Influence of trapped soft/stiff soil layer in seismic site response analysis

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As the ground response analysis serves an integral part of site specific seismic hazard study to obtain design ground motion, a proper and accurate estimation should be of prime importance. The paper presents a study on the effect of trapped soft and stiff soil layer on equivalent linear ground response analysis implemented in computer program STRATA. For this purpose, the concept of normally stiff and inversely stiff soil profiles have been introduced. The study clearly indicates the higher impact of a trapped soft soil layer profile, i.e., inversely stiff soil profile with soft layer, in comparison with trapped stiff layer profile, i.e., inversely stiff profile with stiff layer. For low to moderate ground motions, as the depth of the trapped soft layer increases, peak amplification and peak frequency reduces, and for high intensity input ground motion, significant reduction only in the peak frequencies is observed. On the other hand, as the depth of trapped stiff soil layer increases the outcome of ground response analysis remain quite similar. Peak transfer function, peak frequency, peak spectral ratio and peak spectral acceleration are found to exhibit a COV $\leq 60$ to $100\%$ for all combinations of IS-Soft profiles, whereas, IS-Stiff profiles exhibit a maximum COV $\leq 15$ to $25\%$ for all the considered input ground motions. Computed normalized-root mean square error (Norm-RMSE) values also clearly indicate the higher deviations in the ground response analysis for different combinations of trapped soft soil profiles, from that of normally stiff profile, whereas, trapped stiff layer profiles show lower deviations in the Norm-RMSE values. The profiles with trapped soft layer exhibit a Norm-RMSE value $\leq 0.8$, whereas, trapped stiff layer profiles exhibit a Norm-RMSE value $\leq 0.2$, which clearly demonstrate the large deviations in the outcome of ground response analysis in case of trapped soft layer profiles.

Keywords. Ground response; soil amplification; normally stiff profile; inversely stiff profile; trapped soft layer; trapped stiff layer.

1. Introduction

Widespread destruction from past earthquakes exhibited the need to estimate the site specific seismic hazard. It is a well known fact that a shallow soil deposit may significantly modify the hazard level at the ground surface (Boore et al. 1993; Anderson et al. 1996), which is known as local site effects. Seismic ground response analysis is generally performed to study the local site effects. Thus, ground response analysis (GRA) has become an integral part in a site specific seismic hazard study (Roy and Sahu 2012; Shukla and Choudhury 2012; Desai and Choudhury 2014; Shiuly et al. 2015; Roy et al. 2018). GRA requires small strain shear modulus/stiffness which is generally determined from site specific shear wave velocity ($V_S$) profile. Further, $V_S$ profiles can be
determined from invasive or non-invasive methods of dynamic site characterization. So, dynamic site characterization based on $V_S$ variations with depth is a pre-requisite of GRA. Although invasive methods provide direct measurement of $V_S$, non-invasive methods of site characterization are getting popular now-a-days. Among the invasive methods of characterisation, cross-hole tests, seismic uphole or downhole tests are widely used, whereas, among non-invasive methods of characterisation, multi-channel analysis of surface wave (MASW) testing (Park et al. 1999; Xia et al. 1999; Foti 2000; Roy and Jakka 2017; 2018) and spectral analysis of surface wave (SASW) testing (Nazarian et al. 1983) are generally used. So, a proper and accurate estimation of $V_S$ is essential as the outcome of GRA may be sensitive to this estimated $V_S$ profile. Finally, the design ground motion of a proposed engineering structure is evaluated from site specific GRA.

Now the uncertainties associated with the estimation of $V_S$ and the strain dependent non-linear soil properties may significantly affect the outcome of GRA. Several studies have been performed on the effect of $V_S$ uncertainty and uncertainty in the estimation of strain dependent non-linear soil properties (Bazzurro and Cornell 2004; Rathje et al. 2010; Boaga et al. 2015; Roy et al. 2018). On the other hand, types of input ground motions characterised by frequency content and duration, used in the GRA may also have a significant consequences in addition to the site property and non-linear soil property variability. Different level of shaking of a ground motion may induce different level of non-linearity in a soil medium, which may also affect the outcome of GRA additionally (Bazzurro and Cornell 2004; Rathje et al. 2010; Caballero et al. 2012; Kumar et al. 2015; Mondal and Kumar 2017). Among all these uncertainties, the proper estimation of subsurface $V_S$ profiles is very important, and the outcome of GRA may be quite sensitive to the estimated $V_S$. Now, in a stratified soil deposit, the stiffness, or $V_S$ gradually increases with depth and this kind of profiles can be termed as normally stiff profile. But sometimes, a soft or stiff layer may get trapped in that stratified medium forming an inversely stiff soil profile. So, the proper determination of presence and position of these trapped soft/stiff soil layer, which sometimes may remain undetected in site characterisation, may further affect the GRA outcome. This kind of inversely stiff profiles with trapped soft/stiff layer are often found to exist in an alluvial deposit. The Kolkata city is situated on such a thick alluvial deposit and this kind of inversely stiff profiles are observed here (Nath 2016; Chatterjee 2018; Roy et al. 2018). So, in this article, the concept of normally and inversely stiff soil profiles have been introduced. Normally stiff (NS) profile is defined as a profile which exhibits a gradual increase in stiffness, or in other term $V_S$, and inversely stiff (IS) profile can be defined as a type of soil profile for which the gradual increase in stiffness gets hindered due to the presence of trapped soft/stiff soil layer. Figure 1 illustrates an example of normally stiff and inversely stiff soil profiles. Figure 1(a) depicts a uniform clayey deposit where gradual increase of $V_S$ can be observed forming a normally stiff profile, whereas, figure 1(b and c) represent inversely stiff profiles with trapped soft and stiff clay layer, respectively.

The effect of the presence of soft/stiff soil layer in a stratified soil medium on GRA has not been documented properly and systematically. In this article, an attempt has been made to study and quantify how the GRA gets modified due to the presence of a trapped soft or stiff soil layer. In addition to that, how the different positions of trapped soft/stiff soil layer can affect the GRA outcome has also been studied. Now, the effect of the variability of input ground motions along with different level of shaking has also been studied. The outcome of GRA has been presented in the form of amplification transfer function (TF), spectral ratio (SR) and spectral acceleration (SA). Finally, the extent to which the GRA outcome of inversely stiff profiles vary from that of normally stiff profile has been quantified using normalized-RMSE (root mean square error) values for different combinations of soil profiles.

2. Methodology

Near surface soil deposits can modify an incoming seismic bedrock motion significantly either by amplifying or deamplifying it and the process to quantify the resulting modifications of waves is called seismic ground response analysis (GRA).

2.1 1D ground response analysis

Among different methods of analysis of GRA, commonly used methods are: linear, equivalent linear and non-linear methods (Kramer 1996). In
this study, 1D equivalent linear ground response analysis has been performed using the computer program STRATA. In linear method of analysis, shear modulus and damping values of a soil are considered independent of induced shear strain. But during actual shaking, shear modulus and damping ratio of soil changes with the change in induced shear strain. In equivalent linear method of analysis, this strain dependent non-linear behaviour of shear modulus and damping is approximated using effective shear strain along with an iterative procedure. In equivalent linear analysis, iterative procedure is used to compute strain compatible shear modulus and damping ratio of a soil layer. The effective shear strain is considered as the 65% of the maximum shear strain. As the equivalent linear analysis is an approximation of non-linear analysis, it cannot take into account the actual behaviour of soil stiffness during the period of earthquake shaking. As the method is more computationally efficient and the entire analysis is carried out in frequency domain, equivalent linear method of analysis is more popular and widely used for ground response analysis (Choudhury and Savoikar 2009; Phanikanth et al. 2011; Roy and Sahu 2012; Roy et al. 2018). One dimensional ground response analysis assumes the vertically propagating SH waves through a linear viscoelastic system.

2.2 Details of simulation

In this article, entire simulation has been performed using equivalent linear ground response analysis implemented in computer program STRATA (Kottke et al. 2013). The soil profile with gradual increase in stiffness with depth, i.e., ‘normally stiff’ profile, has been designated as ‘NS’. Profiles with trapped soft/stiff soil layer, i.e., ‘inversely stiff’ profile, has been designated as ‘IS’. In this paper, for convenience, when an inversely stiff profile is formed with trapped soft soil layer, it has been designated as IS-Soft profile and when the inversely stiff profile is formed with trapped stiff soil layer, it has been designated as IS-Stiff soil profile. The entire simulation has been divided into two parts, seismic response of IS-Soft profiles and seismic response of IS-Stiff profiles. Figure 2 presents the considered NS, IS-Soft and IS-Stiff profiles in terms of $V_S$ – depth variation in this study. Figure 2(a) presents the adopted NS profile with gradual increase in $V_S$ with depth, figure 2(b) presents the IS-Soft profile with a trapped soft layer, the soft layer is present in the second layer, and figure 2(c) presents the IS-Stiff profile with a

![Figure 1. Illustration of the concept of (a) normally stiff profile, (b) inversely stiff with soft layer profile, and (c) inversely stiff with stiff layer profile.](image1)

![Figure 2. Variation of $V_S$ with depth (a) normally stiff profile (NS), (b) inversely stiff profile with trapped soft layer (IS-Soft), and (c) inversely stiff profile with trapped stiff layer (IS-Stiff).](image2)
trapped stiff layer. Table 1 presents the details of layer parameters used for those profiles. A total of six layers plus half-space (bedrock) soil model has been considered with \( V_S \) values 100, 200, 300, 400, 500 and 600 m/s, respectively, along with a bedrock velocity of 1600 m/s. The thickness of each layer has been considered as 5 m with a total soil thickness of 30 m. Now to form an IS-Soft soil profile, second layer has been replaced with the lowest velocity layer of velocity 100 m/s, whereas, to form an IS-Stiff profile, second layer has been replaced with the highest velocity layer of velocity 600 m/s. Soil parameters of the profiles have been considered keeping in mind the view of typical variations of \( V_S \) and corresponding density values of a shallow alluvial soil deposit, and similar kind of \( V_S \) and density variations of an alluvial deposit are also observed in many published articles and reports (Nath 2016; Roy et al. 2018; Chatterjee 2018; Bajaj and Anbazhagan 2019).

Now to study the effect of position of occurrence of soft/stiff soil layer, five different positions of the trapped soft/stiff layer with a total of 10 combinations have been considered in the analysis. All the resulting combinations of profiles have been presented in figure 3. Each case has been designated using a series ‘IS-Soft-P1’/‘IS-Stiff-P1’, which says the profile is inversely stiff with trapped soft/stiff layer and the soft/stiff layer position is one, i.e., at 2nd layer. It can be noted that the fifth position of trapped stiff soil layer, i.e., IS-Stiff-P5, basically represents the initial NS profile. Here, one more important aspect worth mentioning is that the parameterisations of all the considered 10 combinations have been done in such a way that all the 10 profiles have a \( V_S,30 \) value, obtained using travel time average, of 244.9 m/s and fall into the category of site class D as per NEHRP site classification. So, the article will also depict how inspite of belonging to the same site class, the GRA of the considered profiles can vary substantially.

For assessing the influence of different frequency contents, two separate earthquake motion records, Loma Prieta earthquake (18/10/1989) and Chichi aftershock earthquake (20/09/1999) with PGA values of 0.357 and 0.133 g, respectively, have been used as input motions in the bedrock. To further study the effect of level of shaking, each earthquake input motion has been scaled to four different level of shaking, 0.01, 0.05, 0.1 and 0.5 g, and separately used as an input ground motion during the analysis. Figures 4 and 5 present the details of input motions of Loma Prieta (1989) and Chichi aftershock earthquake (1999) along with their scaled motions. Figure 4(a) presents the original acceleration time history (figure 4a1), Fourier spectra (figure 4a2) and Response spectra (figure 4a3) of Loma Prieta earthquake (1989) and figure 4(b) shows the acceleration time history (figure 4b1), Fourier spectra (figure 4b2) and Response spectra (figure 4b3) of scaled motions of Loma Prieta earthquake (1989). Similarly, figure 5 depicts the details of Chichi aftershock earthquake (1999) input motion. The Fourier spectra of both the earthquake exhibit a difference in their frequency content. So, how different frequency content affects the outcome of GRA has also been assessed here. Clayey soil has been considered for all the layers and modulus reduction and damping curves have been considered for clayey soil proposed by Vucetic and Dobry (1991).

Results are presented in the form of comparison of amplification transfer function (TF), spectral ratio (SR) and spectral acceleration (SA). Amplification transfer function represents the ratio of Fourier spectra of surface motion to the Fourier spectra of bedrock input motion. Spectral ratio represents another form of amplification which is

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<th>Thickness (m)</th>
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<th>Inversely stiff profile with soft layer</th>
<th>Inversely stiff profile with stiff layer</th>
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basically the ratio of response spectra of surface motion to the response spectra of bedrock input motion. The variations of different parameters, such as peak amplification, peak frequency, etc., have been plotted with bedrock PGA and normalized depth. The normalized depth represents the ratio between the depth to the middle of the soft/stiff soil layer and the total depth, i.e., 30 m. Here top 30 m soil response has been considered as the average $V_s$ of top 30 m used extensively in seismic site characterisation studies (Dobry et al. 2000; BSSC 2003; Boore 2004) and this shallow soil is mainly responsible for local site effects. Finally, to represent the deviations of amplification spectra,
spectral ratio and response spectra from that of NS profile, a quantity, normalized-RMSE has been calculated and plotted with normalized depth. Figure 6 summarizes the entire methodology that has been adopted here. The first column in the figure presents the considered two types of profiles (IS-Soft/IS-Stiff), second column shows the two original input ground motions, third column represents the outcome of the GRA in terms of comparison of amplification transfer function (TF), spectral ratio (SR) and response spectra (RS), fourth column depicts the variation of peak TF/peak frequency/peak SR/peak SA with bedrock PGA or normalized depth and the fifth column shows the plotting of variation of normalized RMSE of TF, SR and RS with normalized depth.

3. Results and discussions

Initially, the outcome of GRA using original and scaled input motions have been presented for both IS-Soft and IS-Stiff profiles. Then the variations of peak TF, peak frequency, peak SR and peak SA, which basically represent the outcome of GRA, with bedrock PGA have been presented. Finally, in order to quantify the deviations of GRA of IS-Stiff profiles from that of normally stiff profile, variations in terms of Norm-RMSE with normalized depth have been quantified and presented.

3.1 Using original input motions

3.1.1 IS-Soft soil profiles

Figure 7 presents the results of GRA for the considered five combinations of IS-Soft soil profiles using original Loma Prieta (1989) and Chichi earthquake (1999) motions. Outcome of the GRA has been presented in the forms of comparison of amplification TF (figure 7a1 and b1), spectral ratio (figure 7a2 and b2) and response spectra (figure 7a3 and b3). Figure 7(a) shows the results of GRA using Loma Prieta (1989) earthquake motion and figure 7(b) presents the results of Chichi aftershock (1999) earthquake motion. The amplification TF (figure 7a1 and b1) shows remarkable variations in terms of peak frequency (frequency at peak amplification) for both the input motions. Amplification TF plots clearly exhibit that as the depth of trapped soft soil layer increases from ground surface, the peak frequency gets shifted towards the left, i.e., peak frequency decreases, and peak amplification gradually reduces a little (figure 7a1 and b1). Maximum amplification is observed for the profile IS-Soft-P1, i.e., when the soft soil layer exists just near to the ground surface. This maximum amplification also depends on the types of input ground motion used, Chichi aftershock motion lead to a little higher amplification (> 4) in comparison with Loma
Figure 6. Schematic of methodology adopted in the entire study. **Column 1**: Soil profiles – IS-Soft/IS-Stiff, **Column 2**: Input motions used, **Column 3**: Comparison of amplification spectra/spectral ratio/response spectra, **Column 4**: Plots of variations of Peak TF/Peak Frequency/Peak SR/Peak SA with bedrock PGA and normalized depth, and **Column 5**: Plots of RMSE of amplification spectra/spectral ratio/response spectra with normalized depth.

Figure 7. IS-Soft profiles: Comparison of amplification spectra (Col. 1), spectral ratio (Col. 2) and response spectra (Col. 3) for (a) Loma Prieta earthquake (1989) and (b) Chichi aftershock (1999) earthquake motion.
Prieta earthquake (1989) motion (<4). So, if a trapped soft layer is found near to the ground surface, the soil profile might exhibit higher amplification. Significant differences are also observed in spectral ratio plots (figure 7a2 and b2) and spectral acceleration plots (figure 7a3 and b3). Both the plots are found to be quite different. In case of Loma Prieta motion (1989), the peak SR values are found to be quite similar for all the combinations of IS-Soft profiles, whereas, for Chichi aftershock motion (1999) IS-Soft-P1 profile distinctly exhibits higher peak SR value in comparison with others. So, the position of trapped soft layer may control the spectral amplification based on the type of input ground motion and the possibility is there that when the trapped soft soil layer exists near the ground surface it may lead to higher spectral amplification. So, the positions of trapped soft soil layer and the type of input ground motion may substantially affect the outcome of GRA.

3.1.2 IS-Stiff soil profiles

Figure 8 presents the results of GRA for IS-Stiff soil profiles using Loma Prieta (1989) and Chichi aftershock earthquake (1999) motions. The plots clearly depict the reduced variations in amplification TF (figure 8a1 and b1), spectral ratio (figure 8a2 and b2) and spectral acceleration (figure 8a3 and b3) of all the five combinations of IS-Stiff soil profiles. So, if there exists a IS-Stiff profile with trapped stiff soil layer below the ground surface, the outcome of GRA will be quite similar irrespective the position of that trapped stiff soil layer. Type of input ground motion exhibits little variation on the outcome of GRA. Loma Prieta motion is showing little lower peak TF (<6) and peak SR values (figure 8a1 and a2), whereas, Chichi aftershock motion is exhibiting little higher peak TF (>6) and peak SR values (figure 8b1 and b2). So, for a particular input ground motion, all the combinations of IS-Stiff profiles with trapped stiff layer may lead to similar kind of GRA but different input ground motion may exhibits little effect in the outcome of GRA.

3.2 Using scaled input motions

3.2.1 IS-Soft soil profiles

Figure 9 presents the results of GRA using scaled input ground motions of Loma Prieta Earthquake (1989). Four different values of scaled PGA, 0.01, 0.05, 0.10 and 0.50 g, have been selected to study how it influences the GRA for different positions of
soft/stiff soil layers. The results clearly depict the significant differences in the resulting GRA for different combinations of IS-Soft profiles. From results, it can be observed that as the depth of the trapped soft layer increases, peak amplification and peak frequency decrease. Figure 9(a–d) show the results of GRA for scaled input motions with PGA values 0.01, 0.05, 0.10 and 0.50 g, respectively. Plots clearly depict that the response of those five combinations of IS-Soft profiles differ considerably in terms of peak amplification when the profiles are subjected to low PGA input motions, i.e., 0.01 and 0.05 g (figure 9a1 and b1). As the intensity of the input motions increases, i.e., for input motions...
with PGA 0.10 and 0.50 g, the differences in the GRA outcomes reduce significantly (figure 9c1 and d1). For low intensity input motion, profiles exhibit higher amplification, whereas, for high intensity input motions, profiles show lower amplifications. At high frequencies, other than fundamental frequency, the amplification spectra shows several high amplification peaks when the profiles are subjected to low PGA input motions, but as the PGA of input motion increases those peaks get flatter. For the profiles IS-Soft-P4 and IS-Soft-P5, when subjected to lowest intensity input motion (0.01 g), GRA outcome exhibit peak amplification at first higher frequency, not at fundamental frequency (figure 9a1). Spectral ratio plots also exhibit higher values when the profiles are subjected to low intensity input ground motions, but for high intensity motions the variations get flatter with lower values (figure 9a2, b2, c2 and d2). The differences in the variation of spectral acceleration of those five combinations of IS-Soft profiles are also found to be quite significant (figure 9a3, b3, c3 and d3).

Figure 10 also presents the similar plots but using Chichi aftershock motion as input ground motion. This input motion has been used to study the influence of different frequency content of input ground motion on GRA. From the plots of amplification transfer function, it can be observed that although the shape of the variations are quite similar to that of Loma Prieta earthquake (1989) motion, the range of variations of peak amplification and peak frequency differ (figure 10a1, b1, c1 and d1) in both the cases. Spectral acceleration plots and spectral ratio plots also exhibit substantial differences from that of Loma Prieta earthquake (1989) input motion. These variations are quantified and presented in the later sections.

3.2.2 IS-Stiff soil profiles

Figure 11 presents the GRA results of IS-Stiff soil profiles using Loma Prieta earthquake (1989) motion as input ground motion. Unlike the IS-Soft profiles, here the differences in amplification transfer functions of those five combinations of IS-Stiff profiles are quite lower in terms of peak frequency and peak amplification (figure 11a1, b1, c1 and d1). Little variations are observed in case of low intensity input ground motion, i.e., scaled motion with 0.01 g PGA value, and the profiles IS-Stiff-P4 and IS-Stiff-P5 exhibit higher amplification than others (figure 11a1). If the higher mode amplification is considered for the input motion with 0.01 g PGA value, then IS-Stiff-P1 shows little higher amplification from the rest at 1st higher mode even though the fundamental mode amplification is lowest from the rest for the same (figure 11a1). So, when a trapped stiff soil layer exists in a vertically layered medium, it can be said that there is negligible differences in the outcome of GRA for different position of the trapped stiff soil layer when the profiles are subjected to high intensity input ground motion. If the input motion intensity is lower, the profile with stiff layer which exists at higher depth may experience little higher amplification, but there is hardly any difference in the peak frequencies. Spectral ratio plots and spectral acceleration plots also exhibit very little variations except in the case of low intensity input ground motion where spectral ratio plot show little variation (figure 11a2).

Figure 12 plots the similar results, but using Chichi aftershock motion as input. Here unlike the Loma Prieta input motion, little higher variations are observed in spectral ratio plots (figure 12a2, b2, c2 and d2). Similar variations are observed for amplification transfer function plots. Here, in case of stronger level of shaking (i.e., motion with 0.5 g PGA), the acceleration transfer function plot exhibits considerable variations and also little shift in peak frequency to the left (figure 12d1), unlike Loma Prieta input motion. So, different types of input ground motions, characterized by different frequency content, can also play a major role in resulting GRA. Spectral acceleration plots also exhibit similar variation except the case of high intensity input motion (i.e., motion with 0.50 g PGA). For high intensity input motion, spectral acceleration plots show little variations, specifically, profiles IS-Stiff-P3, IS-Stiff-P4 and IS-Stiff-P5 exhibit little different ground response than the rest two profiles (figure 12d3).

3.3 Variation of peak TF, frequency, SR and SA with bedrock PGA

Figure 13 plots the variation of peak TF/peak frequency/peak SR/peak SA with bedrock PGA for IS-Soft, IS-Stiff profile combinations along with comparison of COVs using Loma Prieta Input motion. First column of the figure presents the variations of IS-Soft profiles, second column presents the variations for IS-Stiff soil profiles and
third column presents the comparison of coefficient of variation of both the IS-Soft and IS-Stiff profiles. The plots clearly depict that the range of variations gradually increase for peak TF/peak frequency and peak SR for IS-Soft and IS-Stiff profiles (figure 13a1 and a2, b1 and b2, and c1 and c2). The range of variations are higher for IS-Soft profiles in comparison with IS-Stiff profiles. For peak SA reverse trend is observed, SA is found to increase gradually with the increase in bedrock PGA for both IS-Soft and IS-Stiff profiles (figure 13d1 and d2). The range of variations of the above mentioned parameters are quite broader for IS-Soft profiles, but for IS-Stiff profiles variation range
The variations of peak TF/peak frequency/peak SR/peak SA of those five combinations of profiles have been quantified in terms of COVs at each bedrock PGA for both IS-Soft and IS-Stiff profiles separately and plotted in the third column of figure 13. The comparison of COV clearly demonstrates that for all the presented peak parameters exhibit higher COV for IS-Soft soil profiles (max \( \sim 60\% \)), whereas, IS-Stiff soil profiles exhibit quite lower variation in COV (max \( \sim 15\% \)).

So, it can be said from the analysis that when a soft layer gets trapped in a vertically layered medium, it can exhibit a large variation in the GRA based on the position of soft layer and intensity of...
bedrock input motion, whereas, when a stiff layer gets trapped the GRA might be sensitive to the input motion to a lesser degree (in comparison with trapped soft layer), but the position of stiff layer will be quite less sensitive to the outcome of the GRA (figure 13a3, b3, c3 and d3).

Figure 14 also presents similar plots, but using the Chichi aftershock motion as input ground motion. In this case much wider range of variation is observed for both IS-Soft and IS-Stiff soil profiles. The COV values of the respective input motion for all the peak parameters clearly depict
the higher COV variation in comparison with Loma Prieta Earthquake (1989). Here also IS-Soft profiles are found to exhibit higher COV (max ~ 100%) in comparison with IS-Stiff profiles, except for the highest intensity input motion (i.e., motion with 0.50 g PGA) where a little higher COV is observed for IS-Stiff profiles (max ~ 25%). Overall, the position of trapped soft layer is found to affect the outcome of GRA to a greater degree in terms of peak amplification TF, peak frequency, peak SR and peak SA, whereas, the position of stiff soil layer does not affect the GRA outcome much.

Figure 13. Variation of (a) peak TF, (b) peak Frequency, (c) peak SR and (d) peak SA with bedrock PGA for IS-Soft (Col. 1), IS-Stiff (Col. 2) and comparison of variation of COV (Col. 3) using Loma Prieta (1989) input motion.
In order to quantify the deviations of GRA outcomes in terms of amplification TF, SR and SA of IS-Soft and IS-Stiff soil profiles from that of NS (i.e., IS-Stiff-P5 case) profile using a single value, the parameter normalized-RMSE has been introduced. Norm-RMSE can be defined as follows:

$$\text{Norm-RMSE}_{TF,SR,SA} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( \frac{\text{NS}_{TF,SR,SA}}{\text{IS-Soft/Stiff}_{TF,SR,SA}} - 1 \right)^2}$$

(1)

where Norm-RMSE$_{TF,SR,SA}$ is the normalized RMSE computed for acceleration transfer function/
spectral ratio/spectral acceleration, \( NS_{TF/SR/SA} \) is the acceleration transfer function/spectral ratio/spectral acceleration values for normally stiff soil profile, IS-Soft/Stiff \( NS_{TF/SR/SA} \) is the acceleration transfer function/spectral ratio/spectral acceleration values for IS-Soft or IS-Stiff profiles, and \( n \) is the number of data points in the respective curve. Here, the RMSE error or Norm-RMSE, has been computed by normalizing the deviation of each data point with respect to \( NS_{TF/SR/SA} \), i.e., with respect to the standard GRA outcome (TF/SR/SA) of NS soil profile. Lower the value of Norm-RMSE, better is the match with the normally stiff profile. Here, the GRA of normally stiff profile has been considered as standard one and the Norm-RMSE represents the normalized error in GRA (i.e., how much the GRA of IS-Soft/IS-Stiff profile deviates from the GRA of NS profile) due to the trapped soft/stiff soil layer.

The variation of Norm-RMSE has been plotted with normalized depth. Normalized depth represents the ratio of the depth to the middle of the trapped soft/stiff soil layer to max depth (i.e., 30 m). So, a particular normalized depth represents a particular position of trapped soft/stiff soil layer. Figure 15 shows the variation of Norm-RMSE with normalized depth for IS-Soft and IS-Stiff soil profiles for Loma Prieta input motion. For IS-Soft profiles (figure 15a1, a2 and a3), the plots clearly depict that the Norm-RMSE increases with the normalized depth, i.e., position of trapped soft layer, for amplification TF, SR and SA. So, as the position of soft soil layer increases from the ground surface, the output of GRA deviates substantially from that of NS profile, the rate of increase is rapid initially and reduces later on. It can be observed that the variation of Norm-RMSE of SR and Norm-RMSE of SA are identical. This is because the SR represents the ratio between surface SA and bedrock SA and as the bedrock SA is constant for a particular motion, the Norm-RMSE of SR will obviously become identical with that of SA. Now for IS-Stiff profiles (figure 15b1, b2 and b3), the trend is quite opposite to that of IS-Soft profiles. With the increase in normalized depth, Norm-RMSE reduces and as the normalized depth becomes equal to 0.92, the Norm-RMSE value becomes zero which represent the NS soil profile scenario. For IS-Stiff profiles, the maximum Norm-RMSE value observed is \(~0.2\), but a maximum Norm-RMSE of \(~0.7\) is observed for IS-Soft profiles in case of TF, which clearly demonstrate higher deviation in amplification spectra when there exists a trapped soft soil layer. For SR/SA, the the maximum Norm-RMSE is observed 0.05 and 0.6 for IS-Stiff

![Figure 15](image-url)

Figure 15. Variation of Norm-RMSE of amplification TF (Col. 1), SR (Col. 2) and SA (Col. 3) with normalized depth for (a) IS-Soft profiles and (b) IS-Stiff profiles using Loma Prieta (1989) input motion.
and IS-Soft profiles, respectively. Figure 16 presents similar plots but using the Chichi after-shock input motion. Quite similar variations in Norm-RMSE values are obtained for acceleration transfer function, but little higher values are obtained for SR/SA. In this case, a maximum Norm-RMSE value of $\sim 0.8$ is observed in case of IS-Soft profiles for SR/SA and $\sim 0.17$ is observed for IS-Stiff profiles for amplification TF.

4. Conclusions

The paper presents a detailed analysis on how a trapped soft/stiff soil layer influences the outcome of 1D equivalent linear ground response analysis combined with the effect of type and intensity of input ground motion. From the above analysis, following conclusions can be drawn:

1. The presence of trapped soft layer is found to influence the GRA more significantly in comparison with trapped stiff layer. For low to moderate shaking level, as the depth of the soft soil layer increases peak amplification decreases and peak frequency shifts towards the left, i.e., also decreases, whereas, as the depth of stiff soil layer increases the outcome of GRA remain quite similar, only at low intensity motion, little variation is observed. For higher shaking level, the difference in peak amplifications reduces substantially but little reduction is observed in case of peak frequencies.

2. Significant variations in spectral ratios and spectral accelerations are observed for different combinations of IS-Soft soil profiles. When the trapped soft layer exists near to the surface it exhibits higher SR/SA values, and SR/SA values reduce as the depth of soft layer increases. So, when a trapped soft layer exists near to the surface, the possibility is there that the site will experience higher spectral amplification and if a soft layer occurs at large depth, it will exhibit lower amplification if the site is subjected to low to moderate intensity input ground motion. In case of IS-Stiff soil profiles, SR and SA values exhibit lower variation.

3. Peak TF, peak frequency, peak SR and peak SA are found to exhibit a COV $\leq 60$ to 100% for all combinations of IS-Soft profiles, whereas, IS-Stiff profiles exhibit a maximum COV $\leq 15$ to 25% for both the input motions along with all scaled input motions. So, this variation clearly signifies the higher impact of trapped soft soil layer on the site specific GRA than the trapped stiff soil layer.

4. Computed Norm-RMSE values also clearly indicate higher variations in GRA, in terms of amplification TF, SR and SA, for IS-Soft
profiles from that of NS profile, and IS-Soft profiles show very little variation in the Norm-RMSE values. Norm-RMSE values are found to increase gradually with normalized depth for all the considered shaking level in case of IS-Soft profiles, but for IS-Soft profile Norm-RMSE gradually reduces and become zero at a normalized depth of 0.92 (IS-Soft-P5), which basically represent the NS profile case. IS-Soft profiles exhibit a Norm-RMSE value ≤0.8, whereas, IS-Soft profiles exhibit a Norm-RMSE value ≤0.2, which clearly demonstrate the large difference in the outcome of GRA in case of IS-Soft profiles from that of NS soil profile.

5. This study is applicable for normal Kolkata deposit/similar other alluvial deposits where such type of inversely stiff with trapped soft/stiff soil layers are encountered. Depending on the position of that entrapped soft/stiff soil layer the outcome of ground response analysis will vary substantially as is observed from the results of this study and hence this study is beneficial for initial assessment of ground motion variability of such sites.

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