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Site Amplification Factors and Acceleration Response Spectra for Shallow Bedrock Sites – Application to Southern India

Ketan Bajaj and P. Anbazhagan

Department of Civil Engineering, Indian Institute of Science, Bengaluru, India

ABSTRACT

Site amplification coefficients and acceleration design response spectra (ADRS) for the shallow sites in SI are derived based on non-linear site response analysis at 125 locations. Input motions are selected by considering the seismic hazard map for 475 years as return period and inputted at depth where $V_S \geq$ 1,500 m/s. The new site factors, i.e. F_{PGA}, F_a, and F_v, are proposed for Southern India (SI) by classifying the sites seismically considering National Earthquake Hazards Reduction Program (NEHRP). Using the calculated site factor, a new ADRS is developed for SI, which depends on peak ground acceleration and seismic site class. The compatibility of ADRS is further evaluated with NEHRP and BIS:1893.

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Shallow sites; seismic amplification; Southern India; acceleration design response spectrum; site response study

1. Introduction

Southern India was considered as one of the stable landmasses and a region having low to moderate seismicity. Yet, in the last couple of decades, it has experienced damaging earthquakes of magnitude of ~6 and above. The 1967, Koyna (6.6 M_w); 1969, Bhadrachalam (5.7 M_w); 1993, Latur (6.1 M_w); 1997, Jabalpur (5.8 M_w); and most recently Bhuj (2001, M_w 7.6) claimed thousands of lives and caused massive damage to infrastructure (Anbazhagan *et al.* 2016b; Anbazhagan, Sheikh, and Parihar 2013). However, occurrence of moderate to large earthquakes in Peninsular India has immense effect on the society (Anbazhagan *et al.* 2016a). The classic example is 2001, Bhuj earthquake that had killed around 20,000 people, injured another 1,67,000 and destroyed nearly 4,00,000 houses because of poor construction practices (Anbazhagan *et al.* 2016a). Quantifying the amplification of seismic wave in shallow sites for any potential ground shaking in the Peninsular India is becoming critical. Based on the field reconnaissance, Sharma *et al.* (2017) highlighted the damage patterns caused from 2015 Nepal earthquake and further illustrated the strong influence of local geology conditions on the severity of the damage (Sharma and Deng 2019).

Anbazhagan, Kumar, and Sitharam (2010) emphasized that local site effect is majorly responsible for the damage caused because of any earthquake, 2001 Bhuj (7.7 M_w), 1999 Chamoli (6.8 M_w), 2011 Sikkim (6.9 M_w), and 2015 Nepal (7.8 M_w) earthquakes are the latest examples that illustrated the consequences of local site effects in the Indian subcontinent. The details about these earthquakes can be referred from Roger Bilham's

CONTACT P. Anbazhagan anbazhagan@iisc.ac.in; anbazhagan2005@gmail.com Department of Civil Engineering, Indian Institute of Science, Bengaluru, India

website (http://cires1.colorado.edu/~bilham/, last assessed January 2020). Site amplification caused due to local site effects was analyzed by various researchers considering the shallow soil sites of the Indian subcontinent (e.g. Anbazhagan and Sitharam 2008; Boominathan *et al.* 2008; Kamal and Mundepi 2007; Naik and Choudhury 2013). Vipin, Anbazhagan, and Sitharam (2009) proposed the surface PGA map for the return period of 475 and 2475 years by considering the four seismic sites i.e. site class A to D (Building Seismic Safety Council (BSSC) 2003) throughout the SI.

However, most of the above site response studies (e.g. Kamal and Mundepi 2007; Boominathan *et al.* 2008; Anbazhagan and Sitharam) were either confined to the soil column of 30 m depth or less or confined to site-specific analysis of data. In general, input ground motions for site response analysis in Indian cities were either selected randomly from the globally recorded database or simulated considering the scenario-based earthquakes (Bajaj and Anbazhagan 2019c). Further, the site-specific input parameters (i.e. soil properties [stiffness and thickness], depth of input motion, and shear modulus and damping ratio [DR] reduction curves) for site response studies were considered randomly (Anbazhagan *et al.* 2017b; Bajaj and Anbazhagan 2019b). It can be also noted here that the standard spectral shape suggested in IS 1893 (Part 1) (Bureau of Indian Standard) (2016) is for the entire country by accounting the zone factor as a proxy to peak ground acceleration (PGA) (RaghuKanth and Iyengar 2007). This approach neither acknowledges the seismotectonic details in seismic hazard estimation for future nor considers the risk accompanying the response spectrum of the region. Hence, a rational earthquake hazard value needs to be estimated for the designed life of any structure. The underestimation of hazard questioned the safety of the structure and overestimation may lead to uneconomical projects. Hence a comprehensive study of the SI is required by addressing the local site effects. Till date no specific study is available that considered the most representative input parameters for shallow sites in South India for estimating the reliable amplification factor. Hence in this study a detailed site response analysis has been carried out by considering the representative input parameters to reduce the uncertainty in site response results.

In this study, primarily the shear wave velocity (V_S) profile for 125 shallow sites of SI has been developed. These V_S profiles are determined using both Multichannel Analysis of Surface Waves (MASW) survey and converting SPT-N value using region specific correlations developed by Anbazhagan *et al.* (2016b). Out of 125 shear wave velocity profiles, for 76 profiles gathered from MASW and 49 are converted from SPT-N values. One hundred twenty-five V_S profiles are further seismically classified based on time-averaged V_s in the upper 30 m depth (V_{S30}) considering NEHRP (Building Seismic Safety Council (BSSC) 2003). Non-linear site response analysis has been carried out at these 125 profiles. The input ground motions for each site have been considered based on the seismic hazard map developed for 475 years return period at bedrock level. Representative intraplate recorded locally, globally, and simulated ground motions by considering intraplate seismotectonic parameters by Bajaj and Anbazhagan (2019a) has been used as an input in this study. Further soil nonlinearity has been modeled by using representative shear modulus degradation () and DR curves suggested by Bajaj and Anbazhagan (2019b). Depth of input motion has been selected based on the various site response studies conducted worldwide for shallow profiles. The site factors at zero period (F_{PGA}), at short period or 0.2 s (F_a) and long period or 1.0 s (F_v) as recommended by the American Society of Civil Engineer's Standard ASCE 7–10 (American Society of Civil Engineers (ASCE) 2010), the

International Building Code (International Code Council (ICC) 2012), and the AASHTO guide (American Association of State Highway and Transportation Officials (AASHTO) 2011) is derived for the SI. These F_{PGA}, F_a, and F_v factors have been estimated for site class B, C, and D as per NEHRP. The Acceleration Design Response Spectra (ADRS) for the shallow sites in SI has been developed using the new site amplification factors. The compatibility of the new ADRS has been examined with NEHRP and IS 1893 (Part 1) (Bureau of Indian Standard) (2016).

2. Geology and Seismicity of the Southern India

Southern India is considered as one of the oldest geologically evolved and tectonically stable continental crust of the Indian subcontinent. The geological feature of the existing SI is the unification of the different crustal terranes, accumulated because of the geodynamic processes running from mid-Archean to Neo-Proterozoic time and certain sedimentary basins. Significantly SI is distributed as Gneissic complex/Gneissic granulite with extensive formation of greenstone and allied supracrustal belt (Valdiya, 1973). The eastern and western parts of the SI are mostly consisting of coastline having the alluvial fill in the pericratonic rift (Santosh *et al.* 2012). SI can be extensively categorized viz. Deccan Volcanic Province (DVP), Dharwarcraton (DC), South Granulite Terrain (SGT), Cuddapah basin (CB), Bastar Carton and Eastern and Western Ghats; tectonically and geologically (Ghosh, deWit, and Zartman 2004; Gupta 2006). The most prominent carton of the SI i.e. the DC can be further derived namely Eastern Dharwar craton (EDC) and Western Dharwar Craton (WDC) (see Fig. 1).

Tectonically, SI is majorly consisting of various faults, ridges, shear zones, and tectonic lineaments. The tectonic features of the SI have been studied by various researchers (Rastogi 1992; Balakrishnan 1997; Ramasamy 2006). The high concentration of seismicity along the Koyna-Warna region was indicated by Gupta (2006). Gupta (2006) further specified the existence of fault with neotectonics dislocation around Latur region. The fault reactivation along the western part of the Peninsular India (PI) was concluded by John and Rajendran (2008). Balakrishnan, Unnikrishnan, and Murty (2009) developed the new tectonic map of India and highlighted the tectonic features along SGT, Bay of Bengal, and Eastern and Western coast of Peninsular India Shield. The geology and seismotectonic is shown in Fig. 1.

Being a stable continental region, the SI has irregular seismicity. For example, SGT is surrounded by micro seismicity, however, intermediate seismicity is observed near to EDC and high at Koyna-Warna region. Rajendran (2000) concluded that PI has felt eight moderate size earthquakes since last 50 years and most of these earthquakes were spatially coinciding with paleo rifts. Various authors (Gupta 2006; Rai *et al.* 2003; etc.) concluded that strain energy being released in the form of micro earthquakes in PI shield due to the non-uniform plate thickness in the region. Because of the structural disturbance during the geological past, Gupta (2006) also emphasized the spatial variability of seismicity along the PI. Roy (2006) highlighted the moderate to high seismicity in the PI shield, which may be due to the fault reactivation caused by the SW–NE oriented compressional stress acting on the Indian Plate. These seismotectonic activities are further considered in mapping the region-specific seismic hazard parameters of SI for different return period.

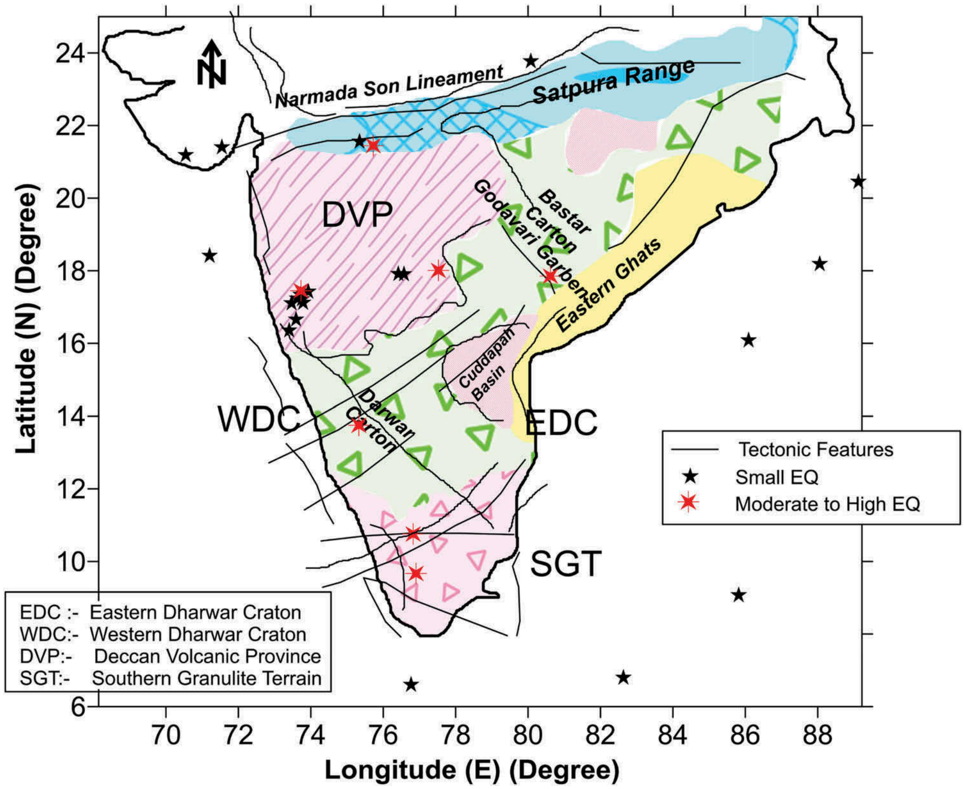

Figure 1. Geological units and the tectonic features in the Southern India (after Bajaj and Anbazhagan 2019a).

3. V_s of Shallow Bedrock Sites

The profiles are of prime importance for any site-specific response study of shallow sites. In this study, V_s profiles are obtained by carrying out MASW survey at various locations close to Standard Penetration Test (SPT). In 125 V_s profiles considered in this study, 76 profiles are from MASW testing and 49 are converted from Borehole SPT-N values.

MASW test setup consists of 24 channels Geode seismograph in combination with 24 vertical geophones with the frequency of 4.5 Hz and 2.0 Hz. All the MASW tests were carried out with geophones interval varying from 1 to 3 m depending on the availability of place. The surface waves are generated by a sledgehammer of 12 kg hitting a 30 cm × 30 cm metal plate ten times. This source was kept on both sides of the receiver array. The distance between the source and first, and last geophone was varied from 5, 10, and 15 m to prevent the near filed and far field effects. The captured raw data is used to obtain the dispersion curves (DC), which is further used to extract the V_S profile at 76 locations. The V_s profiles of each location were determined using window-based programs named SurfSeis 5 and ParkSEIS 2. Detailed information about the processing of the recorded raw data can be referred from Park, Miller, and Xia (1998, 2007) and Xia, Miller, and Park (1999). At each location, DC was extracted for 5–50 Hz. For inverting the DC, 10–15 layered earth model (Park, Miller, and Xia 1998) is used at the primary stage of inversion.

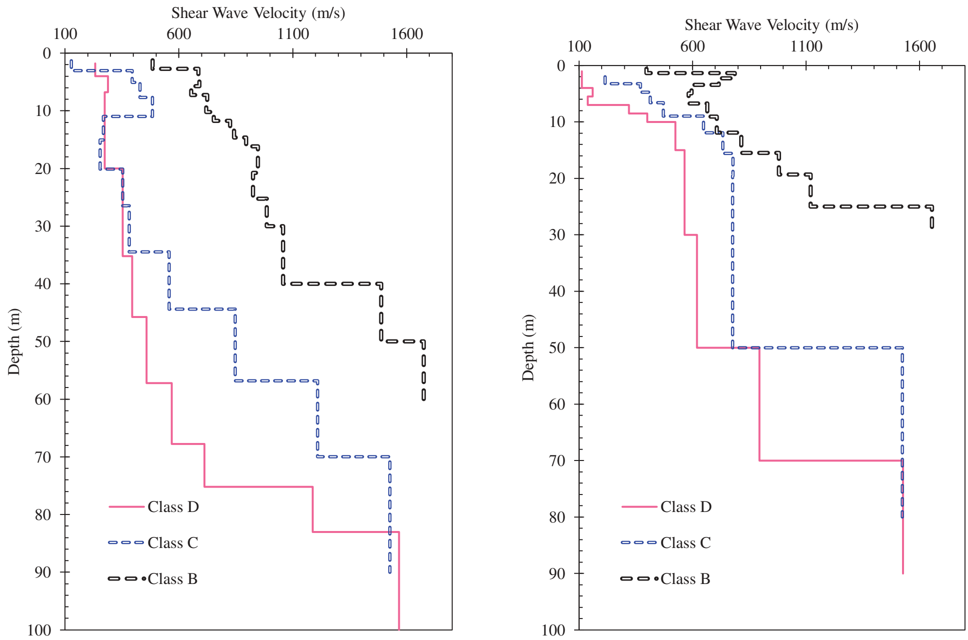

Figure 2. Typical variation of shear wave velocity based for different seismic site class as per NEHRP for (a) group G2 (0.05< PGA<0.13), and (b) group G3 (0.13< PGA<0.222).

Further using an optimization technique (Xia, Miller, and Park 1999), 1D V_s was obtained for each iteration. Several iterations have been done and the match with the lowest root mean square error value (1–7%) between the theoretical and experimental DCs is considered as the final 1D V_s profile of a site. Discussion of field testing, V_S profiles and correlation between SPT N and V_S can be referred from Anbazhagan *et al.* (2016b). Typical shear wave velocity profile for seismic site class B, C, and D as per NEHRP is given in Fig. 2. The depth of soil column varies from 4 to 34 m. The minimum and maximum shear wave velocity at a depth more than 30 m is 456 and 2,157 m/s, respectively. Various researchers (Anbazhagan *et al.* 2016b; Maheshwari, Boominathan, and Dodagoudar 2010; Chatterjee and Choudhury 2013; Mhaske and Choudhury 2011; etc.) have developed site-specific V_S and SPT-N relation for different parts of PI. Anbazhagan *et al.* (2016b) determined the V_S and SPT-N correlation for Bangalore, Chennai, Coimbatore, and Vizag. Further for enhancing the database, 49 borelogs with SPT-N values are converted as V_S profiles using Anbazhagan *et al.* (2016b) region specific correlation. In total 125 V_s profiles are used; 76 profiles are from MASW testing and 49 are converted from Borehole SPT-N values.

4. Input Parameters for Site Response

Various factors that affect the site response study is shear modulus reduction ($G/G_{\max}$) and DR curves, static soil property, depth of water table, depth of input motion. Various $G/G_{\max}$ and DR curves are available for different types of soil. Anbazhagan and Sitharam (2008) used Seed and Idriss (1970) and Schnabel (1973) curves, respectively, for sand and rock sites for site response analysis of Bengaluru. However, Boominathan *et al.* (2008) and Maheshwari, Boominathan, and Dodagoudar (2008) used Seed and Idriss (1970), Idriss (1990), and Schnabel (1973) curves for site response analysis of Chennai city. It can be seen from above that most of the previous studies used available $G/G_{max}$and DR curves. Using the KiK-Net data, Anbazhagan *et al.* (2017a) recommended different curves for different soil deposits for shallow sites. Bajaj and Anbazhagan (2019b) reanalyzed the KiK-Net data by using wide range of G/G_{max} and damping ratios for both shallow and deep profiles. Based on the analysis on residuals, Bajaj and Anbazhagan (2019b) suggested that Electric Power Research Institute (EPRI) (1993), Menq (2003), Zhang, Andrus, and Juang (2005), and Darendeli (2001) G/G_{max} and damping ratio can be used for rock, gravel, sand, and clay predominate profiles, respectively. In this study, information about soil layers are gathered either from drilled borehole or soil laboratory reports for each site, and representative G/G_{max} and DR curves are assigned. G/G_{max} and DR curves suggested by Bajaj and Anbazhagan (2019b) were used for the site response study. Further, in-situ density of each layer is determined using relationship developed by Anbazhagan *et al.* (2016c). The coefficient of lateral earth pressure at rest (K_o) is computed using theoretical relationship between K_o and Poisson's ratio (ν) i.e. $K_o = \nu/(1-\nu)$, where $\nu = \left(V_p^2 - 2V_S^2\right)/\left(2V_p^2 - 2V_S^2\right)$. The depth of ground water table has been considered from the borelogs.

Another important factor in site response study is the depth of bedrock and velocity of the reference rock. Soil thickness plays a vital role for the sites where depth of bedrock is not known or largely uncertain (Barani, Ferrari, and Ferretti 2013). For Indian subcontinent, most of the studies (e.g. Govindaraju and Bhattacharya 2012; Kumar, Anbazhagan, and Sitharam 2012) estimated the amplification factor by inputting the motion at engineering bedrock (i.e. $V_S > 760$m/s) or at the bottommost layer, which may not resulted in reliable estimation of amplification factor (Anbazhagan, Sheikh, and Parihar 2013). For the shallow sites, no significant difference at surface was observed by inputting motion at layer having V_s between 1,385 and 1,868 m/s (Anbazhagan, Sheikh, and Parihar 2013). Various authors (Malekmohammadi and Pezeshk 2015; Aboye *et al.* 2015; etc.) considered different velocities for the reference rock i.e. varying from 1,000 to 1,500°m/s for determining the amplification factor. Kwok and Stewart (2006) estimated the amplification factor by considering bedrock reference as 1,000 m/s. Ghofrani, Atkinson, and Goda (2013) concluded that for the shallow sites the amplification factors determined by inputting ground motion at layer having V_s in the range of 760–1,500 m/s appeared to be similar to the depth of installation where V_s is more than 1,500 m/s. Considering the shallow soil profiles of KiK-Net database, Bajaj and Anbazhagan (2019c, d) concluded that inputting motion at layer having $V_s \geq 1{,}500$ m/s is suitable

for capturing the surface amplification spectra. Hence, to determine the amplification factor for shallow sites of the SI, input motion is given at the layer having velocity 1,500 m/s and above.

5. Selection of Input Motion

Selection of input motion is the crucial component for any site-specific response study. There is a scarcity of the recorded ground motion database for the Indian subcontinent. Recorded ground motions such as 1940 El-Centro, 1985 Mexico, 1989 Loma Prieta, 1994

Northridge, 1995 Hyogoken-Nanbu, 1999 Chi-Chi, etc. had been extensively used for the site response study of the India. Because of lack of recorded ground motions, stochastically simulated ground motions are commonly used worldwide in any site response study. Simulated synthetic ground motions consistent with uniform hazard spectra and hazard values were used by various authors (e.g. Stewart, Liu, and Choi 2003; Baker and Cornell 2006; Haselton *et al.* 2009; Baker *et al.* 2011; Bajaj and Anbazhagan 2019c). Irrespective of approaches used for the seismic hazard analysis, both the simulated and recorded ground motions can be used for site-specific response studies (Ansal and Tonuk 2007). The input base or bedrock motion characteristics that govern the response of any soil column are the frequency content, amplitude, and duration. Selecting one ground motion by considering only amplitude using seismic hazard analysis or seismic hazard deaggregation also may not be a reliable way of estimating site amplification.

A few recorded ground motions at bedrock level are available for the SI but that may not be enough for estimating the surface amplification. The details of the ground motions recorded in Peninsular India can be referred from Bajaj and Anbazhagan (2019b). However, a wide range of recorded motions are available for the intraplate and stable continental region (Anbazhagan *et al.* 2017a). For selecting the ground motion preliminary, the seismic hazard map for return period of 475 years at bedrock level for the SI has been used, considering the design-based earthquake (e.g. American Society of Civil Engineers (ASCE) 2010). The seismic hazard map of the SI is given in Fig. 3. The PGA varies from 0.01 to 0.48 g (Fig. 3). PGA variation has been categorized into four bins as (a) 0.01–0.05 g, (b) 0.05–0.13 g, (c) 0.13–0.2 g, and (d) 0.2–0.48 g. The division in four groups

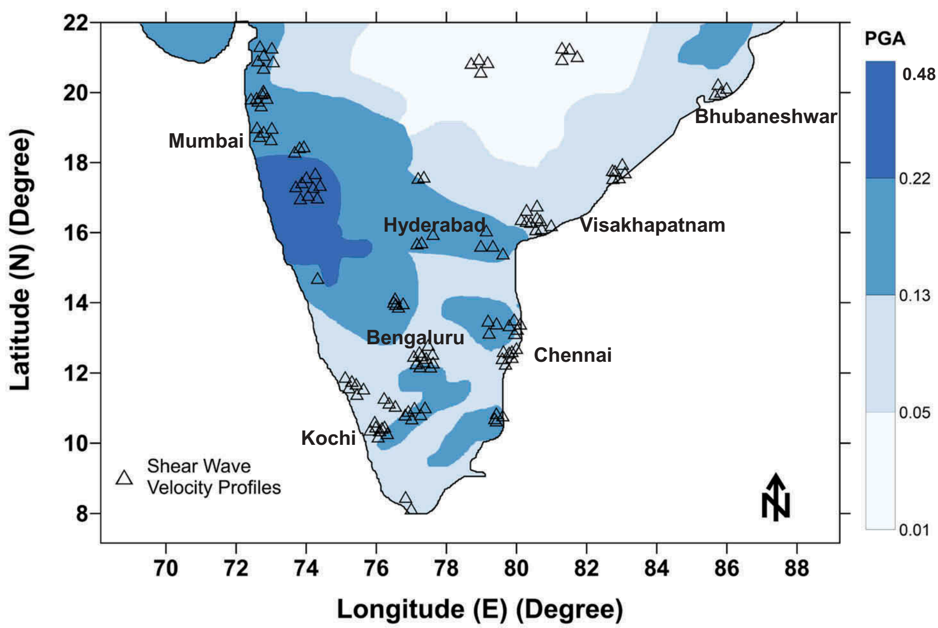

Figure 3. Distribution of PGA for the Peninsular India for a return period of 475 years along with the locations of shear wave velocity profiles.

is synchronizing with seismicity of the past damaging earthquakes in SI. These four groups are referred as group 1 (G1), group 2 (G2), group 3 (G3), and group 4 (G4). Fifty ground-motions that have occurred in the Intraplate region (Australia, Canada, and India) and recorded at rock sites have been used in this study. The significant duration for these four groups varied as (a) 40.38–82.5 s; (b) 48.42–117.34 s; (c) 35.22–55.36 s; and (d) 30.48–42.28 s. Whereas, the frequency of these ground motions varies from 4.22 to 10 Hz for all the four groups. These recorded motions have moment magnitude (M_W), hypocentral distance and PGA value varying from 3.5 to 6.5, 5.0 to 625 km, and 0.01 to 0.45 g respectively. However, the recorded ground motions could not cover the entire range of PGA (i.e. from 0.01 to 0.45 g) required for site response study for each of the site. Hence the stochastically simulated ground motions are also used for unavailable magnitude, distance, and PGA combinations. These synthetic ground motion data has been generated using the Finite-Fault stochastic model (EXSIM) proposed by Motazedian and Atkinson (2005) and further modified by Boore (2009). The detail of the seismological parameters used in simulation of synthetic ground motion is given in Bajaj and Anbazhagan (2019b).

For determining the site amplification, all the 125 sites have been grouped according to the four PGA bins. Further for each site, 10 ground motions have been selected depending on the PGA determined using the seismic hazard analysis and by varying the frequency and duration. For example, if a site “Y” has a PGA value of 0.11 g, it lies in group 2. Firstly, recorded ground motions are selected with PGA varying between 0.10 and 0.12 g. If 10 recorded ground motions are not available between 0.10 and 0.12 g with different frequency and duration, then EXSIM has been used for stochastically simulating these ground motions. Similarly, depending upon the PGA, frequency, and duration of the synthetic ground motions were varied accordingly for different sites in the SI. The details regarding the selection of input motion can be referred from Bajaj and Anbazhagan (2019c).

6. Site Response Study

Various software (SHAKE91, DEEPSOIL, STRATA, etc.) are available for performing one dimensional (1D) total stress ground response analysis. However, for performing both the non-linear and equivalent linear 1D total site response analysis, DEEPSOIL has been widely used. In this study, nonlinear site response analysis has been carried out using DEEPSOIL and more details regarding DEEPSOIL can be referred from Hashash, Musgrove, and Harmon *et al.* (2017). For fitting the $G/G_{\max}$ and DR curve, MRDF-UIUC procedure suggested by Phillips and Hashash (2009) is used. Formulation proposed by Hashash, Phillips, and Groholski (2010) is used to define the estimates of shear strength. Correlation between V_s and undrained shear strength proposed by Dickenson (1994) is used for calculating the static shear stress for the downhole arrays. To represent the small-strain damping, frequency-independent Rayleigh damping suggested by Phillips and Hashash (2009) is used. The thicker layers are subdivided thus a minimum fundamental frequency should be between 15 and 25 Hz (Schnabel, Lysmer, and Seed 1972). It is important to note here that, following Malekmohammadi and Pezeshk (2015), basin and topographic effects are considered small in the SI and are not addressed in this study.

Input parameters such as soil type, shear modulus, unit weight and shear wave velocity are provided as explained above. At each site, 10 input base motions are selected and total 125 × 10 = 1,250 time-domain nonlinear site response analysis have been carried out to comprehend the site response characteristics of SI. For the analysis, ground motion is employed by considering the time domain with an elastic base (Kwok *et al.* 2007). Spectral parameters at surface are estimated and further used for determining the amplification factor.

All the ground motions are applied to the base of the soil column and PGA at each layer is estimated. Typical variation of amplification factor for the sites is presented in Figs. 2 and 4. The amplification factor is defined as the ratio of the intensity measurement of the motion at the soil surface to the corresponding value at the bedrock. The amplification at each period is defined as

$$Amp(T) = \frac{SA_{Soil}(T)}{SA_{Rock}(T)} \quad (1)$$

where, $SA_{Soil}(T)$ and $SA_{Rock}(T)$ is defined as spectral acceleration (SA) of the motion at soil surface and bedrock respectively for the same period . The maximum amplification factor from 10 ground motions has been calculated for each of the site for PGA and peak frequency. No significant amplification has been observed at depth 50 m to input bedrock level (see Fig. 4a). The amplification of 1.06–1.15 is observed from 50 to 100 m, whereas, beyond 50 m, it changes to 2.07–2.93 with depth as it reaches to surface in case of PGA. The amplification variation of 1.04–4.32 has been observed in case of PGA for the SI.

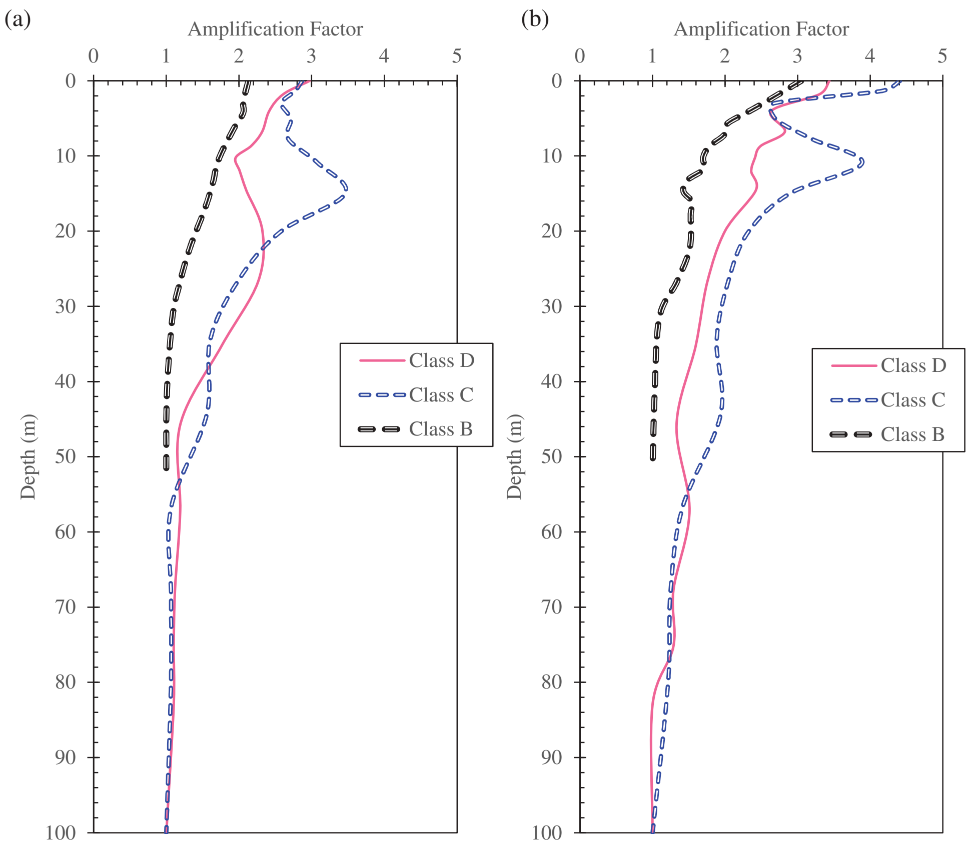

Figure 4. Typical variation of maximum amplification factor with depth (a) PGA and (b) Peak frequency.

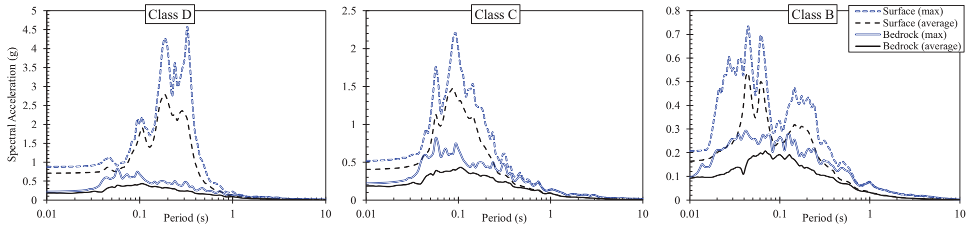

Figure 5. Typical variation of maximum and average surface spectra with respect to maximum and average bedrock spectra.

Further amplification factor is determined for peak frequency (see Fig. 4b). The amplification variation for peak frequency at the surface is observed between 2.08 and 6.38. The variations in response spectra for all the 125 sites have been studied. Typical variation of SA with spectral period for site class B, C, and D is given in Fig. 5. For the same bedrock motion, the response spectra for site class B, C, and D at surface is significantly different in terms of amplitude and spectral period. Similarly, for all the 125 sites the SA and period have been studied and used further in developing the response spectra for the SI.

Koyna-Warna and Satara district is covered by Deccan trap lava flows of late Cretaceous to Palaeogene age and Alluvium of recent to sub-recent origin (Geological Survey of India (Officers of the) 1968). Based on the seismicity parameter, it is observed that this region lies in high seismicity zone. A typical variation of shear wave velocity and bedrock and surface spectra is given as Fig. 6a. It can be observed from Fig. 6a that maximum peak is observed at 0.34 s for this particular site. Near to the Koyna-Warna region the average amplification at the surface varies from 1.72 to 2.87 at zero period and increased to 2.72 to 4.76 between 0.2 and 0.25 s vibration period. The predominant period in the range of 0.2–0.35 s is observed in most part of this region. However, near to Koyna river, high amplification of 5.85–8.98 is observed at vibration period between 0.48 and 0.62 s. The recorded surface PGA for 1967 Koyna earthquake is 0.486 g at an epicentral distance of 13 km (Iyengar and Raghu Kanth 2004). The surface PGA between 0.44 and 0.52 g is observed in the present study near to Koyna-Warna site. A few sites near to Koyna-Warna region and Satara district, high amplification is observed at a depth between 5 and 6 m which may be due to the presence of low velocity region. Even though the depth of bedrock is between 6 and 14 m, high amplification is observed due to the presence of low velocity silty sand and silty clay layers.

The maximum amplification value between 1.51 and 4.82 is observed near to Mumbai region at zero period and it increased to 3.82–7.62 at vibration period between 0.2 and 0.32 s. A typical variation of shear wave velocity profile and bedrock and surface spectra is given as Fig. 6b. It can be observed from Fig. 6b that maximum peak is observed at 0.20 s for this particular site. Pune is majorly covered by Deccan traps belonging to Sahyadri group and Alluvium of recent deposit (GSI report). The maximum amplification near to Pune region is in the range of 2.02–3.84 at zero period. A typical variation of shear wave velocity profile and bedrock and surface spectra is given in Fig. 6c. It can be observed form Fig. 6c that maximum peak is observed at 0.10 s for this particular site. However, dual peaks are observed in few sites in Mumbai and Pune between 0.15 and 0.31 s, which may

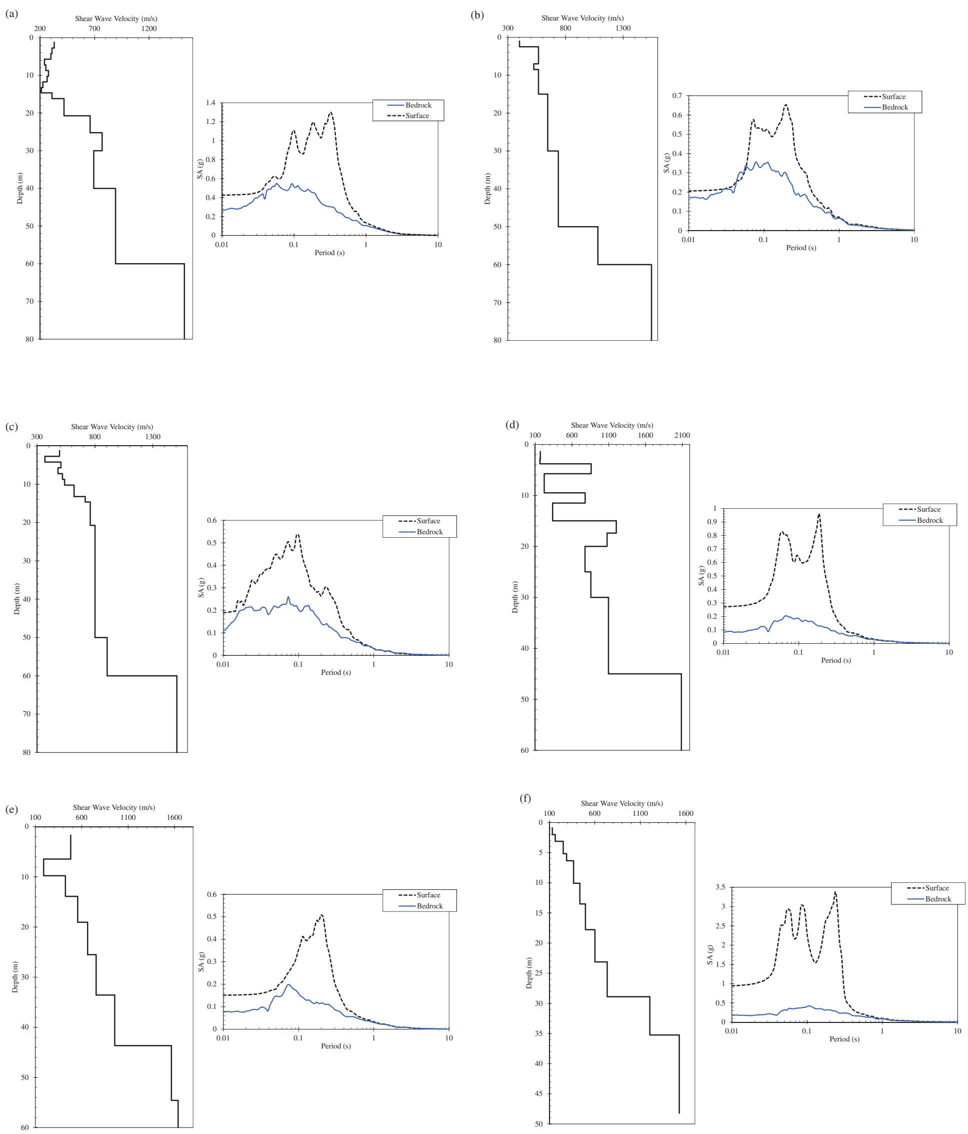

Figure 6. Typical variation of shear wave velocity profile and corresponding bedrock and surface spectra of (a) Koyna site, (b) Mumbai, (c) Pune, (d) Vizag, (e) Bengaluru, and (f) Chennai.

be due to the presence of low velocity region at depth between 4 and 6 m in both the region. It is also observed that for Pune, though the engineering bedrock depth is in between 10 and 20 m but high SA in the range of 0.75–0.98 g has been observed for period range of 0.10–0.23 s in few sites. Surat city lies over a thick pile of alluvium deposits of Quaternary age, devoid of rock exposures. The lithology of the city consists of yellowish to brownish sandy silt/silty clay, blackish to brownish clay, brownish fine sandy silty clay, fine to coarse sand and gravel (GSI report). The engineering bedrock is observed at a depth between 30 and 40 m. In most parts of the city, the amplification between 1.58 and 3.82 is observed at vibration period range of 0.32–0.42 s. Most part of Nagpur lies over the deccan traps, the amplification at zero period is in the range of 1.12–1.42 and it has increased to 1.82–2.21 at the vibration period between 0.12 and 0.21 s.

The principal rock units of the Eastern Ghats are the granite gneisses, the Charnockite series, the Khondalite series and the granites (GSI). One of the major cities of the Eastern Ghats is Vishakhapatnam (Vizag), the primary soil type of Vizag is clayey to gravelly clayey along with moderately deep dark brown soils. A typical variation of shear wave velocity and bedrock and surface spectra are given in Fig. 6d. It can be observed from Fig. 6d that maximum peak is observed at 0.19 s for this particular site. The PGA value of 0.05–0.13 g has increased to 0.15–0.38 g for the vibration period range of 0.18–0.28 s. A typical variation of shear wave velocity profile and bedrock and surface spectra is given as Fig. 6d. It can be observed from Fig. 6d that maximum peak is observed at 0.10 s for this particular site. Hyderabad forms the part of the Pre-Cambrian peninsular shield and is underlain by the Archaean crystalline complex, comprising Pink and grey granites and granite gneisses. The thickness of soil cover varies from 0.5 to 2.0 m and majorly consist of red lateritic, yellow sandy-clay loams, and alluvial black soils. The amplification of 1.12–2.32 at zero period is increased to 2.85–3.15 at vibration period range between 0.18 and 0.21 s. For most of the sites near to the Eastern Ghats the predominant period is in the range of 0.16–0.28 s.

Bengaluru city lies over a hard and moderately dense gneissic basement and most of the city is covered with silty sand and silty clay. For most of the sites, hard rock is available at the range of 8.5–40 m. A typical variation of shear wave velocity profile and bedrock and surface spectra is given in Fig. 6e. It can be observed from Fig. 6e that maximum peak is observed at 0.21 s for this particular site. The amplification at zero period is in the range of 1.63–3.55 in most of the sites, which is slightly less than Anbazhagan and Sitharam (2008). Anbazhagan and Sitharam (2008) reported the predominant frequency in range of 5–12.5 Hz for Bengaluru city. However, in this study, the predominant frequency is derived in the range of 3–9.5 Hz. The reason may be determining the surface response using non-linear site response analysis instead of equivalent linear used by Anbazhagan and Sitharam (2008). Additionally, the variation may be due to using different shear modulus reduction and damping ratio curve and depth of input motion for site response analysis. The eastern and southern parts of Chennai are covered with shallow bedrock (crystalline) while the western and northern areas have Gondwana deposits below the alluvium. The most part of Chennai consists of clays, sands, sandy clays, and occasional boulder or gravel zones (Boominathan *et al.* 2008). A typical variation of shear wave velocity profile and bedrock and surface spectra is given in Fig. 6f. It can be observed from Fig. 6f that maximum peak is observed at 0.21 s for this particular site. The maximum amplification factor in the range of 2.82–4.85 is observed at zero period. However, the predominant period is determined as 0.25–0.38 s, which is different from reported by Boominathan *et al.* (2008). This may be due to using a wide range of input ground motions and depth of input motion at the layer having V_s equal to 1,500 m/s. Ramkrishnan, Kolathayar, and Sitharam (2019) predicted the variation of bedrock PGA for majority of built up area varies from 0.05 to 0.07 g for Mangalore. For the similar places, the amplification factor of 1.15–1.21 has been observed, in the present study.

Coimbatore district forms the part of the upland plateau region of Tamil Nadu. The soil in this region majorly consists of Red calcareous and non-calcareous soil, Black soil, Alluvial, and Colluvial soil. The maximum amplification in this region is observed between 2.25 and 3.82 at zero period and increased to 3.15–5.76 within a period range of 0.14–0.21 s. Similar to Prakash, Kolathayar, and Ramkrishnan (2018), most part of the city has moderate to high amplification factors. Kochi is one among the largest harbor cities in the country and is a part of the Southern Granulite Terrain. It is mostly surrounded by loose sediments of alluvium, clay, loamy sands, silt, laterites, etc., and have vast area of intermittent water bodies. The predominant period near to the city is observed in the range of 0.22–0.38 s. The lithology of Kannur district is grouped under Precambrian, late Tertiary and Quaternary periods, and the Precambrian rocks. Laterite soil is one of the predominant types of soil in the Kannur district which is the weathered product derived under humid tropical conditions. The amplification in the range of 1.32–2.85 at zero period and predominant period in the range of 0.25–0.38 s is observed in this district.

7. Site Amplification Factors

Amplification of a ground motion at different spectral periods can be effectively expressed as amplification factor or site coefficient. Using the recorded acceleration time history, Newmark and Hall (1982) proposed the amplification factors for the acceleration, velocity, and displacement response at various damping values. The SA for periods less than 0.33 s, between 0.33 and 3.33 and above 3.33 s is sensitive to PGA, peak ground velocity, and peak ground displacement, respectively (Hall, Mohraz, and Newmark 1975). Using the acceleration, velocity, and displacement time histories, Malhotra (2006) determined the amplification factors for acceleration, velocity, and displacement sensitive region of spectrum for various damping values. IBC (2003) proposed the site coefficients for short period (corresponding to 0.2 s spectral period) and long period (corresponding to 1 s spectral period) . Whereas, in IS 1893 (Part 1) (Bureau of Indian Standard) (2016), the SA coefficients are capped at 2.5 by classifying soil into three categories based on SPT-N value. F_a defined in the IBC are the average value and F_v are approximately the average $+1\sigma$ (here σ is standard deviation) amplification values (Dobry, Ramos, and Power 1999). In IBC, F_a is estimated for the short-period band 0.1–0.5 s, whereas, F_v is defined over the long-period band 0.4–2.0 s (Dobry, Ramos, and Power 1999). Various authors also (e.g. Aboye *et al.* 2015; Park *et al.* 2012) commented on the wide range of period band for estimating the site coefficients proposed by Borcherdt (1994) and Dobry, Ramos, and Power (1999). Determining the period range is vital part for calculating site-specific F_a and F_v values. Different bins of F_a and F_v are analyzed for better match of the surface spectra for the corresponding case and site. The spectral period range of 0.01–0.15 s and 0.15–1.0 s for F_a and F_v, respectively resulted in the best match of surface spectral spectrum. The site factor representing zero period i.e. F_{PGA} is also determined. For a site class, at each site period, lognormal median of spectral values (RS_{soil}) is calculated using Eq. (2). Ratio of this median surface acceleration (RS_{soil}) to rock SA (RS_{rock}) for each site period is calculated. In the present study $\frac{R_{Soil}}{R_{Rock}}$ is assumed as 1.0 in Eqs. (3) and (4). R_{soil} and R_{rock} is defined as the hypocentral distance for rock and soil station; however, in case of 1D site response analysis R_{soil} is similar to R_{Rock} for the same site, hence $\frac{R_{Soil}}{R_{Rock}}$ is assumed as 1.

Table 1. F_{PGA}, F_a, and F_v values determined for different group and seismic site class.

	Class D			Class C			Class B		
	F_{PGA}	F_a	F_v	F_{PGA}	F_a	F_v	F_{PGA}	F_a	F_v
G1	-	-	-	-	-	-	2.084	2.183	1.285
G2	2.314	3.045	3.106	2.147	2.264	1.507	2.012	1.985	1.202
G3	2.014	2.607	2.223	1.945	2.057	1.442	1.878	1.855	1.138
G4	1.847	1.822	1.957	1.745	1.656	1.352	1.592	1.557	1.141

$$RS_{soil} = \exp\left(\frac{1}{N}\cdot\sum_{i=1}^{N}\log RS_{soil_i}\right) \tag{2}$$

$$F_a = \frac{R_{soil}}{R_{rock}}\frac{1}{0.14}\int_{0.01}^{0.15}\frac{RS_{soil}(T)}{RS_{rock}(T)}dT \tag{3}$$

$$F_v = \frac{R_{soil}}{R_{rock}}\frac{1}{0.85}\int_{0.15}^{1.0}\frac{RS_{soil}(T)}{RS_{rock}(T)}dT \tag{4}$$

The calculated F_a and F_v values from Eqs. (3) and (4), respectively, are given in Table 1. F_a and F_v values calculated in this study is higher as compared to NEHRP. For site class C, for PGA between 0.13 and 0.22 g (i.e. G3), F_a and F_v calculated in this study is 2.537 and 1.442, respectively; however, as per NEHRP estimated F_a and F_v 1.2 and 1.64, respectively. F_v calculated in this study is less than NEHRP for seismic site class C and higher for seismic site class D. Similarly, Silva *et al.* (2000), Borcherdt (2002), and Stewart, Liu, and Choi (2003) obtained F_v values greater than the NEHRP for Site Class D. F_a and F_v calculated in this study is also compared with Parihar and Anbazhagan (2020). For G2, F_a and F_v for site class B determined by Parihar (2014) is 3.414 and 2.303, respectively, which is high as compared to present study (Table 1).

The site factors derived in the present study is suggested only for determining the design spectra for the shallow sites in the SI. The F_{PGA}, F_a, and F_v values defined in the present study is different from previous study that may be justified by (1) variation in presumed bedrock/soil condition; (2) selection of site-specific input ground motions; and (3) variation in the range of spectral period used for estimation of site coefficients. Considering the complete analysis, it is found that the major factors that govern the site coefficients are depth of input motion, shear wave velocity of a soil column, G/G_{max} and DR curves.

8. Proposed Acceleration Design Response Spectra

The site coefficients determined in this study have been further used for developing the ADRS for any site in the SI with known seismic site class. The procedure outlines in American Association of State Highway and Transportation Officials (AASHTO) (2011) can be briefed in four steps: (1) identify the seismic site class as per NEHRP; (2) calculated the PGA at bedrock (PGA_{BR}), SA at 0.2 s i.e. S_S and SA at 1.0 s i.e. S_1 for return period of 475 years from probabilistic seismic hazard maps; (3) for site-specific PGA, S_S and S_1 calculate the corresponding F_{PGA}, F_a, and F_v values (see Table 1); (4) three points of ADRS can be derived as

$$PGA = PGA_{BR} \times F_{PGA} \tag{5}$$

$$S_{DS} = F_a S_S \tag{6}$$

$$S_{D1} = F_v S_1 \tag{7}$$

where, S_{DS} and S_{D1} are the design short period (0.2 s) and design long period (1.0 s) spectral response acceleration at ground surface.

Figure 7 shows the typical comparison of the average surface spectra for site class B for all the four groups with the proposed design spectra and NEHRP design spectra. It can be observed from Fig. 7 that for lower PGA value NEHRP design spectra is predicting less SA value as compared to the observed surface spectra for Peninsular India. Similar observation is noticed for other site classes. Further, the proposed spectra are matching well surface spectra as compared to NEHRP design spectra in all the four cases (see Fig. 7).

Fig 8 shows the comparison of ADRS for site class C and D developed using F_{PGA}, F_a, and F_v defined in the present study. The PGA value used in comparison for group G2, G3, and G4 respectively is 0.07, 0.13, and 0.22 g. ADRS for site class D and C is compared with the ADRS of soft and medium soil for IS 1893 (Part 1) (Bureau of Indian Standard) (2016) respectively in Fig. 8a–b. The PGA values used in constructing ADRS from IS:1823 are 0.07 and 0.22 g. It has observed from Fig. 8 that for the same PGA value (i.e. 0.07 and 0.22 g), ADRS constructed using IS-1893 is underestimating the SA values at short periods and overestimating at long periods.

The site coefficients derived in this study is for 10% probability of exceedance for 50 years. However, Hashash *et al.* (2008) and Park *et al.* (2012) showed the dependency of site coefficients on return period. The short and long period of ADRS derived in this study

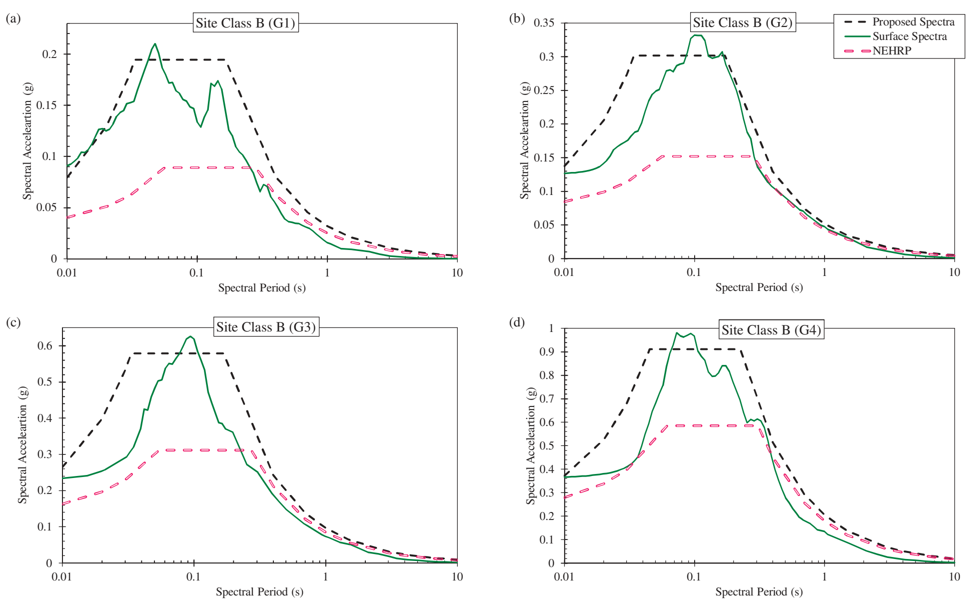

Figure 7. Typical comparison of surface spectra for site class B for (a) Group 1, (b) Group 2, (c) Group 3, and (d) Group 4 with the proposed design spectra and NEHRP.

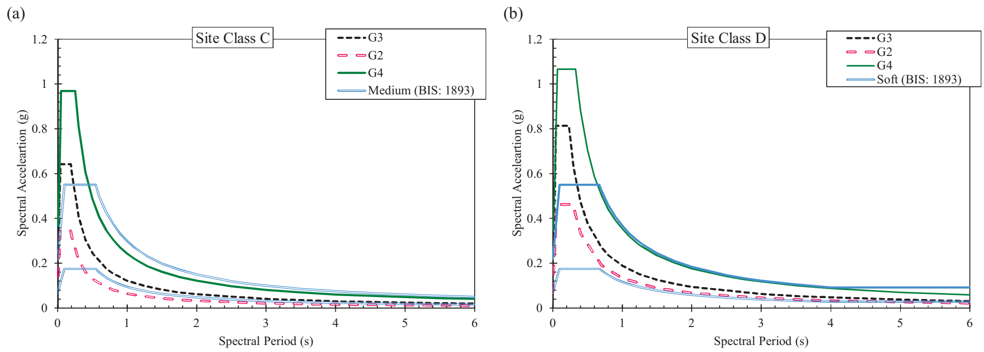

Figure 8. The typical variation of the proposed ADRS with the IS 1893 (Part 1) (Bureau of Indian Standard)(2016) for seismic site class C and D as per NEHRP.

may be further updated by considering Malhotra (2006) procedure based on the recorded ground motions.

9. Conclusion

In the present study, non-linear site response analysis has been carried out for shallow profiles in SI. The V_S profiles at 125 locations have been determined by using both MASW and site-specific V_S and SPT-N value correlations. These sites are classified and characterized based on time-averaged V_s in the upper 30 m depth as per NEHRP seismic site classification. Most of the sites of SI are classified as seismic site class B, C, and D. The input ground motions are selected based on seismic hazard map developed considering return period of 475 at bedrock. The average surface amplification of 1.04–4.32 has been observed in the entire region. For most of the sites maximum SA is observed between 0.05 and 0.4 s. The average amplification in terms of PGA (g) in group G1, G2, G3, and G4 has been noted as 1.85–2.01, 1.08–4.32, 1.72–3.35, and 1.51–1.81, respectively. The site factors F_{PGA}, F_a, and F_v factors have been estimated by classifying sites based on NEHRP for PI. The range of spectral period that has been used for F_a and F_v, respectively, is 0.01–0.15 s, and 0.15–1.0 s. F_v calculated in this study is less than NEHRP for seismic site class C and higher for seismic site class D. These site factors are further used in deriving the ADRS for the SI. NEHRP design spectra is predicting less SA value as compared to ADRS proposed in this study. The ADRS proposed in this study is predicting higher SA values as compared to IS 1893 (Part 1) (Bureau of Indian Standard) (2016). This is the first time such an extensive site response study has been done for determining the F_{PGA}, F_a, and F_v and ADRS for shallow sites in the PI.

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ORCID

P. Anbazhagan http://orcid.org/0000-0001-9804-5423

References

Aboye, S. A., R. D. Andrus, N. Ravichandran, A. H. Bhuiyan, and N. Harman. 2015. Seismic site factors and design response spectra based on conditions in Charleston, South Carolina. *Earthq Spectra* 31 (2): 723–44.

American Association of State Highway and Transportation Officials (AASHTO). 2011. *LRFD bridge design specifications*, second. 286. Washington, DC: AASHTO.

American Society of Civil Engineers (ASCE). 2010. *Minimum design loads for buildings and other structures*. Reston, VA: ASCE Standard. 7–10. 650.

Anbazhagan, P., A. Kumar, and T. G. Sitharam [2010] "Site response of deep soil sites in indo gangetic plain for different historic earthquakes," In: Proceedings of the 5th international conference on recent advances in geotechnical earthquake engineering and soil dynamics, San Diego, CA: Missouri University of Science and Technology.

Anbazhagan, P., A. Prabhakaran, H. Madhura, S. S. Moustafa, and N. S. N. Al-Arifi. 2017b. Selection of representative shear modulus reduction and damping curves for rock, gravel and sand sites from the KiK-Net downhole array. *Natural Hazards* 88: 174–1768. doi: 10.1007/s11069-017-2944-x.

Anbazhagan, P., A. Uday, S. R. Moustafa, and S. N. Al-Arifi. 2016c. Correlation of densities with shear wave velocities and SPT N values. *Journal of Geophysics and Engineering* 13: 320. doi: 10.1088/1742-2132/13/3/320.

Anbazhagan, P., K. Bajaj, G. R. Reddy, V. S. Phanikanth, and D. N. Yadav. 2016b. Quantitative assessment of shear wave velocity correlations in the shallow bedrock sites. *Indian Geotechnical Journal* 46 (4): 381–97. doi: 10.1007/s40098-016-0181-y.

Anbazhagan, P., M. Sreenivas, K. Bajaj, S. S. Moustafa, and N. S. N. Al-Arifi. 2016a. Selection of ground motion prediction equations for seismic hazard analysis of peninsular India. *Journal of Earthquake Engineering* 20 (5): 699–737. doi: 10.1080/13632469.2015.1104747.

Anbazhagan, P., M. N. Sheikh, and A. Parihar. 2013. "Influence of rock depth on seismic site classification for shallow bedrock regions," doi:10.1061/(ASCE)NH.1527-6996.0000088.

Anbazhagan, P., N. M. M. Sheikh, K. Bajaj, S. S. Moustafa, and N. S. N. Al-Arifi. 2017a. Empirical models for the prediction of ground motion duration for intraplate earthquakes. *Search Results* 21: 1001–21. doi: 10.1007/s10950-017-9648-2.

Anbazhagan, P., and T. G. Sitharam. 2008. Mapping of average shear wave velocity for Bangalore region: A case study. *Journal of Environmental and Engineering Geophysics* 13 (2): 69–84. doi: 10.2113/JEEG13.2.69.

Ansal, A., and G. Tonuk. 2007. Source and site factors in microzonation. In *Earthq geotech eng*, ed. K. D. Pitilakis, 73–92. Dordrecht: Springer.

Bajaj, K., and P. Anbazhagan. 2019a. Regional Stochastic Ground-Motion Model for low to moderate seismicity area with variable seismotectonic–Application to Peninsular India. *Bulletin of Earthquake Engineering* 17 (7): 3661–80. doi: 10.1007/s10518-019-00646-9.

Bajaj, K., and P. Anbazhagan. 2019b. Identification of shear modulus reduction and damping curve for deep and shallow sites: kik-net data. *Journal of Earthquake Engineering*. doi: 10.1080/13632469.2019.1643807.

Bajaj, K., and P. Anbazhagan. 2019c. Comprehensive amplification estimation of the indo gangetic basin deep soil sites in the seismically active area. *Soil Dynamics and Earthquake Engineering*. doi: 10.1016/j.soildyn.2019.105855.

Baker, J. W., and C. A. Cornell. 2006. Spectral shape, epsilon and record selection. *Earthquake Engineering & Structural Dynamics* 35 (9): 1077–95. doi: 10.1002/eqe.571.

Baker, J. W., T. Lin, S. K. Shahi, and N. Jayaram. 2011. "New ground motion selection procedures and selected motions for the PEER transportation research program," PEER rep. No 2011/xx. Berkeley: Pacific Earthquake Engineering Research Centre, College of Engineering, University of California, 2011.

Balakrishnan, T. S. 1997. Major tectonic elements of the Indian subcontinent and contiguous areas: A geophysical review. *Memoirs of the Geological Survey of India* 38: 18.

Balakrishnan, T. S., P. Unnikrishnan, and A. V. S. Murty. 2009. The tectonic map of India and contiguous areas. *Journal of the Geological Society of India* 74: 158–70. doi: 10.1007/s12594-009-0119-4.

Barani, S., R. Ferrari, and G. Ferretti. 2013. Influence of soil modeling uncertainties on site response. *Earthquake Spectra* 29: 705–32.

Boominathan, A., G. R. Dodagoudar, A. Suganthi, and R. U. Maheshwari. 2008. Seismic hazard assessment of Chennai city considering local site effects. *Journal of Earth System Science* 117 (S2): 853–63. doi: 10.1007/s12040-008-0072-4.

Boore, D. M. 2009. Comparing stochastic point-source and finite-source ground motion simulations: SMSIM and EXSIM. *Bulletin of the Seismological Society of America* 99: 3202–16. doi: 10.1785/0120090056.

Borcherdt, R. D. 1994. Estimates of site-dependent response spectra for design (methodology and justification). *Earthquake Spectra* 10: 617–54. doi: 10.1193/1.1585791.

Borcherdt, R. D. 2002. Empirical evidence for site coefficients in building-code provisions. *Earthquake Spectra* 18 (2): 189–218.

Building Seismic Safety Council (BSSC). 2003. *NEHRP recommended provisions for seismic regulations for new buildings and other structures—Part 1: Provisions, FEMA- 368; Part 2: Commentary*: FEMA-369Washington D.C:Federal Emergency Management Agency

Chatterjee, K., and D. Choudhury. 2013. Variations in shear wave velocity and soil site class in Kolkata city using regression and sensitivity analysis. *Natural Hazards* 69 (3): 2057–82. doi: 10.1007/s11069-013-0795-7.

Darendeli, M. B. [2001] "Development of a new family of normalized modulus reduction and material damping curves," Ph.D. Thesis, University of Texas, Austin.

Dickenson, S. E. [1994] "Dynamic response of soft and deep cohesive soils during the loma prieta earthquake of October 17, 1989," Ph.D. thesis, Department of Civil and Environmental Engineering, University of California, Berkeley

Dobry, R., R. Ramos, and M. S. Power. 1999. "Site factors and site categories in seismic codes" Technical Report MCEER-99-0010, 81 pp.

Electric Power Research Institute (EPRI). 1993. *Guidelines for Site specific ground motions*. Palo Alto, California: November, TR-102293.

Geological Survey of India (Officers of the). 1968. "A geological report on the koyna earthquake of 11th december 1967, satara district, maharashtra state," Unpublished Report (GSI) 242 pp. (Referred to in the text as GSI Report, 1968).

Ghofrani, H., G. M. Atkinson, and K. Goda. 2013. Implications of the 2011 M9.0 Tohoku Japan earthquake for the treatment of site-effects in large earthquakes. *Bulletin of Earthquake Engineering* 11: 171–203. doi: 10.1007/s10518-012-9413-4.

Ghosh, J. G., M. J. deWit, and R. E. Zartman. 2004. Age and tectonic evolution of Neoproterozoic ductile shear zones in the Southern Granulite Terrain of India, with implications for Gondwana studies. *Tectonics* 23 (TC3006). doi: 10.1029/2002TC001444.

Govindaraju, L., and S. Bhattacharya. 2012. Site-specific earthquake response study for hazard assessment in Kolkata city, India. *Natural Hazards* 61: 943–65.

Gupta, H. K. 2006. Stable continental regions are more vulnerable to earthquakes than once thought. *The Journal of Indian Geophysical Union* 10 (1): 59–61.

Hall, W. J., B. Mohraz, and N. M. Newmark. 1975. *Statistical studies of vertical and horizontal earthquake spectra*. Urbana, Illinois: Nathan M. Newmark Consulting Engineering Services.
Haselton, C. B., J. W. Baker, Y. Bozorgnia, C. A. Goulet, E. Kalkan, N. Luco, T. Shantz, N. Shome, J. P. Stewart, P. Tothong, et al. 2009. Evaluation of ground motion selection and modification methods: Predicting median interstory drift response of buildings. PEER Report 2009–01, Pacific Earthquake Engineering Research Center, University of California, Berkeley.
Hashash, Y. M. A., C. Phillips, and D. R. Groholski. 2010. "Recent advances in non-linear site response analysis," In: Proceedings of the 5th international conference on recent advances in geotechnical earthquake engineering and soil dynamics, San Diego, California
Hashash, Y. M. A., M. I. Musgrove, J. A. Harmon, D. R. Groholski, C. A. Phillips, and D. Park. 2017. *DEEPSOIL 7.0.5," user manual*. Urbana: Board of Trustees of University of Illinois at Urbana-Champaign.
Idriss, I. M. 1990. "Response of soft soil sites during earthquakes," Proc. H. Bolton Seed Memorial Symposium, Vancouver, Canada, May 9, J. M. Duncan (editor) 2: 273–90.
International Code Council (ICC). 2012. *International building code (IBC)*. VA: International Code Council.
IS 1893 (Part 1) (Bureau of Indian Standard). 2016. *Indian standard criteria for earthquake resistant design of structures*, Sixth. Revision. Bureau of Indian Standards: New Delhi.
Iyengar, R. N., and S. T. G Raghu Kanth. 2004. Attenuation of strong ground motion in Peninsular India; *Seismological Research Letters* 79 (5):530–40.
John, B., and C. P. Rajendran. 2008. Geomorphic indicators of neotectonism from the precambrian terrain of peninsular India: A study from the bharathapuzha basin Kerala. *Journal of the Geological Society of India* 71: 827–40.
Kamal,, and A. K. Mundepi. 2007. "Site response studies in Dehradun: First step towards microzonation," Natural hazards, spl vol IGC proceedings of Indian geological congress, Pune, India, pp. 175–81.
Kumar, A., P. Anbazhagan, and T. G. Sitharam 2012. "Site specific ground response study of deep indo-gangetic basin using representative regional ground motions," Geo-Congress, State of art and practice in Geotechnical Engineering. 2012. Oakland California, paper no. 1065.
Kwok, A. O., and J. P. Stewart. 2006. Evaluation of the effectiveness of theoretical 1-D amplification factors for earthquake ground-motion prediction. *Bulletin of the Seismological Society of America* 96: 1422–36. doi: 10.1785/0120040196.
Kwok, O. A., J. P. Stewart, Y. M. A. Hashash, N. Matasovic, R. Pyke, Z. Wang, and Z. Yang. 2007. Use of exact solutions of wave propagation problems to guide implementation of nonlinear seismic ground response analysis procedures. *Journal of Geotechnical and Geoenvironmental Engineering ASCE* 133 (11): 1385–98. doi: 10.1061/(ASCE)1090-0241-(2007)133:11(1385).
Maheshwari, R. U., A. Boominathan, and G. R. Dodagoudar. 2008. Nonlinear seismic response analysis of selected sites in Chennai. Proceedings of The 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG), Goa, India, October 1, pp. 2835–42.
Maheshwari, U. R., A. Boominathan, and G. R. Dodagoudar. 2010. Use of surface waves in statistical correlations of shear wave velocity and Penetration Resistance of Chennai soils. *Geotechnical and Geological Engineering* 28: 119–37. doi: 10.1007/s10706-009-9285-9.
Malekmohammadi, M., and S. Pezeshk. 2015. Ground motion site amplification factors for sites located within the Mississippi embayment with consideration of deep soil deposits. *Earthq Spectra* 31 (2): 699–722. doi: 10.1193/091712EQS291M.
Malhotra, P. K. 2006. Smooth spectra of horizontal and vertical ground motions. *Bulletin of the Seismological Society of America* 96 (2): 506–18. doi: 10.1785/0120050062.
Menq, F. Y. 2003. "Dynamic properties of sandy and gravelly soils," Ph.D. thesis, Department of Civil Engineering, University of Texas, Austin.
Mhaske, S. Y., and D. Choudhury. 2011. Geospatial countour mapping of shear wave velocity for Mumbai city. *Natural Hazards* 59: 317–27. doi: 10.1007/s11069-011-9758-z.
Motazedian, D., and G. M. Atkinson. 2005. Stochastic finite-fault modeling based on a dynamic corner frequency. *Bulletin of the Seismological Society of America* 95: 995–1010. doi: 10.1785/0120030207.

Naik, N., and D. Choudhury. 2013. “Site specific ground response analysis for typical sites in Panjim city, Goa”. Proceedings of Indian geotechnical conference, Roorkee, India.
Newmark, N. M., and W. J. Hall. 1982. Earthquake spectra and design. In *Earthquake engineering research institute*. Berkeley, CA: Earthquake Engineering Research Institute.
Parihar, A. [2014] “Seismic site classification and response studies of shallow bedrock site,” Ph.D. Thesis, Indian Institute of Science, Bengeluru.
Parihar, A., and P. Anbazhagan. 2020. Site Response Study and Amplification Factor for Shallow Bedrock Sites. *IndianGeotechnical Journal* https://doi.org/10.1007/s40098-020-00410-w.
Park, C., R. Miller, and J. Xia. 1998. “Imaging dispersion curves of surface waves on multi-channel record” Society of Exploration Geophysicists Expanded Abstracts, 1377–80
Park, C. B., R. D. Miller, J. Xia, and J. Ivanov. 2007. Multichannel analysis of surface waves (MASW)-active and passive methods. *The Leading Edge* 26: 60–64. doi: 10.1190/1.2431832.
Park, D., K. Dong, J. Chang-Gyun, and P. Taehyo. 2012. Development of probabilistic seismic site coefficients of Korea. *Soil Dynamics and Earthquake Engineering* 43: 247–60. doi: 10.1016/j.soildyn.2012.07.018.
Phillips, C., and Y. M. Hashash. 2009. Damping formulation for nonlinear 1D site response analyses. *Soil Dynamics and Earthquake Engineering* 29 (7): 1143–58. doi: 10.1016/j.soildyn.2009.01.004.
Prakash, E. L., S. Kolathayar, and R. Ramkrishnan [2018] “Seismic risk assessment for coimbatore integrating seismic hazard and land use,” In GeoShanghai International Conference, pp. 117–24, Springer, Singapore.
RaghuKanth, S. T. G., and R. N. Iyengar. 2007. Estimation of seismic spectral acceleration in peninsular India. *Journal of Earth System Science* 116 (3): 199–214. doi: 10.1007/s12040-007-0020-8.
Rai, S. S., K. Priestly, K. Suryaprakasam, D. Srinages, V. K. Gaur, and Z. Du. 2003. Crustal shear velocity structure of theSouth India shield. *Journal of Geophysical Research* 108: 2088. doi: 10.1029/2002JB001776.
Rajendran, C. P. 2000. Using geological data for earthquake studies: A perspective from peninsular India. *Current Science* 79: 1251–58.
Ramasamy, S. M. 2006. Remote sensing and active tectonics of south India. *International Journal of Remote Sensing* 27 (20): 4397–431. doi: 10.1080/01431160500502603.
Ramkrishnan, R., S. Kolathayar, and T. G. Sitharam. 2019. Seismic hazard assessment and land use analysis of mangalore City, Karnataka, India. *Journal of Earthquake Engineering* 1–22. doi: doi:10.1080/13632469.2019.1608333.
Rastogi, B. K. 1992. Seismotectonics inferred from earthquakes and earthquake sequences in India during the 1980s. *Current Science India* 62 (1–2): 101–08.
Roy, A. 2006. Seismicity in the peninsular indian shield: Some geological considerations. *Current Science* 91: 456–63.
Santosh, M., W. J. Xiao, T. Tsunogae, T. R. K. Chetty, and T. Yellapa. 2012. The neoproterozoic subduction complex southern India: SIMS zircon U–Pb ages and implications for gondwana assembly. *Precambrian Research* 192: 190–208. doi: 10.1016/j.precamres.2011.10.025.
Schnabel, P. B. [1973] “Effects of local geology and distance from source on earthquake ground motions,” Ph.D. Thesis, University of Calif., Berkeley.
Schnabel, P. B., J. Lysmer, and H. B. Seed 1972. “SHAKE—a computer program for earthquake response analysis of horizontally layered soil,” Report No. EERC-72/12, University of California, Berkeley
Seed, H. B., and I. M. Idriss. 1970. “Soil moduli and damping factors for dynamic response analyses,” Report No. EERC 70-10, Earthquake Engineering Research Center, University of California, Berkeley, 40p.
Sharma, K., and L. Deng. 2019. Reconnaissance report on geotechnical engineering aspect of the april 25, 2015, Gorkha, Nepal earthquake. *Journal of Earthquake Engineering* 23 (3): 512–37. doi: 10.1080/13632469.2017.1342299.
Sharma, K., M. Subedi, R. R. Parajuli, and B. Pokharel. 2017. Effects of surface geology and topography on the damage severity during the 2015 Gorkha, Nepal earthquake. *Journal of Lowland Technology International* 18 (4): 269–82.

Silva, W. J., S. Li, R. B. Darragh, and N. Gregor. 2000. *Surface geology based strong motion amplification factors for the san francisco bay and los angeles areas, prepared for PG&E PEER–task 5.B*. Berkeley, CA: Pacific Earthquake Engineering Research Center.

Stewart, J. P., A. H. Liu, and Y. Choi. 2003. Amplification factors for spectral acceleration in tectonically active regions. *Bulletin of the Seismological Society of America* 93 (1): 332–52. doi: 10.1785/0120020049.

Valdiya, K. S. 1973. Tectonic framework of India: A review and interpretation of recent structural and tectonic studies. *Geophysical Research Bulletin* 11: 79–114.

Vipin, K. S., P. Anbazhagan, and T. G. Sitharam. 2009. Estimation of peak ground acceleration and spectral acceleration for South India with local site effects: Probabilistic approach. *Natural Hazards Earth System Science* 9: 865–78. doi: 10.5194/nhess-9-865-2009.

Xia, J., R. D. Miller, and C. B. Park. 1999. Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves. *Geophysics* 64: 691–700. doi: 10.1190/1.1444578.

Zhang, J., R. Andrus, and C. H. Juang. 2005. Normalized shear modulus and material damping ratio relationships. *Journal of Geotechnical and Geoenvironmental Engineering ASCE* 131: 453–64. doi: 10.1061/(ASCE)1090-0241(2005)131:4(453).