The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
 ISBN 978-0-367-14328-2

Effect of modulus reduction and damping curves on selection of site-specific seismic design parameters

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ABSTRACT: For any site-specific seismic analysis, selection of modulus reduction and damping curves are important. Since development of these curves requires expertise and diligence, most of the time such curves are adopted from literature based on soil types encountered. In this study, the major objective is to understand the variation in seismic response if such practices are performed. As a case study, artificial earthquake ground motion conforming to Indian standards for the city of New Delhi is developed. Further deconvolution analyses are performed using equivalent linear methods for a possible set of modulus reduction and damping curves adopted from literature. Thus, seismic responses of the site are quantified. These obtained results are then compared with similar responses developed using recommended curves which are confirmed through experimental procedures. It has been found that variation in seismic response obtained henceforth cannot be ignored and it is important to develop site-specific curves.

1 INTRODUCTION

With the help of advanced construction methods and techniques, it is possible nowadays to materialize any form of mega structures. However quantification of hazard events in the future is necessary during the design phase of the structure to ensure its robustness. One such hazard is the possibility to have any tectonic event during the life time of the structure. In most of the cases such possibilities are quantified using some approximate force methods (Pseudo-static approaches) or deformation approaches (Quasi-Static Approaches). However for important structures like dams, gas pipelines, high rise structures etc., using such approximations could be detrimental. For such scenario, Site-specific seismic analysis and design have to be performed.

To perform Site-specific seismic analysis, first, possible ground motion at bed rock level need to be estimated. Various techniques like deterministic(Reiter, 1990) or probabilistic seismic hazard analysis (Algerimissen et al., 1982; Cornell, 1968; Reiter, 1990) could be performed to obtain the same. However in most of the cases, providing foundation at the bed rock level may not be possible owing to the depth of the same. However it has been observed (Gutenberg, 1927; Reid, 1910; Wood, 1908) that ground motion at bed rock could be attenuated along the overlying soil column due to the stiffness variation of the deposits. This could result in amplified/de-amplified motion at the structure founding level and it is highly required to quantify such responses with precision. Researchers have proposed (Schnabel et al., 1972; Zienkiewicz & Taylor, 1989) various techniques (one-dimensional, two-dimensional, three-dimensional methods) to capture such varied seismic responses. To implement these techniques the main input geotechnical parameter(s) could be small-strain shear modulus and modulus reduction/damping curves pertinent to the soil column.

As explained to capture Site-specific seismic responses for structures founded on soil overlying the bed rock, the main input parameter is Site-specific modulus reduction curves (and damping curves) along with small-strain shear modulus. But development of such curves specific for a site is time consuming, iterative and expensive process. Hence in majority of cases, these curves have been adopted from literature based on soil type (Seed & Idriss, 1970), index properties (Vucetic & Dobry, 1991) etc. Thus adoption of such curves becomes subjective. The intention of this study is to understand the impact of such approximations on some main seismic responses like Peak parameters (Peak Ground Acceleration, *PGA*), Amplification Spectrum, Ground motion response, shear stress-strain variation in soil column etc. To accomplish the mentioned objective, a typical soil column (Figure 2(a),Hanumanthrao & Ramana, 2008) corresponding to New Delhi has been adopted along with a possible Site-specific ground motion.

2 GEOTECHNICAL PARAMETERS AND GROUND MOTION GENERATION

As discussed, major geotechnical parameters used for Site-specific response are (1) Small-strain shear modulus and (2) Modulus reduction/Damping curves. First, methodology for obtaining small-strain shear modulus and modulus reduction (and damping) curves will be discussed. This will be followed by the generation of site-specific ground motion.

2.1 *Computation of small-strain modulus & adoption of site-specific curves*

Site-specific small-strain shear modulus (G_s) of soil deposits could be computed (Kramer, 1996)from field tests like Standard Penetration Test (SPT) as shown in Equation No.1 (Here 'ρ' represent mass density of pertaining soil deposit, 'V_s' shear wave velocity of deposits).

$$G_s = \rho V_s^2 \tag{1}$$

As discussed, the study will be performed for a particular soil profile (as shown in Table 1) in New Delhi(Hanumanthrao & Ramana, 2008). The shear wave velocity (V_s) for this soil profile could be computed as per literature (Equation No.4, Hanumanthrao & Ramana, 2008). This correlation between standard penetration number and shear wave velocity is shown in Equation No.2 (Here '*N*' standard penetration number, Hanumanthrao & Ramana, 2008).

Table 1. Representative geotechnical profile for New Delhi (for silty sand)

Depth (m)	SPT 'N'	Vs (m/s)
0		
	7	186
3	9	213
	11	233
6	13	249
	15	262
9	16	273
	18	283
12	19	292
	20	300
15	21	308
	22	315
18	24	321
	25	327
21	26	333
	27	338
24	28	343
	28	348

This computed shear wave velocity is used for the deduction of small strain modulus (as shown in Equation No 1).

$$V_s = 82.6\ N^{0.43}\ m/s \tag{2}$$

The standard soil profile used in this study is shown in Table 1. For this deconvolution study bedrock is assumed at the base of the soil column. Hence at the base, high shear wave velocity (representative of rock, around 760 m/s as per Ministry of Earth Sciences, 2015) is adopted.

Now possible set of Site-specific curves (Modulus reduction and damping) curves need to be adopted for sensitivity study. New Delhi which mainly constitutes Yamuna sand contain silt and clay of varying proportions(Parvez et al., 2004). Mostly, the silt present in New Delhi are non-plastic (Hanumanthrao & Ramana, 2008), however presence of clay fractions need to be accounted. To account for possible high sand fractions, three general modulus reduction and damping curves for sand is adopted (Seed & Idriss, 1970, Figure 1 (a) and Figure 1 (b)). Similarly to account to varying clay fractions, modulus reduction curves and damping curves for soils of varying plasticity index have been adopted (Vucetic & Dobry, 1991, Figure 1(c) and Figure 1(d)). After extensive study on soil deposits (by varying soil fractions and performing cyclic tri-axial tests) in New Delhi it has been concluded (Hanumanthrao & Ramana, 2008) to approximate dynamic behavior of soil as lower bound sand (Seed & Idriss, 1970). In this study variation of seismic response from such proposed behavior from other possible

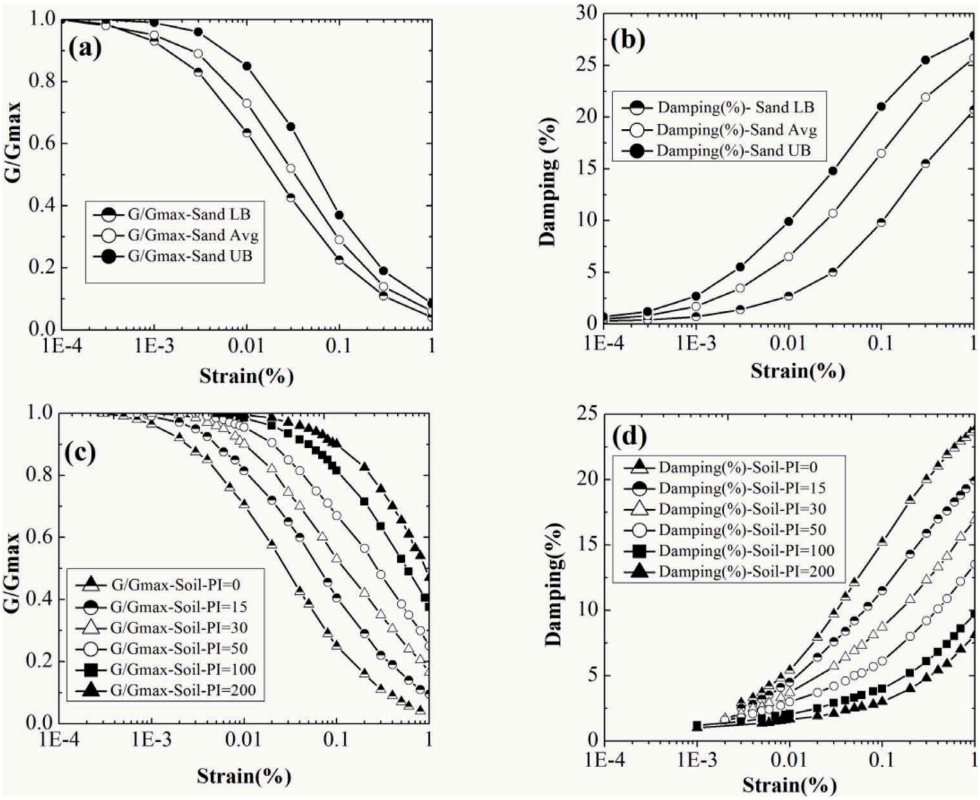

Figure 1. (a) Modulus reduction curves adopted from Seed & Idriss, 1970 (b) Damping curves adopted from Seed & Idriss, 1970 (c) Modulus reduction curves adopted from Vucetic & Dobry,1991 (d) Damping curves adopted from Vucetic & Dobry,1991.

damping and modulus behavior (Sand Avg and Upper bound model in Seed & Idriss, 1970 and soil models of varying plasticity index proposed by Vucetic & Dobry, 1991) will be studied. By such a study it is possible to emphasize the need for development of Site-specific design curves.

2.2 *Generation of artificial ground motion*

Since the relevant geotechnical parameters pertaining to this study have been derived, now the ground motion relevant to this region (New Delhi) has to be deduced. In order to generate such a ground motion, Target response spectrum method (Hou, 1968; Jennings et al., 1968; Liu, 1969) is used. Target response spectrum relevant to New Delhi has been obtained from relevant Indian standard codes (IS 1893,Part 1, 2002). Based on the impending earthquake hazard Indian subcontinent has been divided in to four zones (Zone II-IV, based on increasing tectonic activity). New Delhi falls in the region of high tectonic activity (Zone IV). Indian standards (IS 1893,Part 1, 2002) hence recommend to use a zonal factor (*PGA*) of 0.24g at ground surface. It has been recommended (Ministry of Earth Sciences, 2015) to use a duration of 40.96s for earthquake in New Delhi region. Once the target spectrum and duration has been deduced, artificial ground motion could be generated by using numerical tool like *SIMQKE*(http://nisee.berkeley.edu/elibrary/getpkg?id=SIMQKE2) as given by Equation No.3 (Here '$I(t)$' represents envelope function to ensure the transient nature of earthquakes, '$Z(t)$' represents artificial earthquake, 'A_n' amplitude of sinusoidal waves whose summation gives periodic motion, ω_n and φ_n represent frequency and phase angle of nth contributing sinusoid).

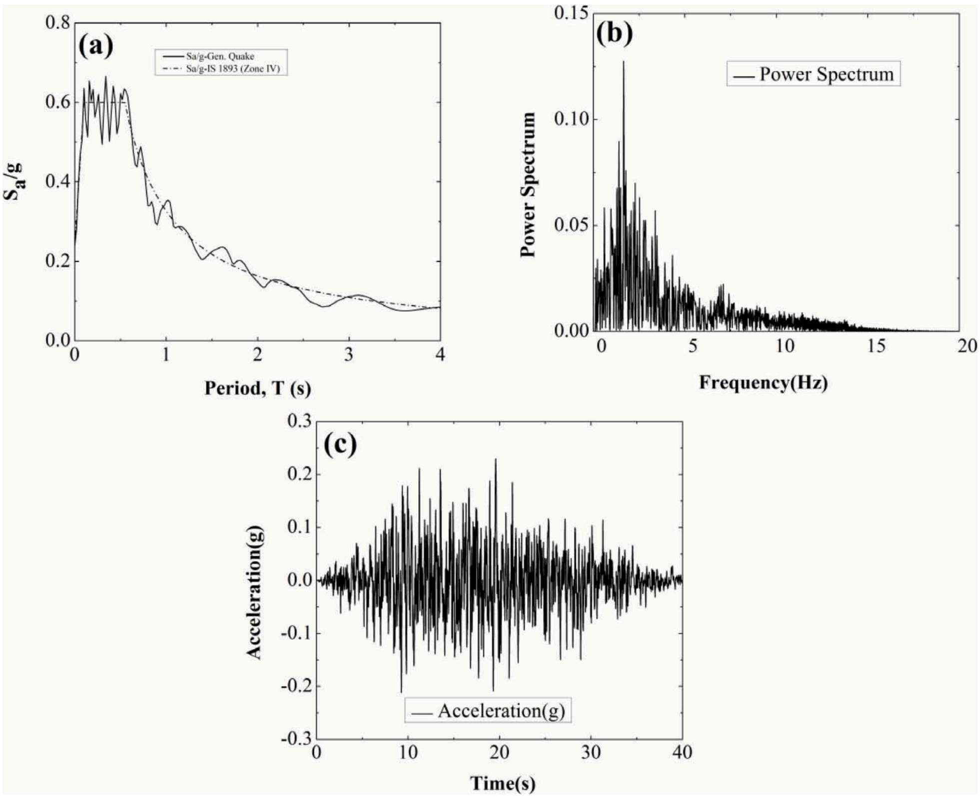

Figure 2. (a) Earthquake spectra comparison between Artificial ground motion and Target (b) Power Spectra generated for artificial ground motion(frequency=0-15Hz) (c) Artificial earthquake developed for this study (Duration=40.96s, PGA=0.24g)

$$Z(t) = I(t)\sum_{i=1}^{n} A_n \sin(\omega_n t + \varphi_n) \tag{3}$$

Once earthquake conforming with specified response spectra, duration and peak ground parameters (like *PGA* in this case) is generated, applicability of the same to this problem need to be ascertained. At first earthquake spectra of artificial ground motion is compared with Target response spectra to confirm the applicability of the approach (as shown in Figure 2(a)). The power spectrum of this artificial ground motion is generated (Figure 2(b)) and it has been found that this ground motion is a "broad band" (0-15Hz) motion as it is expected for earthquakes. Finally, the generated ground motion whose peak parameter ($PGA \approx$ 0.24g) is shown in Figure 2(c).

3 ONE DIMENSIONAL GROUND RESPONSE ANALYSIS FOR DECONVOLUTION

3.1 *Ground response analysis-approach*

As explained in the previous sections, the intention of this study is to understand the variation of various earthquake responses along the soil column when modulus reduction and damping curves are varied. The modulus reduction and damping curves have been identified in **Section 2.1**. The expected ground motion at surface has been generated in **Section 2.2**. Now this ground motion is de-convoluted up to the base of soil column. For such a procedure, one dimensional ground response analysis using SHAKE-91 (https://nisee.berkeley.edu/elibrary/getpkg?id=SHAKE91) has been performed. For such a procedure, the entire soil column is divided into layers of equal thickness (each of 1.5m where Standard penetration N data is available). Layers are numbered progressively in the downward direction from the outcrop. The effective shear strain is taken as 65% of peak strain as it has been found empirically (Kramer, 1996). In equivalent linear analysis (one dimensional in this case), an initial estimate is made for shear modulus (G) and damping (ξ) for preferably low strain level. This estimate is used to compute ground responses like shear strain time histories. Further effective shear strain of each layer (γ_{eff}) is computed from maximum shear strain (γ_{max}) as given in Equation No.4. Their ratio is given by Equation No.5 which is computed from earthquake magnitude (M). Further back computation for new values of shear modulus (G) and damping (ξ) is performed for this effective strain. Such successive iterations were performed for about three to five times(Schnabel et al., 1972). By this method sensitivity of modulus reduction and damping curves on ground response has been deduced.

$$\gamma_{eff} = R_\gamma \gamma_{max} \tag{4}$$

$$R_\gamma = \frac{M-1}{10} \tag{5}$$

4 RESULTS AND DISCUSSION

4.1 *Bed rock spectra*

As explained earlier, deconvolution analysis is performed to obtain the ground motion at the base of soil column. It has been advised (Hanumanthrao & Ramana, 2008) to use lower bound sand (Seed & Idriss, 1970) as representative modulus reduction and damping behavior for Delhi. Hence variation of bed rock response from such an assumption is reported.

Once deconvolution is performed, bed rock spectra are generated for all the set (as mentioned in Section 2.1) of modulus reduction and damping curves. For any spectra two major parameters are of design importance. They are (1) Zero period acceleration (*PGA*, for different ground failure analysis) (2). Maximum acceleration (*MA*, for any time period T in's', pertinent to structures). Bed rock spectra for first set modulus reduction and damping curves (Seed and

Idriss, 1970) are plotted in Figure 3(a). Similarly for the next set of modulus reduction and damping curves (Vucetic & Dobry, 1991) bed rock spectra is shown in Figure 3(b). Thus, from Figure 3(a) and 3(b), Table 2 constituting the above said parameters (*PGA* and *MA*) has been formed. For lower bound sand (Seed & Idriss, 1970), *PGA* of 0.28g and *MA* of 1.14g is obtained from Figure 3(a) and 3(b). It could be clearly seen that, based on the assumption of modulus reduction curves 83% increase (for soil *PI*=0) and 54% decrease (for soil *PI*=200) could be seen for *PGA* (from recommended values) whereas around 99% increase (for soil *PI*=0) and 60% decrease (for soil *PI*>50) could be seen for *MA* (from recommended values). Such variations are not of ignorable amounts and hence the development of Site-specific modulus reduction and damping curves is necessary from the perspective of bed rock spectra.

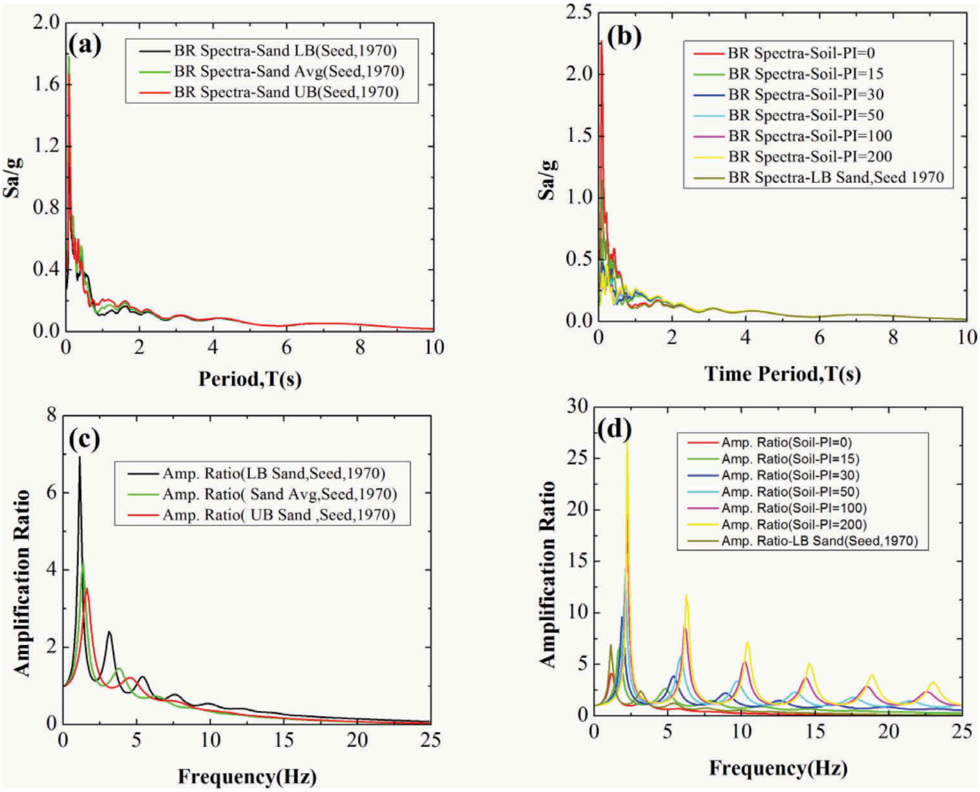

Figure 3. (a) Bed rock spectra obtained using curves as per Seed & Idriss (1970) (b) Bed rock spectra comparison between Vucetic & Dobry (1991) with recommended behavior (Lower bound Sand, Seed & Idriss,1970) (c) Bed rock spectra obtained using curves as per Seed & Idriss, 1970 (d) Amplification ratio comparison between Vucetic and Dobry (1991) with recommended behavior (Lower bound Sand, Seed & Idriss, 1970)

Table 2. Percentage variation for PGA and MA from recommended behavior

Soil type	sand average	sand UB	soil PI=0	soil PI=15	soil PI=30	soil PI=50	soil PI=100	soil PI=200
PGA(g)	0.43	0.39	0.51	0.18	0.15	0.14	0.13	0.13
MA(g)	1.14	1.67	2.27	0.67	0.48	0.45	0.45	0.46
PGA variation (%)	54	39	83	-36	-47	-48	-52	-54
MA variation (%)	56	46	99	-41	-58	-60	-60	-60

Table 3. Ratio of maximum amplification ratios from recommended behavior

Soil type	sand average	sand UB	soil PI=0	soil PI=15	soil PI=30	soil PI=50	soil PI=100	soil PI=200
Maximum amplification ratio	4.21	3.52	4.11	6.73	9.58	13.85	20.74	26.97
Ratio of maximum amplification ratios	0.61	0.51	0.59	0.97	1.38	2.00	2.99	3.89

4.2 *Amplification ratio*

Amplification ratio represents amount by various frequency elements of ground motion gets amplified/de-amplified across the soil column. Like bed rock spectra, amplification ratio along the soil column (plotted between soil surface and bed rock) for the first set of modulus reduction curves is plotted in Figure 3(c). Similarly, for the second set of modulus reduction curves the amplification ratio is plotted in Figure 3(d). For the recommended behavior i.e. lower bound sand (Seed & Idriss, 1970), a maximum amplification ratio of 6.93 is obtained at a frequency of 1.125Hz. For each modulus behavior and damping curve, maximum amplification ratios are obtained. Then the ratio of these amplification ratios to the one obtained as per recommended behavior (6.93 @ 1.125Hz) is reported in Table 3. It could be observed that these ratios vary from 0.51 (for Upper bound Sand, Seed and Idriss, 1970) to 3.89 (for soil PI=200). Such a variation is not of ignorable amounts and hence from the perspective of maximum amplification ratio also site-specific design curves has to be generated.

4.3 *Variation of maximum shear stress-strain along soil column*

During deconvolution analysis, shear stress-strain time history at each soil layers has been noted. From an engineering perspective maximum response of stress and strain along the soil column is plotted. Such a plot could help to conservatively deduce the shear impact on structures at various founding depths. The maximum shear stress along the depth for the first set of modulus reduction (and damping) curves is shown in Figure 4(a).

Similar behavior for the second set of modulus reduction (and damping) curves is shown in Figure 4(b). Following the same procedure strains are shown in Figure 4(c) and 4(d). It is clear from all the observations, that recommended behavior could potentially give higher shear strains (especially at lower depths) and lower shear stresses. As it could be seen from Figure 4(d), with the increase in plasticity index lesser strains will be induced along the soil column. Similarly, from Figure 4(b), assuming higher plasticity index could result in more shear stresses. From all these observations, it is clear that from the perspective of maximum shear stresses and strains induced along the soil column (which is highly significant from engineering perspective) importance of Site-specific modulus reduction and damping curves could not be ignored.

4.4 *Variation of peak ground acceleration along the soil column*

Another important behavior is to understand whether ground acceleration gets amplified/de-amplified along the soil column. First the variation of peak ground acceleration (*PGA*) along the depth for the first set of modulus reduction curves is plotted (Figure 4(e)). No sense of clear amplification is observed along the soil column. But when the next set of modulus reduction curves is used, it is clear that for soils of higher plasticity index (PI > 15) clear sense of site amplification is observed. Thus, behavior of site amplification (in terms of *PGA*) varies significantly with assumption of modulus reduction (and damping) curves. Such behavior is worth noticing when similar convolution procedures are used for getting *PGA* at ground surface (especially for liquefaction analysis).

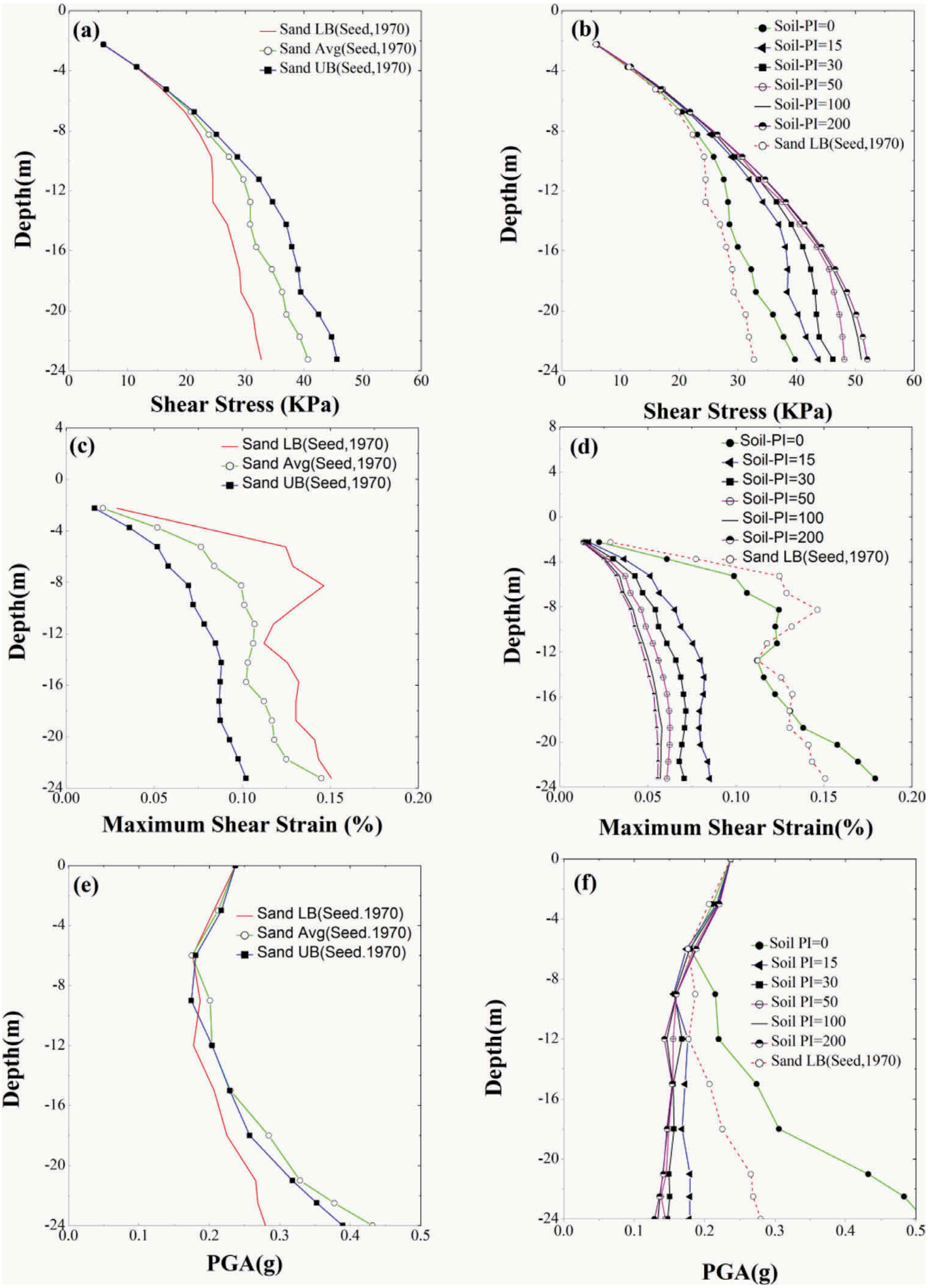

Figure 4. (a) Shear stresses induced on the soil column as per Seed & Idriss (1970) (b) Shear stresses comparison between Vucetic & Dobry (1991) with recommended behavior(Lower bound sand (Seed & Idriss, 1970) (c) Shear strains induced on the soil column as per Seed & Idriss (1970) (d) Shear strains comparison between Vucetic & Dobry (1991) with recommended behavior (Lower bound sand, Seed & Idriss, 1970) (e) *PGA* variation along the soil column using Seed & Idriss (1970) curves (f) *PGA* comparison between Vucetic & Dobry (1991) with recommended behavior(Lower bound sand, (Seed & Idriss,1970)

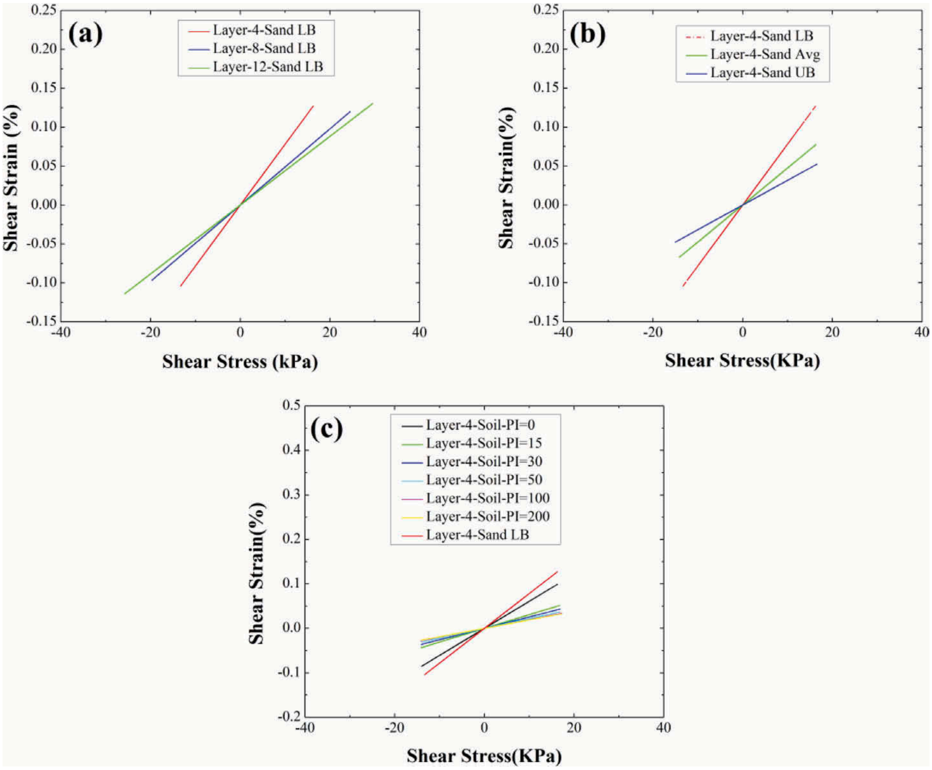

Figure 5. (a) Dependency on the reversal of shear stresses with depth (b) Reversal of shear stresses comparison between various curves as per Seed & Idriss,1970 at the same depth (c) Stress reversal comparison between recommended curves (lower bound Seed and Idriss,1970) and Vucetic and Dobry (1991) approach.

4.5 *Shear stress-strain behavior under earthquake loading*

During the time of earthquake activity, each soil layer is subjected to cyclic loading process. The stress-strain behavior of each soil layers could be then plotted. For the recommended modulus reduction and damping behavior, stress-strain behavior (maximum respective response at different layers) is shown in Figure 5(a). Two main observations at this point could be (1) Flattening of modulus reduction curves with depth (2) Reversal in stress-strain behavior. Flattening of modulus reduction behavior happens with depth, as the small-strain modulus (due to progressive increase in SPT'N') increases with depth (resulting in improved material at higher depth). Another behavior shown here is reversal of stress strain behavior. This is due to the transient behavior of earthquake. However, since non linearity could not be captured, in equivalent linear analysis (as it is done here) nonlinear behavior of stress-strain resulting in hysteresis-loop (and hence energy loss) could not be appreciated. This behavior is consistent even when different set of modulus reduction (or damping) curves are used.

Now the variation of stress strain behavior with recommended behavior need to be noticed. One typical observation (here at fourth layer from the surface) for stress strain behavior and its deviation from first set of modulus reduction behavior (and damping) is shown in Figure 5(b). Similar sort of observations for the next set of modulus reduction and damping curve is shown in Figure 5(c). It could be clearly seen that for the same soil layer (i.e. for the same value of small-strain modulus) high variation is observed for stress-strain reversal and hence equivalent modulus. Such observations remain consistent for all the depths considered. Thus, from the perspective of stress strain reversal, Site-specific modulus reduction and damping curves need to generated.

5 CONCLUSIONS

The seismic behavior of a typical soil column in New Delhi has been studied using Site-specific earthquake. Deconvolution analysis have been performed using equivalent linear methods. The following deductions have been obtained:

a. Major seismic response parameters (like *PGA* and *MA*) has been found to be highly affected by the variation of soil models assuming varying modulus reduction and damping curves.
b. It has been found that site amplification is highly affected by assumption of these curves. Hence higher amplification ratio is obtained for material models assuming high plasticity index.
c. Maximum shear strain induced in the soil column is highly affected by plasticity index. It has been found that material models of higher plasticity index tend to give lesser shear strains. Converse behavior is obtained for shear stresses.
d. Soil models assuming high plasticity index, could handle higher cyclic shear stresses at low strain levels. With the decrease in plasticity index, this capability tends to decrease.

From all the above observations it is clear that assuming soil models based on subjective decisions should be avoided. More elaborate tests for the development of Site-specific curves have to be adopted to ensure the safety of structures against any seismic events.

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