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Effective Depth of Soil Column for Site Response Analysis of Deep Soil Sites

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Abstract

Background: Seismic site response analyses are routinely performed for shallow soil deposits. In the seismic site response studies, depth of input motion which is also called as the depth of half-space or bedrock and is one of the important parameters which influence the amplification and attenuation characteristics of any particular site. **Objectives:** Finding the exact location of bedrock for deep soil deposits is difficult and uneconomical. Hence, there is a need to identify the effective depth of soil column for deep soil sites to get representative site response parameters. **Statistical Analysis:** In the present study, recorded bedrock and surface earthquake data with soil profiles is used to identify the matching modulus and damping curves for widely available deep soil types and investigated the depth of half-space for site response study of deep soil sites. Eleven deep soil profiles having minimum depth of 100m and maximum depth of 800 m with different sets of recorded earthquake time histories from Kiban Kyoshin network are used for the study. Nonlinear site response analyses were carried out using the program DEEPSOIL. Suitable shear modulus and damping curves are identified by a parametric study of varying shear modulus and damping curves for a matching computed response spectrum with the measured response spectrum. Soil properties and model curves are frozen for each profile, which are further used to identify the depth of half space. **Findings:** Perfect matching layer having shear wave velocity and depth has been analysed, the study indicated that location of half-space is independent of depth factor. However, it is noticed in the study that computed response spectrum is close to the measured response spectrum when input is given for layer having shear wave velocity of 760 m/s±100.This layer represents a depth of half space for site response analysis of the deep soil column. **Application:** We can utilize the finding to perform for better accuracy and consistent results based on current findings and same can be used for site response studies.

Keywords: Earthquake, Effective Depth of Soil Column, Input Motion, Response Spectrum, Site Response

1. Introduction

In the seismic site response study, depth of half-space is one of the important parameters which influence the amplification and response characteristics of any particular site. Generally the half-space is placed at the top of bedrock in any site response analysis. Finding the exact depth of the bedrock for shallow soil deposits is easy and input can be given at this level. But, in case of deep soil deposits (depth of soil column >100m) it is difficult and uneconomical to find the exact depth of the bedrock. Hence there is a need to identify the effective depth of soil column for site response studies in deep soil sites. Deep soil deposits in earthquake prone areas have suffered partial or total damage number of times[1].The researchers conducted[2,3] site response analysis and they concluded that the site coefficient developed for 30 m thick soil profile does not represent the site effects at deeper profiles. Deep soil deposits act as a filter and filter out a significant portion of the high frequency content of bedrock acceler-

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ation and shows larger spectral amplification in the long period[4] region. The researchers have done investigation[5-7] to find the depth of half-space for deep soil deposits but, there has been no consensus among them. Chen acknowledged the problem of fixing the depth of input motion and concluded to use the depth of input motion as deep as possible in order to obtain realistic site response estimation. Carried out nonlinear studies of numerous deep soil sites and found that "the amplification and residual pore water pressure response of deep deposits deeper than 100 m or so are similar". In[8] presented study on evaluation of seismic response on dry sandy soil having deposits more than 100m thick. This study indicates that half space depth does not coincide with the bedrock depth and also no preferred depth was proposed in site response analysis. The result showed that authors recommended that the most suitable depth of half-space is a function of the acceleration time history used. It can be noted from the above discussion that limited study exists on depth of input for the seismic response of deep soil deposits, even though now we have a considerable real bedrock and surface earthquake data with deep soil profiles. In the present study, an attempt has been made to investigate how deep a half-space should be placed for seismic response analysis of deep soil deposits, by taking eleven deep soil profiles. In[1] all the profiles ranging from 100m to 800m. The nonlinear site response has been carried out using DEEPSOIL V5.0. Initially, a parametric analysis has been carried out by giving input motion at record depth and by changing the density, shear modulus and damping curves for each type of soil layer. Final density, shear modulus and damping curves are selected by matching estimated surface spectrum with recorded data. Then these final values are used as input and depth of input level has been varied up to shallow depth less than 20 m or shear wave velocity of less than 450 m/s. Calculated surface spectrum is then compared with recorded data to find out depth of half space.

2. Collection of Deep Soil Profiles and Time Histories

The prime objective is to find out the effective depth of soil column of deep soil sites for the seismic site response analysis. The acceleration time histories for bedrock and surface records are collected from Japanese internet source kik-net. Kik net is strong motion seismograph network that monitors throughout the country. Its network contains 700 boreholes installed with high sensitivity seismographs. National researches institute for earth science and disaster prevention since 1996. This data includes the stratification details, subsurface details with p and s wave velocity profiles. Even though tremendous amount of data is available on KiK net, in this study data which has surface spectral values of more than 0.05g for the engineering applications are used.

In the present work eleven deep soil sites were selected which are listed in Table1. The soil and shear wave velocity profiles of these deep soil sites were selected. All sites have mixed soil layers and generally the mixture of Sand, Clay, gravel and silts which are found above the rock layers. Thickness of soil layer varies from few meters to more than 200 meters. These sites are selected based on essential criterion such as depth of borehole, location of bedrock and surface PGA. The site AICH05 and NIGH has two recorded earthquake acceleration time histories with the surface PGA of more than 0.05g and in total eleven analyses has been carried out.

Table 1. Table showing various sites with matched layer and SWV of matched layer

Site Code	Matching layer depth (m)	SWV of matching layer depth (m/s)	Figure no.
AICH05-a	364, 384, 404	730	1,2
AICH05-b	140, 260	670,730	3,4
ISKH07	440, 472, 500, 560, 590	750	5,6
NIGH14-1	20	710	7,8
SZOH26	206, 290	670, 780	9,10
YMTH01	175	600	11,12
FKSH14	106	1030	13,14
AOMH12	96.5	820	15,16
SZOH30	16	830	17,18
NIGH14-2	94	840	19,20
YMTH02	82	510	21,22

3. Non-Linear Analysis of Deep Soil Sites

In a nonlinear site response analysis, the response of a soil deposit is calculated by numerically integrating the wave propagation equation. A time domain step by step integration of equations of motion after using a discrete model is capable of nonlinear analysis. In this work, the nonlinear site response model DEEPSOIL developed by[8] has been used to estimate surface response parameters. DEEPSOIL incorporates several enhancements over currently available nonlinear models. All the soil layers were modelled as the mass, nonlinear spring dashpot system. Each of the soil layers can be modelled as either linear elastic material or pressure dependent nonlinear material. The base of the soil column can be represented either as infinite stiff or visco-elastic half space. DEEPSOIL can be successfully used for any number of soil layers and for any depth and also to perform both the equivalent and nonlinear soil response analysis. The DEEPSOIL V5.0 version with new features including confining pressure pore water generation models and more user friendly interface has been used in this work to conduct the nonlinear site response analysis for deeper soil columns. The DEEPSOIL program was developed to understand the nonlinear soil response for Mississippi embayment where overburden thickness varies from 100m to even 1000m. This software being used by many researchers for the site response[9] study of deep soil sites.

4. Dynamic Properties and Models

Ynamic properties of soil layers play very important role in the seismic response of the site. In order to estimate dynamic property i.e. shear modulus (G_{max}), shear wave velocity and density are required. Since the density values are not available in KiK-net, Gardner's relationship is used to predict initial density of each soil layers. The relationship between shear wave velocity and density was found by Gardner in 1974 as:

$$\boldsymbol{\rho} = \boldsymbol{\alpha}\, \mathbf{V}^{0.25}$$

Where $\boldsymbol{\rho}$ is in g/cm^3, $\boldsymbol{\alpha}$ is 0.31 when $\mathbf{V}$ is in m/sec and 0.23 when $\mathbf{V}$ is in ft/sec.

Similar to dynamic properties, dynamic models parameters such as shear modulus and damping curves plays a significant role in the prediction of seismic response parameters. Use of right shear modulus and damping curves allows representation of the nonlinear behaviour in sufficient detail for many practical purposes. In the absence of site specific dynamic models, one can use existing available models for site response. There are several modulus and damping curves present for each type of materials. In this study the following dynamic model curves are used for respective type of soil layer.

- Sand layer – EPRIcurves[10,11]
- Clay layer[12-14]
- Gravel layer – curves[15,16]
- Rock layer –EPRIcurves[17]

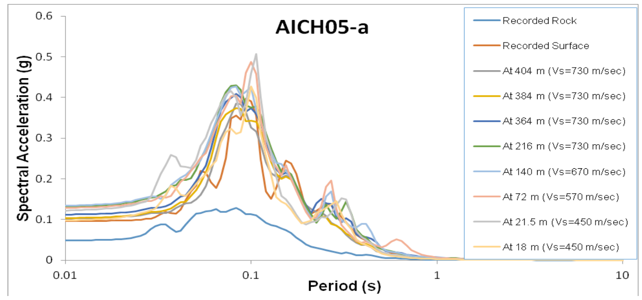

Figure 1. Variation of PSA for site AICH05 – for layers at different depth and corresponding shear wave velocities.

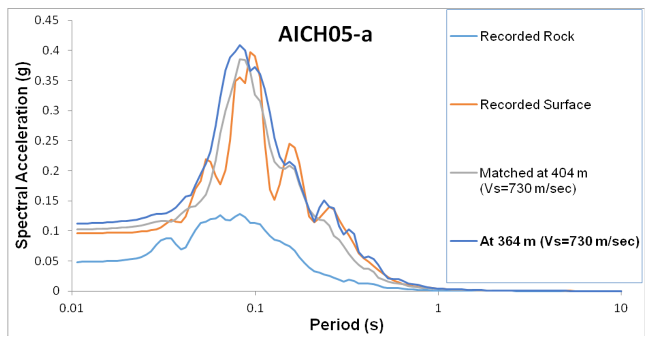

Figure 2. Variation of response spectra for profile AICH05-a showing matched response to surface response.

Each site soil profiles are created by considering dynamic properties and models. The thickness and shear wave velocities remain same and initial density and dynamic models are changeable during parametric study. Number of one dimensional, nonlinear, time domain analyses are carried by varying the appropriate density values and the dynamic property curves (modulus degradation and damping ratio curves) for each site, to get a good match between calculated response and recorded response. For each site about 15 trails are carried out to get good matched results. Figure 1 shows typical parametric study results. For this study the input ground motions are given at recorded depth i.e. deeper depth. From this parametric study of eleven profile and analysis, it is noticed that good matching was found when[10] curves for sand[14] curves for clay[16] curves for gravel and EPRI curves for rock layers are used. It is also noticed that change in shape of spectrum when dynamic model is changed. Change of density values of soil layers can only increase or decrease the peak spectral values up to a certain extent and dynamic curves are the responsible for the shift of predominant time period and large spectral amplification. However more detailed study may be required to discuss above aspects.

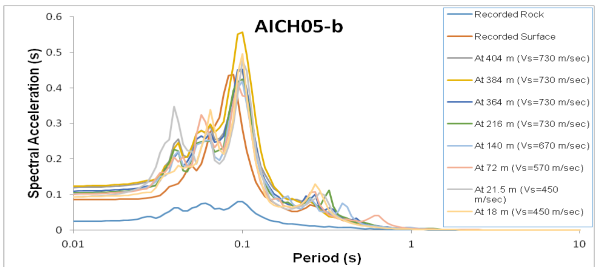

Figure 3. Variation of PSA for site AICH05-b for layers at different depths and corresponding shear wave velocities.

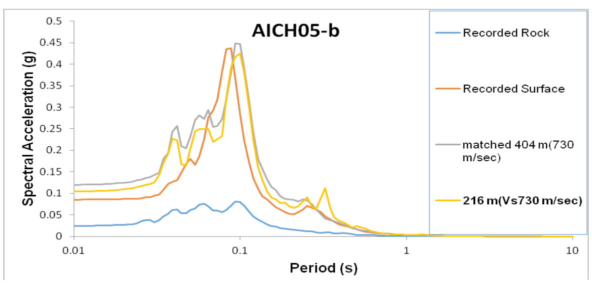

Figure 4. Variation of response spectra for profile AICH05-b showing matched response to surface response.

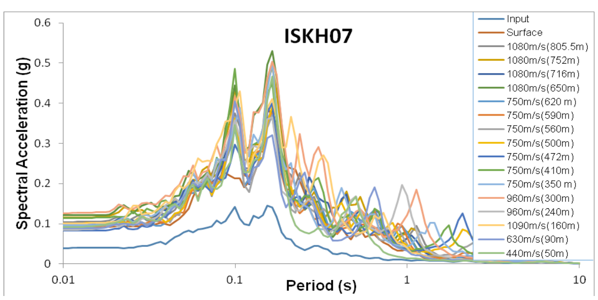

Figure 5. Variation of PSA for site ISKH07 for layers at different depths and corresponding shear wave velocities.

5. Results and Discussion

In the seismic site response analysis model, depth of input plays very important role in surface response parameters, which is called as the depth of half-space or bedrock. Many times the location of half-space cannot be known especially for deeper soil profiles. One of the major problems in the site response of any deep soil sites is to find the depth of half-space in the soil profiles. Since there were no proper guidelines to fix the half-space depth an investigation has been done for the prediction appropriate location of bedrock.

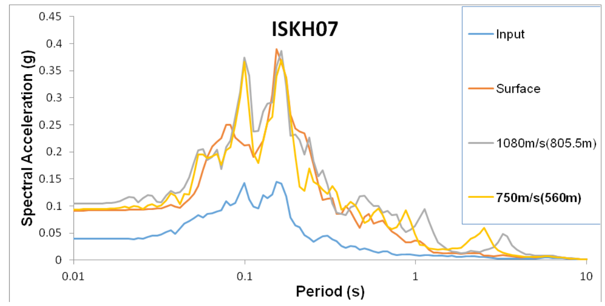

Figure 6. Variation of response spectra for profile ISKH07 showing only matched response to surface response.

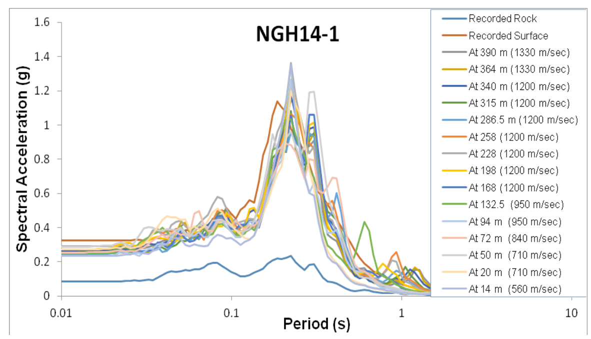

Figure 7. Variation of PSA for site NGH14-1 for layers at different depths and corresponding shear wave velocities.

The following procedure is adopted to predict the depth of input motion.

1. The input acceleration time history is applied at suitable depths. The depths are chosen such that depths where the shear wave velocity value changes and dividing of thick layers to smaller thicknesses (i.e. thickness of 20m or 30m or 40m whichever is convenient).
2. Plot the computed surface response in the form of spectral acceleration variation and compare with the recorded surface response spectrum.
3. Discard the response spectra whichever predicts under and over than the recorded surface spectrum (the difference in PGA and maximum PSA of computed and recorded response spectra exceeds 0.05g),

and retain the spectra whichever predicts similar to recorded surface response spectrum.

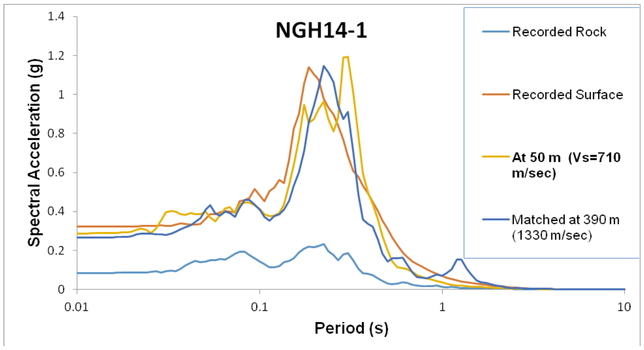

Figure 8. Variation of response spectra for profile NGH14-1 showing matched response to surface response.

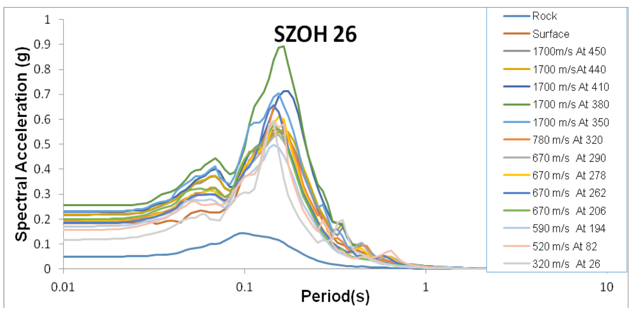

Figure 9. Variation of PSA for site SZOH26 for layers at different depths and corresponding shear wave velocities.

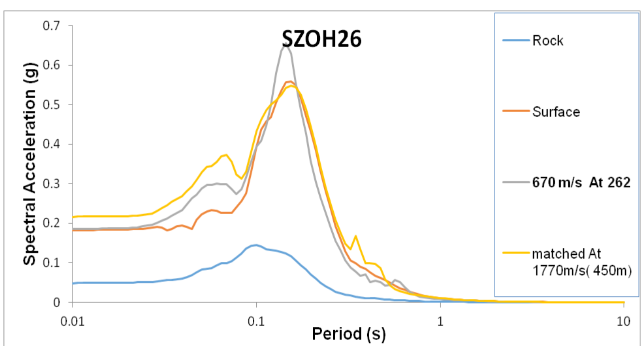

Figure 10. Variation of response spectra for profile SZOH26 showing matched response to surface response.

Figure 1 show the response spectra of site AICH05 (a) when the input ground motion is applied at different level at which the SWV profile changes. It is obvious that the response of the soil will change if the depth of input motion changes, in the Figure 1, we eliminate the response spectra which are predicting higher and lower than the recorded response spectra and remaining spectra which are closely matching with the recorded spectra are plotted in Figure 2. From the Figure 2 it can be observed that the response spectra computed when input motion applied at depths 364m, 384m and 404m where the shear wave velocity value 730 m/sec are predicting almost similar to recorded surface response spectrum. Table 1 shows various sites with matched layer and SWV of matched layer.

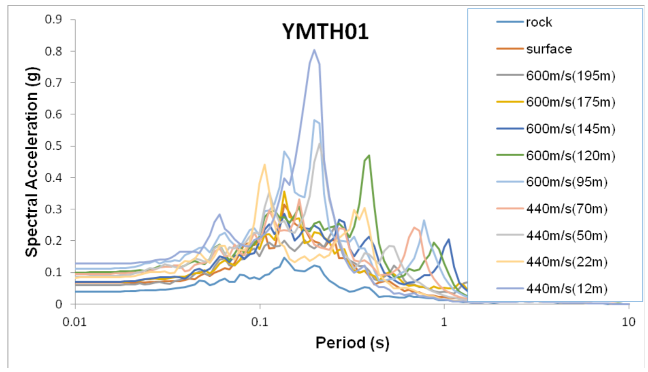

Figure 11. Variation of PSA for site YMTH01 for layers at different depths and corresponding shear wave velocities.

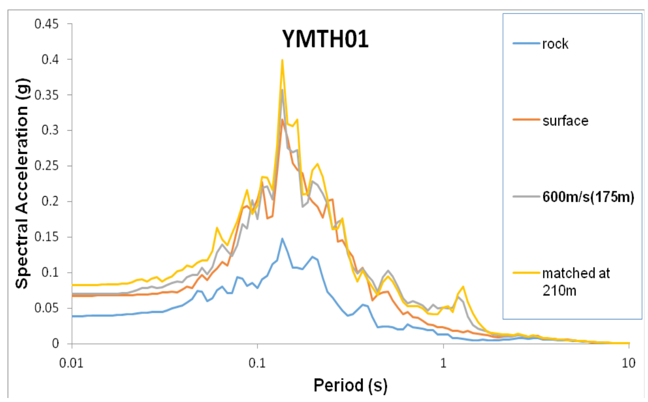

Figure 12. Variation of response spectra for profile YMTH01 showing matched response with surface response.

Examination of Figures 1 to 22 reveals that, the location of half-space should not be a single valued depth factor i.e. it is not possible to fix the particular depth as location of half-space vary for every seismic site response analysis of deep soil sites. Hence it can be conclude that the realistic seismic response of deep soil sites is independent on depth factor. From the Figures 2 and 4 it can be observed that, for the site AICH 05 even though the input motions of different PGA (0.046g and 0.023g) i.e. AICH05-a and AICH05-b is applied for the same site, the predicted surface responses are identical with the recorded surface response when the input motion applied at locations where the array of shear wave velocity values are 670 m/sec to 730 m/sec. From the figure 6 for the site ISKH 07 with an input ground motion of PGA 0.039g, the predicted surface response are matching with the recorded surface response when the input motion applied at locations where the shear wave velocity value is 750 m/sec. From the figure 8 for the site NIGH 14 with input ground motion of PGA 0.084g, the predicted surface responses are matching with the recorded surface response when the input motion applied at locations where the shear wave velocity value is 710 m/sec. From the figure 10 for the site SZOH 26 with an input ground motion of PGA 0.0475g, the predicted surface response are matching with the recorded surface response when the input motion applied at locations where the array of shear wave velocity values are 670 m/sec and 780 m/sec.

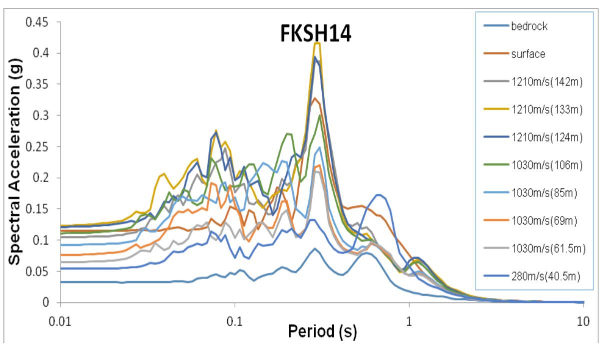

Figure 13. Variation of PSA for site FKSH14 for layers at different depths and corresponding shear wave velocities.

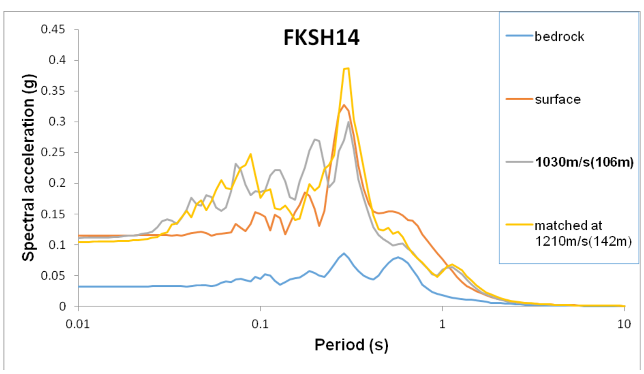

Figure 14. Variation of response spectra for profile FKSH14 showing matched response to surface response.

From the above observations and from Figures 1-22, all the sites with different soil types and rock conditions the predicted surface response approximately matches with recorded surface response wherever the shear wave velocity value generally in the range of 670 m/sec to 780 m/sec with exception to FKSH14 and YMTH02 and reason that can be attributed was unavailability of SWV data value in the range of 600-700 m/s. Hence we can conclude that, for the seismic site response analyses of deep soil sites the depth of half-space can locate approximately where the shear wave velocity varies 760±60 m/sec in order to get reasonable surface response.

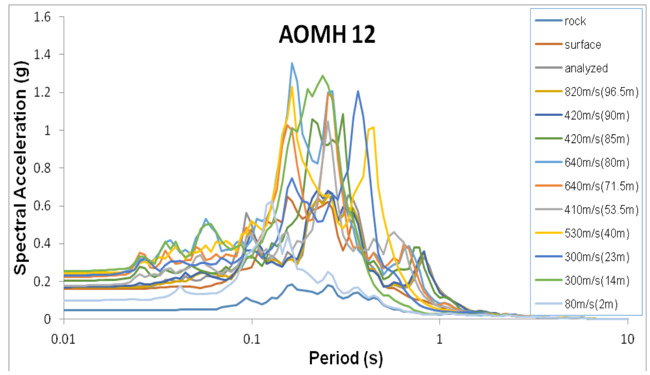

Figure 15. Variation of PSA for site AOMH12 for layers at different depths and corresponding shear wave velocities.

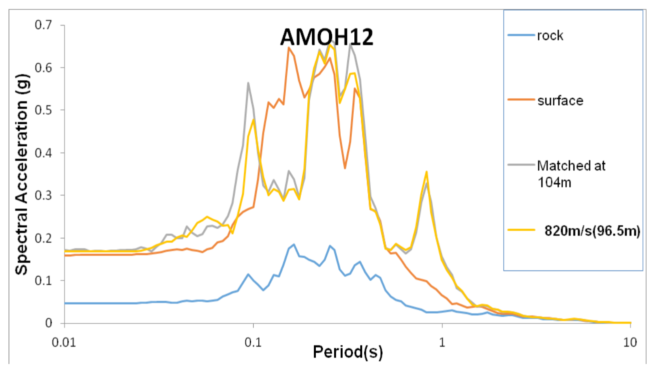

Figure 16. Variation of response spectra for profile AMOH12 showing matched response to surface response

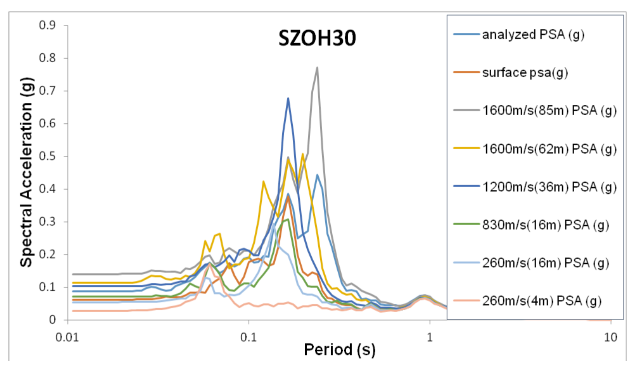

Figure 17. Variation of PSA for site SZOH30 for layers at different depths and corresponding shear wave velocities.

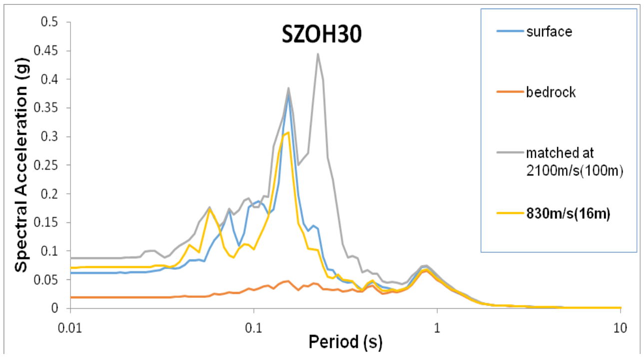

Figure 18. Variation of response spectra for profile SZOH30 showing matched response with surface response.

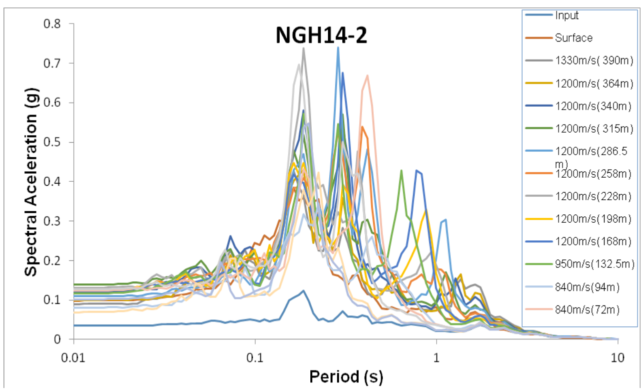

Figure 19. Variation of PSA for site NGH14-2 for layers at different depths and corresponding shear wave velocities.

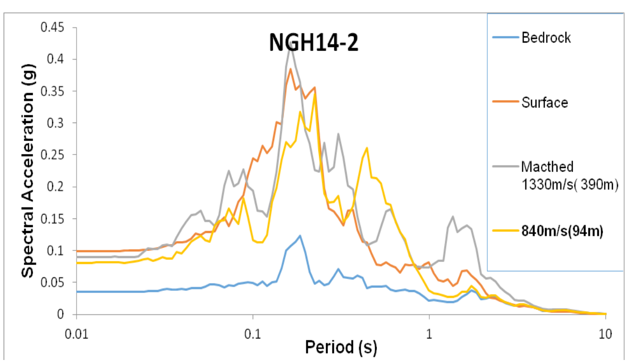

Figure 20. Variation of response spectra for profile NGH14-2 showing matched response to surface response.

6. Conclusions

This study attempts to fix depth of half-space by considering four deep soil sites of different soil type and rock conditions with recorded earthquake data. During this simulation the following observations were made;

1. In[10] curves for sand, In[14] curves for clay, In[16] curves for gravel and EPRI curves for rock type shows good match with the recorded data for the selected soil profiles.
2. Changing of density values of soil layers can only increase or decrease the peak spectral values up to a certain extent (i.e. up to 0.05g to 0.1g) but dynamic property curves are the responsible for the shift of predominant time period and large spectral amplification.

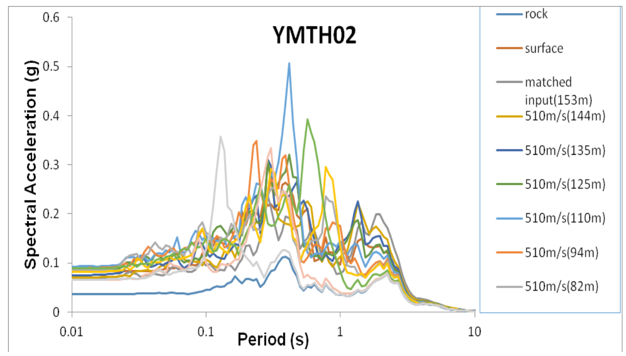

Figure 21. Variation of PSA for site YMTH02 for layers at different depths and corresponding shear wave velocities.

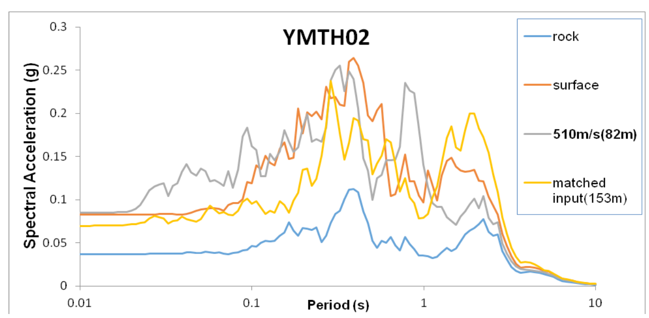

Figure 22. Variation of response spectra for profile YMTH02 showing matched response with surface response.

3. Assuming of appropriate density values does not cause much digression in the spectral amplification of deep soil sites.
4. For deep soil sites the amplification of spectral acceleration at rock surface is negligible and considerable amplification take place in the soil layers.

Later on input ground motion was applied at appropriate depths and the corresponding surface responses were compared with the recorded surface response in the form of acceleration response spectra. The computed response spectra not matching with the recorded response spectrum were discarded and rest of the response spectra matching with the recorded response spectrum were retained. From the retained spectra of all deep soil deposits, we noticed that location of half-space is independent of depth factor and concludes that, for the seismic site response analyses of deep soil sites the depth of half-space can be locate approximately where the shear wave velocity varies 760±60 m/sec in order to get reasonable surface response.

7. Acknowledgements

The deep soil profiles and recorded Ground motion data used in the study was collected from kik-net. The boreholes provided high intensity data required for number of the earthquake analysis and procedures for site response.

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