Nonlinear Ground Response Analysis of Kolkata Soil

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Abstract. Seismic bed-rock motions get amplified or de-amplified depending on the overlying soil deposit and very often found to cause disaster to the overlying structures. Kolkata city is situated on a huge thickness of alluvial Gangetic basin and consists of distinct soil formations, namely, Normal Kolkata deposit, consisting of a thick soft silty clay / clayey silt deposit underlain by stiff clayey soil / silty sand down to considerable depth, and River Channel deposit which consists of a deep deposit of medium/dense/very dense sandy soil present mainly along the Adi Ganga channel. So, in such a scenario when sediment thickness is quite high the study of local site effects should be of primary importance. Few studies have been carried out on local site effects of Kolkata soil using equivalent linear ground response analysis. Although for a weaker motion, equivalent linear (EL) criteria may approximate the non-linear soil behavior quite well, but when a soil is subjected to a strong motion, the EL assumption of soil behavior may not hold true. In this paper non-linear ground response analysis has been carried out using DEEPSOIL program. Synthetic acceleration time history compatible with IS-Code rock level spectra for Zone-III has been used in the study. Variation of peak ground acceleration (PGA), spectral acceleration (SA) and pore water pressure (PWP) variations have been studied for both the deposits. In order to calculate shear wave velocity (V_S) from field N value, a number of V_S-N correlations have been used in the analysis. So, how the selection of different V_S-N correlations affects the outcome of site response analysis has also been studied.

Keywords: DEEPSOIL, Shear Wave Velocity, Spectral Acceleration.

1 Introduction

Seismic bed-rock motions get amplified or de-amplified depending on the overlying soil deposit and very often found to cause disaster to the overlying structures. Kolkata city is situated on a huge thickness of alluvial Gangetic basin. In such a scenario, the study on local site effects becomes an essential part in seismic hazard analysis. General practice for estimation of site specific ground response is to use the linear and equivalent linear method of analysis. For various cities in India, several studies have been carried out to assess the local site effects based on 1D equivalent linear ground response analysis (Anbazhagan and Sitharam, 2008; Roy and Sahu, 2012; Jishnu et. al., 2013; Choudhury and Chatterjee, 2015; Basu et. al., 2017; Puri et. al., 2018; Roy et al., 2018; Dammala et. al., 2019). Few studies were carried out on local site effects of Kolkata soil using equivalent linear ground response analysis (Roy and Sahu 2012; Bhattacharya and Govindaraju 2012; Choudhury and Chatterjee 2015). Although for a weaker motion, equivalent linear (EL) criteria may holds quite well, but when a soil deposit is subjected to a strong shaking, the EL assumption of soil behavior may not simulate the actual behavior. In order to overcome these shortcomings, researchers have started to conduct non-linear ground response analysis where non-linear stress-strain behavior is considered for estimation of shear modulus and damping behavior of soil for the induced shear strain due to earthquake motion. The non-linear analysis was found to predict more realistic site response analysis, whereas, equivalent linear sometimes overestimate the soil response, specifically for strong ground motion. In addition to that, for sandy deposit, variation of pore water pressure can also be predicted in nonlinear analysis which may indicate the initiation of liquefaction and an approximate ground deformation can be evaluated.

Kolkata city covers an area of about 185 sq. km. In most part of the city, buildings, schools, business centers have come up haphazardly. Kolkata, in the past, has suffered enormous damages due to notable earthquakes such as 1897 Great Assam Earthquake, 1906 and 1964 Kolkata Earthquake. The 1964 Kolkata Earthquake epicenter was located over the Eocene Hinge Zone (SEISSAT 2000). IS: 1893 (Part 1)-2002 designates Kolkata on the boundary of Zone III and Zone IV. However, the seismic macrozonation is not enough to forecast the damage scenario in the event of an earthquake. The damage pattern depends on the local geology, vicinity to active faults, geotechnical and geophysical properties of surface and subsurface strata and topography. Mohanty and Walling (2008) presented the microzonation of Kolkata on the basis of PGA variation using a quasi-probabilistic approach considering an attenuation relationship. But, authors did not consider the local site effects. In this context, it may be noted that Kolkata lying on the alluvial Gangetic deposit has two distinct soil formations, i.e., normal Kolkata deposit and river channel deposit. Normal Kolkata deposit consists of a thick soft compressible silty clay/clayey silt down to a depth of about 14.0 m below the existing ground surface followed by stiff/ very stiff/ hard/ very hard clayey deposit with intermediate sand layers down to considerable depth of 40-50 m. The river channel deposit existing along the old AdiGanga channel consists of medium/ dense/ very dense sandy deposit down to considerable depth. These local soil conditions with increasing urbanization and industrialization in Kolkata and adjoining areas makes it necessary to consider microzonation in order to prevent huge loss in terms of life and economy due to future earthquakes.

In the present study, an attempt has been made to evaluate the non-linear site response analysis of normal Kolkata and river channel soil deposits. DEEPSOIL software has been used in this purpose. In order to calculate shear wave velocity from field N value, a number of V_S-N correlations have been used in the analysis. So, how the selection of different V_S-N correlations affects the outcome of site response analysis has also been studied.

2 Methodology

Seismic ground response analyses have been carried out to estimate the response of stratified soil (in term of PGA variation, variation of excess PWP and response spectrum) subjected to a considered bed rock motion. The commonly applied analysis methods are: Linear, Equivalent linear and Non-linear (Kramer, 1996). Linear analysis methodology is based on the assumption that shear modulus and damping is strain independent and constant for each layer. The equivalent linear method of ground response analysis was developed to analyze the non-linear response of soil using frequency domain analysis with the aid of linear transfer functions. Equivalent linear method is an approximation method in which the non-linear behavior of the soil (i.e., strain dependent shear modulus and damping) is modelled in terms of equivalent linear properties (secant shear modulus and damping which is strain-independent for a range of strain) corresponding to effective shear strain using iterative procedure (Kramer, 1996). The iterative procedure is governed by the target of finding a compatible shear modulus and damping for a particular effective shear strain. Generally, the effective shear strain is considered to be 65% of the maximum shear strain developed in the layer (Kramer, 1996). In the frequency domain analysis, the strain time histories obtained for each layer are used to identify the maximum strain which is further used in the estimation of effective shear strain. The computed effective shear strain for a given soil layer is used to estimate the corresponding strain-compatible shear modulus and damping based on an iterative technique initiating from the small-strain shear modulus and damping. This process is repeated until a convergent solution is obtained. The main limitation of the equivalent linear analysis is the consideration of soil layer as a linear visco-elastic material, in which constant shear moduli and damping is used throughout each iteration of the analysis. Though, this method is computationally convenient and provides reasonable results, but it is incapable to represent the change in soil stiffness that actually occurs during the earthquake shaking (Kramer, 1996). Hence, the nonlinear methodology was adopted, which is complex but realistic stress-strain behavior of soil can be modelled for accurate measurement of soil behavior using direct numerical integration in the time domain. The present study utilizes nonlinear (NL) methods of analyses through DEEPSOIL, to perform ground response analyses. The computer program DEEPSOIL has been developed to perform one dimensional (1-D) ground response analyses (Hashash et al, 2011). DEEPSOIL facilitates linear and EQL analyses in the frequency domain; and linear and non-linear analyses in the time domain. Nonlinear-effective stresses without PWP dissipation approach in the time domain has been chosen in this study to observe the soil response under earthquake loading.

In this study, 1-D site response analysis based on effective-stress nonlinear method is carried out, using DEEPSOIL. The modulus reduction and damping curves for each soil layer are obtained (Ishibashi and Zhang 1993). These curves are fitted using the MRDF fitting procedure (Phillips and Hashash 2009), to calculate the nonlinear stress-strain model parameters. Pore-water pressure generation following the non-masing load/unload/reload criteria has been incorporated. The stress strain curves are obtained to represent the loading (1) and unloading/reloading (2) conditions, respectively.

$$\tau = \frac{G_0 \gamma}{1 + \beta \left(\frac{\gamma}{\gamma_r} \right)^s} \qquad (1)$$

$$\tau = F(\gamma_m)\left[2\frac{G_0\left\{\frac{(\gamma-\gamma_{rev})}{2}\right\}}{1+\beta\left\{\frac{(\gamma-\gamma_{rev})}{2\gamma_r}\right\}^s} - \frac{G_0(\gamma-\gamma_{rev})}{1+\beta(\gamma_m-\gamma_r)^s}\right] + \frac{G_0(\gamma-\gamma_{rev})}{1+\beta(\gamma_m-\gamma_r)^s} + \tau_{rev} \quad (2)$$

where, γ is the given shear strain, γ_r is the reference shear strain, β and s are the dimensionless curve fitting constants, γ_{rev} is the reversal shear strain, τ is the shear stress, τ_{rev} is the reversal shear stress, γ_m is the maximum shear strain, $F(\gamma_m)$ is the reduction factor, G_0 is the initial tangent shear modulus.

The soil profile for Normal Kolkata and River Channel soil deposit used in the present analysis is presented in Table 1 and 2 respectively. The direct measurement of shear wave velocity (V_s) of the subsurface with respect to site specific conditions yields accurate V_s profiles. Now, in the absence of such direct (invasive/ non-invasive) V_s measurement, an empirical relations using standard penetration test (SPT)-N value can be adopted to calculate shear wave velocity. The V_s profiles for the proposed site is obtained from the V_s-N correlations proposed by, Maheswari et. al. (2010), and Nath (2016). Two different set of correlations by Nath (2016), one is simplified for all soils and other one is lithology specific, have been used in the analysis. Different V_s-N correlations have been adopted so that the uncertainty associated with the selection of V_s-N correlations can also be accounted. Estimated shear wave velocity profiles using those adopted correlations have been presented in Fig. 1 & 2 for Normal Kolkata and River Channel deposit, respectively.

Table 1. Bole-log details of normal Kolkata soil deposit

Depth (m)	Soil Description	Unit weight (kN/m^3)	$\frac{\text{In soil}}{N\ \text{value}}$	LL (%)	PL (%)
1.5	Fill	17	2	53	25
3	Soft brownish clayey silt	18.5	5	53	25
12.5	Soft dark grey/ grey silty clay with decayed vegetation & organic matter	17.5	3	56	20
16.5	Stiff bluish grey silty clay with kankar	20.9	12	62	18
18.5	Stiff to very stiff molted brown clayey silt with sand	20.8	16	35	18
25.5	Dense to very dense yellowish/ brownish silty sand	20	47		
30	Very stiff to hard molted grey clayey silt to silty clay with	20.5	29	50	29

sand

Table 2. Bole-log details of River channel soil deposit

Depth (m)	Soil description	Unit weight (kN/m^3)	N-value
2	Fill	17	5
6	Loose brownish grey sandy silt	18	11
27	Dense to very dense bluish grey silty sand	19.5	42
30	Very dense grey fine to medium sand	20	50

The site can be classified as site class D with respect to average 30m N-value and V_s-value respectively according to National Earthquake Hazards Reduction Program (NEHRP) and International Building Code. According to IS: 1893 (Part 1)-2002, Normal Kolkata deposit has been assumed to be situated in Zone 3 and with respect to 30m average N-value, Normal Kolkata deposit can be categorized as 'Soft soil' site. The bedrock was assumed to be with unit weight of 25 kN/m^3 and V_s of 2000 m/s to simulate rigid bedrock condition. Spectrum compatible acceleration time history has been generated from San Fernando (1971) earthquake with wavelet-based spectrum compatible time history generation software WAVGEN. Original Earthquake is shown in Fig. 3a and corresponding response spectrum is shown in Fig. 3b. The compatible time history and the comparison of compatible response spectra with IS-code spectra are shown in Fig. 3c & d, respectively. Table 3 summarizes different information of the earthquake time history of San Fernando (1971) earthquake. The peak bedrock acceleration (PBRA) of the compatible motion was 0.157g.

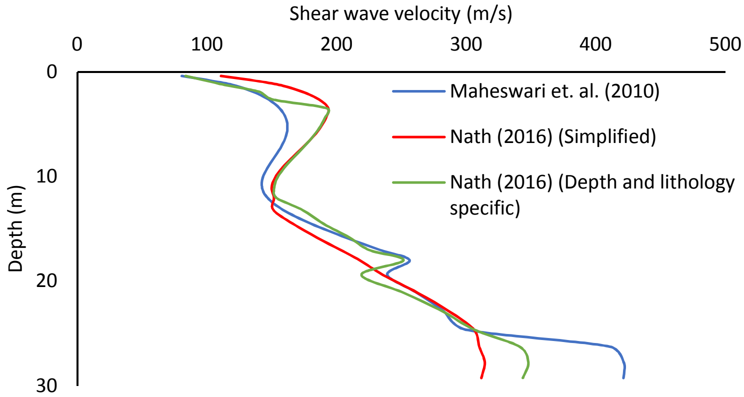

Fig. 1. Generated Shear wave velocity profiles using different adopted V_s-N correlations for Normal Kolkata soil deposit

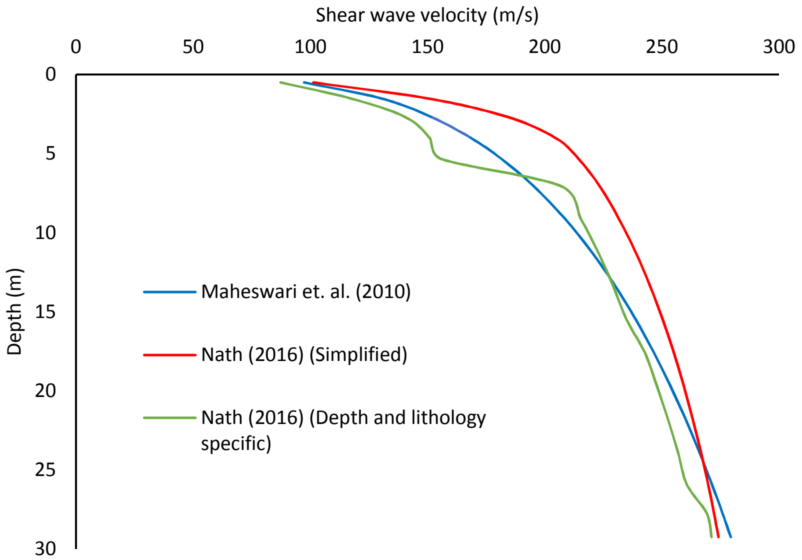

Fig. 2. Generated Shear wave velocity profiles using different adopted V_s-N correlations for River Channel soil deposit

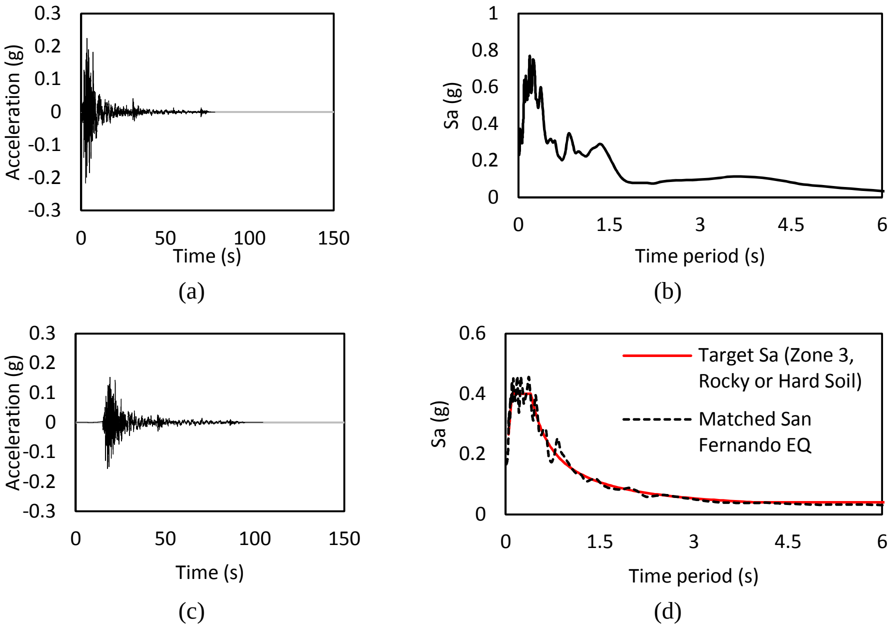

Fig. 3. (a) Acceleration time history of San Fernando (1971) earthquake, (b) response spectra, (c) compatible time history with IS-code spectra and (d) comparison of compatible response spectra with IS-code spectra

Table 3. Details of the earthquake time history used in the analysis

Earthquake	San Fernando
Year	1971
Recording Station	LA - Hollywood Stor FF
Moment Magnitude	6.61
PGA (g)	0.225
Significant Duration (s)	13.14
Distance to rupture (km)	22.77
Mechanism	Reverse

3 Results

The site response parameters are presented in terms of peak horizontal acceleration at the ground surface (PHA/PGA), maximum pore water pressure variation (PWP) and response spectral acceleration (SA) for 5% damping.

3.1 For Normal Kolkata deposit

Figure 4 presents the variation of peak ground acceleration (PGA) with depth. The results clearly depicts that there is a gradual increase in the PGA values up to a depth of 10m, after that a little de-amplification occurs, then again PGA increases at the surface level. Overall, there is an increase in the PGA values from 30m depth where bed-rock is assumed. PGA at the ground surface varies between 0.337g to 0.380g. A nearly similar trend of PGA variation is observed for all the adopted V_s-N correlations. Little difference is observed between 10m to 15m depth. Figure 5 shows the variation of maximum pore water pressure (PWP) ratio with depth. Maximum pore water pressure ratio is defined as the ratio of PWP at a particular depth to the effective vertical stress at that depth. Pore water pressure response is quite flat up to a depth of nearly 18m but from 18m to nearly 25m there is a buildup of excess pore water pressure. The reason is probably up to 18m depth the soils mostly consist of clayey silt/ silty clay and between depths of 18m to 25m there exists dense to very dense yellowish/ brownish silty sand and within these strata generation of PWP is observed. Maximum PWP ratio sharply increases at nearly 20m depth and this variation also differs for different adopted correlation. The lithology specific correlation V_s-N correlation of Nath (2016) shows the maximum variation. This increase in maximum PWP ratio indicates the possibility of liquefaction from any future earthquake with higher PGA. Figure 6 presents the variation of spectral acceleration for 5% damping. A peak spectral acceleration of nearly 1.4g is observed at a period of 0.09s. The simplified V_s-N correlation of Nath (2016) exhibits the lowest peak spectral acceleration of nearly 1.0g among the three adopted correlations.

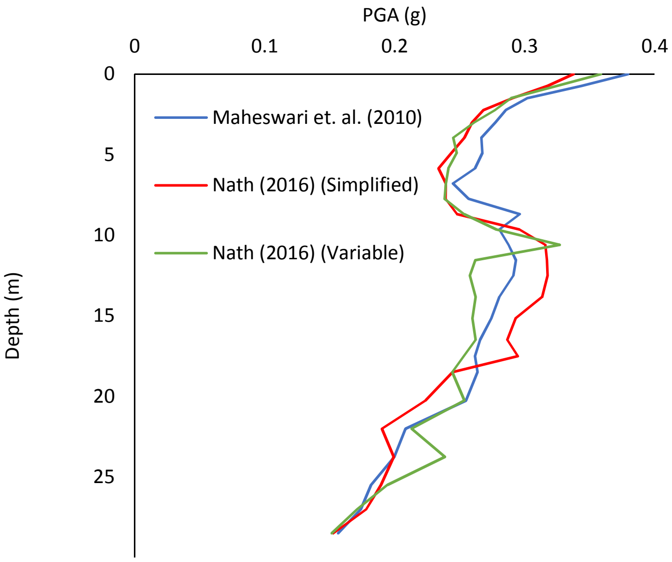

Fig.4. PGA variation with depth for Normal Kolkata deposit

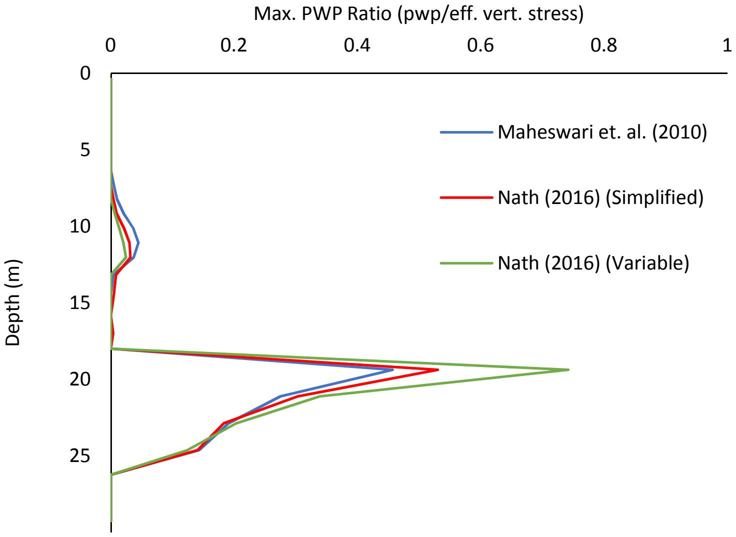

Fig.5. Variation of maximum PWP ratio with depth for Normal Kolkata deposit

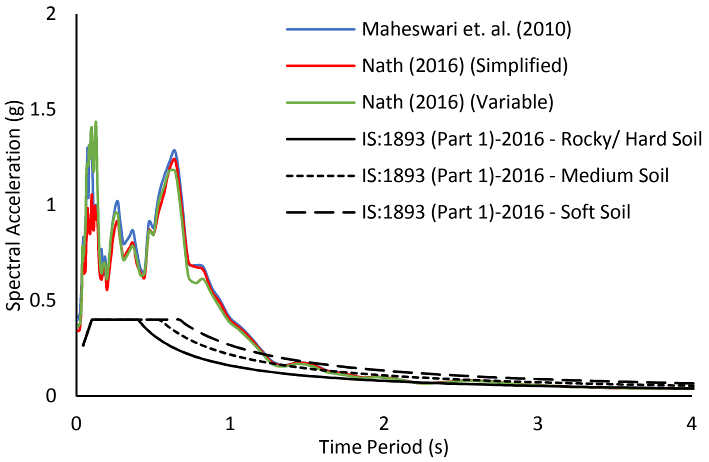

Fig.6. Variation of spectral acceleration at 5% damping for Normal Kolkata deposit

3.2 For River Channel deposit

Figure 7 presents the results of variation of PGA with depth for different adopted V_s-N correlations. The graph shows a gradual increase in the PGA values towards the surface. Surface PGA varies between 0.21g to 0.24g for the V_s-N correlations taken in the study. Here the simplified correlation proposed by Nath (2016) exhibits the maximum PGA at the surface.

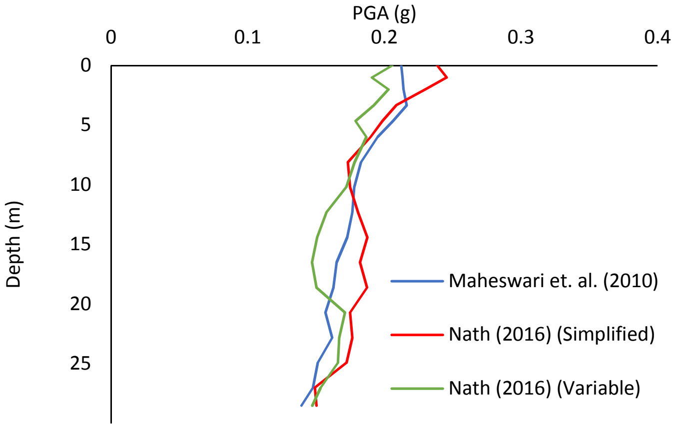

Fig.7. PGA variation with depth for River channel deposit

Figure 8 represents the variation of maximum PWP ratio with depth for the different considered correlations. The values of maximum PWP ratio up to a depth of nearly 5m reaches approximately 1.0 which signify the initiation of liquefaction of the soil strata. The top 5m soil of River Channel deposit consists of loose brownish grey sandy silt which may liquefy during the seismic excitation. Below 5m there exists dense to very dense bluish grey silty sand with very high N values and the graph also shows that for rest of the depth the PWP ratio is quite less which signifies the reduced possibility of liquefaction beyond this depth.

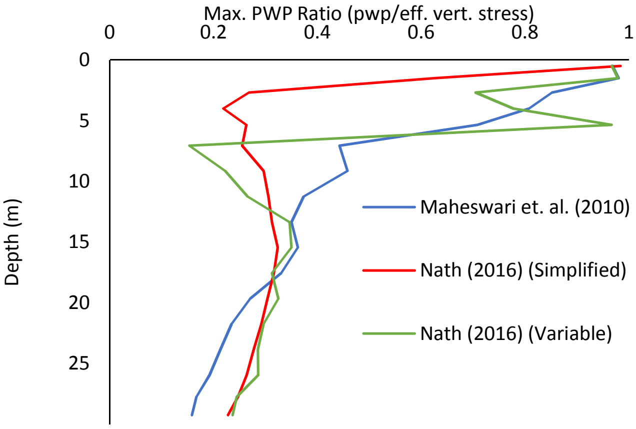

Fig.8. Variation of maximum PWP ratio with depth for River Channel deposit

Figure 9 presents the variation of spectral acceleration at different time periods. A peak spectral acceleration of 1.0g is observed at a period of 0.64s. All the three adopted correlations approximately predict similar peak spectral acceleration.

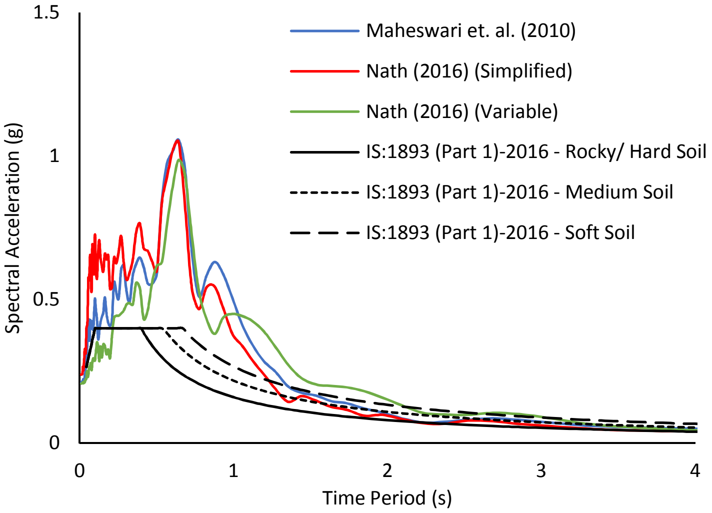

Fig.9. Variation of spectral acceleration at 5% damping for River channel deposit

4 Conclusions

The paper presents a study of nonlinear ground response analysis of Kolkata soil. Two soil profiles examined for ground response analysis were the Normal Kolkata soil deposit and River Channel soil deposit. Acceleration time history of San Fernando (1971) earthquake compatible with IS-code rock level spectra has been used for the ground response analysis. Three different sets of V_s-N correlations have been used in the analysis to study the variations due to adopted correlations. The observations from the study are summarized as follows

1. A substantial amount of amplification is observed for both the considered Normal Kolkata deposit and River channel deposit. Amplification of bedrock PGA is more significant for Normal Kolkata deposit than river channel deposit. This is probably due to the reason that River Channel deposit consists of mainly sandy silt/silty sand/ sand which exhibited lesser amplification.
2. Maximum excess PWP ratio reaches nearly one at top 5m of River Channel deposit, which signifies the probability of liquefaction for any future earthquake. Whereas, Normal Kolkata deposit doesn't show any possibility of liquefaction but at a depth between 18 to 25m where a silty sand stratum exists, the analysis shows a little rise in the PWP ratio. Although there is a build-up of PWP but the possibility of liquefaction is very remote at such huge depth, but a stronger shaking with higher PGA value may cause the soil to liquefy at this depth.
3. Normal Kolkata soil deposit shows higher spectral acceleration in comparison with River channel deposit. The peak spectral accelerations for Normal Kolkata and River Channel deposits are nearly 1.4g and 1.0g respectively. Predicted peak spectral acceleration is quite different for different adopted correlations for Normal Kolkata deposit but exhibits similar peak value for River channel deposit.

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