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ORIGINAL PAPER

Prediction of different depth amplifications of deep soil sites for potential scenario earthquakes

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Abstract

Deep soil basin is one of the geographical features which significantly alter the response to earthquakes. Around the world, there are regions where bedrock is at a substantial depth upon which are different layers of soil. Larger depths of soil alter the response toward earthquakes and have been reported in the past. Indo-Gangetic Basin (IGB) of India is one of the seismically vulnerable deep soil basins of the Asian continent. The present paper attempts to study the site amplifications in IGB at the surface and different depths to understand the amplification behavior of the deep soil basins worldwide. Sixteen different probable scenario earthquakes are identified based on past seismic gaps, history and seismic studies and simulated at 270 sites covering whole deep soil region of the IGB. Representative depths of input motion, density, shear wave velocity, location of the water table, suitable shear modulus reduction and damping curves have been used. One-dimensional nonlinear site response analysis was carried out using DEEPSOIL. Peak ground acceleration (PGA), peak spectral acceleration (PSA), amplification factors using the ratio of zero period, peak spectral acceleration, site factors F_a and F_v as per the National Earthquake Hazards Reduction Programme (NEHRP) and spectral accelerations at specific periods of 0.2 and 1 s are calculated and deliberated at the surface and also at different layers up to 100 m depth. Maps for spatial variation in average and maximum values of amplification as well as site factors have been presented. Average values of F_{PGA}, F_{PSA}, F_a and F_v at the surface were found in the range of 1.16–7.94, 1.13–7.93, 1.43–7.89 and 2.11–7.51, respectively. Around 14% of sites in the IGB have amplification values at subsurface levels exceeding those at corresponding surface levels. Amplifications observed at the subsurface level are less than that of the surface for a considerable number of sites.

Keywords Seismic amplification · PGA · PSA · F_a · F_v · F_{PGA} · F_{PSA} · Indo-Gangetic Basin · Spectral amplification · Site response studies · Site factors

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1 Introduction

Ground response analyses are meant to determine how soil deposits respond to the hard layer or bedrock motions where there are no significant changes in ground motion parameters. Soil amplification studies estimate the effects of local soil conditions on various parameters like amplitude and frequency content of seismic motions. Geometry and subsurface material properties of soil, the topography of the site, input motion characteristics are some of the main factors which determine the extent of influence on input motions (Kramer 1996). It has been observed that soft sediments experience larger earthquake damages in comparison to firm rock outcrops. This is evident from numerous past earthquakes like 1995 Kobe, 1994 Northridge, 1989 Loma Prieta and 1985 Mexico City earthquakes. In India, some major earthquakes (2015 Nepal, 2001 Bhuj, 1934 Bihar–Nepal, etc.) have also signified the role of local site conditions, affecting the level of damage caused to the existing infrastructure. Ground motions amplified in layers of sediment beneath buildings are responsible for huge damage levels despite the earthquake being relatively distant and only moderate in size. Considering earthquake damages due to site amplification, the study of seismic hazard and ground response is essential. It has become mandatory for the design of important structures in any seismically active area across the globe.

Recently in India, several site-specific response studies and estimation of amplification values have been attempted. But a considerable number of ground response analyses for different areas in India were carried out after 2004 (Sitharam et al. 2007). Majority of these (Kumar et al. 2016, Jishnu et al. 2013, Kumar et al. 2012, Hanumantha Rao and Ramana 2008, Kamatchi et al. 2008, Mahajan et al. 2007) are limited to the use of soil data up to 30 m depth. Also, Mahajan et al. (2007), Govindaraju and Bhattacharya (2008), Phanikanth et al. (2011), Kumar et al. (2013), and Jishnu et al. (2013) considered a limited number of locally recorded ground motions while Kumar et al. (2016) used ground motions that were recorded worldwide for the site response study irrespective of the seismic background of IGB**.** Different researchers (Anbazhagan and Sitharam 2008, Boominathan et al. 2008, Kamatchi et al. 2008, Hanumantha Rao and Ramana 2008 and Kumar et al. 2013) stochastically simulated the ground motions considering regional seismicity and seismotectonic parameters for site characterization and site response studies.

IGB is a geologically active area of sedimentation mostly filled with soft and thick alluvial deposits close to the very active seismological plate boundary, Himalayan belt. It has experienced devastating earthquakes in the past, which caused absolute destruction to local infrastructure and incurred severe losses to life. However, limited attempts have been made to estimate the effects of local site conditions amplifying the intensity of earthquake shakings. Also, the current Indian seismic code lacks provisions for site amplification and soil liquefaction for the design of structures in the region. Till present, no comprehensive studies have been carried out to estimate the effects due to local site conditions at various depths or layers which arise due to the presence of deep soil deposits in the IGB. The main objective of this study is to estimate site-specific amplifications at 270 sites throughout the IGB at the surface as well as different depths due to scenario earthquake motions possible in the region. Till now, only randomly selected worldwide or locally recorded earthquake motions have been utilized. For the first time, we have attempted to carry out site response analysis using site-specific ground motions by systematic simulation of futuristic earthquakes. The present study was performed using measured shear wave velocities (Vs) as described by Bajaj and Anbazhagan (2019a) while considering representative density from Vs of each layer as per Anbazhagan et al. (2016), reliable depth level of input motion as per Bajaj and Anbazhagan (2019b) and selected shear modulus reduction and damping curves as suggested by Anbazhagan et al. (2017) and Bajaj and Anbazhagan (2019d). Site-specific response parameters, viz. peak ground acceleration (PGA), spectral acceleration (PSA), amplification factors, viz. zero periods of spectral acceleration (F_{PGA}), peak spectral acceleration amplification (F_{PSA}), are evaluated. At the surface, spectral amplification factors corresponding to specific periods of 0.2 s and 1 s have also been estimated. Site factors (F_a and F_v) as per the NEHRP guidelines have also been presented at the surface and different depths. Average and maximum values of amplification factors and site factors are estimated for the first time at the surface as well as the multiple depth levels of 5, 10, 20, 50 and 100 m. It was observed for large portions of IGB that F_{PGA}, F_{PSA}, F_a and F_v , at surface, varied in the range of 3–6, 2–6, 3–6 and 5–8, respectively. The observed variations in amplification with depth can be related to other deep soil basins worldwide, and therefore, other deep sites also need further investigations. In the present study, we found that IGB sites show more amplifications for longer periods as compared to short periods. This is well in accordance with a higher natural period of deep soil sites.

2 Study area and earthquakes

The IGB (shown in Fig. 1) was formed as a result of post-collision between the Indian and the Asian plates. It is a well-known foredeep depression and was formed during the Cenozoic growth of the Himalayas. The Ganga Plain occupies an area of around 2,50,000 km^2 and lies more or less within longitudes 77°E and 88°E and latitudes 24°N and 30°N (Bajaj 2019). IGB is an active area of sedimentation and is receiving a considerable amount of sediments from the Himalayan highland. In India, IGB stretches across the states of Punjab, Haryana, Bihar and Uttar Pradesh (UP). The sedimentation of the Punjab region can be divided into (1) Older alluvium, (2) Newer alluvium, (3) Aeolian deposits (Bajaj 2019).

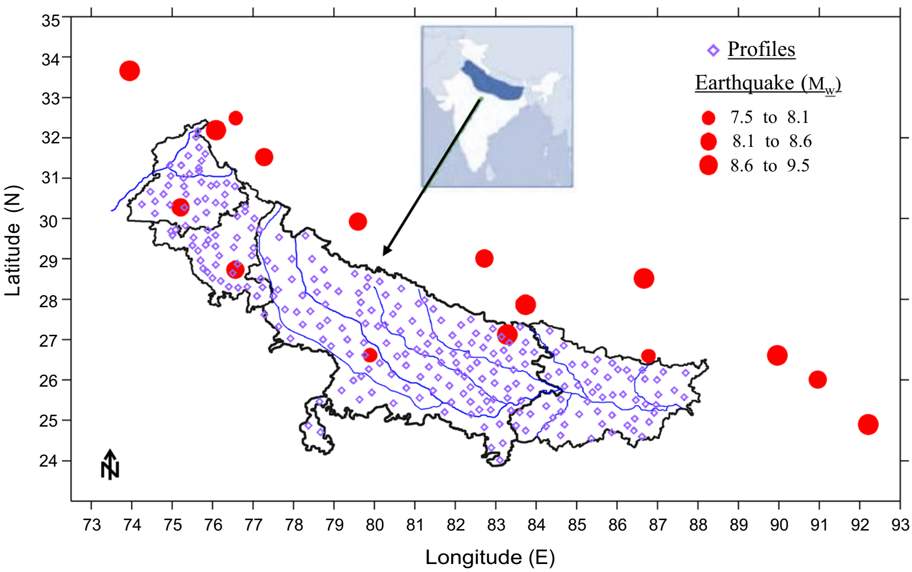


Fig. 1 Sites considered in IGB and 16 scenario earthquakes

Additionally, IGB is under heavy seismic risk because of its nearness to the seismically active Himalayan Belt. Extensive damage has been reported in the basin due to past earthquakes (Ambraseys 2000). Das et al. (2006) described the Indo-Gangetic basin as a moderately active region when compared to the regions of Himalayas. Authors also examined that strike-slip faults are the main cause of earthquakes in the region. Several researchers worked on the seismicity of the Himalayan region and few also on ground motion prediction equations (GMPEs), seismic hazard analysis and site response studies. National Disaster Management Authority (India) NDMA (2011) and Nath and Thingbaijam (2012) developed the Probabilistic Seismic Hazard Analysis (PSHA) map for whole India considering areal sources. NDMA (2011) revealed that PGA varies from 0.04 to 0.12 g and 0.03 to 0.05 g throughout IGB for 2 and 10% probability of exceedance in 50 years, respectively. Nath and Thinbaijam (2012) arrived at PGA values of 0.08–0.3 g and 0.2–0.8 g for this seismic study area for a return period of 475 and 2475 years, respectively. Rahman et al. (2018) predicted the hazard value for IGB as 0.04–0.21 g and 0.07–0.31 g for 10 and 2% probability of exceedance in 50 years. Bajaj (2019) also worked out seismic hazard analysis of IGB and reported that PGA value varies from 0.06 to 0.58 g and 0.04 to 0.22 g, respectively, for 2 and 10% probability of exceedance in 50 years, employing the best suitable GMPEs by systemic selection and analysis.

The literature clearly shows that seismicity of a Himalayan region can cause considerable earthquake hazards such as ground motion amplification, ground failures and liquefaction in IGB (Ambraseys 2000, Hough and Bilham 2008). So, understanding the seismic hazards in IGB is necessary. After reviewing the seismicity of North India, about 16 possible scenario earthquakes were identified with potential maximum size arrived based on multiple approaches by Bajaj (2019). Few studies were carried out to measure the dynamic properties of IGB soil columns. Hough and Bilham (2008) developed Medvedev–Sponheuer–Karnik (MSK) intensity maps and showed 1– 3 units and even higher intensity in the basin. The value of 3 was observed close to floodplains and river banks. Srinagesh et al. (2011) also concluded amplification in PGA by a factor of 2–4 due to the presence of softer materials in the IGB. These results were arrived based on limited data and analysis without knowing proper shear wave velocity profiles of IGB sites. Bajaj and Anbazhagan (2019a) carried out passive and active Multichannel Analysis of Surface Wave (MASW) tests and measured shear wave velocity up to a depth of 500 m and at times reached a depth where Vs value of 1500 m/s or more was observed. In this study, scenario ground motions at bedrock are generated at each of the 270 sites (marked in Fig. 1) whose shear wave velocities were measured by Bajaj and Anbazhagan (2019a). The spatial variations in between the sites have been achieved using interpolation. Despite the large distance between the study sites, this study marks the first comprehensive attempt to study deep soil basin for scenario earthquakes in the world, including India, as well. Simulation procedure and data analysis are discussed in the subsequent sections.

3 Simulation of input ground motions

Input ground motions play a major role in amplification, spectral shape and other response parameters. Ground motion records that we use in any geotechnical analysis including site response studies should describe the potential earthquake hazards at the site, i.e., magnitude, hypocentral distance, source mechanism, site conditions, directivity and other related effects. In this regard, many factors are considered while selecting earthquake motions to establish better results. The ISO 19,901–2 (2017) appendix states that during the selection of earthquake records, the tectonic setting and the site conditions of the past records should match with those of the structure's site. According to Ansal et al. (2012), set of motions selected for site-specific studies need to be scaled to the target spectrum for better compatibility with the records. The Federal Emergency Management Agency (FEMA) suggests that selecting motions with similar spectral shapes to that of target spectrum reduces the need for scaling and modification to perform analysis (Haselton et al. 2012). In the absence of recorded ground motions, researchers across the world make frequent use of stochastically simulated ground motions in site response studies (Ansal and Tonuk 2007, Baker and Cornell 2006). Frequency content, duration and amplitude are the main input motion characteristics that usually govern the response of any soil deposit. Hence, it may not be a reliable way of estimating site amplification considering only amplitude using seismic hazard analysis or seismic hazard disaggregation. So, in this study, 16 potential earthquakes of maximum possible magnitudes (shown in Fig. 1) originating in and around the IGB have been identified based on the recommendations from the literature (Das et al. 2006) and have been synthetically simulated at 270 sites of the study area. Region-specific seismotectonic parameters derived and adopted by Bajaj and Anbazhagan (2019c) have been considered to simulate the earthquakes ranging from M_w 7.5 to 9.0. The details regarding the location, magnitude, strike and dip of scenario earthquake sources used in the study are presented in Table 1. More discussion about seismotectonic parameters and its application in simulation of ground motions in the region can be found in Bajaj and Anbazhagan (2019c). The earthquake motions are purposely selected, taking into account the possibility of earthquakes affecting the IGB in future. To arrive at better results, the ground motions were simulated at each site based on region-specific seismotectonic parameters and using Finite-Fault stochastic model (EXSIM), introduced by Motazedian and Atkinson (2005) and further modified by Boore (2009). When hypocentral distance exceeds a particular limit, surface waves

Table 1 Coordinates and other related parameters of different earthquake sources

Latitude (°N)	Longitude (°E)	Earthquake origin	Strike (°)	Dip(°)	Magnitude (M_w)
26.6	79.9	Rind River, Uttar Pradesh	318	30	7.5
32.5	76.6	Dhar Samel, Himachal Pradesh	322	55	7.8
26.61	86.82	Bakdhauwa, Nepal	100	30	8.0
26.0	91.0	Dhontola, Assam	292	40	8.1
31.5	77.3	Jhamach, Himachal Pradesh	317	14	8.2
30.26	75.21	Bathinda, Punjab	270	15	8.3
29.9	79.62	Garhser, Uttarakhand	280	7	8.4
28.7	76.59	Jhajjar, Haryana	305	12	8.5
28.99	82.75	Sunhoo, Nepal	295	11	8.5
28.5	86.7	Tingri, Xigaze, Tibet, China	108	75	8.6
27.87	83.79	Gejha, Rampur, Nepal	270	15	8.6
32.2	76.1	Laharn, Himachal Pradesh	299	19	8.6
33.71	73.97	J&K	318	29	8.8
27.12	83.33	Pokhar Bhinda, Uttar Pradesh	260	13	8.8
26.6	90	Gurufela F.V., Assam	216	72	9.0
24.89	92.25	Karimganj, Assam	253	20	9.0

start dominating. Here, geometric spreading with a transition distance of 40 km has been used as an input parameter to represent a transition to surface wave spreading. Low time step duration of 0.02 s is employed to reduce the potential errors in current site response studies (Phillips et al. 2012). Figure 2a shows acceleration time histories of few simulated ground motions for a typical IGB site. These synthetic motions possess a wide range of frequencies, durations and PGAs, also depicted in the figure. Figure 2b shows simulated acceleration time histories at different study sites corresponding to a particular scenario earthquake of M_w 8.8. It also illustrates the variation in PGA with hypocentral distance for a particular earthquake. Generally, PGA decreases as we move away from the earthquake location. However, many times, lesser PGA is observed at nearby sites compared to the distant ones which may be due to different geological properties along different paths and the directivity of the fault rupture.

Throughout the IGB, the simulated input motions have a wide range of bedrock PGA varying from 5.1×10^{-5} g to 0.651 g. Figure 3a shows the maximum possible bedrock PGA over the IGB due to the 16 earthquakes, and Fig. 3b shows the bedrock PGA distribution due to an earthquake of M_w 8.5. From Fig. 3b, it is observed that at sites far from the epicenter, PGA reduces significantly**.** Analyzing any profile for which input PGA is very low yields insignificant results in the site response studies. Therefore, it is necessary to acknowledge selecting a minimum input PGA level. It may be noted here that there is no clear approach toward selecting ground motions for site response studies based merely on bedrock PGA. The FEMA suggests that surface PGA greater than 0.1 g affects ordinary structures (Arnold 2006). The value has been suggested considering structures built as per the US standard construction practices. Taking into account the substandard Indian construction practices and engineering and non-engineering structures in the region, we concluded that even a surface PGA less than 0.01 g in the study area may affect the existing

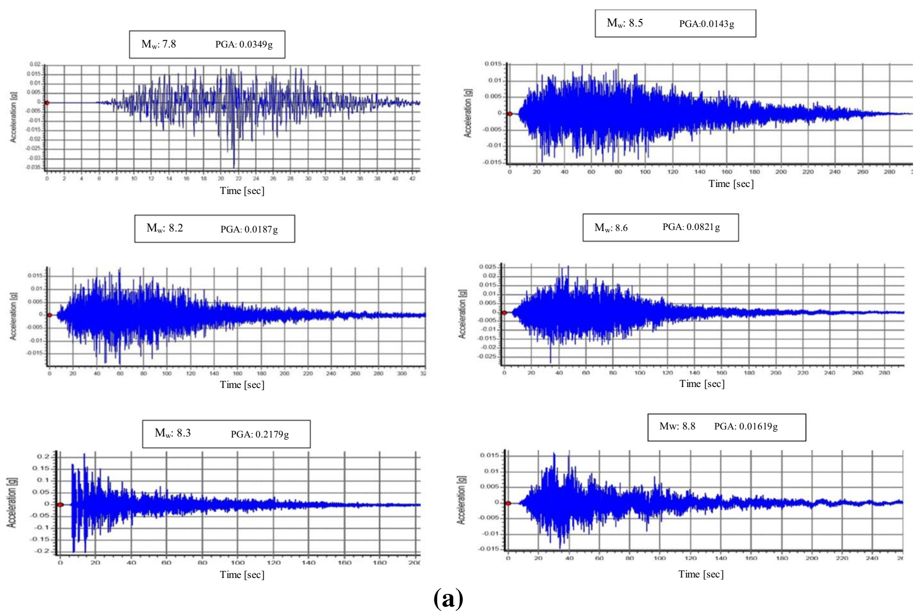
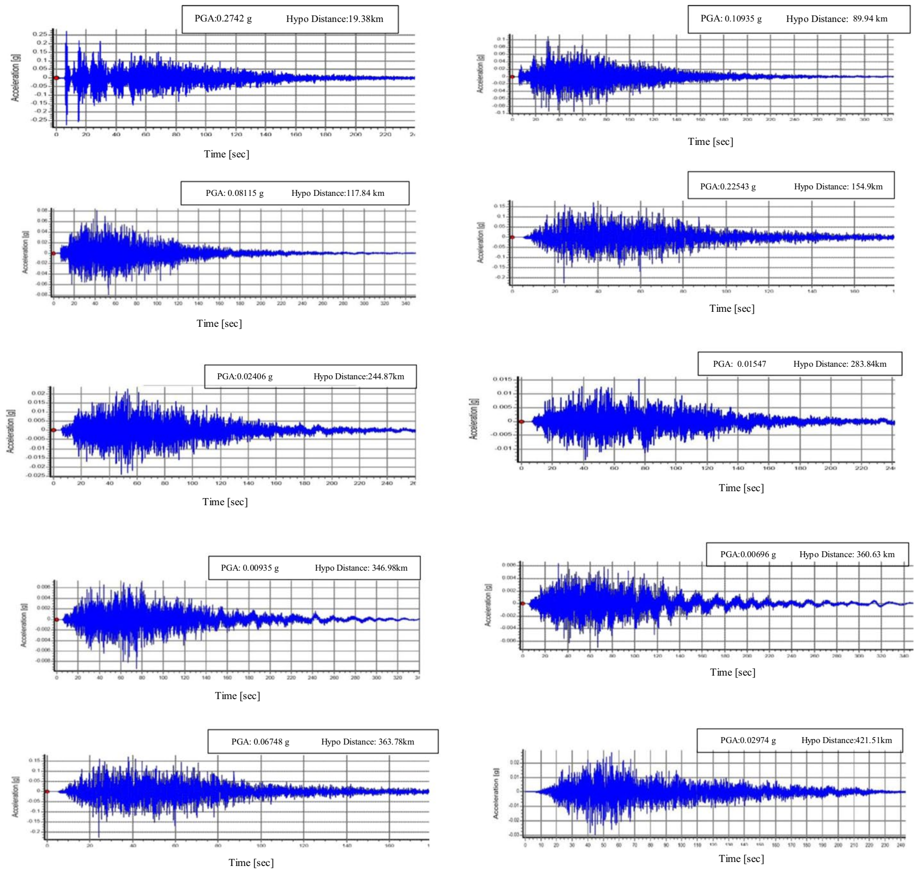


Fig. 2 **a** Acceleration time histories of different simulated motions at a typical IGB site. **b** Acceleration time histories due to a single synthetic earthquake at some typical IGB sites



(b)

Fig. 2 (continued)

structures. So, all the ground motions with bedrock PGA ≥ 0.005 g have been inputted to record the site response at each study location. Figure 3c shows the variation in average PGA values of such earthquake motions. This also accounts for any earthquake motion which may get highly amplified despite low bedrock PGA. Major simulation input parameters, as used by Bajaj and Anbazhagan (2019c) including stress drop, focal depth, duration, fault dimensions, etc., are listed in Table 2.

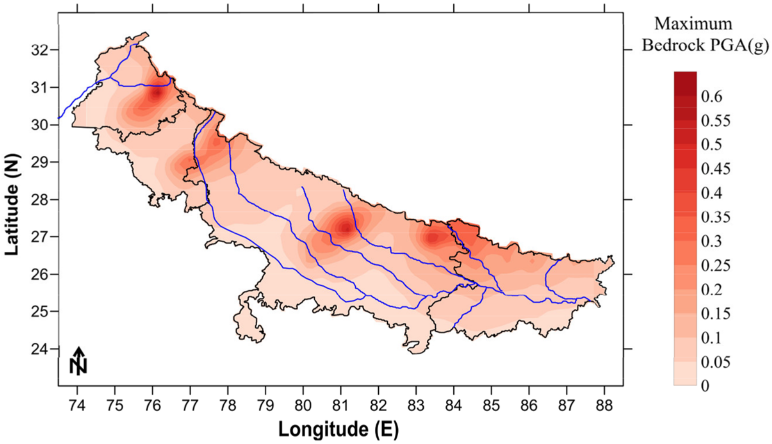
4 Input soil parameters for site response studies

Dynamic properties of soil are essential parameters in analyzing the soil behavior and its earthquake interaction. Apart from ground motion parameters, input soil parameters and method of analysis also determine the accuracy of site response results. Important soil parameters include layer thickness, shear-wave velocity, density, soil model (shear modulus reduction and damping curves) and depth of input motion. So, at each site, it becomes imperative to assign depth of input motion, representative shear modulus

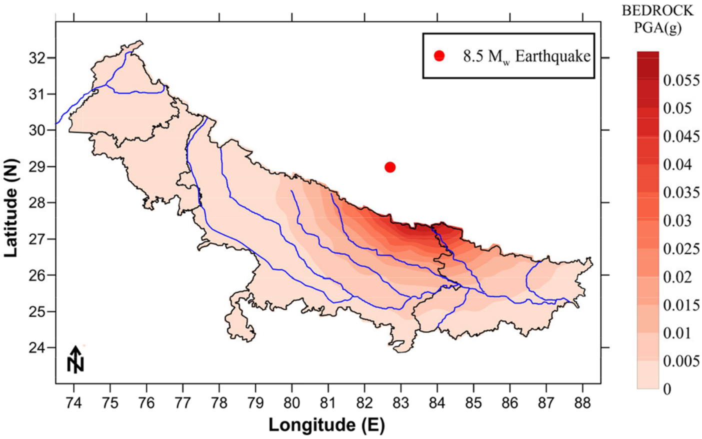
Fig. 3 **a** Variation in maximum possible bedrock PGA over IGB from all 16 potential scenario earthquakes. ▶ **b** Bedrock PGA distribution of single simulated potential earthquakes of M_W 8.5 throughout IGB. **c** Variation in average bedrock PGA over IGB from all 16 potential scenario earthquakes

reduction and damping ratio curves, density of soil layers, shear wave velocity, pore water pressure generation and location of the water table to obtain reliable results. Most of the studies related to the Indian subcontinent are usually confined to a soil column of only 30 m depth or borehole termination depth less than 50 m or depth corresponding to shear wave velocity of layer less than 760 m/s ± 10% within 70 m of depth. Bajaj and Anbazhagan (2019b) reported that inputting ground motions at the soil layer where Vs value < 1500 m/s do not predict reliable amplification at deep soil sites. In this study, ground motions are inputted at layers having shear wave velocity ≥ 1500 m/s to estimate local site effects. Figure 4 shows depths of input as used by Bajaj and Anbazhagan (2019b). Spatial variation in depth of input motion is relatively complex over the area. Minimum input depth is about 50 m located in the southern part of the IGB and maximum of 300 m, north of the IGB. In the regions of Punjab and Haryana, shear wave velocities Vs ≥ 1500 m/s are noticed at depths ranging from 100–300 m. Majority of Punjab has this input depth (at which Vs ≥ 1500 m/s) varying from 200 to 300 m. In Uttar Pradesh (UP), depth of input motion is found to vary significantly in southern areas having Vs ≥ 1500 m/s at less than 100 m depth and some upper regions with the input depth > 300 m**.** In the case of Bihar, the central part is found to have this input motion depth ranging from 200 to 300 m, while in lower parts; depth varies from 100 to 200 m. Only a relatively small upper region of Bihar shows input depth greater than 300 m.

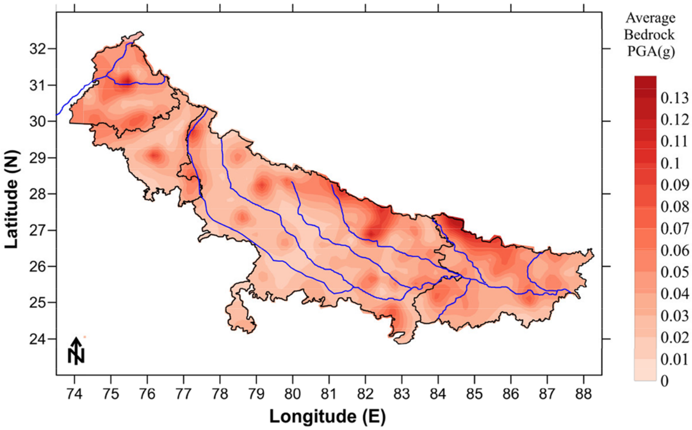
Over the years, different shear modulus and damping ratio values for various materials have been presented by several researchers. Widely used curves for site response analysis were developed by researchers (Seed and Idriss 1970, EPRI 1993, Vucetic and Dobry 1991, Ishibashi and Zhang 1993, Seed et al. 1986, Sun et al. 1988) and many more to represent the dynamic behavior of the soil column. Unlike for shallow profiles, Hardin and Drnevich (1972), Kokusho (1980) and several other researchers also noticed how confining pressure affects the dynamic soil properties for deep profiles. In India, usually, site response studies are worked out by taking into consideration only a set of limited shear modulus and damping curves, without knowing its appropriateness and applicability for the in-situ soil type. Anbazhagan et al. (2017) showed that the use of improper shear modulus damping curves may lead to unreliable estimation of seismic response parameters and therefore arrived at suitable shear modulus reduction and damping curves for different deep soil sites studying KiK-Net recorded data of earthquakes both at bedrock and the surface. This was further revised by Bajaj and Anbazhagan (2019d) as they added more KiK-Net downhole array network data to select representative shear modulus and damping ratio curves for the soils by categorizing it into sand, gravel, rock and clay. As of now, very limited attempts have been made to develop dynamic curves for soils in the IGB. In the absence of such curves, the representative curves suggested by Bajaj and Anbazhagan (2019b) are used for the site response studies of deep sites of IGB. At each site, soil layers have been identified based on nearby available borehole data. Curves depending on soil type and depth layer to reflect confining pressure have been utilized. In case of rock or hard layer, EPRI (1993) curve and Zhang et al. (2005) curve have been used depending on whether Vs ≥ 800 or Vs < 800 m/s , respectively, for deposits of Quaternary type. For gravel sites with known particle size, Menq (2003) has been used otherwise


Maximum
Bedrock PGA(g)
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Latitude (N)
Longitude (E)
N

(a)


BEDROCK
PGA(g)
8.5 M$_w$ Earthquake
0.055
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Latitude (N)
Longitude (E)
N

(b)


Average
Bedrock
PGA(g)
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Latitude (N)
Longitude (E)
N

(c)

Table 2 Major parameters used in simulation of input motions for the study

S. No.	Parameter	Distribution	Mean
1	Stress drop (MPa)	Log-normal	$\ln(\Delta\sigma)_{150} = \begin{cases} 0.36M_W + 0.008, & M_W < 5.5 \\ 150, & M_W \geq 5.5 \end{cases}$
			$\ln(\Delta\sigma)_{100} = \begin{cases} 0.32M_W + 0.147, & M_W < 5.5 \\ 100, & M_W \geq 5.5 \end{cases}$
			$\ln(\Delta\sigma)_{50} = \begin{cases} 0.25M_W + 0.383, & M_W < 5.5 \\ 50, & M_W \geq 5.5 \end{cases}$
2	Focal depth (km)	Normal	$\text{Depth} = \begin{cases} 30 \pm 10, & M_W > 6.0 \\ 50 \pm 10, & M_W < 6.0 \end{cases}$
3	Duration (s)	Normal	$\text{Tp} = \begin{cases} R_h \times 16.8/60, & R_h < 60km \\ 16.8 + 0.05 \times (R_h - 60), & R_h \geq 60km \end{cases}$
4	Fault dimension	Normal	Blaser et al. (2010) for different fault orientation
6	κ (s)	Normal	0.01

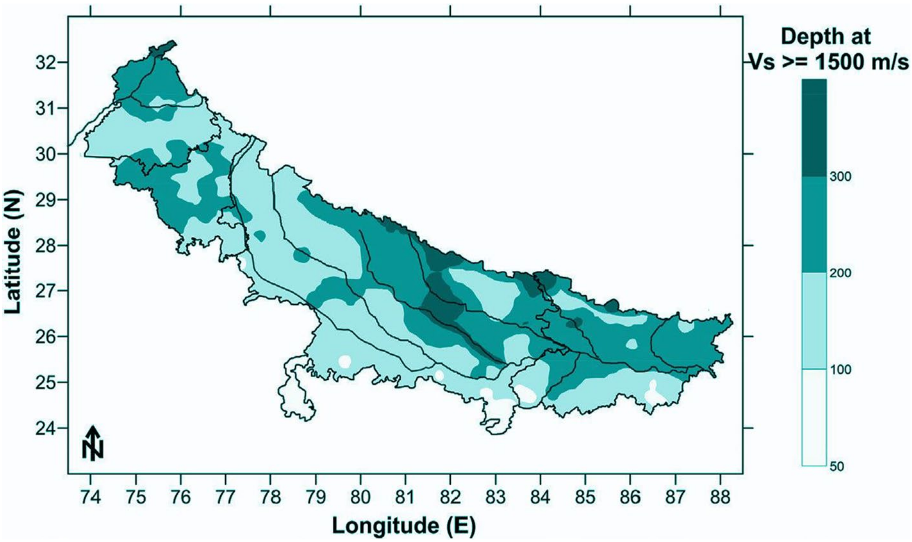


Fig. 4 Depth of input as per shear wave velocity at IGB by Bajaj and Anbazhagan(2019b) for site response studies

Zhang et al. (2005) for deep gravel profiles. Zhang et al. (2005) has also been used for deep sand deposits. For deep clay and silt sites, Darendeli (2001) has been used.

5 Site response analysis

Influence of local site effects should be properly evaluated to account for the effects produced by earthquakes. In this regard, the overall accuracy of the site response analysis plays a vital role. Site-specific data, as discussed above, are collected to perform site response analysis. Detailed site response analyses have been carried out to evaluate the characteristics of ground motion at the surface and other depth levels of different soil columns in the IGB. The analysis includes solving the wave propagation equation for a site with definite properties and different input motions. Different software programs (DEEPSOIL, SHAKE91 etc.) are available to carry out one-dimensional (1D) site response analysis. In our present study, we have used DEEPSOIL V7 to perform 1D nonlinear site response analyses at 270 locations (shown in Fig. 1) of IGB. 1D nonlinear analysis using DEEPSOIL is widely used for deep soil sites' response analysis, which was delicately developed for response studies of deep soil sites (Hashash et al. 2001). For fitting the shear modulus reduction and damping ratio curve, MRDF-UIUC procedure as proposed by Phillips and Hashash (2009) has been used. To define the estimates of shear strength, formulations suggested by Hashash et al. (2010) have been considered. Frequency-independent Rayleigh damping, as proposed by Phillips and Hashash (2009), has also been used. The nonlinear behavior of soil is regulated through a model developed by Konder and Zelasko (1963) and further modified by Matasovic et al. (1993). Masing rules (Mei et al. 2015) are the basis for unloading and reloading formulations. As discussed earlier, motions with bedrock PGA $\geq$ 0.005 g have been used as input. A total of 1606 time acceleration histories have been inputted in IGB sites, and each site is analyzed for different earthquake motions having varying magnitude and hypocentral distance combinations. Inputting a higher number of ground motions at a particular site increases the reliable estimation of seismic site response parameters (Rathje et al. 2010). The minimum number of motions for which a site has been analyzed is 3, and the maximum number of motions inputted at an IGB site was 10. On average, numbers of motions applied throughout the IGB profiles are 5–7. The only factor that governed the number of motions a site was analyzed for, is an input PGA $\geq$ 0.005 g at any site. The output of the analysis includes peak ground acceleration values at each layer, response spectrum and spectral parameters of amplified ground motions. Spectral acceleration response at 5% damping at the surface and other

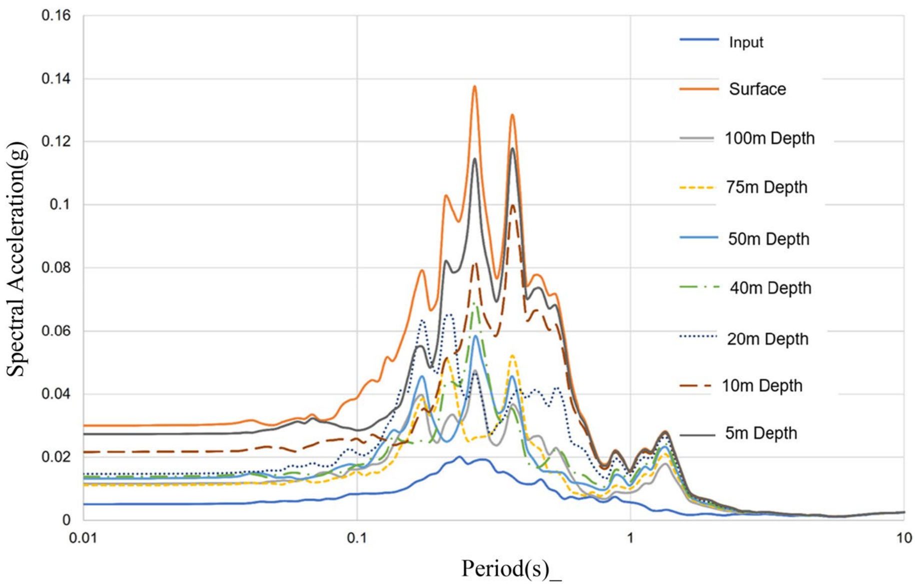


Fig. 5 Response spectra of input and amplified motions at different depth levels of the selected site

depth were calculated. Figure 5 shows the typical response spectra of input and amplified motions passing through different layers at a selected site. It can be clearly seen that the input spectrum is considerably modified after passing through different layers, and this modification depends on stiffness and model behavior of different layers. Figure 6 shows the surface PGA variation due to an earthquake of M_w 8.5 originating in Nepal. This figure illustrates that the parts of Uttar Pradesh and Bihar are more affected by this earthquake. The observed surface PGA near the earthquake origin is 0.13 g due to bedrock PGA of 0.05 g, and it reduces to around 0.05 g in the distant areas of Uttar Pradesh and Haryana for a corresponding bedrock PGA of 0.01 g. Values of surface PGA ranging from 0.01 to 0.13 g have been observed for the state of Bihar, whereas the bedrock PGA was found to vary from 0.005 to 0.05 g. The above discussion can be referred in detail from the comparison of Fig. 6 with Fig. 3b. Sites far away like the western areas of Haryana and Punjab experience little or no shaking at all (very less bedrock PGA, Fig. 3b) due to this particular ground motion and have not been analyzed for this earthquake.

6 Surface amplification and site factors

As the stress waves propagate through the multiple layers of soil, they undergo amplification as the stiffness of soil layers generally decreases on moving toward the surface. Amplification of the ground motion at any site is often regulated by the soft surface layer which traps the seismic energy between the soft soil layers and the underlying dense/rock layers. This trapping is due to impedance contrast between the two layers. Different soil properties and thicknesses of each subsurface or surface layers play a major role in controlling different characteristics of the ground motions. Ground motion amplification relates to the ratio of any intensity measurement of the motion at the soil surface to that of bedrock. The earthquake amplitudes are generally described by the peak ground acceleration values.

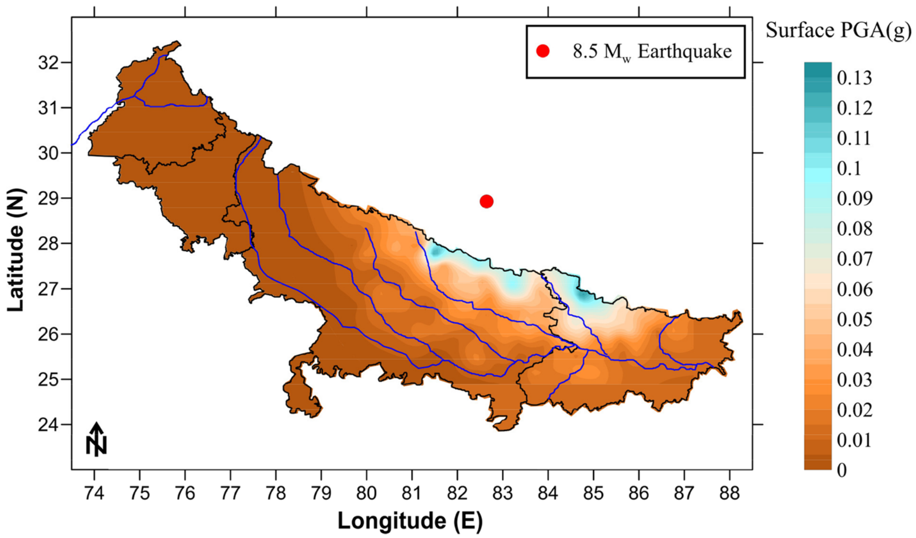


Fig. 6 Spatial variation in zero period and peak spectral acceleration values in IGB for the earthquake of M_w 8.5

However, building codes use the parameters like spectral acceleration, corresponding frequency or period for structural design purposes. Motions with higher peak acceleration values are generally more destructive than those with lower ones. To estimate and quantify local site effects in the IGB region and study the behavior of ground motions at the 270 profiles, various parameters like F_{PGA}, F_{PSA}, F_a, F_v, $F_{PSA(0.2\ s)}$ and $F_{PSA(1.0\ s)}$ have been determined from the results obtained out of site response analysis.

Zero period amplification factor, F_{PGA}, is determined as the ratio of Peak Ground Acceleration at ground surface or any other depth level to that of bedrock for the same earthquake motion at a particular site.

$$F_{PGA} = \frac{\text{PGA at surface or any depth}}{\text{PGA at input level}} \tag{1}$$

Similarly, F_{PSA} corresponds to the ratio of maximum spectral acceleration value at surface or any other depth level to that of bedrock for the same earthquake motion at the same site.

$$F_{PSA} = \frac{\text{PSA at surface or any depth level}}{\text{PSA at input level}} \tag{2}$$

Site factors represent the ratio of spectral ordinates for a particular site condition to the value of the ordinates that would be expected for the reference condition. These specific factors as per provisions are F_a, which is defined over a low-period range (T = 0.1–0.5 s), and F_v, defined over a mid-period range (T = 0.4–2.0 s), where T is the time period. Site factor F_a is used to represent the short-period portion of the response spectrum while F_v for the long-period (Liam and Adrian 2005). At each spectral period, RS_{soil}, i.e., lognormal median of spectral values is determined using Eq. 3. In the present study, the assumed value for R_{soil}/R_{rock} is 1.0 in Eqs. 4 and 5 as the hypocentral distance for rock and soil station is similar. Further, same hypocentral distances for rock and soil station are assumed. The F_a and F_v were calculated as suggested by Borcherdt RD (1994).

$$\text{RS}_{\text{soil}} = \exp\left(\frac{1}{N} \cdot \sum_{i=1}^{N} \log \text{RS}_{\text{soil}i}\right) \tag{3}$$

$$F_a = \frac{R_{\text{soil}}}{R_{\text{rock}}} \frac{1}{0.4} \int_{0.1}^{0.5} \frac{\text{RS}_{\text{soil}}(T)}{\text{RS}_{\text{rock}}(T)} dT \tag{4}$$

$$F_v = \frac{R_{\text{soil}}}{R_{\text{rock}}} \frac{1}{1.6} \int_{0.4}^{2} \frac{\text{RS}_{\text{soil}}(T)}{\text{RS}_{\text{rock}}(T)} dT \tag{5}$$

where RS_{soil} and RS_{rock} are response spectra of soil and rock at given spectral period T, respectively. R_{soil} and R_{rock} are the hypocentral central distances at soil and rock stations, respectively.

$F_{PSA(0.2\ s)}$ and $F_{PSA(1.0\ s)}$ are the ratios of spectral accelerations at the surface to that of bedrock corresponding to specific periods of 0.2 and 1 s, respectively. It has been noticed that these amplification factors and site factors vary from site to site with changing soil parameters. Furthermore, these quantities also vary for different simulated motions at a

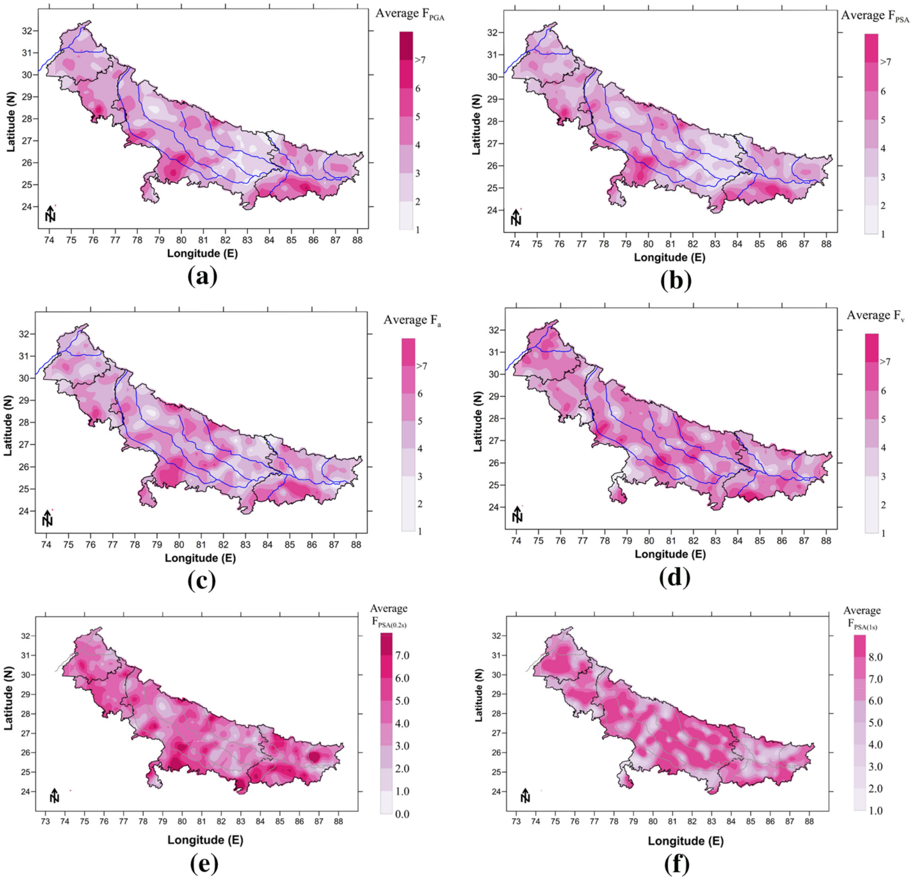


Fig. 7 Spatial variation in average **a** F_{PGA}, **b** F_{PSA}, **c** F_a, **d** F_v, **e** $F_{PSA(0.2\ s)}$, **f** $F_{PSA(1.0\ s)}$ at the surface due to simulated motions

particular site. Figures 7a–f show spatial variation in average F_{PGA}, F_{PSA}, F_a, F_v, $F_{PSA(0.2)}$ and $F_{PSA(1.0\ s)}$, respectively, at the surface due to the considered scenario earthquakes throughout the IGB. The central region of the IGB, majorly UP, has lower F_{PGA} and F_{PSA} values ranging from 1 to 3 and 2 to 4, respectively. Figures 7a and b illustrate that many regions of Bihar have F_{PGA} values of 5 or more along with some lower regions of Punjab. In the case of F_{PSA}, values between 4 and 7 or more are observed in Bihar. The eastern UP has F_{PGA} values ranging from 3 to 5 with the exception of around 6 at several sites, whereas for F_{PSA} , the values lie below 3. Figures 7c and d show the variation in short and long period site factors, respectively. In UP, the F_a varies between 2 and 6 with values exceeding 7 in the extreme southern region of the state. In Haryana, values lie between 3 and 5. Punjab has relatively lower values lying between 2 and 4. F_a observed in Bihar ranges between 3 and 6 with nearly 7 at some sites. Long-period amplification F_v has a higher value of 6 or more in the regions of Southern Bihar and UP. For the state of Punjab, the F_v values range from 4 to 6. The boundary shared by UP and Bihar also has values between 4 and 6. For the eastern parts of UP, values vary between 3 and 4. The major area of UP has long period values of 4–6. It was observed that for the regions of Punjab and Haryana F_v ranged between 5 and 7 with some sites exceeding 7. At most of the sites, $F_{PSA(0.2\ s)}$ varies between 1 and 7 with a few exceptions of higher than 7. The detailed variation is shown in Fig. 7e. $F_{PSA(1.0\ s)}$ values are relatively higher than $F_{PSA(0.2\ s)}$ for the sites in IGB and exceed 8 at several sites as evident in Fig. 7f.

In this study, higher amplification values are noticed when compared to other studies for the region, which may be due to the inclusion of wide spectrum of input ground motions for each site and average values are mapped, whereas other considered only higher PGA

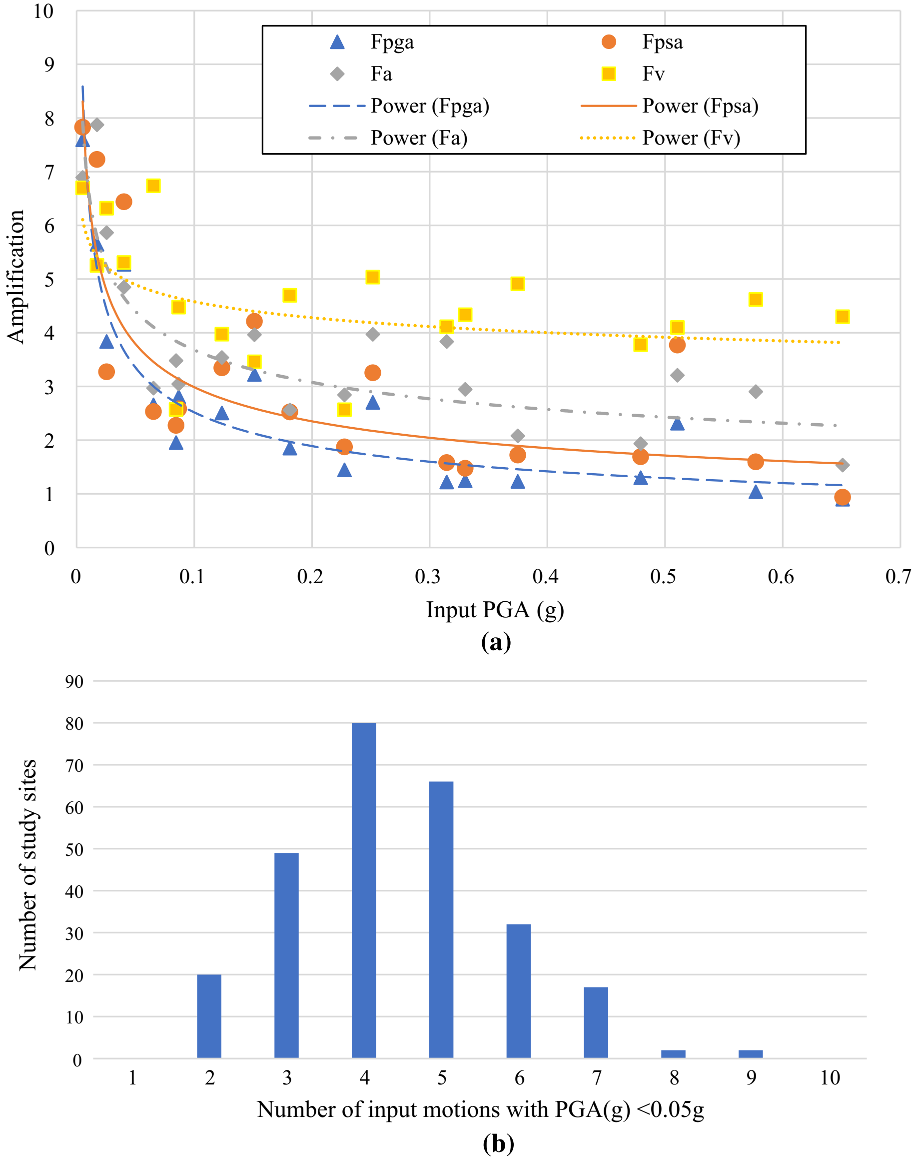


Fig. 8 **a** Variation in F_{PGA}, $F_{PSA,\ Fa}$ and F_v versus the bedrock PGA of typical site, **b** No, of sites with a corresponding number of input motions with PGA < 0.05 g

ground motions. Figure 8a shows the amplification factors $F_{PGA,}$ F_{PSA} F_a and F_v versus respective bedrock PGA of typical IGB site. It is also observed that at the same site, generally lower the PGA, higher the amplification factor or site factor as shown in Fig. 8a. These results are in agreement with Bajaj and Anbazhagan (2017) and Kumar et al. (2015). Higher amplifications are observed for input motions with PGA < 0.05 g. Figure 8b shows a histogram chart that relates the number of study sites observed vs the number of input motions with PGA < 0.05 g. High amplification of weak motions (low PGA) may be disastrous for the structure and therefore need to be taken into account to mitigate the losses from earthquakes. Further, the variation in amplification factors has been studied, and considerable values were observed at each site. So, the average and maximum values of these factors are arrived at each site and used to prepare maps.

In order to understand and depict the spatial variation in F_{PGA}, $F_{PSA,}$ F_a and F_v factors, maps representing the average and maximum values at the surface and various depth levels have been plotted covering the whole of IGB. Plots potraying the variation in F_{PGA}, $F_{PSA,}$ F_a and F_v at the surface due to a typical earthquake of M_w 8.8 are shown in Fig. 9. Figure 10 shows the spatial variation in maximum values of F_{PGA}, $F_{PSA,}$ F_a and F_v at the surface throughout IGB. From Fig. 10a, the maximum amplification of PGA ≥ 7 has been observed in the southern part of UP and may have resulted on account of loose soil deposits. Maximum F_{PGA} has been found to vary from 2 to 7 or higher over the IGB with uneven distribution. This uneven distribution may be attributed to the complex geology of the area. In Bihar and UP, amplification values ≥ 6 have been observed at the majority of sites. In the central UP, amplification values of 2–4 have been observed at many sites which may be attributed to higher stiffness of the soil layers. In Punjab and Haryana, the maximum value of amplification factor as much as 5–7 is seen over a larger portion of the area. A similar trend with different values in the variation in $F_{PSA,}$ F_a and F_v has been studied and is shown

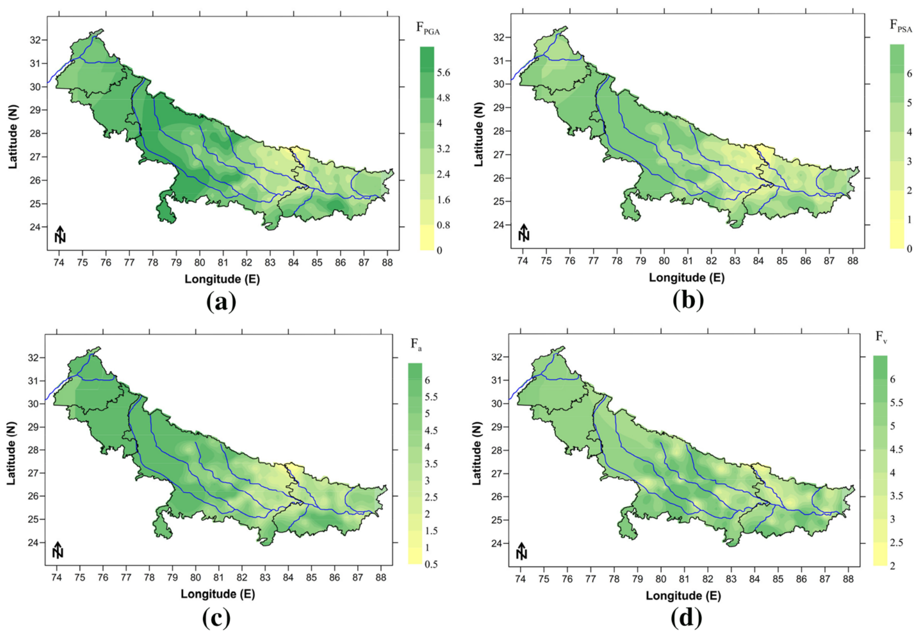


Fig. 9 Variation in **a** F_{PGA}, **b** F_{PSA}, **c** F_a, **d** F_v at the surface due to a single earthquake of Mw 8.8

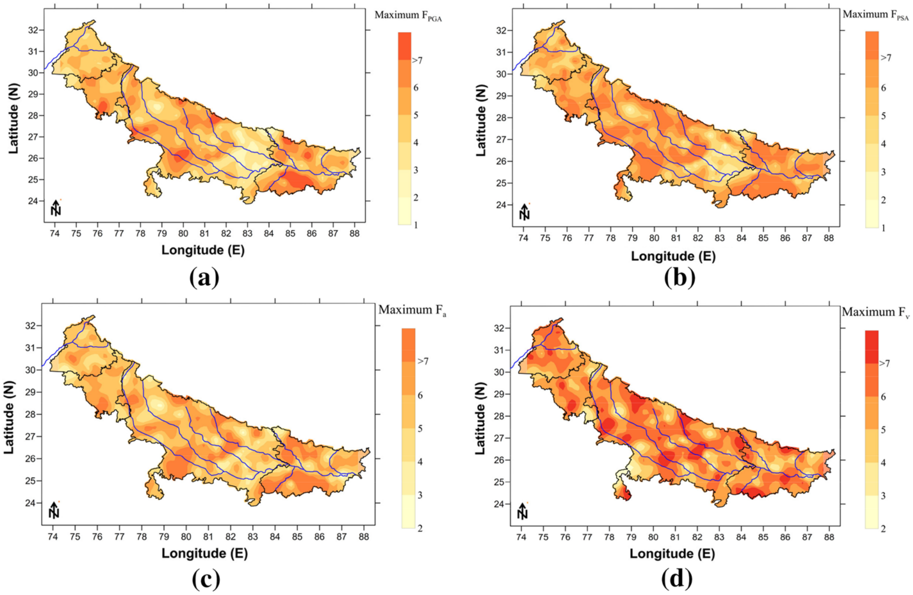


Fig. 10 Spatial variation in maximum values of **a** F_{PGA}, **b** F_{PSA}, **c** F_a, **d** F_v at the surface throughout IGB

in Fig. 10b–d, respectively. Comparison of average and maximum amplification is shown in Fig. 3c. It is obvious that average and maximum amplifications are observed more at the sites where corresponding bedrock PGA is low and vice versa.

7 Depth-wise variation in amplification and site factors

The effective utilization of available underground space has become a global trend and plays a vital role while planning the city modernization. It is therefore imperative to study in detail different aspects of earthquake sub-ground motion at separate depth levels to attain the higher level of excellence in the seismic design and safety of underground infrastructure and utilities like pipelines, underlying communication cables, etc. The variation in ground motion characteristics for input motions up to a depth of 100 m is investigated in this paper with the aim that it would benefit the earthquake hazard mitigation, design of deep and shallow foundations and different underground structures.

Variations in the site amplification with depth are in agreement with characteristics of different vibration modes. Generally, on moving toward the surface from the bottom in the soil layers, the amplification effects gradually increase. This may be associated with a general increase in shear wave velocity and density of soil strata as we move down the soil column. This causes the impedance contrast to increase as we move up toward the surface. In most of the studies, only amplification at the surface is given due relevance irrespective of subsurface profile. At numerous profiles, it was found that velocity at layers below the surface is lower than at the surface, i.e., there occurs no increase with depth. So, in this regard, amplification along the depth is studied here. Figure 11a–c and d show the variation in F_{PGA}, F_{PSA}, F_a and F_v with the depth at typical IGB site. These plots reveal the changes in F_{PGA}, F_{PSA}, F_a and F_v as we move toward

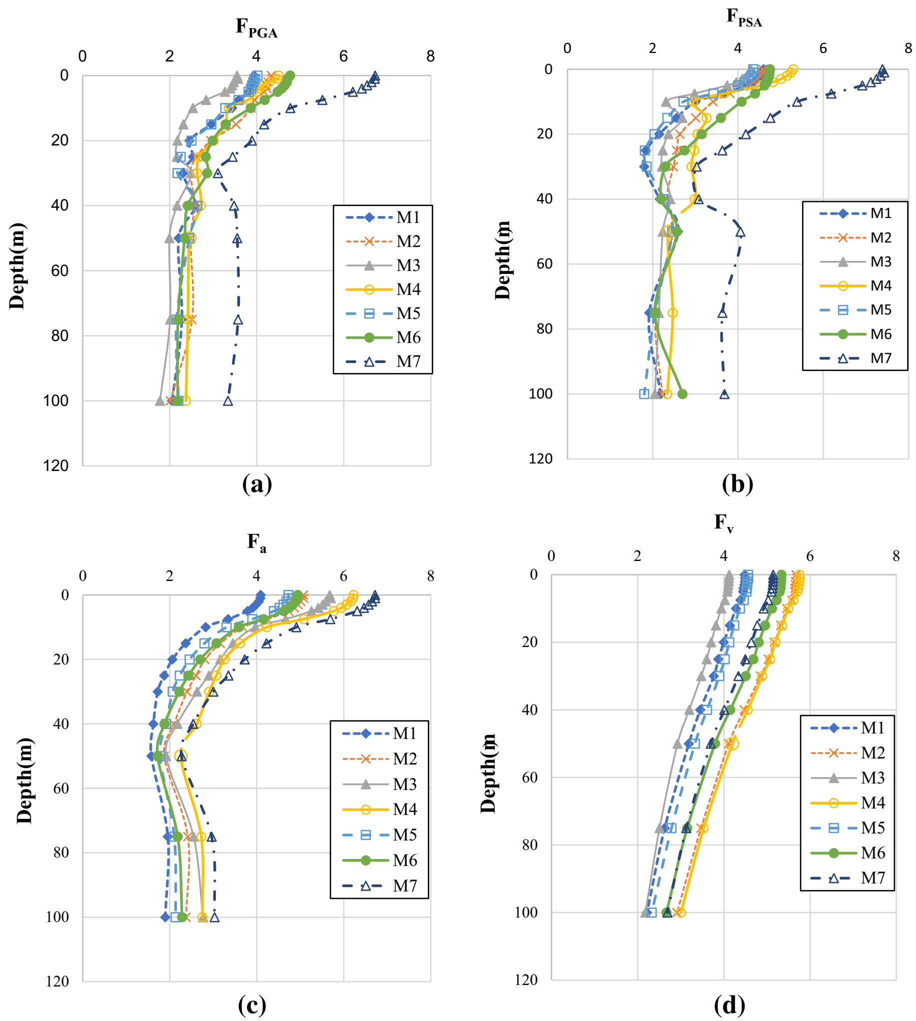


Fig. 11 Variation in **a** F_{PGA},**b** F_{PSA}, **c** F_a, **d** F_v along the depth column at various typical IGB sites

the bedrock are notable up to a depth of around 50 m, and the layers below show less or more constant values for these parameters. It is evident that, at many sites, the amplification at certain subsurface level surpasses the values at the surface corresponding to certain or all ground motions. In Bihar, the depth-wise variation in amplification factors reveal that the percentage of sites having higher subsurface amplification values are 34% for F_{PGA}, 33% for F_{PGA},13% for F_a and 16% for F_v. Likewise, in Punjab and Haryana percentage of sites showing this behavior is 28%, 21%, 7% and 12% for FPGA, F_{PSA}, F_a and $F_{v.}$, respectively. A similar trend is observed in UP but with a relatively lower percentage of sites; 17% for F_{PGA},10% for F_{PSA}, 4% for F_a and 2% for F_v. On an average, higher amplifications at subsurface levels are noticed at 24% of sites in Bihar, 17% of sites of Punjab and Haryana and 4% of Uttar Pradesh. In a broader context, 14% of IGB sites show this behavior. This may be due to low shear velocity layers at depths compared to the surface. Depth-wise average amplification plots for different IGB sites are shown in Fig. 12. Figure 12a shows the average depth-wise variation in $F_{PGA,}$ and Fig. 12b shows that of F_{PSA}.

Figures 13, 14, 15, 16 show the spatial variation in amplification factors and site factors F_{PGA}, $F_{PSA,}$ F_a and F_v, respectively, over IGB. Each of these figures: a, b, c, d and e represents the variation at a depth of 5, 10, 20, 50 and 100 m, respectively. Figure 13 shows the F_{PGA} variation at selected depth levels. Sizeable areas of Punjab, Haryana and western UP show similar decreasing behavior in F_{PGA} values. The values recede from 4 at the upper layers to 1.5–2 at 100 m depth. Considering eastern UP, the F_{PGA} values decrease from around 2 to 1–1.5. In Bihar, the values subside from 2 to 4 at the near the surface to 1.5–2.5 at a depth of 100 m.

Figure 14 shows the F_{PSA} variation in the IGB region at the depth levels of 5, 10, 20, 50 and 100 m. In UP, except for small regions in the southern part, the values fall from 2–5 to 1–2. For Punjab and Haryana, the F_{PSA} decreases from 2–4 at 5 m depth to 1.5–3 at 100 m depth. Bihar also shows a similar decreasing trend with values dropping from 2–5 near the surface to 3.5–1.5 at deeper depths (100 m).

In Fig. 15, in the eastern UP, the value of F_a decreases from 4.5 to 1.8, whereas, in major areas of Southern UP, F_a values come down from 7.5 at 5 m depth to 2.5 at 100 m depth. In the states of Punjab and Haryana, the F_a declines from 5.5 to 2.6. In Bihar, except for some regions in its southern part, the F_a values diminish moderately as we move down from the surface.

Figure 16 shows the F_v at various depth levels. Like the short period site factor F_a, the F_v also behaves similarly with a decreasing trend down the depth column. In UP, considering the central region, the values subside from 6 to 2.5, except its south-eastern regions where

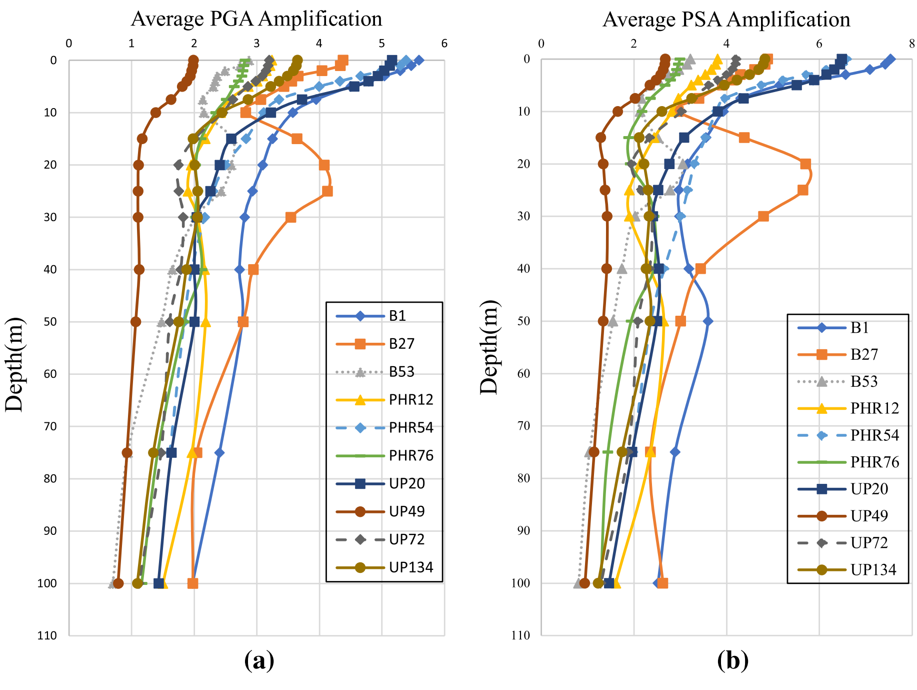


Fig. 12 Depth-wise variation in **a** average F_{PGA} **b** average F_{PSA} up to 100 m

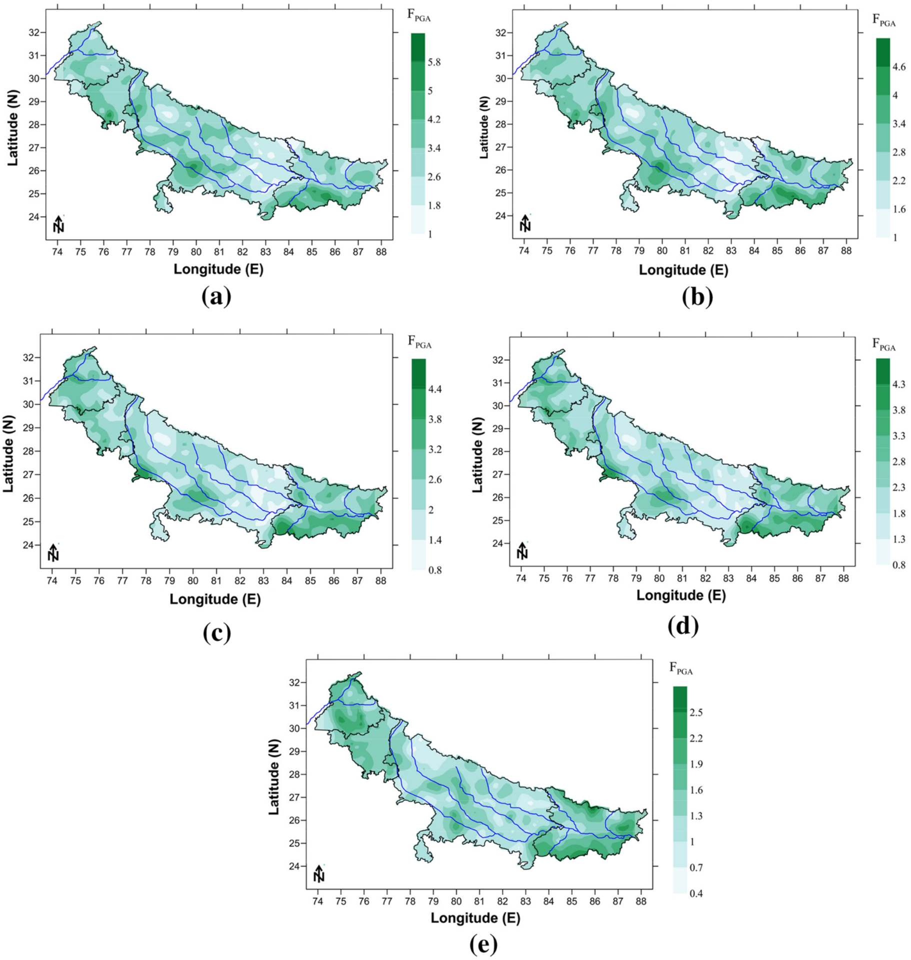


Fig. 13 Spatial variation in F_{PGA} throughout IGB at the depth of **a** 5 m; **b** 10 m; **c** 20 m; **d** 50 m and **e** 100 m

the F_v values being lower near the surface show a marginal decrease from 2 at upper depth levels to 1.5 at 100 m depth. For larger portions of Punjab and Haryana, the F_v values recede from around 5 to 2. Figure 17 shows the variation in effective stress at various typical IGB study sites with depth. It is observed that for any IGB location, the effective stress increases with the depth. Figures 18a, b, c and d represent the variation in maximum strain with the depth at the typical sites of PHR (Punjab and Haryana Region), Bihar and Uttar Pradesh (UP), respectively. Figures reveal that subsurface strain levels are maximum within 50 m from the surface for a typical ground motion at a typical IGB location.

These results shall be highly valuable in different underground construction projects at different depth levels, where subsurface amplification or acceleration may be higher than that at ground levels and may thus be helpful in avoiding earthquake risks to a certain extent. Since the variation in these factors is huge throughout IGB, the range of average values of these has been calculated. Table 3 presents the range of average amplification

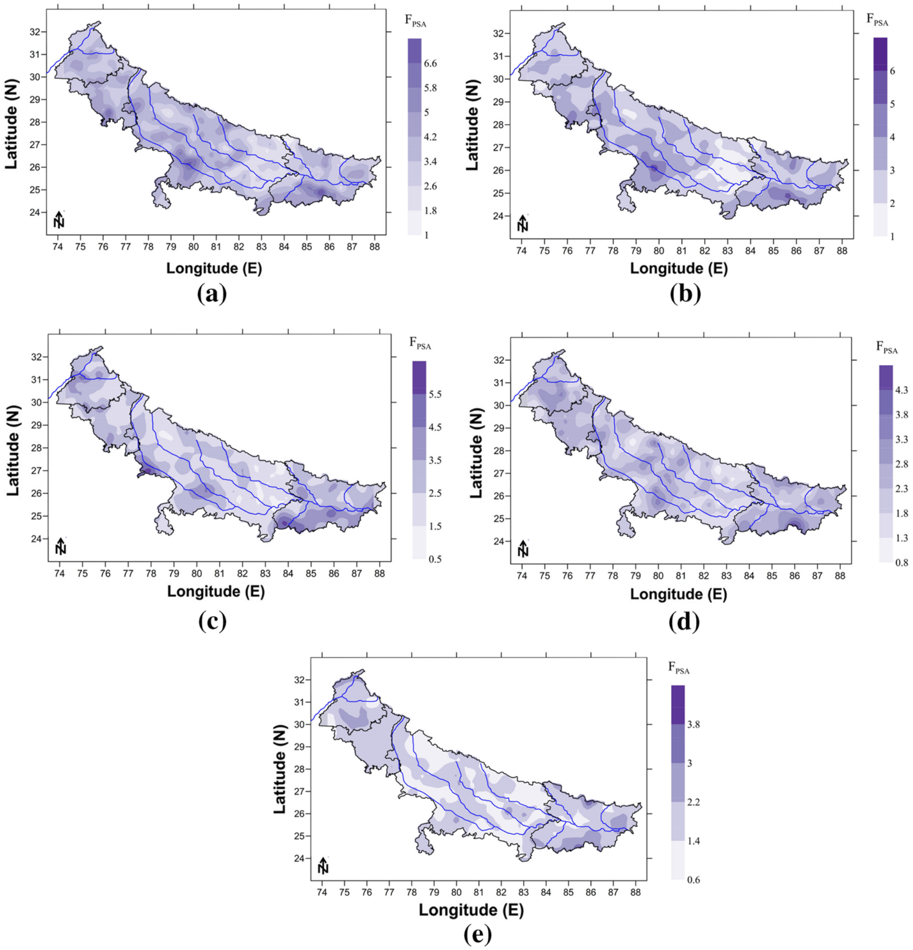


Fig. 14 Spatial variation in F_{PSA} throughout IGB at the depth of **a** 5 m; **b** 10 m; **c** 20 m; **d** 50 m and **e** 100 m

factors at different depths of the IGB due to scenario earthquakes considered in the region. These phenomena need proper modelling for valuable substructures like nuclear power plants, dams and other underground structures in the deep soil region like IGB.

8 Conclusions

In this study, nonlinear analysis for 270 deep soil sites in the IGB has been carried out. This was done using 16 different probabilistic future scenario earthquakes with maximum magnitude. Amplifications of these earthquakes in the deep basin of IGB, considering the local site effects have been studied. Different maps have been plotted to understand the behavior at the surface and different depth levels up to 100 m. Variation in surface PGA, amplification factors and site factors over the geography has been analysed for the whole IGB. Site factors F_a and F_v have been determined for 0.1–0.5 and

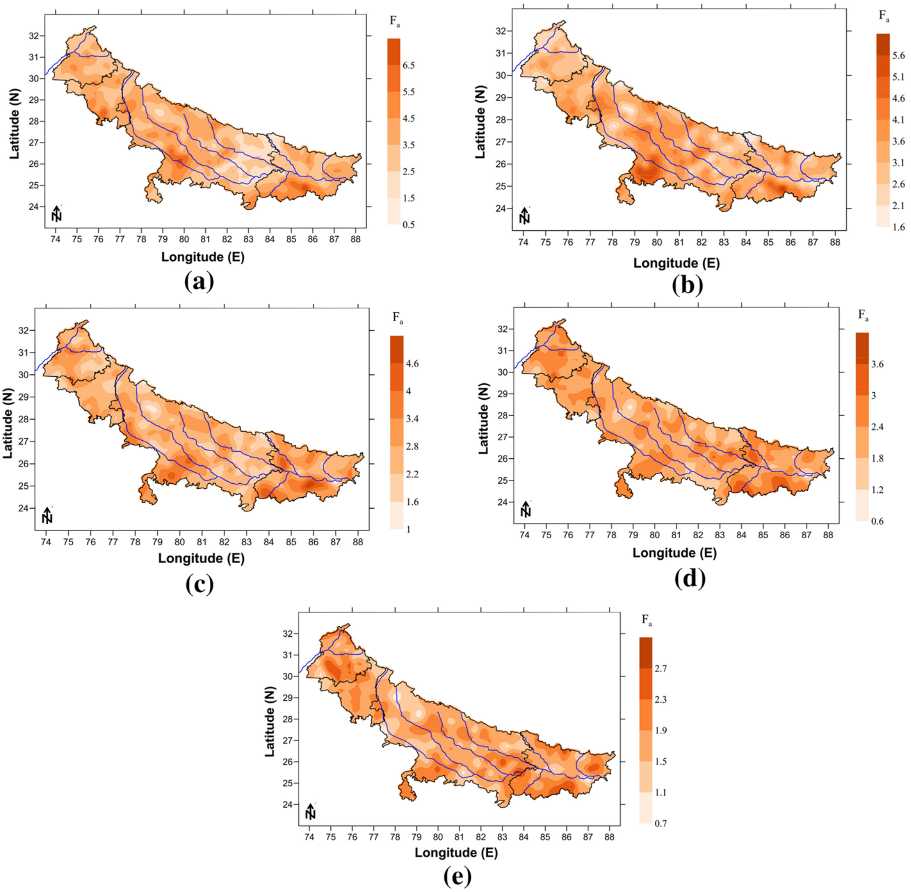


Fig. 15 Spatial variation in F_a throughout IGB at the depth of **a** 5 m; **b** 10 m; **c** 20 m; **d** 50 m and **e** 100 m

0.4–2.0 s, respectively, as suggested by the NEHRP. Spectral amplifications corresponding to periods 0.2 s and 1 s have been studied. Range of average amplifications and site factors for surface, and different depths have also been presented. Variation in amplification with the depth was evaluated along with the trends in site amplification. It is for the very first time that such a comprehensive study has been carried out for futuristic probable earthquakes. The following are some of the main conclusions drawn from our study:

1. The area is under high seismic risk because of nearby identified and unidentified earthquake sources. Potential bedrock PGA used for analyses varies from 0.005 to 0.651 g due to 16 probable earthquakes.
2. Site-specific factors play a significant role in the modification of earthquake parameters in IGB. Due to the larger depth of soil columns, the earthquake waves tend to amplify as they approach the surface. At certain profiles, the soil column extends up to 500 m.

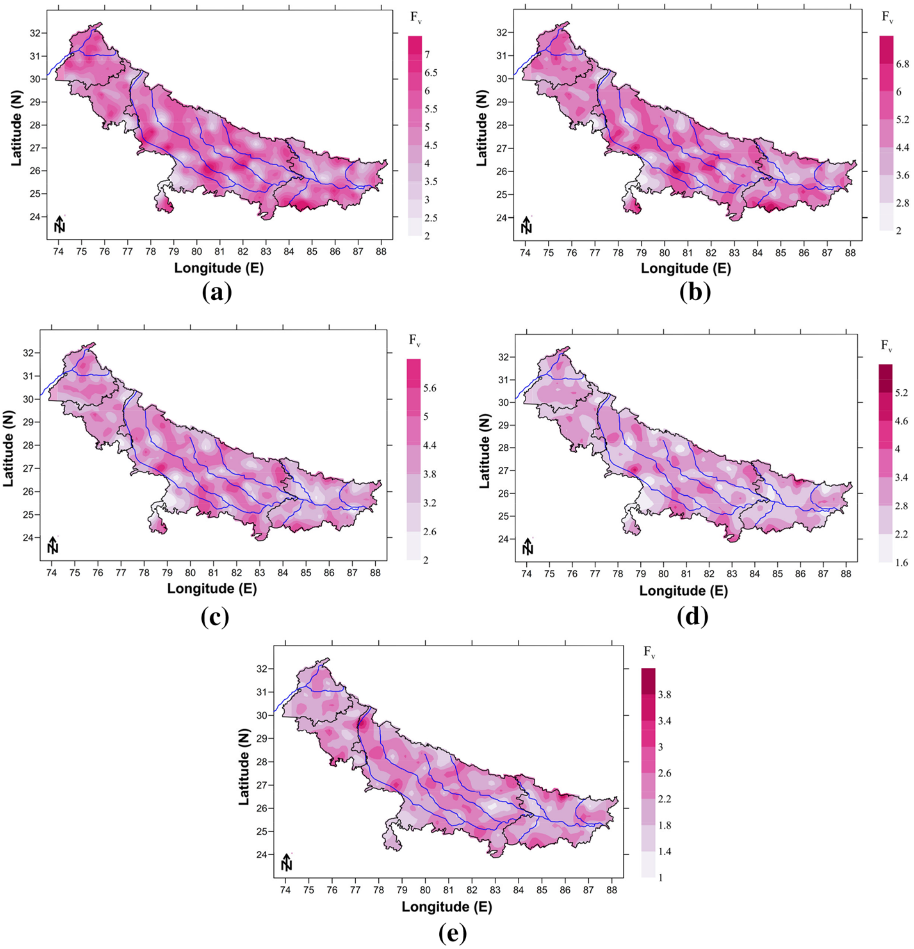


Fig. 16 Spatial variation in F_v throughout IGB at the depth of **a** 5 m; **b** 10 m; **c** 20 m; **d** 50 m and **e** 100 m

So, even a moderate earthquake may cause a higher shaking as it reaches the surface soil layers.

3. The surface PGA due to the synthetic motions varies widely from 0.012 to 1.182 g throughout the IGB sites, and maximum surface PGA was observed at sites near the earthquake epicenters.
4. The average values of F_{PGA}, $F_{PSA,}$ F_a and F_v at the surface were found to vary from 1.16 to 7.94, 1.13 to 7.93, 1.43 to 7.89 and 2.11 to 7.51, respectively. Most of the areas show PGA amplification in the range 3 to 6. The lower boundary of the IGB shows higher values for these parameters. High spectral amplifications at longer periods and peak spectral amplifications are observed over the area.

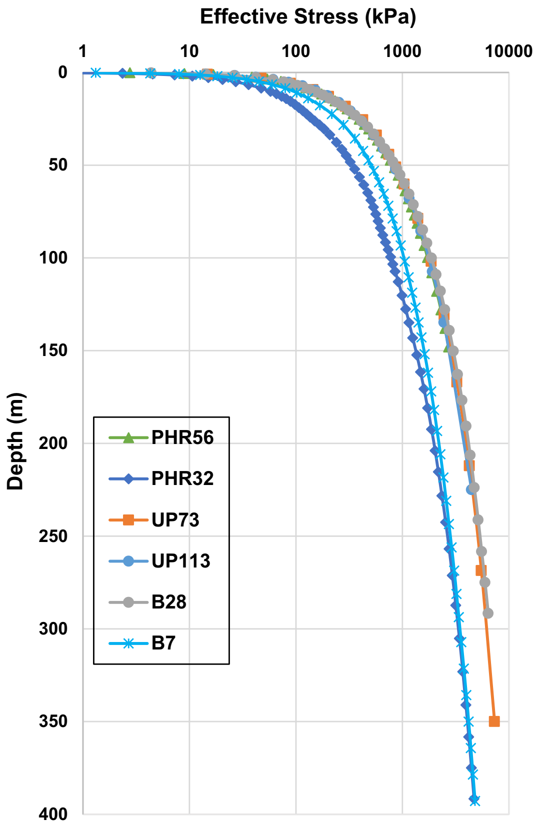


Fig. 17 Depth-wise variation in effective stress at typical IGB locations

5. $F_{PSA(0.2)}$ and $F_{PSA(1.0\ s)}$ at surface show complex behavior over IGB, and the latter is relatively higher.
6. Majority of deep soil sites (mostly alluvial) tend to amplify more at long periods than shorter periods, as evident from the surface and other depth-wise F_a and F_v maps. These parameters are important for different civil engineering applications.
7. For a particular site, amplifications F_{PGA} and F_{PSA} and site factors F_a and F_v vary significantly up to a depth of around 50 m, and beyond this depth, variations are relatively less.
8. This study shows that loose/soft layers below the surface in deep soil sites result in higher amplification than surface value, which needs to be accounted while designing underground structures.

Although this study considered rigorous analysis of 270 study sites in IGB for 16 scenario earthquakes, this is a macro-level study, and the interpolated results may not be so accurate. The better results could be achieved out by carrying out micro-level studies in the future considering a greater number of closely spaced study sites focussing on other potential seismic sources and additional earthquake parameters for simulation as well. Further, micro-level studies shall also take into account the heterogeneity in the bedrock depth and subdivision of areas based on subsoil thicknesses.

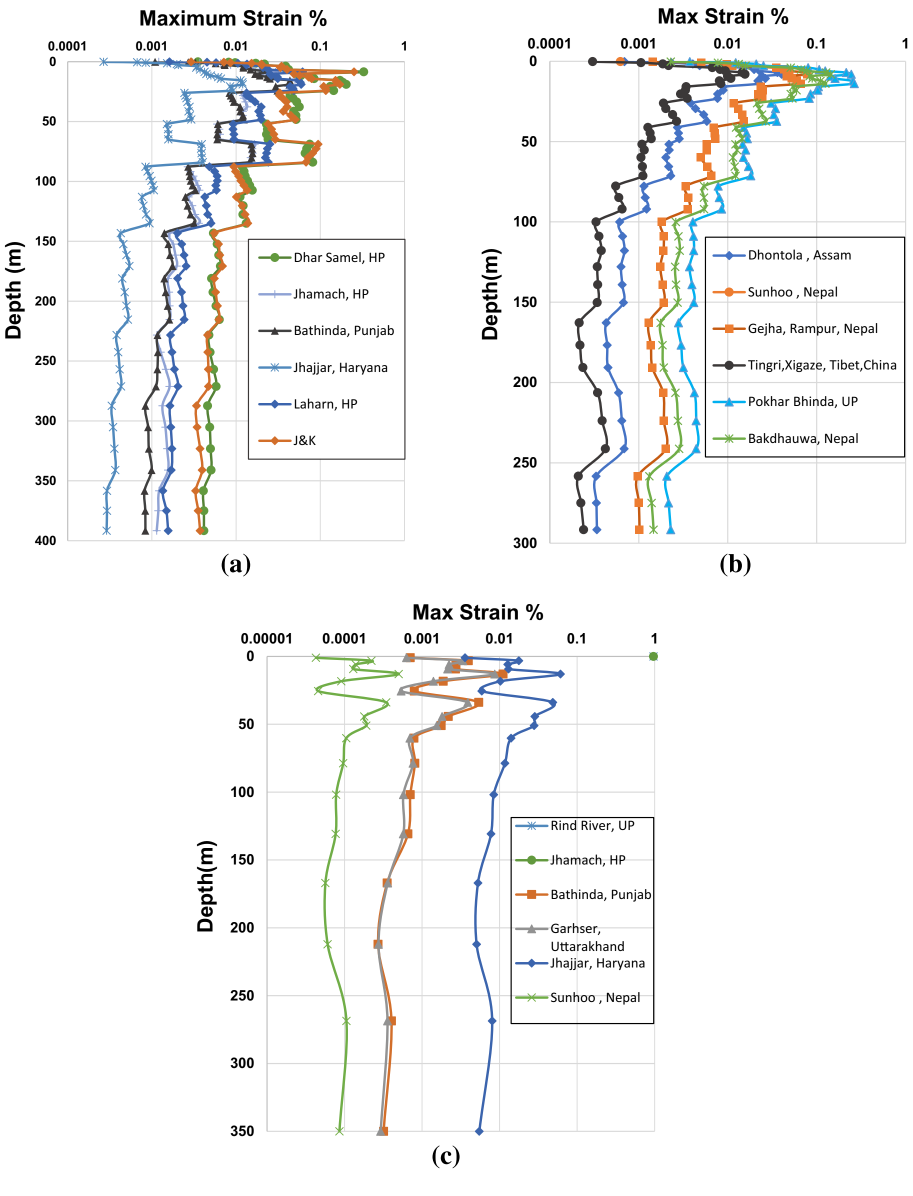


Fig. 18 Depth-wise variation in maximum strain at a typical site at **a** Punjab Haryana (PHR), **b** Bihar and **c** Uttar Pradesh (UP)

Table 3 Average values of amplification and site factors at different depth levels up to 100 m

Depth (m)	Range of average amplifications and site factors			
	F_{PGA}	F_{PSA}	Fa	Fv
0	1.16–7.94	1.13–7.93	1.43–7.89	2.11–7.51
1	1.16–7.76	1.11–7.80	1.42–7.84	2.11–7.49
2	1.14–7.42	1.09–7.71	1.41–7.71	2.10–7.47
3	1.11–7.04	1.06–7.58	1.38–7.56	2.10–7.41
4	1.07–6.65	1.03–6.97	1.35–7.18	2.09–7.39
5	1.03–5.42	1.00–6.86	1.32–6.87	2.09–7.38
7.5	0.96–5.10	0.94–6.41	1.21–6.23	2.08–7.34
10	0.94–4.69	0.91–6.54	1.14–5.72	2.06–7.29
15	0.84–4.54	0.87–6.23	0.91–5.51	1.91–7.24
20	0.63–4.41	0.60–5.93	0.71–4.95	1.36–7.18
25	0.63–4.27	0.60–5.83	0.70–4.88	1.31–6.95
30	0.61–4.24	0.58–5.70	0.69–4.72	1.30–6.57
40	0.58–3.53	0.53–5.25	0.66–4.69	1.29–5.67
50	0.55–4.01	0.51–4.93	0.61–4.02	1.28–5.25
75	0.51–3.17	0.51–4.11	0.54–3.94	1.23–4.64
100	0.47–2.84	0.50–4.09	0.49–3.08	1.21–4.22

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Approved.

Consent to participate Yes.

Consent for publication Yes.

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