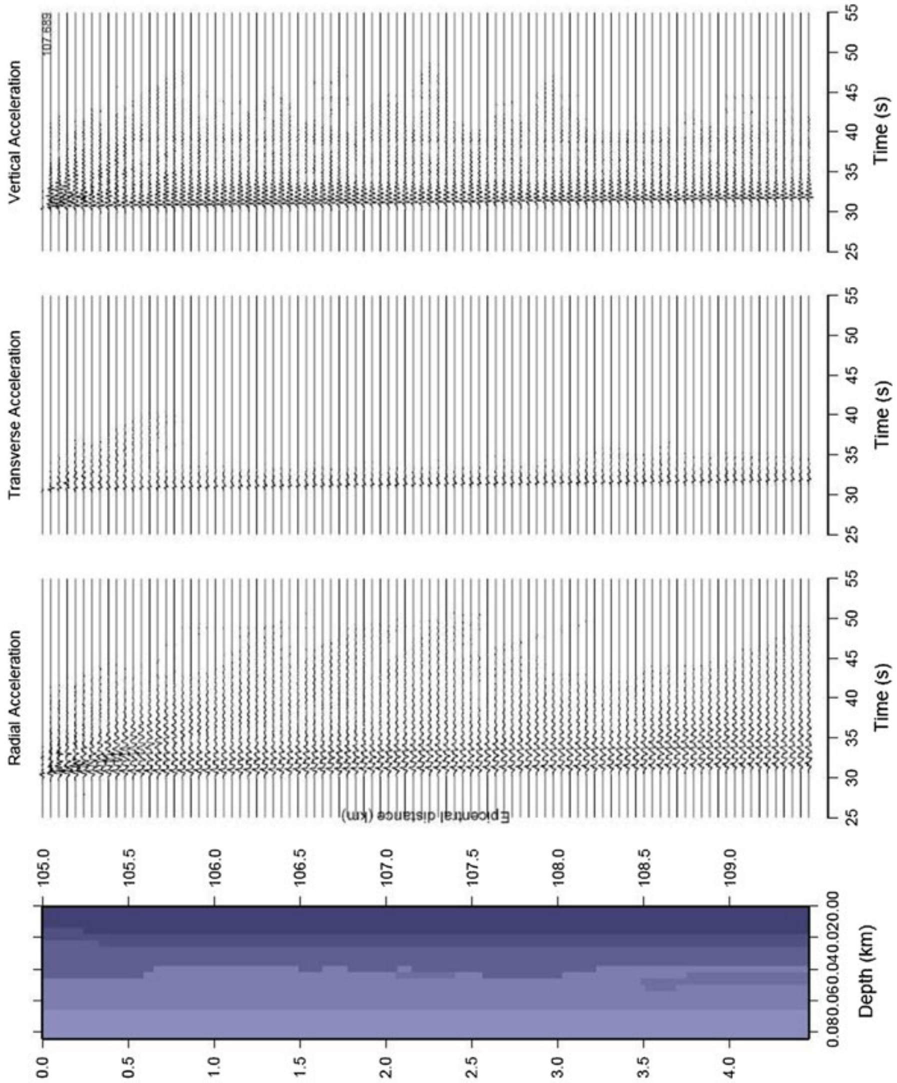

Figure 11
Accelerograms along DD′ profile for the three components of ground motion. The maximum amplitude A_{MAX} is given in cm/s^2

radial component at 0.7 Hz, while the vertical and transverse components show similar amplifications (around 6) at 1.4 and 0.7 Hz, respectively (Fig. 6).

The maximum A_{MAX} for the BB′ profile is observed in the radial component equal to 0.17 g at an epicentral distance of about 97 km that corresponds to the river channel (Fig. 7). The A_{MAX} for vertical and transverse components are 0.10 g and 0.03 g, respectively. Figure 8 depicts the RSR with the maximum amplification observed for the radial component with RSR of 8 at 1.0 Hz followed by a vertical component with RSR equal to 6 at 1.7 Hz and a transverse component with RSR of 5 at 1.0 Hz. The maximum amplification is consistently within the frequency range of 1.0–2.0 Hz (Fig. 8).

The maximum A_{MAX} for the CC′ profile is 0.15 g, observed for the radial component, followed by 0.12 g for the vertical component and 0.05 g for the transverse component (Fig. 9). The RSR distribution for the CC′ profile shows amplifications as large as 10 for the radial component at 1.0 Hz. For the vertical and transverse components, the amplification is 8 at 1.7 Hz and 6 at 1.0 Hz, respectively (Fig. 10).

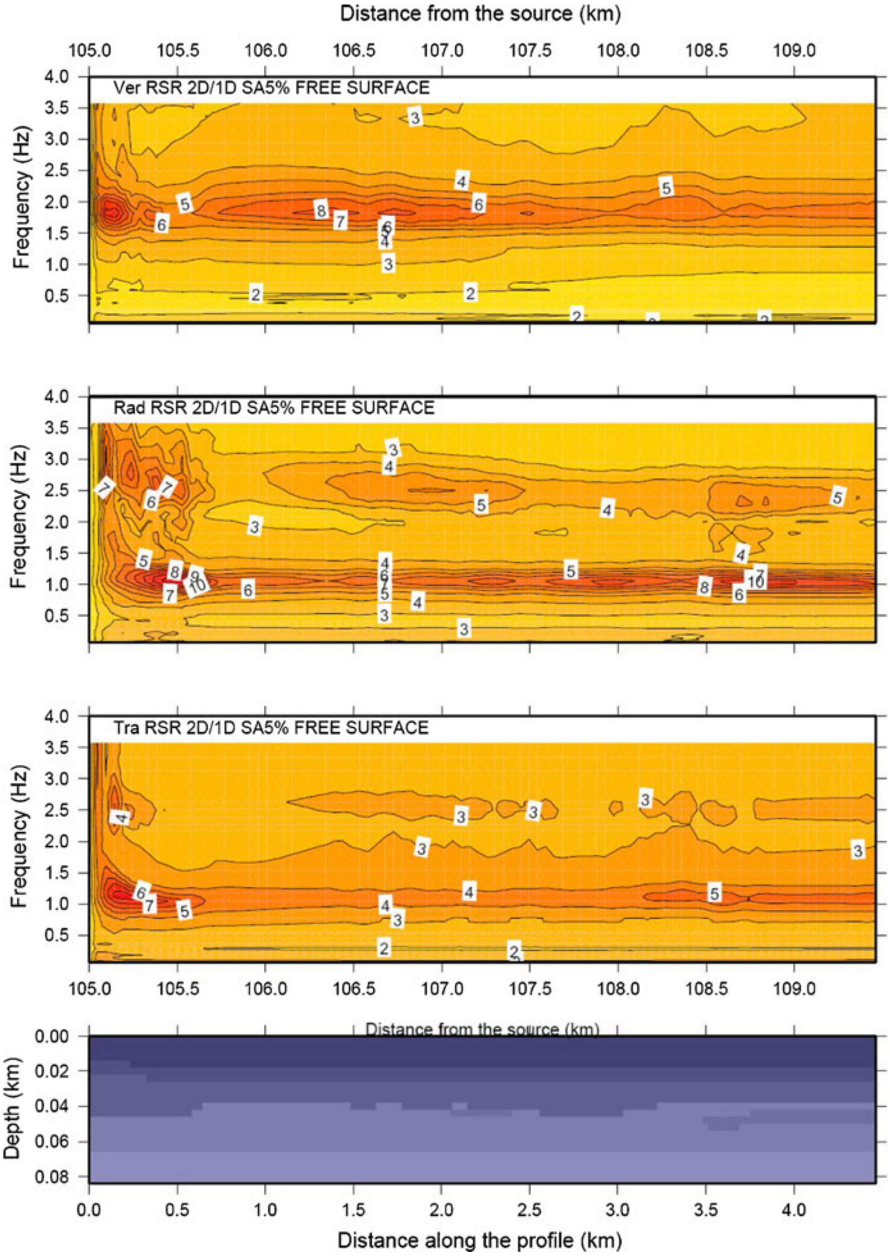

Figure 12
Response spectra ratio (RSR) versus frequency and epicentral distance along the DD′ profile. A 5% damping is assumed

For the DD′ profile, the maximum A_{MAX} for the vertical component is about 0.1 g at an epicentral distance of around 105 km from the source. The A_{MAX} for radial and transverse components are 0.10 and 0.05 g, respectively (Fig. 11). The RSR distribution versus frequency and epicentral distance shows clear amplification for the transverse and vertical components at specific frequencies. For the transverse component, the maximum computed RSR is 7 at 1.2 Hz while for the vertical component, the computed RSR is 8 at the slightly higher frequency of 1.7 Hz. The RSR at the radial component shows distinct amplifications of 10 at 1.0 Hz, and 7 at 2.5 Hz (Fig. 12).

Table 3

Intensity value, for different intensity scales, corresponding to a peak ground acceleration of 0.17 g

Intensity scale	Intensity degree
MSK-76 (Medvedev, 1977)	VIII
EMS–1992 (Lliboutry, 2000)	VIII
MCS (ING–NT4.1.1, Panza *et al*., 1997)	X
MCS (ISG–NT4.1.1, Panza *et al*., 1997)	IX
MM (Modified Mercalli)	VII
RF (Rossi–Forel)	VIII

7. *Discussion and Conclusion*

Site specific synthetic seismograms are generated along four profiles oriented in a N–S direction across the northern and southern part of Kolkata. Profile AA′ samples the northern part while BB′, CC′ and DD′ sample the southern part of the megacity. Looking at the nearby seismicity, the source used to generate the synthetic seismogram along the four profiles has been placed in the epicentral area of the 1964 Calcutta earthquake (M_b: 5.2). The source is located to the south of the profiles at a distance of 96.5 km from the nearest modeled site.

The hazard is estimated in terms of A_{MAX} and RSR. The computation of the A_{MAX} of the three components for the four profiles shows that the peak acceleration varies in the range from 0.05 to 0.17 g.

A comparative study of various seismic intensity scales with respect to acceleration shows that the expected intensity range for Kolkata is from VII to X (Lliboutry, 2000; Murphy and O'Brien, 1977; Medvedev, 1977; Richter, 1958; Panza *et al*., 1997). Table 3 lists the various intensity scales corresponding to $A_{MAX} = 0.17$ g. Based on the results of our modeling, Kolkata can experience severe damage from earthquakes, worse than that observed in 1964, and the peak acceleration may exceed the level of 0.08 g predicted by GSHAP.

The maximum RSR is seen along the CC′ and DD′ profile with amplifications of more than 6 in all the three components in the frequency range from 1.0 to 2.0 Hz. The frequency range at which most of the amplification is observed is 1.0–2.0 Hz and the highest amplifications occur in areas corresponding to the loose soil condition of Kolkata. The region of Kolkata is not only prone to the hazards of ground motion and amplification but it is susceptible to liquefaction and lateral spreading, because the thick Holocene alluvium deposits are likely to soften during an earthquake. The information supplied by NDSHA can be readily used to tackle this kind of non-linear problem as described, e.g. by Romanelli *et al*., (1998).

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