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Development of smooth surface response spectra for the Intra and Inter plate region of India

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ABSTRACT: In the present study, acceleration design-response spectra (ADRS) for Intra and Inter plate region have been proposed for different seismic site classification as per NEHRP. Nonlinear site response analysis has been performed at different subsurface profiles and surface spectra have been derived. The site factors in terms of short period or 0.2 s (F_a) and long period or 1.0 s (F_v) for both the regions has been estimated. For different NEHRP site class, site factors are derived. Finally, using these site factors, ADRS for both the regions have been proposed. This is the first time such extensive study has been done for developing the ADRS for the Intra and Inter plate region of India for different seismic site class.

1 INTRODUCTION

Local site conditions have great influence on ground surface motion and structural damage caused by an earthquake event. The Indian subcontinent (IS) has one of the most diverse seismotectonic and seismicity. The high level of seismicity is associated with the Himalaya tectonic province will result in site amplification in the contiguous Indo-Gangetic deep alluvial deposits to the south, due to any major earthquake in future. Whereas, low to moderate level of seismicity in the Southern India causing high amplification due to shallow thin layers. Past earthquakes in India (1934 Bihar-Nepal; 2001, Bhuj; 2015 Nepal earthquake) have highlighted the influence of site amplification due to local site effect. However, in the present Indian standard code design spectrum is not based on seismic site classification with amplification coefficients like other modern codes viz. Eurocode or ASCE or IBC.

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 recent examples that explained the effect of thick deposits on site-specific damage in the Indian subcontinent. These local site effects should be quantified properly for minimizing the earthquake induced effects that depends on the accuracy of the site response analysis. Various researchers have studied the local site effect and estimated amplification factors considering shallow sites for the Indian subcontinent (e.g. Boominathan et al. 2008; Anbazhagan and Sitharam, 2008; Naik and Choudhury, 2013; Kumar et al., 2016 etc.). Most of these studies are either limited to soil column of 30 m depth or provided the lay out for the site-specific response analysis. Moreover, in the previous site response studies, the input ground motions were either selected randomly from global database or simulated based on the occurred earthquake scenario. Till today there are no comprehensive studies available for estimating and differentiating the local site effect for the deep and shallow deposits of IGB considering the measured V_s profiles for more than 100 m depth.

Hence in this study, the recorded ground motions at different locations in India are used to study the spectral signature of Intra and Inter plate region. Initially, the recorded rock ground motions have been used for developing the acceleration design response spectra at bedrock for both the regions by deriving the site factors. 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 adopted by the modern codes e.g. the AASHTO guide (AASHTO 2011) has been derived for both the regions. Further, the subsurface profiles have been classified based on NEHRP (BSSC, 2003) seismic site classification.

For each site class, surface spectra for both the regions have been determined using the non-linear site response analysis. Finally, the obtained surface response spectra for different site class has been used in deriving the respective site factors. This is the first time; such an extensive study has been done for developing the response spectra for the Intra and Inter plate region of India for different seismic site class.

2 STUDY AREA

For determining the new design response spectra for the IS both deep (the Indo Gangetic Basin) and shallow bedrock sites (the Southern India) are considered. The Indo Gangetic Basin (IGB) is the foredeep depression that is situated between the Indian Peninsular shield and the Himalayan region. IGB inhabits an area around 250,000 km^2 and lies roughly between longitude 74° E, and 88° E and latitude 24° N and 32° N (See Figure 1). Various researchers (e.g. Sastri et al., 1971) defined asymmetry in the basement thickness of the IGB High neotectonic activity and reactivation of tectonic features and lineaments are acknowledges by various researchers (e.g. Singh, 1996 etc.). Despite of surrounded by the active faults and ridges, IGB is contiguous to the most seismically active Himalayan region and experiencing the strong compressional stress conditions. Any large to moderate earthquake in the Himalayan region may result in massive destruction in the IGB due to site amplification and liquefaction.

Southern India (SI) is considered as one of the oldest geologically evolved and tectonically stable continental crust of the Indian subcontinent. The seismotectonic of the SI is majorly consist of various faults, ridges, shear zones and tectonic lineaments. Various researches (Rastogi, 1992; Ramaswamy, 2006) defined the tectonic feature of the SI. Additionally, SI is having an irregular seismicity. As, micro seismicity is reported in the South Granulite Terrain, Eastern Dharwar craton is surrounded by intermediate seismicity, and Koyna-Warna region and Deccan Volcanic Province has high seismicity. The SI is also marked in Figure 1.

3 SELECTION OF INPUT MOTION

Selection of bed-rock 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; and 1999, Chi-Chi etc. had been extensively used for the IS. Because of the lack of recorded ground motions, stochastically simulated ground motions are commonly used worldwide in any site response study (e.g. Baker and Cornell, 2006; etc.). Irrespective of approach 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

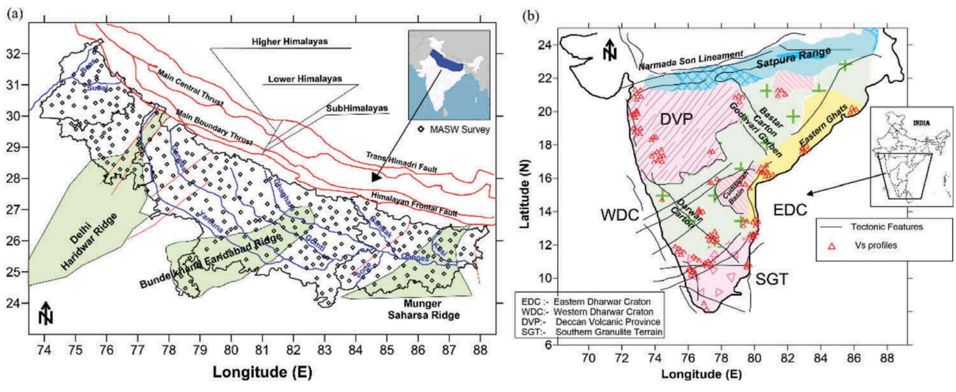

Figure 1. Study area and the location of subsurface profile used in the present study

governs 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.

The recorded ground motions at bedrock level are available for the Himalayan and southern India. For selecting the ground motion preliminary, the seismic hazard map for return period of 475 years at bedrock level for the IGB and SI has been used. The PGA for IGB and SI respectively vary from 0.03 to 0.24 g and 0.01 to 0.48 g respectively. The entire PGA variation of the IGB and SI has been divided into four bins see Table 1.

Anbazhagan et al. (2018) and Anbazhagan et al. (2017) collected the wide range of ground motion data respectively for the Himalayan and Stable continental region of the world including Peninsular India. For selecting the recorded ground motion, seismic hazard map at bedrock for return period of 475 years has been used. Fifty ground-motions that are occurred in the Himalayan region and recorded at rock sites have been used in IGB. Similarly, 50 ground-motions that are occurred in the Intraplate region (Australia, Canada and India) and recorded at rock sites have been used in SI. However, the recorded ground motions could not cover the entire range of PGA required for site response study. Hence the stochastically simulated ground motions are also used. 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).

4 SITE RESPONSE ANALYSIS

As IGB and SI lack in recorded ground motion data corresponding to different soil sites. Hence to derive the surface spectra for different soil types, detailed site response analysis has been carried out at different shear wave velocity (V_S) profiles measured in IGB and SI

(See Figure 1). To obtain the deep V_S in the IGB, both active and passive multichannel analysis of surface wave (MASW) survey has been carried out at 275 V_S profiles (See Figure 1a). In SI, both MASW and site-specific V_S and SPT-N relation have been used to get 125 shallow V_S profiles (See Figure 1 b). MASW test set up used in this study consist of 24 channels Geode seismograph in combination with 24 vertical geophones with the frequency of 4.5 Hz and 2.0 Hz. MASW survey has been carried out in both the regions by varying the geophones spacing from 1 to 5 m depending on the availability of space. For generating the active data, sludge hammer of 12 kg is strike ten times against a 30 cm x 30 cm plate, by varying the source offset distance as 5, 10, and 15 m. Passive roadside survey has been used by considering different sampling intervals (2 ms to 8 ms) and recording times (30 sec to 120 sec) are used to enhance the dispersion curve quality. To obtain the V_S profiles at each location window-based programs named 'SurfSeis 5′ and 'ParkSEIS 2′ have been used. Details information about the processing of the recorded raw data can be refereed from Park et al. (2008) and Xia et al. (1999). Out of 275 profiles, more than 60 % of the profiles have V_{S30} between 183 to 357 m/s. The details about the variation of V_S in the entire IGB can be referred from Bajaj and Anbazhagan (2018). The depth of soil column varies from 4 to 34 m in the SI. More detail about the V_S profiles in the SI can be referred from Anbazhagan et al. (2016).

Shear modulus (G/G_{max}) and damping curve, and input ground motion are another critical parameter for any site response study. For rock, gravel, sand and clay predominate profiles,

Table 1. Bins of PGA used for selecting ground motions for the IGB and SI

	IGB		SI	
1	GI1	0.03 to 0.08 g	GS1	0.01 to 0.05 g
2	GI2	0.08 to 0.13 g	GS2	0.05 to 0.13 g
3	GI3	0.13 to 0.18 g	GS3	0.13 to 0.20 g
4	GI4	0.18 to 0.24 g	GS4	0.20 to 0.48 g

EPRI (1993), Menq (2003), Zhang et al. (2005) and Darendelli (2001) G/G_{max} and damping ratio respectively has been used (Bajaj and Anbazhagan, 2018 b).

For performing the one-dimension non-linear site response analysis, DEEPSOIL (2017) has been used. Each ground motion is inputted at the bottom most layer having V_S equal to 1500 m/s (Ghofrani et al., 2011). For each site, 10 input ground motion has been selected based considering the PGA value at bedrock. Hence in total 275 × 10 = 2750 and 125 × 10 = 1250 nonlinear analysis have been carried out to comprehend the site response characteristics of the IGB and SI respectively. Spectral parameters at surface have been estimated and further used for determining the surface response factor and site amplification factors.

5 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. IBC (2003) proposed the site coefficients for short period (corresponding to 0.2 s spectral period) F_a and long period (corresponding to 1 s spectral period) F_v. Whereas, in BIS:1893 (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 +1σ amplification values (Dobry et al., 1999). In IBC, F_a is estimated for the short-period band 0.1–0.5 sec, whereas, F_v is defined over the long-period band 0.4–2.0 sec (Dobry et al., 1999). Various authors (e.g. Park et al., 2012; Aboye et al., 2015) commented on the wide range of period band for estimating the site coefficients by Borcherdt (1994) and Dobry et al. (1999). Hence, determining the period range is vital part for calculating site-specific F_a and F_v values. Different vibration period bins of F_a and F_v are analyzed for better match of the surface spectra for a site. Based on the analysis, the range of spectral period that resulted in the best match is 0.01-0.35 s for F_a and 0.35-1.25 s for F_v in case of the IGB. 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 in case of the SI. The site factor representing zero period i.e. F_{PGA} is also determined. For a site class, at each spectral period, lognormal median of spectral values (RS_{soil}) is calculated using equation 1. Ratio of this median surface acceleration (RS_{soil}) to rock spectral acceleration (RS_{rock}) for each site period is calculated. In the present study R_{Soil}/R_{Rock} is assumed to 1.0 in equation 2, 3, 4 and 5 as the hypocentral distance for rock and soil station is similar.

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

$$F_{aI} = \frac{R_{soil}}{R_{rock}}\frac{1}{0.34}\int_{0.01}^{0.35}\frac{RS_{soil}(T)}{RS_{rock}(T)}dT \tag{2}$$

$$F_{vI} = \frac{R_{soil}}{R_{rock}}\frac{1}{0.9}\int_{0.35}^{1.25}\frac{RS_{soil}(T)}{RS_{rock}(T)}dT \tag{3}$$

$$F_{aS} = \frac{R_{soil}}{R_{rock}}\frac{1}{0.14}\int_{0.01}^{0.15}\frac{RS_{soil}(T)}{RS_{rock}(T)}dT \tag{4}$$

$$F_{vS} = \frac{R_{soil}}{R_{rock}}\frac{1}{0.85}\int_{0.15}^{1.0}\frac{RS_{soil}(T)}{RS_{rock}(T)}dT \tag{5}$$

The F_{aI} and F_{vI} values for equation 2 and 3 is corresponding to the IGB, whereas F_{aS} and F_{vS} values for equation 4 and 5 corresponding to the SI. The calculated F_a and F_v for the IGB and SI are respectively given as Tables 2 and 3.

F_{aI} and F_{vI} calculated in this study is higher than NEHRP in case of the IGB. For site class C, for GI3, F_{aI} and F_{vI} calculated in this study is 1.61 and 2.48 respectively, however as per NEHRP estimated F_a and F_v 1.2 and 1.68 respectively. Further these values are compared with the deep soil site response study carried out by Aboye et al. (2015) and Malekmohammadi and Pezeshk (2015). For site class E with V_{S30} equal/less than 180 m/s and PGA between 0.03 to 0.08 g, F_a and F_v values calculated from Aboye et al. (2015) are 1.98 and 3.32 which is lower as compared to the present study (See Table 2) Similarly, for site class E, with V_{S30} equal to 180 m/s and PGA between 0.03 to 0.08 g, F_a and F_v values calculated from Malekmohammadi and Pezeshk (2015) and present study respectively are 1.592 and 4.390, and 3.063 and 4.159. F_a value calculated in this study has significant variation as compared to the NEHRP, Aboye et al. (2015) and Malekmohammadi and Pezeshk (2015).

F_{aS} and F_{vS} values calculated in this study is higher as compared to NEHRP. For site class C, for GS3, F_{aS} and F_{vS} 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_{vS} calculated in this study is less than NEHRP for seismic site class C and higher for seismic site class D. Similarly, Borcherdt (2002), and Stewart et al. (2002) 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 (2014). 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 3).

The site factors derived in this study is recommended only for constructing Acceleration design response spectra (ADRS) for the IGB. The F_{PGA}, F_a and F_v values derived in this study is different from previous study may be due to (1) difference in input layer; (2) region-specific ground motions data; and (3) representative region-specific input parameters. Based on the overall analysis, the major factors that affects the site coefficients are depth of input motion, shear wave velocity of a soil column, G/G_{max} and damping ratio curves.

Table 2. Proposed site coefficients for all the four groups with respect to sites for the IGB.

	Class E			Class D			Class C			Class B		
	F_{PGA}	F_{aI}	F_{vI}	F_{PGA}	F_{aI}	F_{vI}	F_{PGA}	F_{aI}	F_{vI}	F_{PGA}	F_{aI}	F_{vI}
GI1	3.013	3.063	4.159	1.869	2.310	3.287	1.422	1.938	2.887	1.015	1.305	1.933
GI2	2.710	2.749	3.839	1.680	2.184	2.894	1.354	1.793	2.609	1.013	1.305	1.765
GI3	2.595	2.521	3.206	1.572	2.092	3.023	1.314	1.609	2.483	1.010	1.261	1.561
GI4	2.321	1.586	2.765	1.362	1.324	2.161	1.290	1.022	1.246	1.001	1.016	1.048

Table 3. Proposed site coefficients for all the four groups with respect to sites for the SI.

	Class D			Class C			Class B		
	F_{PGA}	F_{aS}	F_{vS}	F_{PGA}	F_{aS}	F_{vS}	F_{PGA}	F_{aS}	F_{vS}
GS1	-	-	-	-	-	-	2.084	2.183	1.285
GS2	2.314	3.045	3.106	2.147	2.264	1.507	2.012	1.985	1.202
GS3	2.014	2.607	2.223	1.945	2.057	1.442	1.878	1.855	1.138
GS4	1.847	1.822	1.957	1.745	1.656	1.352	1.592	1.557	1.141

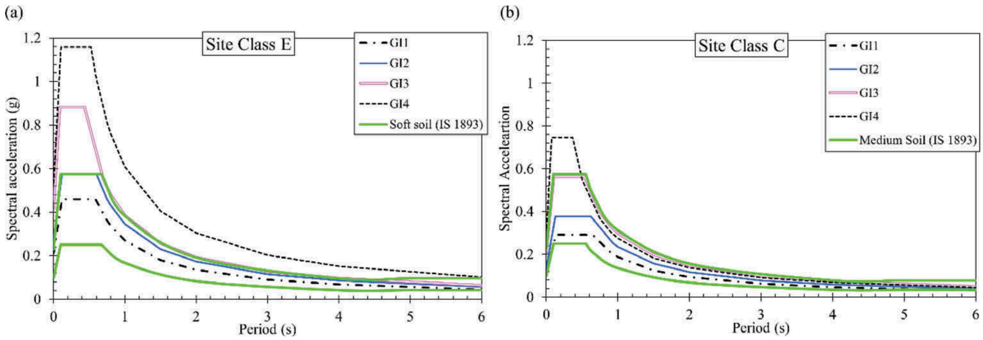

Figure 2. Typical acceleration response spectrum for (a) Seismic site class E and (b) Site Class C with BIS:1893 (2016)

6 PROPOSED ACCELERATION DESIGN RESPONSE SPECTRA

The site coefficients determined in this study has been further used for developing the acceleration design response spectra for any site in the SI with known seismic site class. The procedure outlines in 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 sec (S_S) and SA at 1.0 sec (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; (4) three points of acceleration design response spectra (ADRS) can be derived as

$$PGA = PGA_{BR} \times F_{PGA} \tag{6}$$

$$S_{DS} = F_a S_S \tag{7}$$

$$S_{D1} = F_v S_1 \tag{8}$$

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 2 shows the comparison of ADRS for site class E and site class C constructed using F_{PGA}, F_{aI} and F_{vI} derived in this study. The PGA value used in comparison for group GI1, GI2, GI3 and GI4 respectively is 0.07, 0.1, 0.16 and 0.23 g. ADRS for site class E and C is compared with the ADRS of soft and medium soil for IS-1893 (2016) respectively. Figure 3 shows the comparison of ADRS for site class C and D developed using F_{PGA}, F_{aS} and F_{vS}. The PGA value used in comparison for group GS2, GS3 and GS4 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 (2016) respectively. It has observed that for the same PGA value, ADRS constructed using IS-1893 is underestimating the spectral acceleration values at short period and overestimating at long period in both the cases

7 CONCLUSION

In the present study, non-linear site response analysis has been carried out for deep and shallow profiles in the IGB and SI. The input ground motions are selected based on seismic hazard map developed considering return period of 475 at bedrock. The bedrock PGA of 0.03-0.24 g increased to 0.1-0.75 g at surface in case of the IGB. The average surface amplification of 1.04 to 4.32 has been observed in the SI. The site factors F_{PGA}, F_a and F_v factors have been estimated by classifying sites based on NEHRP for the IGB and SI. F_a and F_v have been calculated for period range 0.01-0.35 s and 0.35-1.25 s respectively. 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 in case of SI.

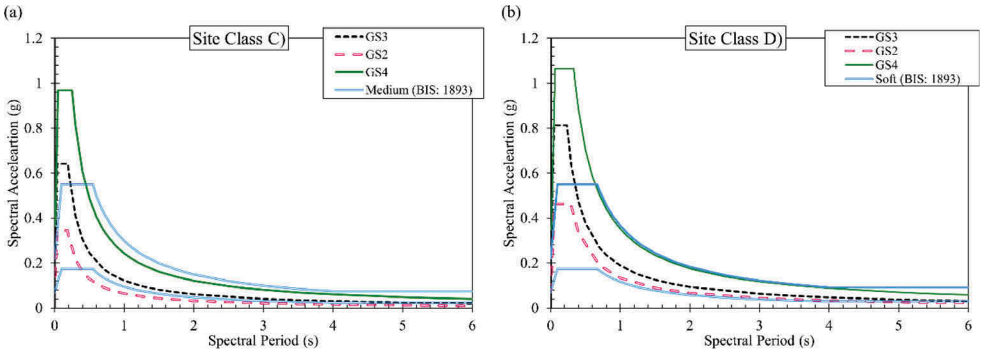

Figure 3. The typical variation of the proposed ADRS with the BIS:1893 (2016) for seismic site class C and D as per NEHRP

The newly derived site factors for IGB and SI is more representative than NEHRP as region parameters are used to arrive results. Considering the newly derived site factors, ADRS for IGB and SI have been derived. It has further observed that for the same PGA value, ADRS constructed using IS-1893 is underestimating the spectral acceleration values as compared to present study for deep and shallow basins. This is the first time such an extensive study has been done for determining the F_{PGA}, F_a and F_v and ADRS for deep sites in the IGB and SI.

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