Taylor & Francis
Taylor & Francis Group

Geomechanics and Geoengineering
An International Journal

ISSN: 1748-6025 (Print) 1748-6033 (Online) Journal homepage: https://www.tandfonline.com/loi/tgeo20

Development of correlation between SPT-N value and shear wave velocity and estimation of non-linear seismic site effects for soft deposits in Kolkata city

Srijit Bandyopadhyay, Aniruddha Sengupta & G.R. Reddy

To cite this article: Srijit Bandyopadhyay, Aniruddha Sengupta & G.R. Reddy (2019): Development of correlation between SPT-N value and shear wave velocity and estimation of non-linear seismic site effects for soft deposits in Kolkata city, Geomechanics and Geoengineering

To link to this article: https://doi.org/10.1080/17486025.2019.1640898

Published online: 22 Jul 2019.

GEOMECHANICS AND GEOENGINEERING
https://doi.org/10.1080/17486025.2019.1640898

Development of correlation between SPT-N value and shear wave velocity and estimation of non-linear seismic site effects for soft deposits in Kolkata city

Srijit Bandyopadhyay[a,b], Aniruddha Sengupta[c] and G.R. Reddy[a]

[a]Seismic Structure and Engineering Section, Bhabha Atomic Research Centre, Mumbai, India; [b]Homi Bhabha National Institute, Mumbai, India; [c]Civil Engineering Department, Indian Institute of Technology, Kharagpur, India

ABSTRACT

In the present paper, the site-specific response spectra at bedrock level are generated by deterministic seismic hazard analysis and soil amplification study for Kolkata (India) is performed. The site-specific bedrock spectra are obtained by enveloping 10 response spectra corresponding to 10 attenuation relationships with pga 0.104 g. Eighteen seismic downhole test data upto 50 m depth are collected from various sites in Kolkata, along with the SPT-N value profile. An empirical relationship between shear wave velocity and SPT-N value is proposed considering nonlinear power law for soft soil. The results of this study can be used for site response study of Kolkata. The average (V_s^{30}) of Kolkata soil varies from 146 to 295 m/sec. As per NEHRP classification, the sites are classified as Class D and E. Nonlinear soil amplification study is conducted in all borehole locations and uncertainty of soil parameters, like shear wave velocity with plasticity of soil, are considered. A total of 1170 soil profiles are analyzed, and site-specific response spectrum is proposed. A maximum surface PGA of 0.18 g is obtained corresponding to 3.8 times amplification in peak spectrum. The proposed acceleration time history and the response spectra may be used for design and safety evaluation of infrastructures in Kolkata.

ARTICLE HISTORY
Received 26 March 2019
Accepted 20 June 2019

KEYWORDS
Soil amplification; design response spectra; Shearwave velocity; Kolkata city

1. Introduction

It is a well-established fact that the response of ground due to an earthquake depends on myriads of factors such as magnitude and characteristics of earthquake, and local geology of the site. Ground motion contributes a major role in causing damages to the structures (Narayan 2005, 2010, 2012, Oprsal *et al.* 2005). The loss of life and damages to the properties may be reduced by designing structures with realistic ground motions. Generally, seismic waves propagate in the upward direction through different layers of earth. In the process, the energy content decreases due to radiation and material damping. But amplification increases with reduced wave motion due to stiffness and material damping of the soil. Large damages were observed during the Mexico City Earthquake of 19 September 1985, due to local site effects (Flores-Estrella *et al.* 2007). It is reported that a part of Mexico city is located over an ancient lake bed with varying shear wave velocity of 40 m/sec to 90 m/sec. Below this sediment, a layer with a shear wave velocity 500 m/sec is encountered. The amplification of ground motion to an order of 3 to 20 was occurred due to the high impedance contrast between the top layer and bottom layer (Dobry *et al.* 2000). The ground failures during the 1989 Loma Prieta Earthquakes are studied by Kayen and Mitchell (1997). The peak ground acceleration (PGA) at sites underlain by rock and stiff alluvium varies between 0.08 g and 0.12 g. Whereas, two times amplification of motion was observed compared to the rock site at the deep soft soil deposits and at the artificially consolidated soil. Damage pattern from various past earthquakes like 1985 Mexico earthquake, 1989 San Fransisco earthquake, 2001 Bhuj Earthquake it was observed that local soft soil plays an essential role in ground amplification (Zeng 1996, Tsuda *et al.* 2006, Govindaraju and Bhattacharya 2012).

Soil amplification study has been conducted in many Indian cities by a number of researchers (Anbazhagan and Sitharam 2008, Shiuly and Narayan 2012, Roy and Sahu 2012, Rao and Rathod 2014, Kumar *et al.* 2014, Basu *et al.* 2017, Dammala *et al.* 2017, Bashir and Basu 2018). As per seismic zoning map of India, Kolkata city is located in the border of seismic Zone III, and Zone IV, and an earthquake magnitude 6 (M_w) and more may be expected. The proposed PGA value of an expected maximum considered earthquake (MCE) in Kolkata between 0.16 and 0.24 g, which are corresponding MCE value of zone III and zone IV. A number of researchers (Mohanty and Walling 2008, Govindaraju and Bhattacharya 2012, Shiuly and Narayan 2012, Nath *et al.* 2014) have performed seismic hazard and soil amplification study for

CONTACT Srijit Bandyopadhyay srijit15@gmail.com

Kolkata city. In previous study, soil amplification have been performed by equivalent linear methods. In equivalent linear approach, the material properties such as shear modulus (G) and damping (ζ) is constant in each layer for entire duration of earthquakes, irrespective to strains are large or small for a given time. An iterative procedure is adopted to determine the value of G and ζ for each layer. Details of this procedure are explained in Hartzell *et al.* (2004). Two main weaknesses are associated with the equivalent linear approach. First, equivalent linear approach overattenuate the high frequencies at high levels of strain. Second, equivalent linear approach can overestimate the resonant-frequency amplitudes and shear stresses compared with nonlinear analysis.

Ground response analysis is a special field of geotechnical engineering. A number of local soil parameters, like shear modulus degradation curve with soil shear strain, shear wave velocity are required for soil amplification study. Low strain shear modulus (G_{max}) of soil, is determined from the shear wave velocity of soil. During the last few decades, various in situ and laboratory methods to estimate shear wave velocity (V_s) of soil have been developed by researchers. V_s can be obtained from various laboratory test ultrasonic pulse test, resonant column test, and piezometric bender element test. But results from laboratory tests are influenced by small sample size and disturbances during sampling. One of the drawbacks is, if soil samples are disturbed during collection then laboratory test results are inaccurate. To overcome these, various in situ tests like seismic refraction test and reflection test, multi-channel analysis of surface wave test ($MASW$), spectral analysis of surface wave test ($SASW$), Seismic downhole and cross-hole test are performed to obtained shear wave velocity profile of soils. During seismic downhole test, seismic wave sources are placed at the ground surface, and receivers are placed inside the borehole at the different depth. Source to receiver distance and travel time of compression wave (P-wave) and shear waves (S-waves) are measured to obtained shear wave velocity (V_s) and compression wave (V_p) of the site. Shear wave velocity determination is an expensive procedure. More overall this procedure requires expert knowledge, good equipment and it is not possible to conduct many tests at all the times. Thus, empirical correlations have been developed between static field test, such as SPT-N value, and dynamic shear wave velocity by many researchers (Akin et al 2011, Athanasopoulos 1970, Ohta and Goto 1978, Imai 1981, Seed and Idriss 1981, Pitilakis *et al.* 1992, Lee 1992, Rollins *et al.* 1998, Kiku 2001, Jafari *et al.* 2002, Ulugergerli and Uyanik 2006, Dikmen 2009, Karim *et al.* 2010). In any geotechnical site information, SPT-N value information is readily available, so, the V_s soil profiles can be easily predicted from the SPT-N values. In seismic micro-zonation study for the Indian city of Chennai, shear wave velocity was determined by Boominathan *et al.* (2007) from corrected SPT-N values of soil using correlations given by Japanese Road Association (Lee 1992). Hanumantharao and Ramana (2008) and Mhaske and Choudhury (2011) was developed a correlation between V_s and SPT-N value for two Indian cities, Delhi and Mumbai, respectively. Chatterjee and Choudhury (2013) also proposed a relationship between SPT-N value and V_s for Kolkata soil.

In this study, first, a relationship between V_s and SPT-N value for Kolkata soft soil is established. Then, deterministic seismic hazard analysis (DSHA) of Kolkata is performed. The outcome of this present study consists of deterministic response spectra of horizontal ground motion, Spectrum compatible time histories are developed, and site response studies are conducted considering soil nonlinearity.

2. General setting of the study area and regional geology

Megacity Kolkata is bounded by latitude 22°27′ N to 22°40′ N, and longitude 88°18′ E to 88°28′ E. The area of the city covers up to 205 sq km. As per latest census (2011), Kolkata is the third most populous city in India with a population of 14.1 million. Kolkata is the capital of West Bengal, India and hub to many commercial and financial companies. In recent times, many high rise buildings, elevated bridges are being constructed within the city and thus the suitable hazard study of the city is very much required. Figure 1 shows the city of Kolkata.

Number of researchers (Shiuly and Narayan 2012, Govindaraju and Bhattacharya 2012, Nath *et al.* 2014) have described local seismo-tectonic features of Bengal basin. Details of tectonic features of the study area are shown in Figure 2. West Bengal subsurface and most of the part of Bangladesh are in the Bengal basin. The southern part of the basin is open to the Bay of Bengal, where it passes to Bengal deep-sea fan which is almost 3000 km long and 1000 km wide with a sediment thickness of 12 km. Indian shields area are exposed one side of Bengal basin with disappearance below a blanket of alluvium within the basin. Salt *et al.* (1986) subdivided the Bengal basin into three parts such as eastern deeper basin, middle shelf zone and western scrap zone. The west and north-west part of the Bengal Basin is bounded by basin margin fault zone and east and south west part of the

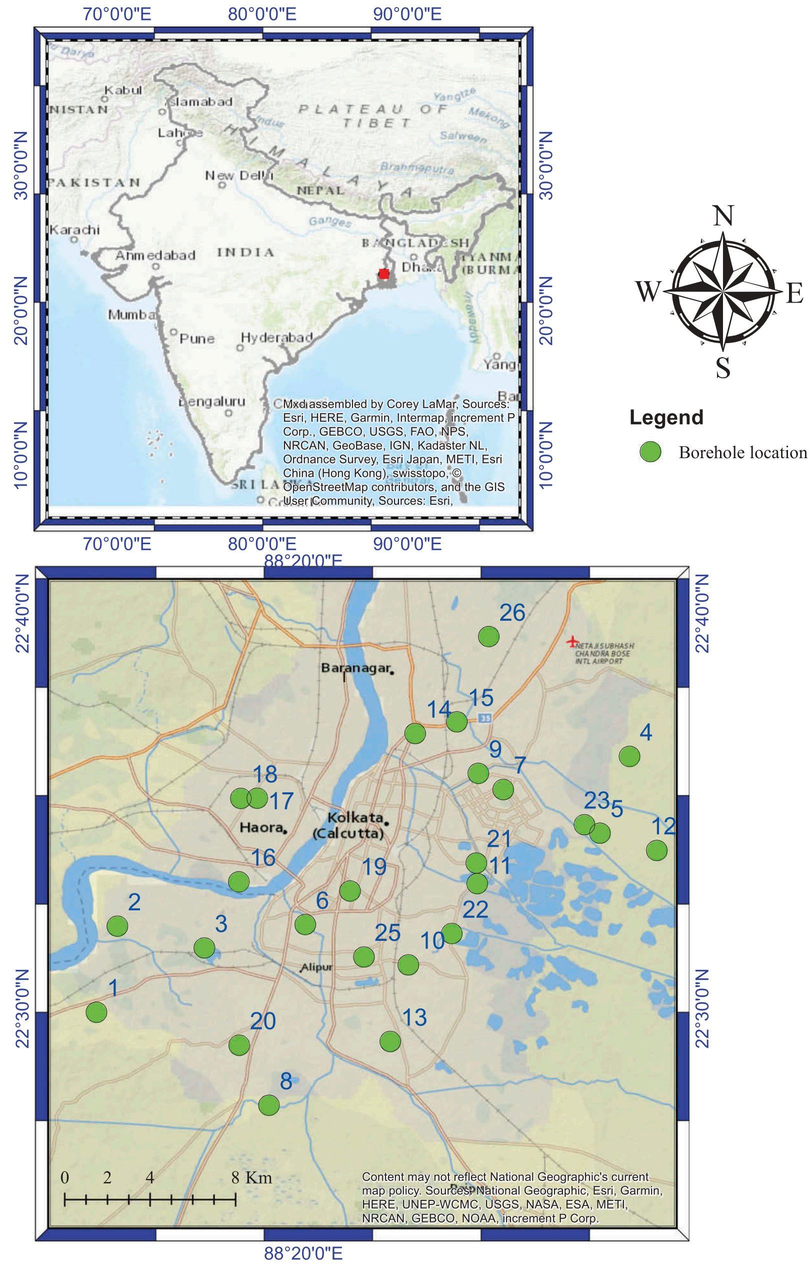


Figure 1. Location of Kolkata city in India and BH locations in Kolkata city used in this study.

basin area is bounded by The Eocene Hinge Zone (EHZ) and constituted a broad shelf zone. EHZ demarcates the deeper basin from Indian plateau. EHZ has differential thickening and zone has given rise to a belt of possible flexures and faulting during Oligocene and Miocene section Salt *et al.* (1986). Kolkata is located over western part of the hinge zone across which sediment thickness and facies significantly vary from self-area in the west to the deep basinal part in the east. Calcutta Mymansingh Eocene Hinge Zone associated with gravity high and magnetic low and possibly represents zone of numerous en-echelon faults over the Eocene Sylhet limestone. The major fault systems in study region are Garhomoyana-Khandaghosh Fault (GKF), Rajmahal Fault (RF),Dhubri Fault (DHF), Jangipur-Gaibandha Fault (GGF), Pingla Fault, Sylhet Fault (SF) Debagram Bogra Fault (DBF), Dauki Fault (DF), Sainthia Bahmani Fault (SBF). The total sedimentary thickness below Kolkata is of the order of 7500 m above crystalline basement; off which top 350–450 m is Quaternary, followed by 4500–5500 m of Tertiary sediment and 600–800 m of Perm-Carboniferous Gondwana rock (Dasgupta and Acharyya 2006).

Available earthquake record shows that in last three centuries, Kolkata and its nearby regions have experienced about 30 seismic events due to ‘near-source’ and

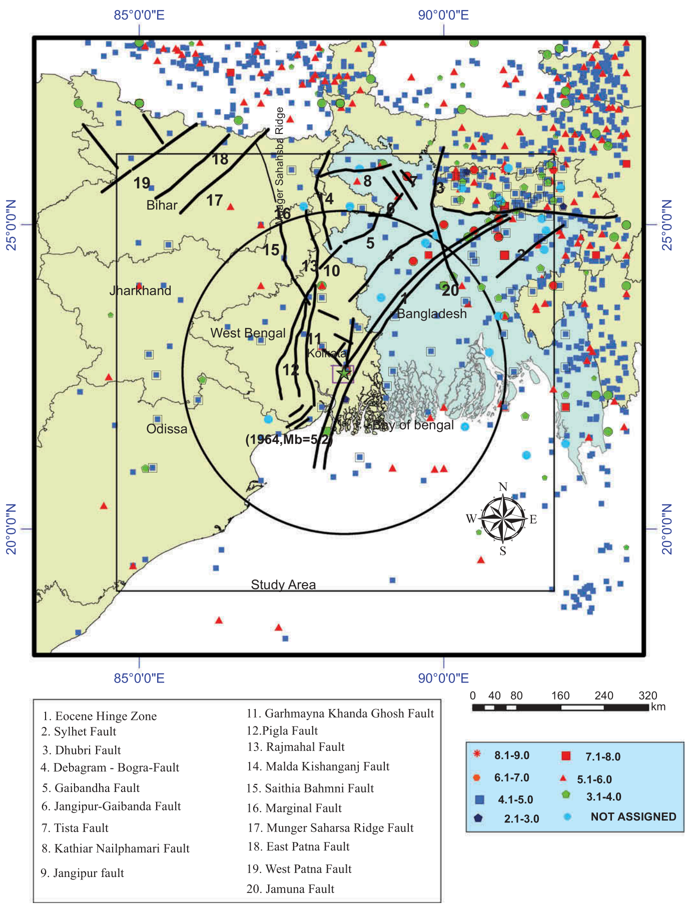


Figure 2. Seismotectonic map for Kolkata city and surrounding region.

'far-source' earthquake. During the 29 September 1906 (M = 5.0, epicentre located just north of Kolkata city) Calcutta Earthquake, many buildings within the city suffered major cracks. The earthquake was of the order of VI-VII on the Rossi-Forel scale. The 15 April 1964 (M = 5.0, the epicentre is on the south of Kolkata) Kolkata Earthquake with VI intensity on the Mercalli (MMI) scale caused damages within the city. Both the earthquake's epicentres were located on EHZ. The Bihar–Nepal Earthquake of 15 January 1934 (M = 8.3, the epicentre was located 480 km from city) with intensity of VI on MMI scale, Srimangal earthquake of 8 July 1918 (M = 7.6, epicentral distance of 350 km), Dubhri Earthquake of 3 July 1930, and the earthquakes of 1st September 1803, 26th August 1833, and 31st December 1881 also caused significant damages to Kolkata.

3. Local geology of Kolkata city

Kolkata city is located 150 km from the Bay of Bengal, right over the Ganges delta. The regional slope of this city is North to South. The flat topography of Kolkata is an average 6.4 m above MSL. To get a better understanding about the local geology, total of 81 boreholes data around the Kolkata are collected from a consulting agency C.E.Testing and analysed. The data consist of SPT-N value, density, plasticity limits, the friction angle of the soil strata at a different depth, etc. The subsurface geology of Kolkata is reconstructed from these borehole data. Data are collected by keeping in view that data should be widely distributed in the study area. To determine SPT-N values of soils, standard penetration test was conducted in 150 mm diameter boreholes at every 1.5 to 2 m interval. Typical soil profile of Kolkata are presented in Figure 3 and Figure 4. As may be observed from the figures, on an average, top 12–13 m depth of soil strata are very soft silty clay. This layer is very much unconsolidated for which very low N-value of less than 10 is observed. Below the top layer, average 20-m thick dense to very dense grey sticky clay layer with N-value varies between 15 and 30 is observed. This sudden increase in N value may indicate the boundary between the

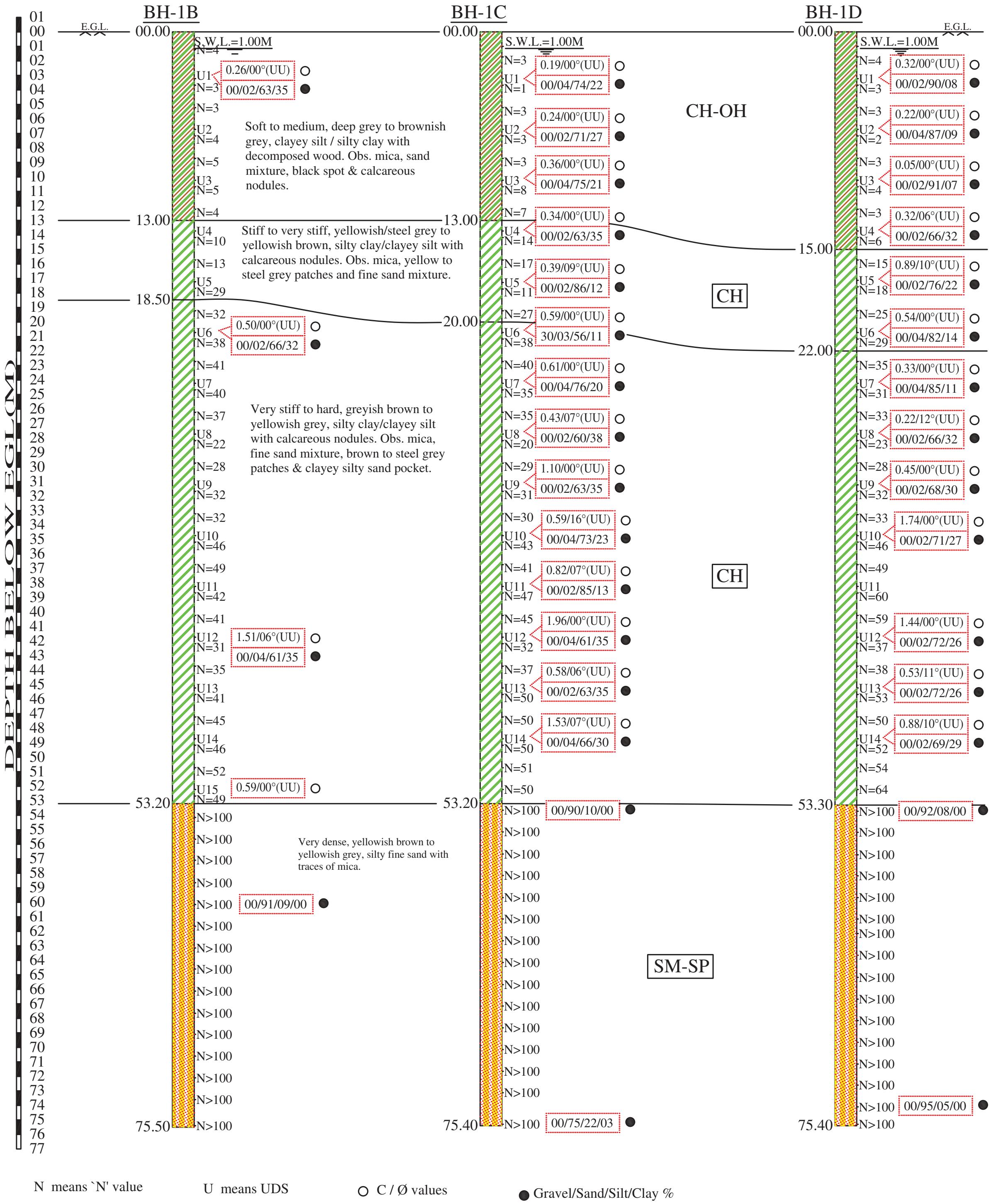


Figure 3. Variation of soil profile along with depth (Site-1).

Holocene sediments and Pleistocene sediments Nandy (2007). A coarse sediment consisting of silt or fine to medium sand and coarse sand with or without pebbles with N-value more than 100 is encountered below 33 m. Below 50 m depth, very dense, yellowish brown to yellowish grey, silty fine sand is observed. The groundwater table is noticed at a shallow depth of 1 m. Variation of the plasticity index of soil along with soil depth and atterburg limits chart are shown in Figures 5 and 6 respectively. Similar soil profile for Kolkata is also observed by other researchers (Shiuly and Narayan 2012, Chatterjee and Choudhury 2013). Dasgupta and Acharyya (2006) have reported a -613 m deep borehole in Kolkata (at Beleghata ID hospital). Their data indicate that top 42 m of Kolkata is a sticky clay with kankar at the bottom, followed by

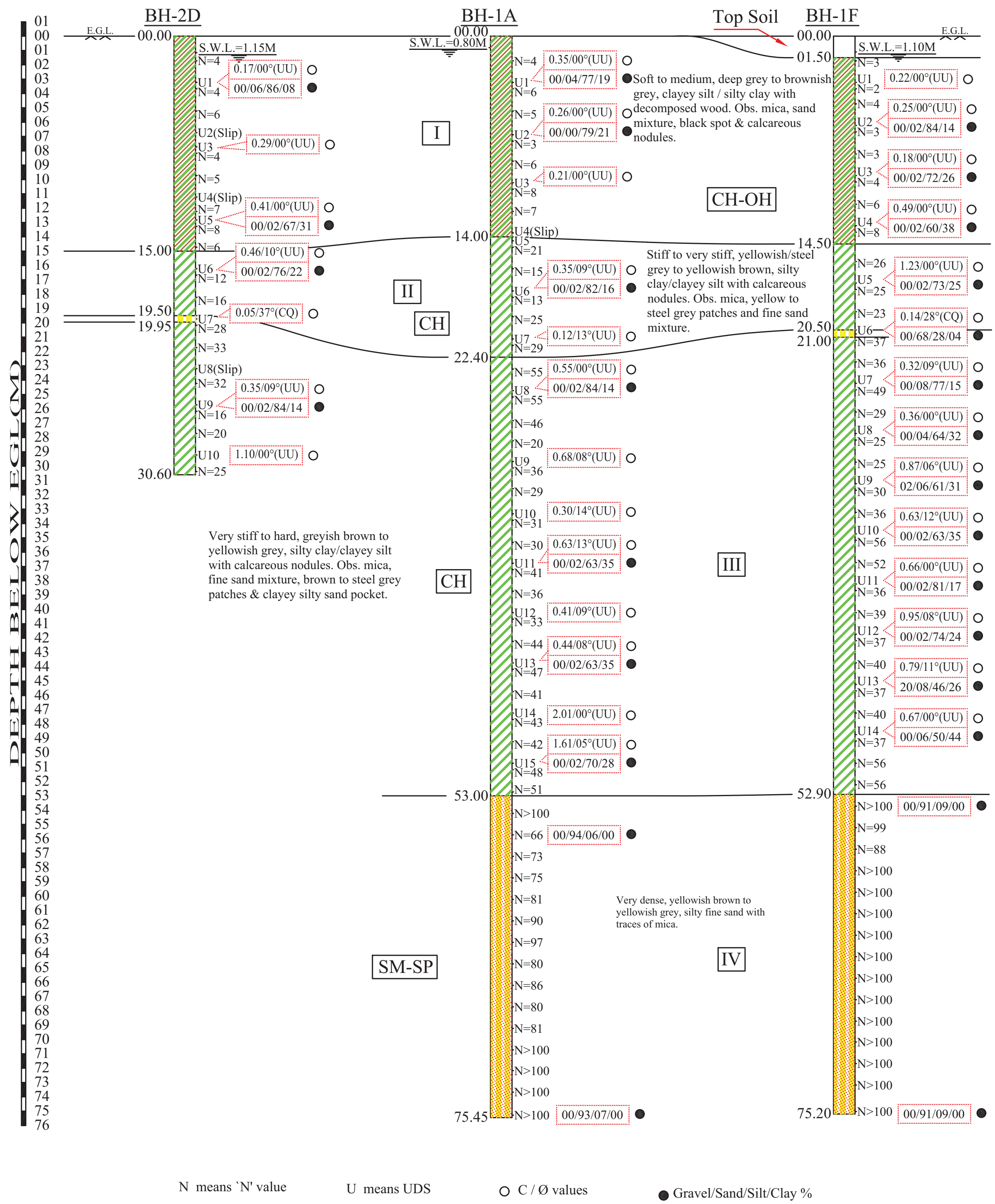


Figure 4. Variation of soil profile along with depth (Site-3).

261 m thick coarse sand with very thin silt/clay partings at regular intervals. They have reported another clay layer after this. Similar soil profiles are also reported in other two deep borehole locations one in the western part of the city and another one at the periphery of Kolkata (Garia).

To study the dynamic characteristic of a site, the shear wave velocity profile of the site is required. In reality, the shear wave velocity profile of the study area is limited. Among 81 borehole data, only 18 bore log data have extra shear wave velocity profile information up to 50 m depth. Apart from this, another 8 shear wave velocity profile data

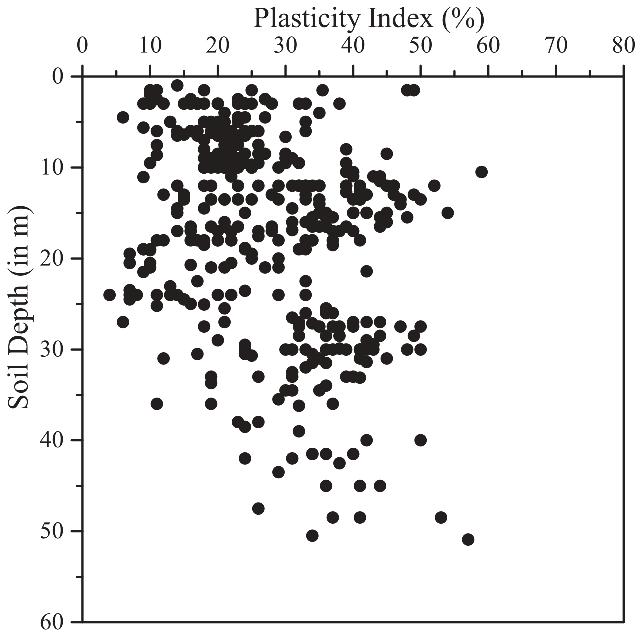


Figure 5. Variation Plasticity index of soil profile along with depth.

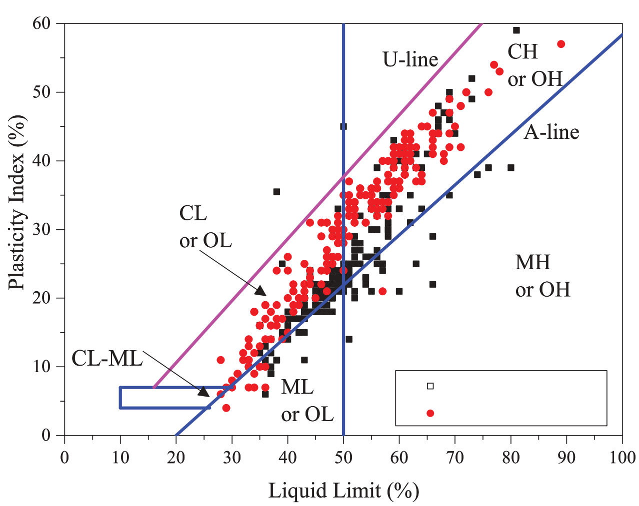


Figure 6. Atterberg limits chart showing representative values of soils which exhibit clay-like, sand-like, or intermediate behaviour.

are collected from Chatterjee and Choudhury (2013). All the downhole test data are shown in Figure 1 and also reported in Table 1. Figure 7 shows the shear wave velocity profile within Kolkata. In the top 13 m, the shear wave velocity is varying from 70 to 150 m/s. After that, a uniform increase in the shear wave velocity profile is observed. At a few sites (such as, at site number 5,6,12,15), a sudden decrease in the shear wave velocity is observed after 30 m of depth. At the other sites, a change in the slope of shear wave velocity profile is observed. The shear wave velocity between 600 and 850 m/sec is observed after 50 m. At a Bishnupur location near Kolkata, a shear wave velocity of 1048.27 m/sec is observed at 700 m depth. A shear wave velocity of the order of 1890.17 m/s is also obtained from the same seismic refraction survey line (Reddy *et al.* 1998) for the bedrock.

4. Deterministic seismic hazard analysis of Kolkata city

The seismic hazard analysis at a location may be done in two ways – by the deterministic method (DSHA) and by the probabilistic method of analysis (PSHA). In a PSHA, the hazard at a site due to an earthquake is obtained in a probabilistic sense considering the possibility of earthquakes of varying magnitude and distance from the study area. In a DSHA, the ground motion of a site is determined for an earthquake of fixed magnitude at a known fault with the shortest distance between sources to site distances (Barani and Spallarossa 2017). In this study region, seismic sources are uncertain and due to lack of instrumental data, recurrence interval of the regional large earthquake is not well defined. In this regard, deterministic seismic hazard analysis is performed to find out the maximum considered earthquake (MCE) at bedrock level which is then utilised in soil amplification study. For this study, all faults of the study area are considered to obtain a major fault system. For generation of seismo-tectonic map, around the 300 km radial distance from kolkata city, earthquake data have been collected from three major earthquake data sources, such as the US Geological Survey/National Earthquake Information Center (USGS/NEIC, http://neic.usgs.gov.us), the International Seismological Centre (ISC, http://www.isc.ac.uk), and the Indian Meteorological department (IMD). Collected earthquake data for the period of 1765–2016 and tectonic sources which are identified and used in this analysis are shown in Figure 2. Seismo-tectonic information is also collected from Shiuly and Narayan (2012). The maximum considered earthquake for each seismogenic source is identified from the maximum magnitude earthquake occurred close to or on that seismogenic source plus one intensity extra. Due to the scarcity of strong ground motion record, it is impossible to generate a ground motion prediction equation (GMPE), and attenuation model for the region. For seismic hazard study in Bangladesh, Al-Hussaini *et al.* (2015) used attenuation models, which are developed for the western USA. The Western USA has an active tectonic region, which is similar to the Bengal basin region and both tectonic regions have fractured rock and soil. Trianni *et al.* (2014) also used attenuation model which was developed based on the western USA, and applicability of this model for Bengal basin region is also reported. According to the tectonic

Table 1. Bore hole loaction used in this study.

Site No	Site location	Lattitude	Longitude	Vs,30	N,30	Site Class	Data Collected Source
1	At Maheshtala High School	22°2′54.33″	88°14′45.17″	225	7.4	Class D	CETST Lab
2	At Metiabruz Recreation Club	22°32′05.04″	88°15′17.14″	186	7	Class D	CETST Lab
3	Nature Park (Garden Rich Area)	22°31′32.066″	88°17′29.018″	174	4.64	Class E	CETST Lab
4	Eco Park (Rajarhat)	22°36′22.829″	88°28′14.91″	169	4	Class E	CETST Lab
5	Newtown (Rajarhat)	22°34′26.542″	88°27′30.156″	147	3.01	Class E	CETST Lab
6	Calcutta University Campus (Alipore)	22°32′07.500″	88°20′02.700″	286	17	Class D	CETST Lab
7	Opposite of 6no. Tank, Saltlake	22°35′32.600″	88°25′03.200″	178	3.9	Class E	CETST Lab
8	Shitala Mandir, Thakurpukur	22°27′33.100″	88°19′07.600″	178	4.72	Class E	CETST Lab
9	Lake Town Foot Bridge, VIP Road	22°35′57.100″	88°24′25.500″	181	4.5	Class D	CETST Lab
10	Kashba Post Office, Ballygunj	22°31′06.400″	88°22′39.100″	220	9.6	Class D	CETST Lab
11	Nicco Park, Chingrighata	22°3′09.600″	88°24′23.800″	170	5.7	Class E	CETST Lab
12	SRCM Road, Rajarhat	22°34′00.200″	88°28′56.400″	296	15	Class D	CETST Lab
13	Layellka Math, Baghajatin	22°29′09.800″	88°22′11.700″	180	5.8	Class D	CETST Lab
14	Kheyali Math, Paikpara	22°36′57.600″	88°22′49.400″	147	3.49	Class E	CETST Lab
15	Tarun Samity, Dum Dum	22°37′15.500″	88°23′52.900″	180	4.6	Class D	CETST Lab
16	Bengal Engineer & Science University, Howrah	22°33′12.500″	88°18′21.700″	177	4	Class E	CETST Lab
17	Rupak Sangha, Dumurjala, Howrah	22°35′19.400″	88°18′49.800″	162	4.2	Class E	CETST Lab
18	Shibaji Sangha, Dumujala, Howrah	22°35′19.068″	88°18′24.637″	170	5	Class E	CETST Lab
19	Park street	22.5496°	88.3529°	240	DNA	Class D	Chatterjee and Choudhury (2013)
20	Ho Chi Min Sarani	22.4845°	88.3062°	175	DNA	Class E	Chatterjee and Choudhury (2013)
21	Beliaghata Road	22.5614°	88.4062°	214	DNA	Class D	Chatterjee and Choudhury (2013)
22	E.M.Bypass	22.5316°	88.3959°	171	DNA	Class E	Chatterjee and Choudhury (2013)
23	Rajar Hat	22.5776°	88.4518°	162	DNA	Class E	Chatterjee and Choudhury (2013)
24	Batanagar Township	22.5121°	88.2172°	190	DNA	Class D	Chatterjee and Choudhury (2013)
25	Panditya Road	22.5218°	88.3588°	187	DNA	Class D	Chatterjee and Choudhury (2013)
26	Belgharia	22.6569°	88.4115°	171	DNA	Class E	Chatterjee and Choudhury (2013)

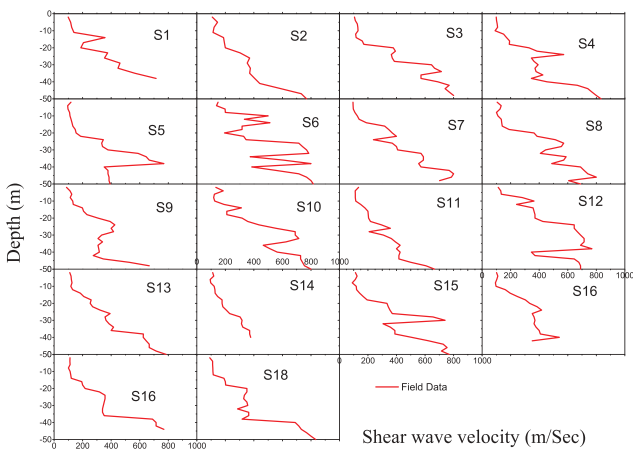


Figure 7. Shear wave velocity profile for various locations of Kolkata city.

condition, variability of ground motion is captured by considering three base case scenarios. One corresponds to shallow crustal earthquakes in the active crustal region, and the other two scenarios are earthquake from stable continental regions and subduction zones. Therefore, depending upon the compatibility of tectonic environments GMPEs are selected from the literature. In this present study, 10 different GMPEs are considered and reported in Table 2. PGA and response spectral shapes are obtained from 10 GMPEs and envelop of all spectra is used for analysis. Among these 10 GMPES, Boore *et al.* (2014), Idriss (2013), Choiu (2013), Campbell and Bozorgnia (2013), Abrahamson *et al.* (2013) are developed for active crustal zone, for shear wave velocity around 750 m/sec to 1000 m/sec. The other two GMPEs Youngs *et al.* (1997) and Zhao *et al.* (2006) are developed for subduction zone, and rest of the GMPEs (Toro 2002; Atkinson and Boore 2006; Campbell and Bozorgnia 2003) are developed for stable continental regions.

Table 2. Ground motion prediction equation adopted from the study.

GMPE	
Abrahamson *et al.* (2013)	ASK14
Boore *et al.* (2014)	BSSA14
Campbell and Bozorgnia (2013)	CB14
Choiu (2013)	CY14
Idriss (2013)	I14
Youngs *et al.* (1997)	Young
Zhao *et al.* (2006)	Zho
Toro (2002)	Toro02
Campbell and Bozorgnia (2003)	CB03
Atkinson and Boore (2006)	AB06

4.1. Peak ground acceleration

For seismic analysis of structures, the peak ground acceleration (PGA) is one of the important parameters. The global seismic assessment programme (Zhang *et al.* 1999) estimates PGA of Kolkata between 0.08 g and 0.13 g with 10% probability of exceedance in 50 years. The variation of PGA obtained in this present study for different GMPEs are given in Table 3. From Table 3, it is noticed that the Eocene Hinge Zone (EHZ) shows the highest hazard. Among the 10 GMPEs, Youngs *et al.* (1997) show the highest value for PGA. The values of PGA and their corresponding

Table 3. PGA variation PGA with GMPEs.

Fault Name	Magnitude	Distance (km)	Ground motion prediction equation (GMPE) (g)									
			ASK14	**BSSA14**	**CB14**	**CY14**	**I14**	**Young**	**Zho**	**Toro02**	**CB03**	**AB06**
1 Eocene Hinge Zone	5.9	36	0.03234	0.05134	0.0.050	0.034	0.03488	0.1043	0.018273	0.0135	0.0419	0.0457
2 Debagram Bogra Fault	6.7	137	0.0115	0.0236	0.014	0.01305	0.009	0.03402	0.003286	0.0149	0.0141	0.0291
3 Garhomoyana-Khandaghosh Fault	5.7	55	0.014	0.027	0.024	0.016	0.01586	0.053	0.00703	0.006	0.0207	0.0169
4 Dauki Fault	8.7	387	N-A	N-A	N-A	N-A	N-A	0.046	0.00281	0.0303	0.0181	0.0285
5 Sylet Fault	7.6	290	0.006	0.005	0.00649	0.008	N-A	0.025	0.00131	0.0229	0.0109	0.0209
6 Sainthia Bahmani Fault	6.2	182	0.0033	0.005	0.00507	0.004	N-A	0.012	0.0097	0.0055	0.0065	0.0115
7 Dhubri Fault	6.9	256	0.0038	0.004	0.0046	0.005	N-A	0.014	0.00301	0.012	0.0073	0.0137

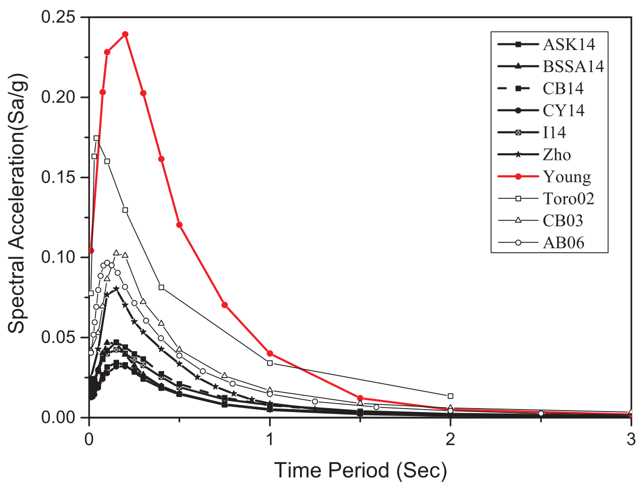


Figure 8. Bedrock spectra obtained from various GMPEs.

response spectra are presented in Figure 8. The response spectra obtained from GMPE, Youngs *et al.* (1997), envelopes all the other response spectra and it is selected for the generation of spectrum compatible time histories for the study area. The PGA to peak spectral value ratio is found to be 2.18 for this response spectrum. However, Indian standard code (BIS 2002) proposes this ratio be 2.5.

4.2. Spectral compatible time history for study area

There is no previous record of strong ground motion available for the Kolkata region. Due to lack of earthquake data for the site, synthetic time histories may be developed, or bedrock motions may be obtained from site-specific response spectra. Here, site-specific response spectra have been developed for Kolkata. ASCE (2000) has given the procedure to generate the spectrum compatible time history.

For the generation of time histories, trapezoidal time history envelop function is considered with the rise time of 1 sec, duration of motion of 7 sec, and decay time of 5 sec. These correspond to an earthquake of magnitude 6–6.5 (ASCE 2000). Figure 9 shows the spectrum compatible time histories and their corresponding response spectrum.

To consider a wide range of frequencies in spectrum, real earthquakes are also considered in the analysis. Based on this study, two North American records, San Fernando (09/02/1971) and Northridge (17/01/1994), are selected. Their time histories are shown in Figure 10. All these earthquake motions are arithmetically scaled down to PGA of 0.104 g. The elastic response spectra at 5% damping of these earthquake records are shown in Figure 10(b,d). Chowdhury *et al.* (2015) also considered these two earthquakes in his study.

5. N value vs shear modulus relationships

The low strain shear modulus of soil is essential parameters which are used in a site response study. The low strain shear modulus G_{max} of soil are obtained from shear wave velocity as per Equation 1

$$G_{max} = \rho V_s^2 \tag{1}$$

where ρ is density of the soil.

It is always recommended to obtain the shear wave velocity profile at a site from various in situ tests. Due to cost involvement, it is not feasible to conduct shear wave velocity test in a project. The SPT N-values for the subsoils are more readily available as they are widely used to characterise the subsoil profile at a site (NEHRP 2003). An empirical relationship between V_s and SPT N-value can be made to generate the V_s profile at a site. In the present study, only 18 boreholes have complete data of shear wave velocity profile with SPT-N value. In 18 boreholes, total of 414 numbers dataset of SPT-N value vs V_s data is available and used for regression analysis. Number of correlations between the V_s and the SPT N-value are collected from the literature and shown in Table 4. Chatterjee and Choudhury (2013) have proposed a correlation between V_s and SPT N-value for Kolkata city. Figure 11 shows the comparison among the

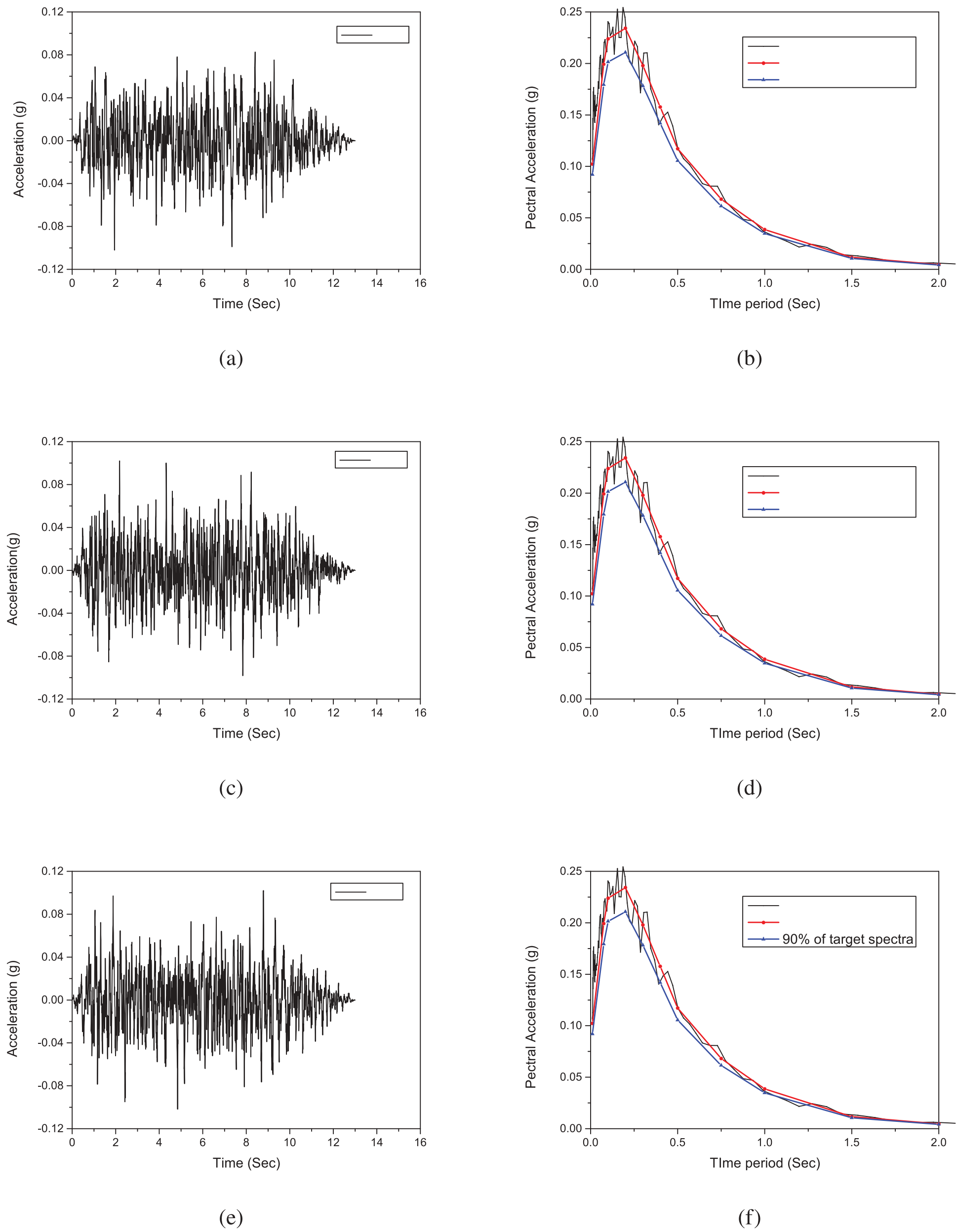


Figure 9. a,c,e, shows three spectrum compatible time histories, and b,d,f shows corresponding response spectra of TH-1, Th-2 and TH-3 with target spectrum.

correlations between the measured SPT N-value and V_s. It may be observed that all the existing correlations predict a lesser value for V_s at SPT N-value of 40 and above. As shown in Figure 7, the on an average, top 12-13 m depth of Kolkata soil, which has soil type soft clayey silt/silty clay with N-value in the range of 4 to 10 and SPT N-value and V_s in the range of 150 m/sec. But after that, the SPT N-value and V_s increases with depth as the comparatively hard stratum are encountered. A new relationship is developed based on the measured SPT N-value and measured V_s for the Kolkata soil using nonlinear regression analysis employing power model. The basic power law model is given by Equation 2 (Haldar and Mahadevan 2000). In the relationship, the independent variable is SPT N-value and response variable is V_s.

$$V_s = aN^b \tag{2}$$

where a and b are power law parameters. The transformed equation in linear form is given by Equation 3.

$$ln(V_s) = ln(a) + bln(N) \tag{3}$$

where $ln(a)$ is denoted by a_0. The values of a_0 and b are obtained by least square method. Details are given in Haldar and Mahadevan (2000). The coefficient of

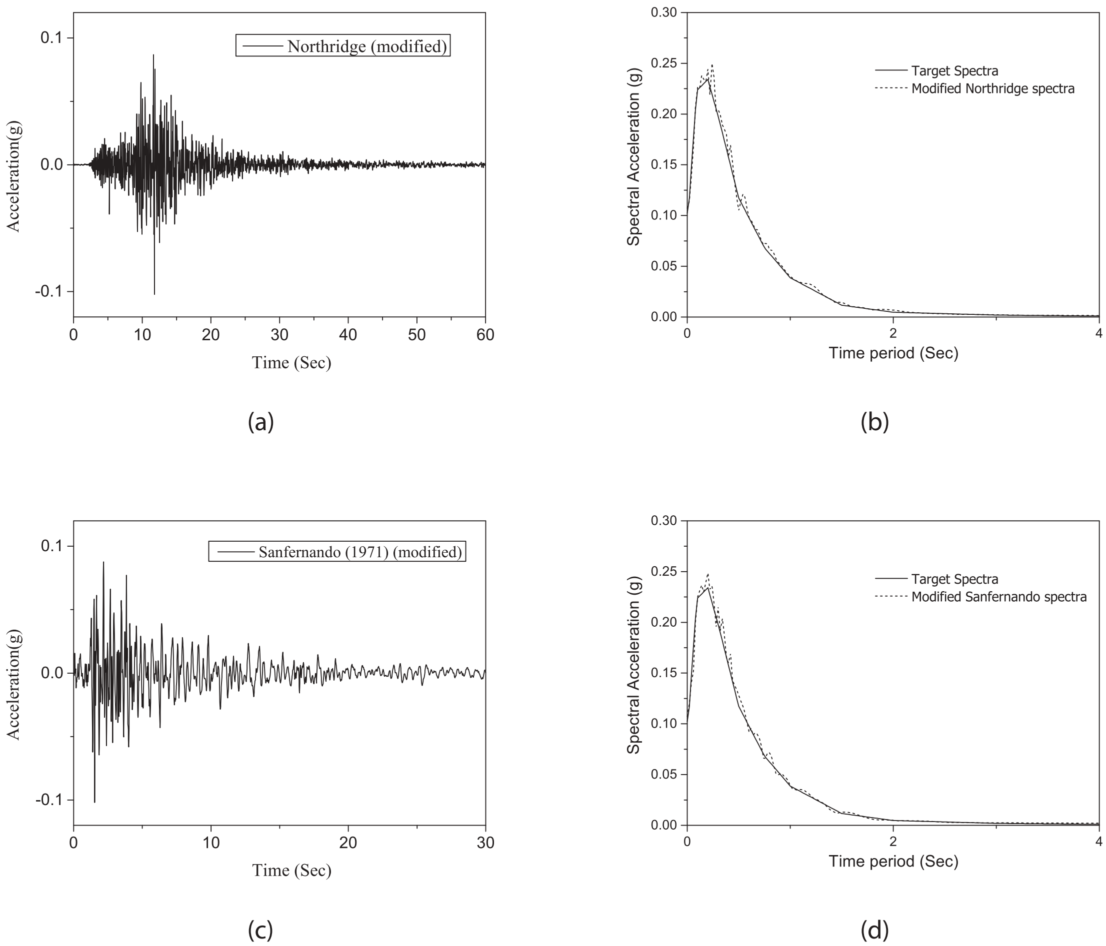


Figure 10. a,c, shows modified spectral compatible real earthquake, and b,d corresponding comparison of response spectra of Northridge earthquake, and Sanfernando Earthquake.

regression, denoted by R^2, is the proportion of the variance of the dependent variable. It varies between 0 and 1.

$$R^2 = \frac{\sum_{i=1}^{n} (V_s' - \bar{V}_s)^2}{\sum_{i=1}^{n} (V_s - \bar{V}_s)} \tag{4}$$

where the mean shear wave velocity is $\bar{V}_s$. For the Kolkata subsoil, one correlation has been proposed for clayey silt/silty clay, where SPT N-values are less than 10. Another correlation has been put forward for the soil type stiff to very stiff silty clay/clayey silt (CH) where SPT N-values are more than 10. Both the correlations are given by Equation 5.

$$\begin{aligned} V_s &= 87.18N^{0.32}, \text{ For, very soft to soft clayey silt/silty clay} \\ V_s &= 41.74N^{0.65}, \text{ For, stiff to very stiff silty clay/clayey silt (CH)} \end{aligned} \tag{5}$$

where N is uncorrected SPT N-value. The value of R^2 for the first and second correlations are 0.85 and 0.8316, respectively.

Rahman *et al.* (2018) reported that a correlation between uncorrected SPT N-value with V_s shows a much better match than with the corrected SPT N-value. Thus, in this present study, the uncorrected between SPT N-values are considered for the development of the above two correlations. The existing correlations developed by Chatterjee and Choudhury (2013) and other existing relationships used for Kolkata subsoils (Iyisan 1996, Shiuly and Narayan 2012) are compared with the proposed correlations in Figure 12. It may be observed from the figure that the proposed nonlinear empirical relationships predict the V_s profile for the Kolkata subsoil quite well. $V_{s,30}$ and N_{30} of 26 sites are calculated, and variation of $V_{s,30}$ and N_{30} are observed in 147 to 296 and 3.01 to 17, respectively. As per the guideline proposed by NEHRP (2003), Kolkata is in Class D (stiff soil) to Class E (soft soils). The value of V_s^{30} varies from 180 to

Table 4. Correlations between SPT N value and shear wave velocity (Vs) for all soils considered in the present study.

Sl. No.	Authors	Corelation
1	Imai and Yoshimura (1970)	$V_s = 76N^{0.33}$
2	Ohba and Toriumi (1970)	$V_s = 84N^{0.31}$
3	Ohsaki and Iwasaki (1973)	$V_s = 82N^{0.39}$
4	Fujiwara (1972)	$V_s = 92.1N^{0.337}$
5	Imai and Yoshimura (1972)	$V_s = 91N^{0.337}$
6	Imai and Yoshimura (1970)	$V_s = 90N^{0.34}$
7	Ohta and Goto (1978)	$V_s = 85.35N^{0.348}$
8	Seed and Idriss (1981)	$V_s = 61N^{0.5}$
9	Imai (1982)	$V_s = 97N^{0.31}$
10	Sykora and Stokoe (1983)	$V_s = 100.5N^{0.329}$
11	Athanasopoulos (1970)	$V_s = 107.6N^{0.36}$
12	Zheng (1987)	$V_s = 116.1(N + 0.3185)^{0.202}$
13	Lee (1990)	$V_s = 57.4N^{0.49}$
14	Iyisan (1996)	$V_s = 51.5N^{0.516}$
15	Kiku (2001)	$V_s = 68.3N^{0.292}$
16	Yokota *et al.* (1981)	$V_s = 121N^{0.27}$
17	Mhaske and Choudhury (2010)	$V_s = 72N^{0.40}$
18	Hanumantharao and Ramana (2008)	$V_s = 82.6N^{0.43}$
19	Kalteziotis *et al.* (1992)	$V_s = 76.2N^{0.24}$
20	Jafari *et al.* (2002)	$V_s = 22N^{0.85}$
21	Dikmen (2009)	$V_s = 58N^{0.39}$
22	Hasancebi and Ulusay (2007)	$V_s = 90N^{0.309}$
23	Maheswari *et al.* (2010)	$V_s = 95.64N^{0.301}$
24	Sitharam and Anbazhagan (2008)	$V_s = 78(N60CS)^{0.4}$
25	Chatterjee and Choudhury (2013)	\

360 m/sec and below 180 m/sec for Class D and Class E, respectively.

6. Soil amplification study of Kolkata region

In previous earthquakes, like the 1985 Mexico City Earthquake, and 2001 the Bhuj earthquake, it is observed that ground responses are depended on the soil condition. The ground response of the soil profile subjected to an earthquake depends upon the fundamental frequency of the soil column, which is related to the V_s of the soil and given by Equation 6.

$$f_{soil} = \frac{V_s}{4H} \tag{6}$$

where height of the soil column is H.

The frequency of the soil column depends upon the V_s of the soil layers. So, for a soil amplification study accurate representation of the variation of shear wave velocity with depth is very important. A soil amplification study depends on (1) Selection of motion for the region, (2) Idealisation of soil stratification and use of proper geotechnical parameter and (3) evaluation of the response at surface level. In the present site amplification study, data collected from 26 numbers of boreholes (18 shear wave profile collected form consulting agency, and other 8 boreholes shear wave profile obtained from the literature) and 5 sets of different spectrum compatible time histories are considered.

Generally, uncertainties and spatial variability of soil parameters, like V_s, layer thickness, soil plasticity, the variation of shear modulus and damping ratio with strain, etc., are incorporated through statistical analysis. Rao and Rathod (2014) reported that, among all these parameters, V_s and the thickness soil layer, are the most sensitive parameters. In this study, uncertainty in the determination of soil parameters is incorporated by considering the variation of G_{max} between best estimate value times $(1 + C_v)$ and best estimate value divided by $(1 + C_v)$. Here, C_v is a factor to account for the uncertainty in soil parameters. To consider a wide

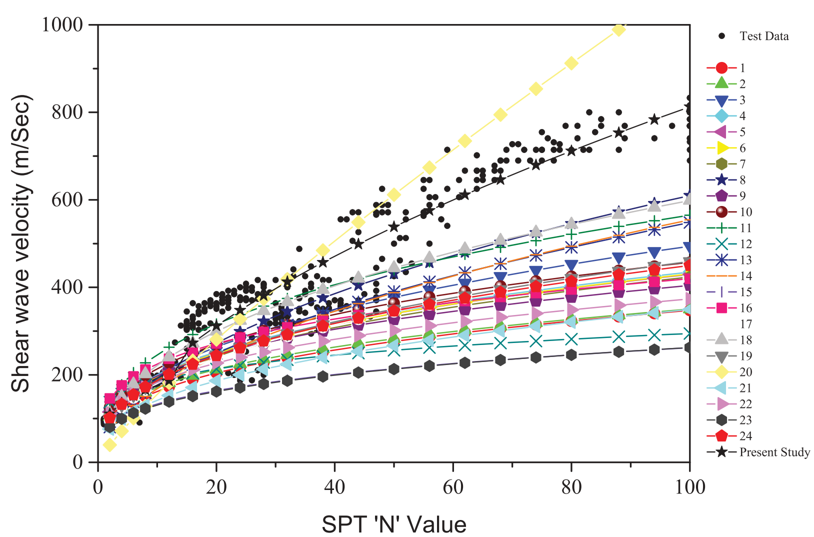


Figure 11. Comparison of N value and Shearwave velocity relation between test data and worldwide available empirical relationships.

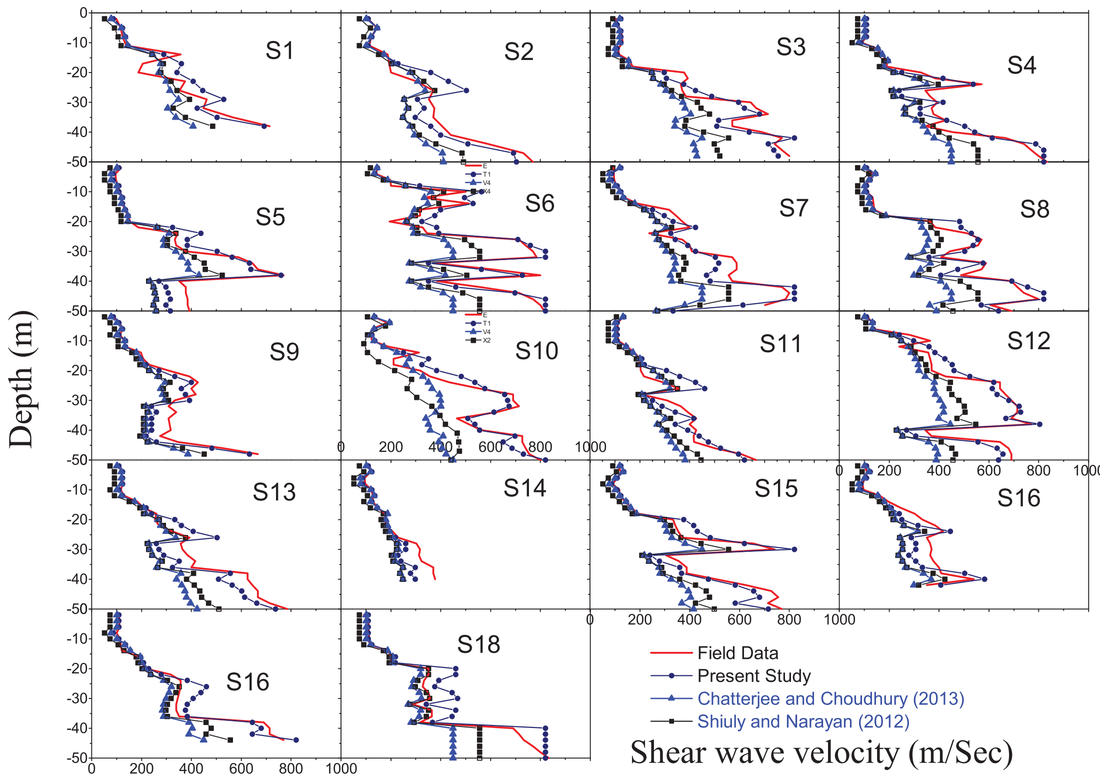


Figure 12. Comparison Shearwave velocity profile for various locations of Kolkata city.

range of uncertainty, C_v value of 0.5 is considered in this study. So, for particular boreholes, three different shear wave soil profiles are considered.

6.1. Modelling of the soil column

The 1-D site amplification study, considering effective stress-based nonlinear method, is performed using a 1-D wave propagation software, DEEPSOIL (Hashash *et al.* 2015). For the nonlinear time domain analysis, Newmark's integration technique is utilised. In the present study, the soil layers up to a depth of 50 m are considered. In time domain analysis, the following equations are solved.

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + k\{u\} = -[M]\{I\}\ddot{u}_g \qquad (7)$$

where [M] is mass matrix, [C] is damping matrix and [K] stiffness matrix. $\{\ddot{u}\}$,$\{\dot{u}\}$ and $\{u\}$ is a relative modal acceleration, relative velocity and relative displacement, respectively. To account the dynamic behaviour of soil under seismic excitation, dynamic properties of soil, such as shear modulus degradation curve with shear strain, which depends upon the plasticity of a soil for cohesive soil and density of a soil for cohesionless soil are used. Due to lack of dynamic soil test data for Kolkata soils, various dynamic soil test data are collected from published literature around the world and India, where dynamic tests were performed in various soft soils, which have similar soil properties like study area. Okur and Ansal (2007) conducted cycle tests of 98 soil samples of different soil types such as ML, MH, CL, CH, which was collected at various locations of Turkey with depth varies 2.5 m to 23.55 m, and plasticity index varies from 9 to 40. Kumar *et al.* (2018) estimated dynamic properties for cohesive soil in Guwahati region, which is located in north eastern part of India. Yang *et al.* (2006) determined dynamic properties of soft soils in Shanghai location. The variation of $G - \gamma$ curve is obtained from literatures. The variations of the shear modulus degradation curve of the soil with shear strain are shown in Figure 13. In the present study, soft clay model proposed by Sun *et al.* (1988) is used, whereas for stiffer clay, the model suggested by Vucetic and Dobry (1991) are used based on plasticity index properties. In case of sandy soil, the curves proposed by Darendeli (2001) are utilised. The nonlinear stress-strain model parameters are obtained by fitting the curves using the MRDF fitting procedure as proposed by Phillips and Hashash (2009); Kumar *et al.* (2014). The backbone curves of soil model are incorporated using pressure dependent hyperbolic model proposed by Kondner (1963) and further modified by Matasović and Vucetic (1993). The shape of the backbone curves for the loading part is represented by Equation 8.

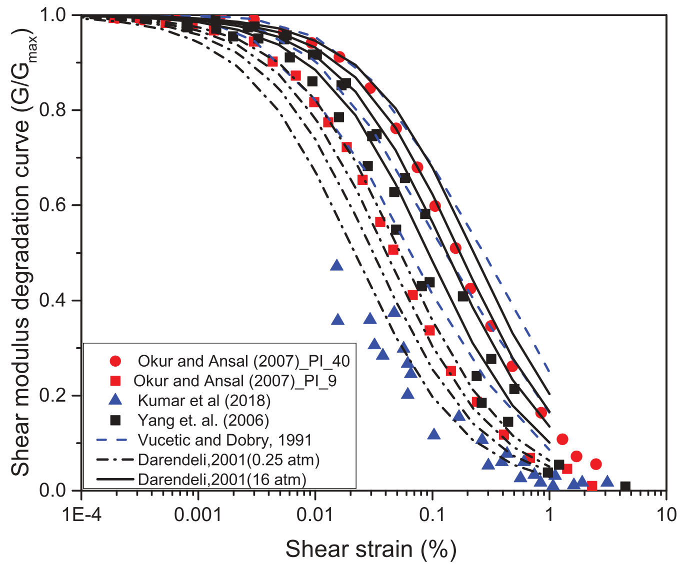


Figure 13. Variation of degradation of shear modulus with shear strain for different plastic limit and different types of soils.

$$\tau = \frac{G_0 \gamma}{1 + \beta(\frac{\gamma}{\gamma_r})^s} \tag{8}$$

where $G_0 =$ initial shear modulus, $\gamma =$ shear strain, $\tau =$ shear strength, and β, γ_r, b are the model parameters. The previous model was modified by Hashash and Park (2001) by relating the γ_r with confining stress as shown in Equation 9

$$\gamma_r = Referencestrain\left(\frac{\sigma_v^{'}}{Referencestress}\right) \tag{9}$$

The unloading part of the backbone curves is given by Equation 10.

$$\tau = F(\gamma_m)[2\frac{G_0((\gamma - \gamma_{rev})/2)}{1 + \beta((\gamma - \gamma_{rev})/2\gamma_r)^s} - \frac{G_0(\gamma - \gamma_{rev})}{1 + \beta(\gamma_m - \gamma_s)^s}] + \frac{G_0(\gamma - \gamma_{rev})}{1 + \beta(\gamma_m - \gamma_s)^s} + \tau_{rev} \tag{10}$$

where γ_{rev} reversal shear strain, γ_r reference shear strain, τ_{rev} reversal shear stress, $F(\gamma_m)$ reduction factor, γ_m maximum shear strain. The small strain damping is also depended upon confining pressure and represented by Equation 11

$$\zeta = \frac{Dampingratio}{\sigma_v^{'}} \tag{11}$$

The variation of shear modulus degradation curve depends on confining pressure and plasticity of a soil. For Kolkata soil, the plastic limit varies from 10 to 45 % with the mean of 25%. In this study, to take care of the variation of plastic limit, the upper and lower bound values are considered for each layer. Total 1170 numbers (26 (boreholes) × 5 (base time history) × 3 (shear wave profile) × 3 (Plasticity vales) = 1170) of soil profiles are generated and simulations are performed to take care of the uncertainty. As an outcome of the analysis, time histories of ground motion, shear stress and shear strain at any depth, fundamental frequency of soil column and response spectra are obtained.

The site-specific response spectrum of Kolkata is presented in Figure 14. The proposed spectra is compared with soft soil spectra as recommended in IS-1893 (BIS 2002) and Euro code (EuroCode 2005) spectra for Class D for 0.18 g PGA. The PGA of the proposed spectra is 0.18 g and the ratio of PGA to the spectral peak of the

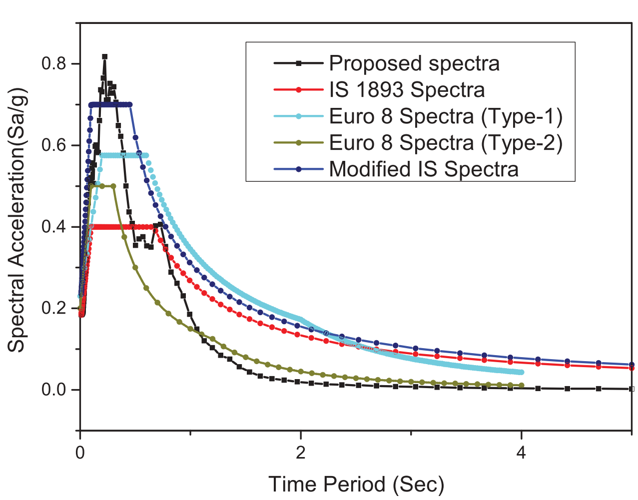
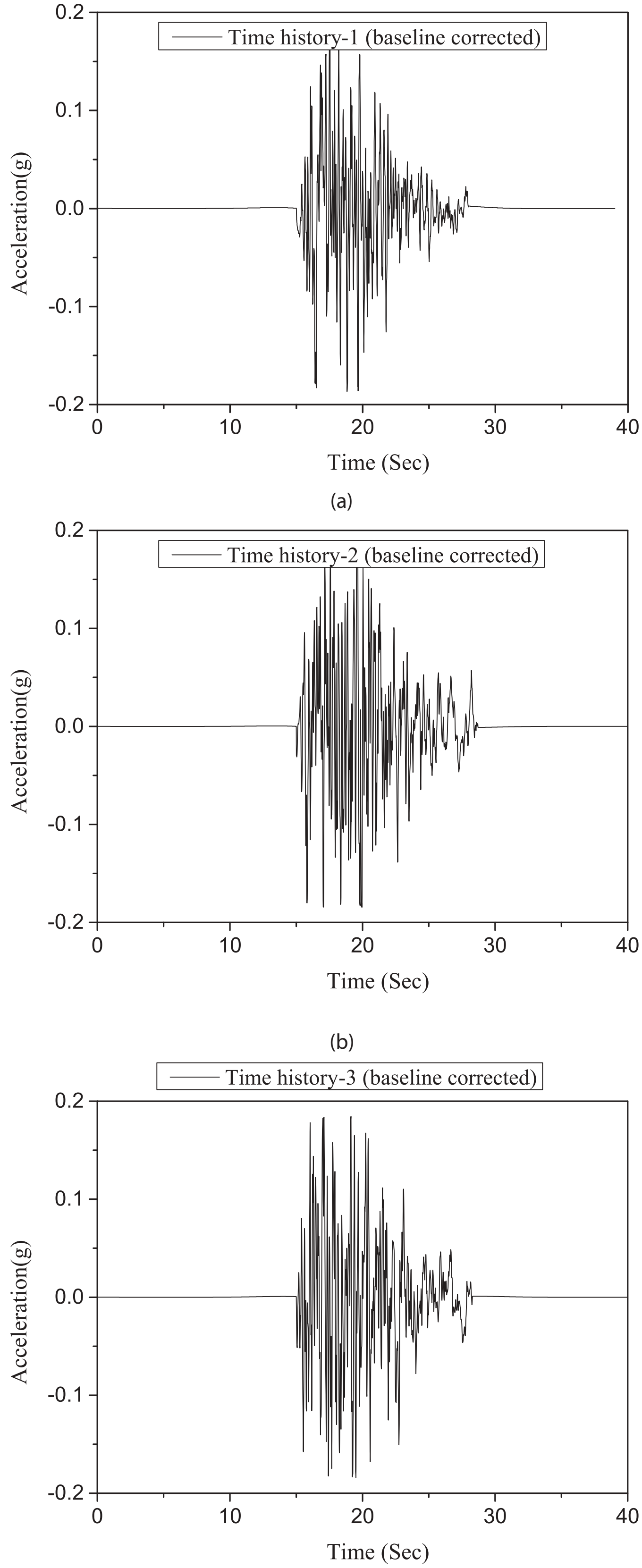


Figure 14. Proposed response spectra of Kolkata city.



(c)

Figure 15. a,b,c are three proposed spectrum compatible time history.

proposed spectra is 3.48 whereas, Indian standard code is suggested a value of 2.5 for this ratio. It may be also observed that, at a period greater than 1 sec, IS spectra gives the higher value than the proposed spectra. Similar behaviour is also observed for Euro code spectra for Type-1. As an outcome of the present study, an attempt is made to modify the spectral acceleration shape, proposed by IS-1893 (BIS 2002), and it is given in Equation 12. A modified spectral shape for Kolkata city with PGA 0.18 g is shown in Figure 14.

$$\frac{s_a}{g} = \begin{cases} 1 + 28T \ for \ 0 \leq \ T \ \leq \ 0.1 \\ 3.8 \ for \ 0.1 \leq T \ \leq \ 0.5 \\ 1.687/T \ for \ T \ \geq \ 0.5 \end{cases} \quad (12)$$

The spectrum compatible time histories at the surface level are important for the structural design of buildings, etc. Three spectrum compatible time histories, as shown in Figure 15, have been developed for use by engineers for the seismic design of structures in the Kolkata region.

7. Conclusion

In the present study, site-specific response spectra for Kolkata have been developed by deterministic seismic hazard analysis considering local geology.

(1) Peak ground acceleration of engineering bedrock spectra are obtained from DSHA and three sets of response compatible time histories are generated.
(2) A new empirical relationship has been developed between shear wave velocity and uncorrected SPT N-value. It is one of the important parameters for site response study. The magnitude of average shear wave velocity of the study regions varies 147 to 298 m/sec, and as per NEHRP guidelines, the site is classified as site class D and E.
(3) Soil amplification analysis for Kolkata is carried out considering the uncertainties in soil parameters, such as shear wave velocity and plasticity index of soils. Nonlinear site response analyses are performed. A total of 1170 simulations have been performed and a mean response spectrum is obtained for the site.
(4) From the present study indicates the PGA at surface level increased to 0.18 g as compared to the bedrock PGA of 0.102 g due to the presence of alluvial deposits.
(5) The response spectrum is compared with the Indian standard spectra (BIS 2002) for soft soil site and a PGA of 0.184 g is proposed at the ground surface. This PGA value exceeds the 0.16 g PGA value for Kolkata recommended by IS 1893 (BIS 2002), corresponding to a maximum considered earthquake.
(6) Amplification of peak spectral value to PGA is found to be 3.48, whereas IS Code suggests an amplification of 2.5 times in peak spectral value.
(7) A modified response spectra has been proposed for the city of Kolkata with PGA value of 0.184 g.

Acknowledgments

The authors gratefully acknowledge Dr. Suman Ray, Chief Executive Officer and Mr. Sudip Nath, Chief Engineer of C.E. Testing, West Bengal, India, for their support and help to obtain soil data of Kolkata region.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Abrahamson, N.A., Silva, W.J., and Kamai, R., 2013. *Update of the AS08 ground-motion prediction equations based on the NGA-West2 data set*. Berkeley, CA: Pacific Earthquake Engineering Research Center, University of California.

Akin, M.K., Kramer, S.L., and Topal, T., 2011. Empirical correlations of shear wave velocity (vs) and penetration resistance (spt-n) for different soils in an earthquake-prone area (erbaa-turkey). *Engineering Geology*, 119 (1–2), 1–17. doi:10.1016/j.enggeo.2011.01.007

Al-Hussaini, T.M., Chowdhury, I.N., and Noman, M.N., 2015. Seismic hazard assessment for Bangladesh – old and new perspectives. *In*: *First International Conference on Advances in Civil Infrastructure and Construction Materials*. Dhaka: Military Institute of Science & Technology, 841–856.

Anbazhagan, P. and Sitharam, T., 2008. Seismic microzonation of Bangalore, India. *Journal of Earth System Science*, 117 (2), 833–852. doi:10.1007/s12040-008-0071-5

ASCE, 2000. *Seismic analysis of safety-related nuclear structures and commentary*. New York, NY: American Society of Civil Engineers.

Athanasopoulos, G., 1970. Empirical correlations vso-nspt for soils of Greece: a comparative study of reliability. *WIT Transactions on The Built Environment*. 15. doi:10.2495/SD950031

Atkinson, G.M. and Boore, D.M., 2006. Earthquake ground-motion prediction equations for eastern North America. *Bulletin of the Seismological Society of America*, 96 (6), 2181–2205. doi:10.1785/0120050245

Barani, S. and Spallarossa, D., 2017. Soil amplification in probabilistic ground motion hazard analysis. *Bulletin of Earthquake Engineering*, 15 (6), 2525–2545. doi:10.1007/s10518-016-9971-y

Bashir, A. and Basu, D., 2018. Revisiting probabilistic seismic hazard analysis of Gujarat: an assessment of Indian design spectra. *Natural Hazards*, 91 (3), 1127–1164.

Basu, D., Dey, A., and Kumar, S.S., 2017. One-dimensional effective stress non-masing nonlinear ground response analysis of IIT Guwahati. *International Journal of Geotechnical Earthquake Engineering (IJGEE)*, 8 (1), 1–27. doi:10.4018/IJGEE

BIS, I., 2002. Criteria for earthquake resistant design of structures. *General Provisions and Buildings (fifth Revision) Pt*, 1, 2002.

Boominathan, A., *et al.* 2007 Seismic hazard assessment considering local site effects for microzonation studies of Chennai city. *In*: *Proceedings of Microzonation A workshop at Indian Institute of Science*. Bangalore, pp 94–104. doi:10.1094/PDIS-91-4-0467B

Boore, D.M., *et al.*, 2014. Nga-west2 equations for predicting pga, pgv, and 5% damped psa for shallow crustal earthquakes. *Earthquake Spectra*, 30 (3), 1057–1085. doi:10.1193/070113EQS184M

Campbell, K.W. and Bozorgnia, Y., 2003. Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. *Bulletin of the Seismological Society of America*, 93 (1), 314–331. doi:10.1785/0120020029

Campbell, K.W. and Bozorgnia, Y., 2013. *NGA-West2 Campbell-Bozorgnia ground motion model for the horizontal components of PGA, PGV, and 5%-damped elastic pseudo-acceleration response spectra for periods ranging from 0.01 to 10 sec*. Berkeley, CA: Pacific Earthquake Engineering Research Center, University of California.

Chatterjee, K. and Choudhury, D., 2013. Variations in shear wave velocity and soil site class in Kolkata city using regression and sensitivity analysis. *Natural Hazards*, 69 (3), 2057–2082. doi:10.1007/s11069-013-0795-7

Choiu, B., 2013 Update of the Choiu and Youngs nga ground motion model for average horizontal component of peak ground motion and response spectra. Peer report 2013/07. p. 105, pacific earthquake engineering research center. University of California, Berkeley, CA

Chowdhury, S.S., Deb, K., and Sengupta, A., 2015. Behavior of underground strutted retaining structure under seismic condition. *Earthquakes and Structures*, 8 (5), 1147–1170. doi:10.12989/eas.2015.8.5.1147

Dammala, P.K., *et al.*, 2017. Dynamic soil properties for seismic ground response studies in northeastern India. *Soil Dynamics and Earthquake Engineering*, 100, 357–370. doi:10.1016/j.soildyn.2017.06.003

Darendeli, M.B., 2001. *Development of a new family of normalized modulus reduction and material damping curves*. Dissertation (PhD). Austin, TX: University of Texas at Austin.

Dasgupta, S. and Acharyya, A., 2006. Seismic hazard assessment and microzonation: approach for greater kolkata urban agglomeration. *In*: *Interactive Meet in Seismic Microzonation*. Locknow

Dikmen, Ü., 2009. Statistical correlations of shear wave velocity and penetration resistance for soils. *Journal of Geophysics and Engineering*, 6 (1), 61. doi:10.1088/1742-2132/6/1/007

Dobry, R., *et al.*, 2000. New site coefficients and site classification system used in recent building seismic code provisions. *Earthquake Spectra*, 16 (1), 41–67. doi:10.1193/1.1586082

EuroCode, P., 2005. *Eurocode 8: design of structures for earthquake resistance-part 1: general rules, seismic actions and rules for buildings*. Brussels: European Committee for Standardization.

Flores-Estrella, H., Yussim, S., and Lomnitz, C., 2007. Seismic response of the mexico city basin: a review of twenty years of research. *Natural Hazards*, 40 (2), 357–372. doi:10.1007/s11069-006-0034-6

Fujiwara, T., 1972. Estimation of ground movements in actual destructive earthquakes. *In*: *Proceedings of the fourth European symposium on earthquake engineering*. London, pp 125–132

Govindaraju, L. and Bhattacharya, S., 2012. Site-specific earthquake response study for hazard assessment in Kolkata city, India. *Natural Hazards*, 61 (3), 943–965. doi:10.1007/s11069-011-9940-3

Haldar, A. and Mahadevan, S., 2000. *Probability, reliability, and statistical methods in engineering design*. New York: John Wiley & Sons.

Hanumantharao, C. and Ramana, G., 2008. Dynamic soil properties for microzonation of Delhi. *India. Journal of Earth System Science*, 117 (2), 719–730. doi:10.1007/s12040-008-0066-2

Hartzell, S., Bonilla, L., and Williams, R.A., 2004. Prediction of nonlinear soil effects. *Bulletin of the Seismological Society of America*, 94 (5), 1609–1629. doi:10.1785/012003256

Hasancebi, N. and Ulusay, R., 2007. Empirical correlations between shear wave velocity and penetration resistance for ground shaking assessments. *Bulletin of Engineering Geology and the Environment*, 66 (2), 203–213. doi:10.1007/s10064-006-0063-0

Hashash, Y., *et al.* 2015 Deepsoil 6.1, user manual. Board of Trustees of University of Illinois at Urbana-Champaign. Urbana Google Scholar

Hashash, Y.M. and Park, D., 2001. Non-linear one-dimensional seismic ground motion propagation in the Mississippi embayment. *Engineering Geology*, 62 (1–3), 185–206. doi:10.1016/S0013-7952(01)00061-8

Idriss, I., 2013. *NGA-West2 model for estimating average horizontal values of pseudo-absolute spectral accelerations generated by crustal earthquakes*. Berkeley, CA: Pacific Earthquake Engineering Research Center, University of California.

Imai, T., 1981. P-ans s-wave velocities of the ground in Japan. *Proceedings 9th ISCMFE* 2. Tokyo, 257–260

Imai, T., 1982. Correlation of n value with s wave velocity and shear modulus. *In*: *Proceedings 2nd ESOPT*, Amsterdam, 57–72.

Imai, T. and Yoshimura, M., 1972. *The relation of mechanical properties of soils to p and s wave velocities for soil ground in Japan*. Japan: Urana Research Institute, OYO Corp.

Imai, T. and Yoshimura, Y., 1970. Elastic wave velocity and soil properties in soft soil. *Tsuchito-Kiso*, 18 (1), 17–22.

Iyisan, R., 1996. Correlations between shear wave velocity and in-situ penetration test results. *Teknik Dergi-tmmob Insaat Muhendisleri Odasi*, 7, 371–374.

Jafari, M.K., Shafiee, A., and Razmkhah, A., 2002. Dynamic properties of fine grained soils in south of Tehran. *Journal of Seismology and Earthquake Engineering*, 4 (1), 25.

Kalteziotis, N., Sabatakakis, N., and Vassiliou, J., 1992. Evaluation of dynamic characteristics of Greek soil formations. *In*: *Second Hellenic conference on geotechnical engineering*, vol 2., 239–246. Greek.

Karim, H.H., Fattah, M.Y., and Hasan, A.M., 2010. Evaluation of some geotechnical propertie and liquifaction potential from seismic parameters. *Iraqi Journal of Civil Engineering*, 6 (3), 30–45.

Kayen, R.E. and Mitchell, J.K., 1997. Assessment of liquefaction potential during earthquakes by arias intensity. *Journal of Geotechnical and Geoenvironmental Engineering*, 123 (12), 1162–1174. doi:10.1061/(ASCE)1090-0241(1997)123:12(1162)

Kiku, H., 2001. In-situ penetration tests and soil profiling in adapazari, turkey. *In*: *Proceedings 15th ICSMGE TC4 Satellite Conference on Lessons Learned from Recent Strong Earthquakes*. August 25, 2001, Istanbul, Turkey, pp 259–265

Kondner, R.L., 1963. A hyperbolic stressstrain formulation for sands. *Proceedings of the 2nd Pan-American Conference on SMFE*, 1, 289–324.

Kumar, S.S., Krishna, A.M., and Dey, A., 2014. Nonlinear site-specific ground response analysis: case study of Amingaon, Guwahati. *In*: *15th Symposium of Earthquake Engineering (15SEE-2014)*. India: Roorkee.

Kumar, S.S., Krishna, A.M., and Dey, A., 2018. Dynamic properties and liquefaction behaviour of cohesive soil in northeast India under staged cyclic loading. *Journal of Rock Mechanics and Geotechnical Engineering*, 10 (5), 958–967.

Lee, S.H.H., 1990. Regression models of shear wave velocities in Taipei basin. *Journal of the Chinese Institute of Engineers*, 13 (5), 519–532. doi:10.1080/02533839.1990.9677284

Lee, S.H.H., 1992. Analysis of the multicollinearity of regression equations of shear wave velocities. *Soils and Foundations*, 32 (1), 205–214. doi:10.3208/sandf1972.32.205

Maheswari, R.U., Boominathan, A., and Dodagoudar, G., 2010. Use of surface waves in statistical correlations of shear wave velocity and penetration resistance of Chennai soils. *Geotechnical and Geological Engineering*, 28 (2), 119–137. doi:10.1007/s10706-009-9285-9

Matasović, N. and Vucetic, M., 1993. Cyclic characterization of liquefiable sands. *Journal of Geotechnical Engineering*, 119 (11), 1805–1822. doi:10.1061/(ASCE)0733-9410(1993)119:11(1805)

Mhaske, S.Y. and Choudhury, D., 2010. Gis-based soil liquefaction susceptibility map of Mumbai city for earthquake events. *Journal of Applied Geophysics*, 70 (3), 216–225. doi:10.1016/j.jappgeo.2010.01.001

Mhaske, S.Y. and Choudhury, D., 2011. Geospatial contour mapping of shear wave velocity for Mumbai city. *Natural Hazards*, 59 (1), 317–327. doi:10.1007/s11069-011-9758-z

Mohanty, W.K. and Walling, M.Y., 2008. Seismic hazard in mega city Kolkata, India. *Natural Hazards*, 47 (1), 39–54. doi:10.1007/s11069-007-9195-1

Nandy, D., 2007. Need for seismic microzonation of Kolkata megacity. *In*: *Proceedings of workshop on microzonation*. Bangalore, India: Indian Institute of science, vol 2627

Narayan, J., 2005. Study of basin-edge effects on the ground motion characteristics using 2.5-d modelling. *Pure and Applied Geophysics*, 162 (2), 273–289. doi:10.1007/s00024-004-2600-8

Narayan, J., 2010. Effects of impedance contrast and soil thickness on basin-transduced rayleigh waves and associated differential ground motion. *Pure and Applied Geophysics*, 167 (12), 1485–1510. doi:10.1007/s00024-010-0131-z

Narayan, J., 2012. Effects of p-wave and s-wave impedance contrast on the characteristics of basin transduced rayleigh waves. *Pure and Applied Geophysics*, 169 (4), 693–709. doi:10.1007/s00024-011-0338-7

Nath, S., *et al.*, 2014. Earthquake scenario in West Bengal with emphasis on seismic hazard microzonation of the city of Kolkata, India. *Natural Hazards and Earth System Sciences*, 14 (9), 2549. doi:10.5194/nhess-14-2549-2014

NEHRP FEMA. 2003. *NEHRP recommended provisions for seismic regulations for new buildings and other structures:-part 1: provisions*. FEMA. Vol. 302. Berkeley, CA: University of California.

Ohba, S. and Toriumi, I., 1970. Dynamic response characteristics of Osaka plain. *In*: *Proceedings of the annual meeting AIJ (in Japanese)*, Washington, DC.

Ohsaki, Y. and Iwasaki, R., 1973. On dynamic shear moduli and poisson's ratios of soil deposits. *Soils and Foundations*, 13 (4), 61–73. doi:10.3208/sandf1972.13.4_61

Ohta, Y. and Goto, N., 1978. Empirical shear wave velocity equations in terms of characteristic soil indexes. *Earthquake Engineering & Structural Dynamics*, 6 (2), 167–187. doi:10.1002/eqe.4290060205

Okur, D. and Ansal, A., 2007. Stiffness degradation of natural fine grained soils during cyclic loading. *Soil Dynamics and Earthquake Engineering*, 27 (9), 843–854. doi:10.1016/j.soildyn.2007.01.005

Oprsal, I., *et al.* 2005 Deterministic earthquake scenario for the basel area: simulating strong motion and site effects for basel. Prep. Available from http://geomff cunicz/-> people->IvoOprsal [Accessed 03 Feb 2019].

Phillips, C. and Hashash, Y.M., 2009. Damping formulation for nonlinear 1d site response analyses. *Soil Dynamics and Earthquake Engineering*, 29 (7), 1143–1158. doi:10.1016/j.soildyn.2009.01.004

Pitilakis, K., Anastasiadis, A., and Raptakis, D., 1992. Field and laboratory determination of dynamic properties of natural soil deposits. *In*: *Proceeding 10th World Conference on Earthquake Engineering*, vol 3, Spain, 1275–1280.

Rahman, M.Z., Kamal, A.M., and Siddiqua, S., 2018. Near-surface shear wave velocity estimation and vs 30 mapping for Dhaka city, Bangladesh. *Natural Hazards* 92 (3), 1687–1715.

Rao, K.S. and Rathod, G.W., 2014. Seismic microzonation of indian megacities: a case study of NCR Delhi. *Indian Geotechnical Journal*, 44 (2), 132–148. doi:10.1007/s40098-013-0084-0

Reddy, P., Prasad, A., and Sarkar, D., 1998. Velocity modelling of Bengal basin refraction data-refinement using multiples. *Journal of Applied Geophysics*, 39 (2), 109–120. doi:10.1016/S0926-9851(98)00006-8

Rollins, K.M., *et al.*, 1998. Shear modulus and damping relationships for gravels. *Journal of Geotechnical and Geoenvironmental Engineering*, 124 (5), 396–405. doi:10.1061/(ASCE)1090-0241(1998)124:5(396)

Roy, N. and Sahu, R., 2012. Site specific ground motion simulation and seismic response analysis for microzonation of Kolkata. *Geomechanics and Engineering*, 4 (1), 1–18. doi:10.12989/gae.2012.4.1.001

Salt, C., Alam, M., and Hosssain, M., 1986. Current exploration of the hinge zone area of southwest Bangladesh. *In*: *Proceeding 6th Offshore SE Asia Conference*, Singapore, 20–31.

Seed, H. and Idriss, I., 1981. Evaluation of liquefaction potential sand deposits based on observation of performance in previous earthquakes. *In*: *ASCE National Convention (MO)*, St. Louis, MO, 481–544.

Shiuly, A. and Narayan, J., 2012. Deterministic seismic microzonation of Kolkata city. *Natural Hazards*, 60 (2), 223–240. doi:10.1007/s11069-011-0004-5

Sitharam, T. and Anbazhagan, P., 2008. Site characterization using geotechnical and geophysical techniques for seismic microzonation of urban areas. *In*: *Proceedings of international geotechnical conference on development of urban areas and geotechnical engineering* vol 131147. Russia I: Saint Petersburg.

Sun, J.I., Golesorkhi, R., and Seed, H.B., 1988. *Dynamic moduli and damping ratios for cohesive soils*. Berkeley, CA: Earthquake Engineering Research Center, University of California Berkeley.

Sykora, D. and Stokoe, K., 1983 Correlations of in situ measurements in sands of shear wave velocity, soil characteristics, and site conditions. Report gr 83–33. Civil Engineering Department, University of Texas at Austin

Toro GR, 2002. Modification of the toro et al.(1997) attenuation equations for large magnitudes and short distances. Risk Engineering Technical Report

Trianni, S.C.T., Lai, C.G., and Pasqualini, E., 2014. Probabilistic seismic hazard analysis at a strategic site in the Bay of Bengal. *Natural Hazards*, 74 (3), 1683–1705. doi:10.1007/s11069-014-1268-3

Tsuda, K., *et al*., 2006. Site-response estimation for the 2003 miyagi-oki earthquake sequence considering nonlinear site response. *Bulletin of the Seismological Society of America*, 96 (4A), 1474–1482. doi:10.1785/0120050160

Ulugergerli, E.U. and Uyanik, O., 2006. Statistical correlations between seismic wave velocities and spt blow counts and the relative density of soils. *Journal of Testing and Evaluation*, 35 (2), 187–191.

Vucetic, M. and Dobry, R., 1991. Effect of soil plasticity on cyclic response. *Journal of Geotechnical Engineering*, 117 (1), 89–107. doi:10.1061/(ASCE)0733-9410(1991)117:1(89)

Yang, L., *et al*. 2006. A study on the dynamic properties of soft soil in Shanghai. *In*: *Soil and Rock Behavior and Modeling*, China, 466–473.

Yokota, K., Imai, T., and Konno, M., 1981. Dynamic deformation characteristics of soils determined by laboratory tests. *OYO Tec Rep*, 3, 13–37.

Youngs, R., *et al*., 1997. Strong ground motion attenuation relationships for subduction zone earthquakes. *Seismological Research Letters*, 68 (1), 58–73. doi:10.1785/gssrl.68.1.58

Zeng, X., 1996. A simple procedure to calculate the fundamental frequency of horizontal soil layers. *Geotechnique*, 46 (4), 757–760. doi:10.1680/geot.1996.46.4.757

Zhang, P., *et al*. 1999 Global seismic hazard assessment program (gshap) in continental asia

Zhao, J.X., *et al*. 2006. Attenuation relations of strong ground motion in Japan using site classification based on predominant period. *Bulletin of the Seismological Society of America*, 96 (3), 898–913. doi:10.1785/0120050122

Zheng, J., 1987. Correlation between seismic wave velocity and the number of blow of spt and depths. *In*: *Selected Papers from the Chinese Journal of Geotechnical Engineering-1985*, China. ASCE, p. 92–100.