Chapter 39
Site-Specific GRA to Quantify Ground Motion Amplification for Bettiah Site: A Case Study

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Introduction

Site-specific ground response analysis (GRA) is one of the major concerns to evaluate the ground motion amplification for seismic hazard assessment or seismic microzonation of any area. Site-specific GRA provides the ground motion amplification at any required depth, which is further utilized to develop the design response spectra for the design of earthquake resistance structures [1]. Therefore, considering the present scenario of earthquakes such as the Bhuj earthquake (2001), the Sikkim earthquake (2011), and the Nepal earthquake (2015), the seismic GRA can be performed at any construction site, however, is of utmost importance in an earthquake-prone area. During the Nepal earthquake (2015), many structures in Bihar were severely damaged though the epicentre was very far from the centre of Bihar. As per IS:1893 [2], Bihar comes under the seismic zone III and zone IV, therefore, site-specific GRA becomes one of the significant aspects to foresee the potential consequences for amplification or amplification of the strong ground motions at the ground surface before the design of the structure. Seismic GRA can be analysed using one-dimensional (1D) linear, 1D equivalent linear or nonlinear approach with the assumptions that the soil layers and materials below the soil layers are horizontal and extend to infinity in the lateral direction. The equivalent linear (EL) approach is based on total stress conditions, whereas nonlinear soil behaviour is approximated by equivalent linear response of soil, whereas the nonlinear approach is based on effective stress conditions wherein

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nonlinear soil behaviour is accurately modelled to predict the GRA with water pressure generation model as well as the coupling of pore pressure generation response and soil behaviour. GRA studies carried out by several researchers, mentioned in Table 39.1, also indicate that the ground response analysis is one of the fundamental requirements for the design of earthquake-resistant structures [1–12]. Kumar et al. [13] have performed the seismic vulnerability of Kathmandu City (Nepal) based on the Nepal 2015 earthquake. The range of peak ground acceleration and peak spectral acceleration was found to be in the order of 0.21–0.42 g and 0.74–1.50 g, respectively. Based on the liquefaction potential index, it was concluded that 6 sites out of 10 sites are at high risk of liquefaction. Kumar et al. [14] have performed one-dimensional equivalent linear GRA for Guwahati city and recommended that GRA of any region considering its regional dynamic soil properties is the best option to obtain more realistic outcomes. During the literature study, it was found that seismic GRA for the Bihar region was scanty, and therefore, GRA was carried out to observe the site-amplification at the construction site of Bettiah, Bihar.

Methodology

Seismic GRA can be performed either by 1D linear or 1D equivalent linear or 1D nonlinear analysis to estimate the seismic response of stratified soil profile at any specific site in terms of ground acceleration profile, response spectrum, and stress–strain histories. Every mythology has its advantage and disadvantages. In the linear approach, the shear modulus (G) and damping ratio (ξ) are assumed to be constant throughout a particular layer. The equivalent linear (EL) approach approximates the actual nonlinear variation of G and ξ of soil with shear strain, whereas in nonlinear (NL), the realistic behaviour of soil, i.e. nonlinear response of soil is incorporated accurately. In the present study, one-dimensional nonlinear GRA has been performed at the selected location, i.e. Bettiah site in Bihar using the DEEPSOIL software [15] with 18 numbers of borehole data. In this approach, the nonlinear inelastic stress–strain behaviour of soil is considered to evaluate the equations of motion in small time steps which have been referred to obtain the appropriate soil properties to be used in that time steps.

Nonlinear Time Domain Analysis

In contrast with comparable direct recurrence area investigation, the time–space nonlinear strategy is better in anticipating solid ground movement and it additionally permits significant pore water strain to be incorporated. The precision of forecasts which relies upon the constitutive model depiction of soil conduct and for powerful vertical pressure investigation, exactness of expectation additionally relies upon the precision of pore water pressure age reaction model just as the coupling of pore water

Table 39.1 Summary of the literature review

Authors	Location	Software used	Methodology	Remarks
Akhila et al. [3]	Kolkata	DEEPSOIL	1D equivalent linear	PGA of the city range was reported in the range of 0.1–0.34 g
Bashir et al. [4]	Agartala	DEEPSOIL	1D nonlinear	To confirm the sanctity of exact-based evaluation of liquefaction potential. A critical spatial variety of ground reaction risk over the entire region is expected
Puri et al. [5]	Harayana	DEEPSOIL	1D equivalent linear	Cyclic reaction accounted for utilizing standard shear modulus corruption and damping curves. PGA (g) values for selected 77 sites vary from 0.073 to 0.396 g
Gupta et al. [6]	Harayana	DEEPSOIL	1D equivalent linear	The analysis is done using spectrum compatible acceleration time histories and the amplification factor varies from 1.25 to 1.84
Jishnu et al. [7]	Kanpur	SHAKE2000 and OPENSEES	1D nonlinear and 2D nonlinear	Examined the conduct of a more profound soil layer under solid ground movement as far as the overabundance pore pressure improvement, liquefaction potential, and post-liquefaction settlement

(continued)

Table 39.1 (continued)

Authors	Location	Software used	Methodology	Remarks
Kumar et al. [8]	Guwahati	DEEPSOIL	1D equivalent linear	Seven different recorded earthquake motions were adopted of M_w range 6.1–8.1. Fourier amplification at the surface varies from 4.14 to 8.99 for a frequency of 1.75–3.13 Hz
Ranjan et al. [9]	Dehradun	SHAKE2000	MASW	Spectral acceleration varies from 0.06 to 0.37 g for the frequency range of 1–10 Hz. Different zones of shear wave velocity and spectral acceleration have been classified
Kumar and Krishna [10]	Guwahati	DEEPSOIL	1D equivalent linear	Fourier amplification of ground motion at the surface is in the range of 4.14–8.99 for a frequency band of 1.75–3.13 Hz for the range of input motion PGA 0.1–0.34 g
Singhai et al. [11]	Guwahati	DEEPSOIL	1D nonlinear and 1D equivalent linear	The generation of excess PWP indicates a reduction in stiffness and shear strength of soil resulting in changes in the soil behaviour. PGA values of NL approach with excess PWP dissipation are approx. 35–95% lesser than the EL approach

Table 39.1 (continued)

Authors	Location	Software used	Methodology	Remarks
Desai et al. [12]	Mumbai	SHAKE2000	1D equivalent linear	Seismic amplification varies from 2.53 to 4.14 for a frequency band of 1.75–3.5 Hz

pressing factor and conduct of the soil. In nonlinear response methodology, to represent the nonlinear behaviour of soil, the following expressions (dynamic equilibrium and equations of motion) are required to be solved discrete-time augmentations in the time domain.

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]\{I\}\ddot{u}_g \qquad (39.1)$$

where $[M]$ represents the mass matrix, $[C]$ represents the damping matrix, $[K]$ represents the stiffness matrix, $\{\ddot{u}\}$ represents the relative acceleration, $\{\dot{u}\}$ represents the relative velocity, $\{u\}$ represents the relative displacements, $\{I\}$ represents the unit vector, and $\ddot{u}_g$ represents the acceleration of the base of the soil column.

Excess Pore Water Pressure Generation and Dissipation Model

Excess pore water pressure generation and dissipation exist at the same time during ground shaking. Due to strong ground shaking, excess pore pressure induces in the soil which creates excessive settlement, loss of strength in the soil, and other damages due to a decrease in effective stress and shear strength of the soil. Excess pore pressure dissipation can remarkably affect the magnitude of excess pore pressure achieved during ground shaking which depends on the permeability of soil and drainage conditions. The loss of excess pore pressure model is assumed to occur only in the vertical direction and is based on Terzaghi's 1D consolidation theory.

$$\frac{\partial u}{\partial t} = C_v \frac{\partial^2 u}{\partial z^2} \qquad (39.2)$$

where C_v represents the coefficient of consolidation in the vertical direction. In the present study, the pore water pressure model proposed by Matasovic and Dobry (1993) for sand and proposed by Matasovic and Vecetric (1995) for clay was used to determine a curve fitting procedure in the absence of laboratory results. These curve fitting parameters have been considered as per Hashash et al. [15].

Pressure-Dependent Hyperbolic Model

Pressure-dependent modified hyperbolic model has been used to define the stress–strain relationship developed in the soil due to the cyclic loading–unloading phenomenon. The modified hyperbolic model, proposed by Matasovic (1993), is based on the strain-independent hyperbolic model proposed by Konder and Zelasko (1963). This modified hyperbolic model is also called modified Matasovic-Konder-Zelasko (MKZ) and expressed as

$$\tau = \frac{G_o \gamma}{1 + \beta \left(\frac{\gamma}{\gamma_r}\right)^s} \tag{39.3}$$

where G_o represents the initial shear modulus, τ represents the shear strength, γ represents the shear strain, β, s, and γ, are the model parameters. β and s are utilized to adjust the shape of the backbone curve. Further, the shear stress and confining pressure are coupled to make soil profile pressure dependent as follows [15]

$$\gamma_r = \text{Reference strain} \left(\frac{\sigma'_v}{\text{Reference stress}}\right)^b \tag{39.4}$$

where σ'_v represents the effective vertical stress, reference stress is the vertical effective stress, γ_r is reference stress, and b represents the curve fitting parameter of the backbone curve.

Modulus Reduction and Damping Ratio Curves

Due to the unavailability of site-specific curves, representing dynamic soil properties, the modulus reduction and damping ratio curves existing in the DEEPSOIL were utilized in the analysis. In the present investigation, to characterize the dynamic feature of sands and clays, the standard curves for modulus reduction and damping ratio proposed by Seed and Idriss [16] and Vucetic and Dobry [17] have been considered from the database of DEEPSOIL [15]. The plasticity index (PI) values were chosen in the range of 20–23% for clay layers.

Shear Wave Velocity Profile for Soils

Shear wave velocity (V_s) is one of the significant input parameters in seismic GRA studies. In the present study, the correlations between V_s with SPT-N values, listed in Table 39.2, were used to evaluate V_s profiles. Due to uncertainty in the selection of V_s profiles, the average value of the correlations, listed in Table 39.2, have been used.

Table 39.2 Correlations for estimation of average V_s

S No.	Author(s) name	Correlations	Soil type
1	Imai and Tonouchi [18]	$V_s = 97 \, N^{0.314}$	Applicable for all soils
2	Iyisan [19]	$V_s = 51.5 \, N^{0.516}$	
3	Kiku et al. [20]	$V_s = 68.3 \, N^{0.292}$	
4	Hasencebi and Ulusay [21]	$V_s = 90 \, N^{0.309}$	
5	Maheshwari et al. [22]	$V_s = 95.64 \, N^{0.301}$	
6	Hanumantharao [23]	$V_s = 82.6 \, N^{0.43}$	
7	Dikmen [24]	$V_s = 58 \, N_{0.39}$	

Fig. 39.1 Variation of shear wave velocity with SPT-N values for BH-PN-2
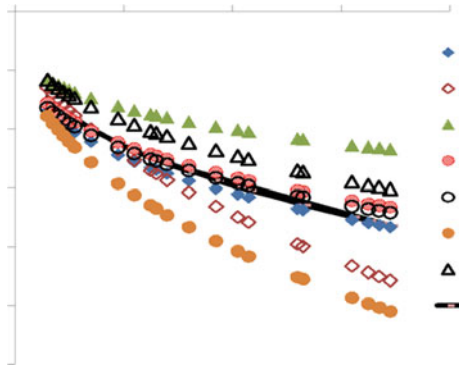
Further, the average value of V_s profile, shown in Fig. 39.1, was used at BH-PN-2. Similarly, the average correlations between V_s with SPT-N were evaluated for all 18 boreholes and utilized for seismic GRA.

Study Area

Bettiah is situated near the Indo-Nepal border and 225 km from the northwest of Patna, Bihar (India). Bettiah is an administrative head office of the West Champaran, Bihar, which lies between 26°48′05″N latitude and 84°30′10″E longitude. The district comes under the seismic zone IV, as per IS-1893 [2], and therefore has a moderate to high damage risk from earthquakes. To characterize the soil properties, soil exploration data was obtained from 18 boreholes (namely, BH-AL, BH- PL-1, BH-PL-3, BH- PL-5, BH- PL-7, BH-AN, BH- PN-2, BH- PN-4, BH- PN-6, BH-AM, BH-PM-1, BH- PM-3, BH- PM-5, BH-AB, BH- PB-0, BH-PB-2, BH-PB-4, BH- PB-6) between Bettiah -Kumar Bagh Station or Road Ch-29.00 km of NH-727 and Ch-0.00 of SH-105 in the Samastipur Division (Fig. 39.2). It was observed from all of the boreholes, having a terminating depth of 40 m, that the site consists of
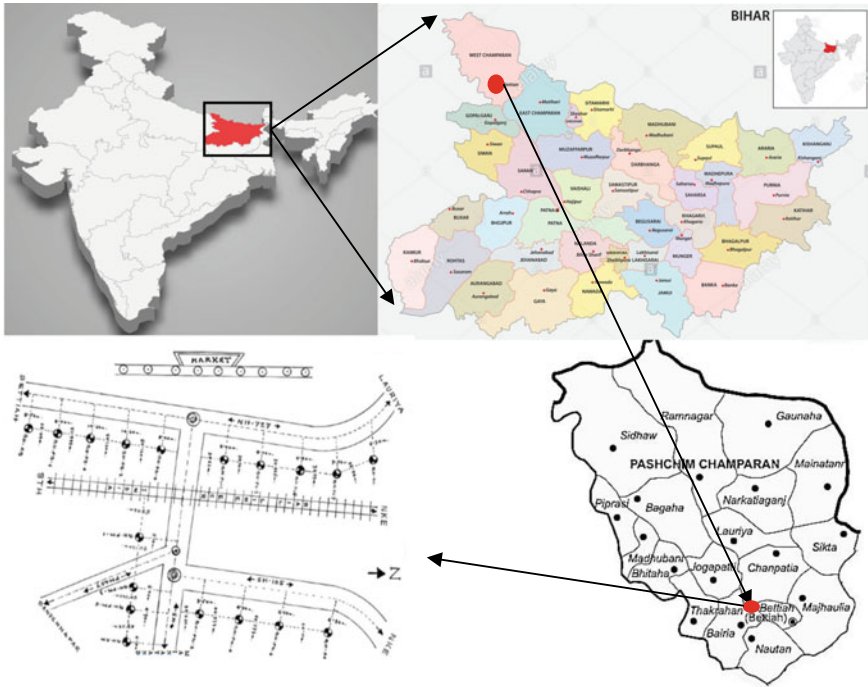
Fig. 39.2 Location of Bettiah Site and all 18 boreholes

clayey, silty, and sandy soil with a remarkably high-water table between 0.8 and 1.6 m from the ground surface. Also, the bulk density at all 18 boreholes varies from 18–19 kN/m^3 and the plastic limit for silty and clayey soil was in the range of 20–23%.

Input Strong Ground Motion

In this study, three acceleration time histories obtained from the 2011-Sikkim earthquake (M_w 6.9) of PGA 0.16 g (recorded motion), 0.286 g (scaled motion), and 0.43 g (scaled motion) are chosen as input motion to represent low, moderate high, and very high seismic hazards. The acceleration time histories of all three input motions are presented in Fig. 39.3.
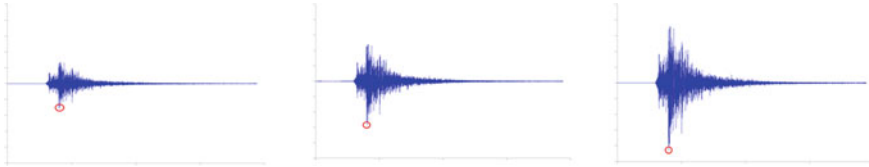
**Fig. 39.3** Acceleration time histories of input motion

Results and Discussions

One-dimensional nonlinear seismic GRA was carried out for all 18 boreholes at the site, Bettiah (Bihar), with the consideration of excess pore water pressure generation and dissipation using the DEEPSOIL computer programme. Utilizing three acceleration time histories, the results were obtained in terms of the variations in acceleration, maximum shear strain, shear stress ratio, and pore water pressure ratio along with depth for all boreholes, which is presented and discussed in the following sections.

Significance of Input Motion on GRA

To analyse the effect of earthquakes of different energy levels (reflected by different PGA), one borehole BH-PN-2 has been selected among 18 boreholes. At borehole BH-PN-2, a clayey layer was found at the depth of 35 m below the ground surface. Figure 39.4a–d presents the variations in acceleration, shear strain, shear stress ratio, and pore water pressure ratio along with depth at BH-PN-2 using acceleration time histories of PGA = 0.16, 0.286, and 0.43 g. From Fig. 39.4a, it can be seen that at a specific depth between 35.4 and 37.5 m, variation of PGA varies in the range of 0.231–0.545 g which shows the chance of wave amplification. Figure 39.4b indicates higher shear strain at the depth of 35 m, which might be due to the relatively softer soil. It has also been observed that the value of strain subjected to PGA = 0.286 g is higher than that obtained from the input motion of PGA = 0.16 and 0.43 g may be due to the high energy content of input motion. The shear stress ratio is one of the important indexes to predict the liquefaction susceptibility behaviour of stratified soil. The stress ratio greater than 1 at any depth reflects the shear stress employed at the soil is greater than the effective vertical stress causing liquefaction.

Figure 39.4c represents the distribution of shear stress ratio along with depth by using input motion of PGA = 0.16, 0.286, and 0.43 g. It has been observed that the distribution of shear stress ratio within the stratified soil layers is less than 1, which shows there is no chance of the occurrence of liquefaction. If the PWP ratio at any depth of stratified layered soil is less than 1, then no liquefaction occurred at any depth from the ground surface. However, if the excess PWP ratio becomes 1 then liquefaction is inevitable. Figure 39.4d presents the variations of PWP ratio along with depth using input motions of PGA = 0.16, 0.286, and 0.43 g for BH-PN-2.
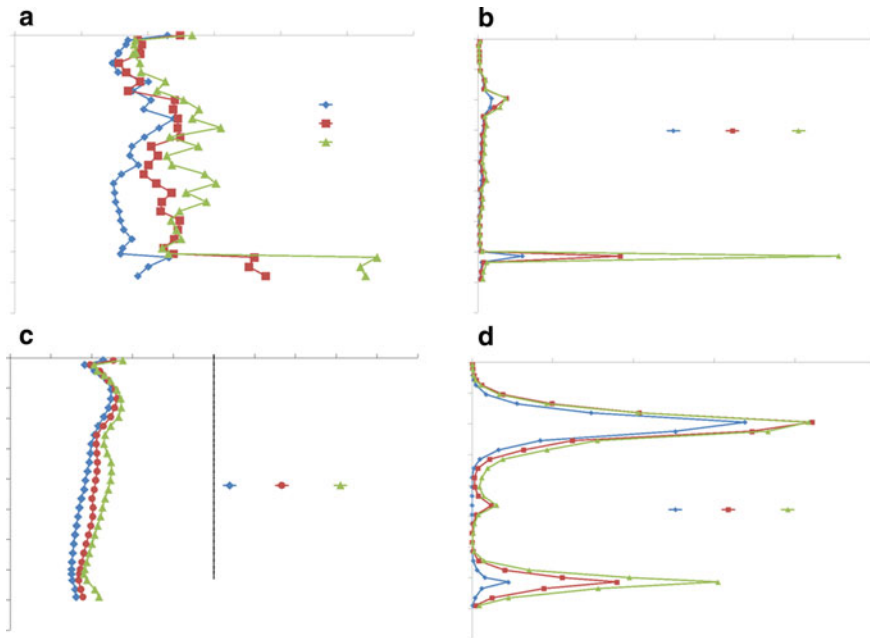
Fig. 39.4 Effects of variation **a** maximum acceleration, **b** max. strain, **c** max. stress ratio, and **d** max PWP ratio with depth using 0.16, 0.286, and 0.43 g input motion at BH-PN-2

From Fig. 39.4d, the PWP ratio is found to be 0.67 at the depth of 11.25 m using 0.16 g PGA motion, which shows there is no chance of occurrence of liquefaction. However, with input motions of PGA 0.286 and 0.43 g, the PWP ratio was nearly 0.83 and 0.84, respectively, at depth 9.75 m below the ground surface which might hint the initiation of the liquefaction stage.

Significance of Subsoil Profiles on GRA

GRA considering a single borehole might give some idea about the amplification or de-amplification of seismic waves but cannot predict the response for the larger area. Therefore, the seismic-resistant design based on the response of a single borehole will not be judicious since the soil, as well as soil conditions, varies from place to place. Figure 39.5a–d presents the variations in acceleration, shear strain, shear stress ratio, and pore water pressure ratio along with depth for all boreholes using acceleration time histories of PGA = 0.286 g. The variations in acceleration at the ground surface were found to be in the range of 0.18–0.42 g, in Fig. 39.5a. Therefore, it can be stated that the amplification factor (AF-ratio of obtained maximum acceleration at a different depth to the maximum acceleration of input motion) varies from 0.708

to 1.7 for a PGA of 0.286 g, which shows that the soils of a specific site of Bettiah are capable of amplifying during earthquake motions. It has also been observed that acceleration at the ground surface for borehole BH-PB-4 is higher than the other one. Figure 39.5b shows the accumulation of high shear strain at 14.25 m at BH-PL-5 and 35.7 m at BH-PN-2 which indicates more energy loss during seismic loading. The development of high shear strain may cause permanent deformation in the ground. Therefore, it is recommended to evaluate the strain-dependent dynamic soil behaviour before the construction.

Figure 39.5c represents the distribution of maximum shear stress ratio along with depth at all 18 boreholes using input motion of PGA = 0.286 g. The maximum shear stress ratio at the ground surface was found to be in the range of 0.18 to 0.42. The increasing values of the stress ratio also hint at the increase in the tendency of soil liquefaction or cyclic mobility. From Fig. 39.5d, considering input motion of PGA = 0.286 g, it can be seen that the maximum increase in PWP ratio is found 0.84 in BH-PM-5 and 0.939 in BH-AN at depth 8.25 m, 0.93 in BH-PN-4 at depth 11.25 m, 0.919 in BH-PN-6 at depth 17.25 m from the ground surface and 0.89 in BH-PM-5 at depth 15.75 m. These values of the PWP ratio indicate the initiation of
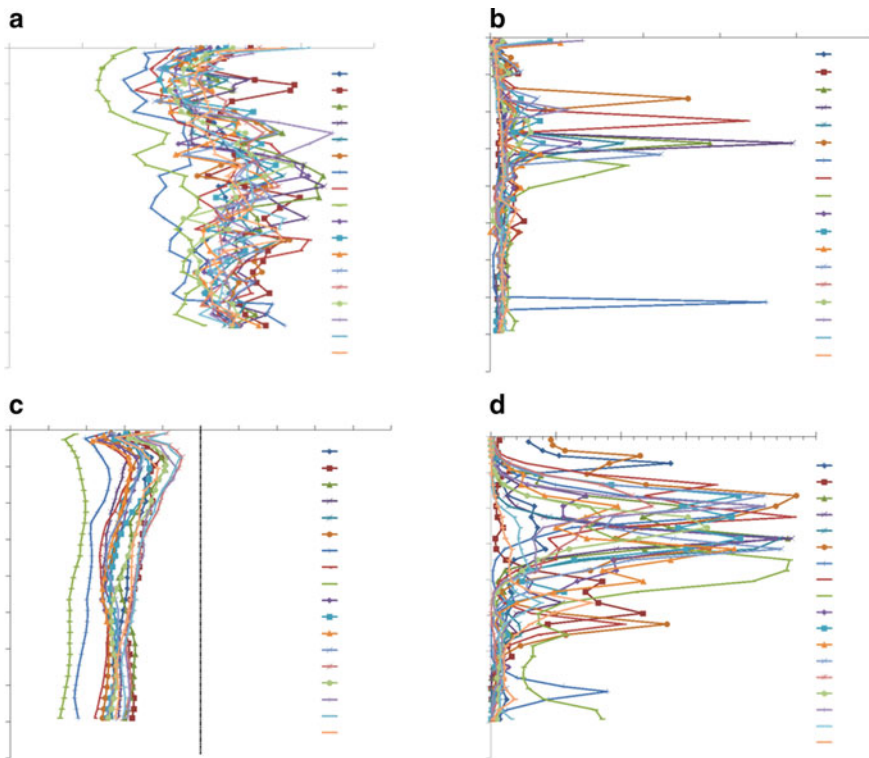
Fig. 39.5 Effects of variation **a** maximum acceleration, **b** max strain, **c** max stress ratio, and **d** max PWP ratio with depth using 0.286 g input motion at all 18 boreholes

Table 39.3 Amplification of PGA

Input PGA (g)	0.16	0.286	0.43
AF of all boreholes	1.178–2.452	0.708–1.7	0.528–1.194

soil liquefaction at most of the borehole when analysed with higher input motion. Moreover, the conditions of soils (such as loose or stiff) at any depth or any location are more responsible for the higher or lower amplification, higher or lower shear strain, higher or lower stress ratio, and higher or lower PWP ratio. Hence, for an accurate assessment of ground acceleration variations, stress ratio variations, strain variations, or liquefaction potential, a detailed study needs to be performed.

Nonlinear GRA has also been carried out for 18 boreholes with the input motion of PGA = 0.16 and 0.43 g. However, the results of the same have not been presented here due to brevity. During analysis, it was observed that AF varies from 1.178 to 2.452 for PGA of 0.16 g, from 0.708 to 1.7 for PGA of 0.286 g, and from 0.528 to 1.194 for PGA of 0.43 g (Table 39.3). These AF values indicate that the amplification of seismic wave is higher corresponding to the lower value of input motion and vice versa. Thus, it can be stated that there is ample chance of amplification of seismic waves at the Bettiah site. Therefore, it can be recommended that the GRA needs to perform before the construction of any soil-supported structures in the Bettiah region.

Conclusions

One-dimensional nonlinear seismic GRA was performed, with the consideration of excess pore water pressure generation and dissipation, using the DEEPSOIL computer programme for 18 boreholes located in the Bettiah district (Bihar). Three acceleration time histories obtained from the 2011-Sikkim earthquake of $M_w = 6.9$, of PGA 0.16 g (recorded motion), 0.286 g (scaled motion), and 0.43 g (scaled motion) have been chosen to represent low, moderate high, and very high seismic hazards. Based on the analysis, the following conclusions have been drawn.

- AF varies from 1.178 to 2.452 for PGA of 0.16 g, from 0.708 to 1.7 for PGA of 0.286 g, and from 0.528 to 1.194 for PGA of 0.43 g. Therefore, it can be stated that there is ample chance of amplification of seismic waves at the Bettiah site; hence, it is recommended that the GRA is required to perform before the construction of any soil-supported structures in the Bettiah region.
- The development of high shear strains (up to 5%) may cause permanent deformation in the ground. Therefore, it is recommended to evaluate the strain-dependent dynamic soil behaviour before the construction.
- The maximum shear stress ratio at the ground surface was found to be in the range of 0.18 to 0.42, which indicates that the tendency of cyclic mobility or soil liquefaction might increase with increasing stress ratio.

- The maximum increase in PWP ratio was 0.84 in BH-PM-5 and 0.939 in BH-AN at depth 8.25 m, 0.93 in BH-PN-4 at depth 11.25 m, 0.919 in BH-PN-6 at depth 17.25 m from the ground surface, and 0.89 in BH-PM-5 at depth 15.75 m, which indicate the initiation of soil liquefaction at most of the borehole when analysed with higher input motion.

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