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Seismic response analysis of layered soils considering effect of surcharge mass using HFTD approach. Part I: basic formulation and linear HFTD

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Abstract. Seismic ground response analysis is one of the most important issues in geotechnical earthquake engineering. Conventional seismic site response and free field analysis of layered soils does not consider the effect of surcharge mass which may be present on the top layer. Surcharge mass may develop extra inertial force to the soil and, hence, significantly affect on the results of seismic ground response analysis. Methods of analysis of ground response may also be categorized into time domain and frequency domain concepts. Simplicity in developing analytical relations and accuracy in considering soil dynamic properties dependency to loading frequency are benefits of frequency domain analysis. In this part of the paper, seismic ground response is analyzed using transfer function method for soil layers considering surcharge mass on the top layer. Equation of motion, wave equation, is solved using amended boundary conditions which effectively take the impact of surcharge mass into account. A computer program is developed by MATLAB software based on the solution method developed for wave equation. Layered soils subjected to earthquake loading were numerically studied and solved especially by the computer program developed in this research. Results obtained were compared with those given by DEEP SOIL computer program. Such comparison showed the accuracy of the program developed in this study. Also in this part, the effects of geometrical and mechanical properties of soil layers and especially the impact of surcharge mass on transfer function are investigated using the current approach and the program developed. The efficiency and accuracy of the method developed here is shown through some worked examples and through comparison of the results obtained here with those given by other approaches. Discussions on the results obtained are presented throughout in this part.

Keywords: seismic analysis; ground response; surcharge mass; layered soils; transfer function method

1. Introduction

Ground response analysis is one of the most important issues in geotechnical earthquake engineering problems. To reach the ground surface, earthquake waves travel perhaps tens of kilometers through the tick rock formation (bedrock) and then travel in the extent of only tens of meters through thin layers of surface soils. Despite the fact that bedrocks are much ticker than surface soil layers, however, earthquake waves are much more affected when they travel through

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soils than they do in the rock (Kramer 1996).

From the beginning of 70's, many researchers have been studying site effect problems and been conducting ground response analysis using various approaches. Equivalent linear method introduced by Schnable *et al.* (1972) calculates nonlinear response where the soil parameters are repeatedly corrected according to the effective strain developed until an acceptable convergence is reached. The method is one of the most popular and applicable concept in modeling the non-linear behavior of soil subjected to earthquake loading. It is used for evaluating the nonlinear seismic response of soil layers in a fast and manageable fashion. Assimaki and Kausel (2002) have also used equivalent linear analysis for ground response analysis. Borja *et al*. (1999) have conducted the nonlinear ground response analysis using Finite Element Method (FEM). Yoshida *et al.* (2002) developed relations to evaluate the effect of frequency of the earthquake loading on the effective shear strain levels obtained in equivalent linear analysis. The method developed by Yoshida et al. ensures a fast converging calculation. However, it requires two key parameters including frequencies corresponding to the maximum shear strain and that of the earthquake loading. Presti *et al.* (2006) conducted earthquake ground response analysis in time domain using finite difference method associated with Wilson-θ step-by-step procedure. The method proposed by Presti *et al.* (2006) appears to be enough accurate, however, it requires numerous input parameters necessary to define the nonlinear soil behavior. Wood and Hutchinson (2012) investigated the effect of impact load on the half-space motion using finite element method. To obtain the time histories and response spectra at various distances from the impact load, extensive parametric analysis were carried. The results were found to be useful for analysis of structures resting on the ground subjected to impact load. Jayaram *et al*. (2011) conducted a study on the spectral acceleration correlation from Japanese earthquake ground motion data including data from both crustal and subduction zone earthquakes. The effects of ground motion model, earthquake source mechanism, seismic zone, site condition, and source to site distance on estimated correlations were evaluated and discussed. Some differences in correlations between earthquake source zones and earthquake mechanism were observed and tables of correlations coefficients for each specific case were provided. Stewart and Kwok (2008) criticized the equivalent linear approach for one-dimensional seismic ground response analysis and proposed the nonlinear analysis instead. He suggested that when input motions are from ground surface recording, full outcropping motion should be used without converting to a "whitin" condition. He found that site amplification to be generally under predicted at high frequencies and over predicted at the elastic site period where a strong level resonance occurs that is not seen in the data. He postulated that this bias resulted from over predicting. Nakamura (2013) studied the time domain evaluation of the frequency dependent dynamic stiffness and proposed a simple hysteretic damping model which satisfied the causality condition. The model was applied to nonlinear analysis of soil deposits which took the effect of strain amplitudes dependency of the soil especially two layered soil models. The response behavior was compared with the common nonlinear models such as Ramberg-Osgood and SHAKE models.

Hybrid frequency time domain (HFTD) is, in fact, a procedure that takes the advantage of both the time domain and the frequency domain methods to optimize the solution particularly for nonlinear problems (Wolf 1986, Darber and Wolf 1988). In summary, by HFTD method, the equation of motion is solved in frequency domain and the nonlinearities are accounted for by the time domain analysis. Hashash and Park (2002) verify nonlinear analysis in time and frequency domain by viscous damping formulation and high motion frequency propagation. Choudhury and Savoikar (2009) considered equivalent linear analysis of municipal solid waste (MSW) using

DEEP SOIL software designed by Hashash *et al*. (2008).

Most of studies conducted in the past on the subject of earthquake ground response analysis ignore the effect of surcharge mass which may overlain surface layer of the soil deposits. Many large structures such as concrete dams or spread footings behave as surcharge mass on the ground surface. These massive structures induce extra inertial forces to the soil due to the ground motions which may significantly affect and alter the results of ground response analysis. This response which differs from a free field motion, can be attributed to the earthquake soil-structure interaction. Moreover, surcharges overlain the ground surface may cause increase in the resulting shear stresses developed in the area of pressure bulb underneath the surcharge. Therefore, shear modulus of soil is changed as the results of changes in induced shear strain.

Transfer function approach is an alternative approach to conduct site response analysis which is basically simple, fast, and accurate enough to guarantee a reasonable solution.

In this study, the effect of surcharge mass overlain the surface layer on the site response is studied. A computer program named as *SURCHRESPONSE* (Saffarian 2013) has been developed in this study which is based on the analytical solution developed here using transfer function. Case studies have been carried in which the effect of changes in geometrical and physical / mechanical properties of the soil layers on the responses obtained are presented. Discussions on the results obtained are also presented in the paper.

2. Transfer function

In their simplest definition, transfer functions are particular analytical formula relating the calculated surface motion to the corresponding bedrock motion induced by earthquake incident waves. Transfer function may be formulated for 1-D site response analysis or, in matrix notation, for 2-D analysis. However, and despite some limitations, the most popular approach appears to be 1-D method which is applicable for most soil formations with horizontal layering. In development of the equation of motion for surcharged layered soils, a prime concern is to define the boundary conditions which significantly differ from that of commonly used for free field motion (no surcharge). Earthquake excitation is defined as base motion which is commonly described as time-history of acceleration recorded at bedrock. This stage is, however, does not basically differ from that applied in commonly analyzed free field site response problems (Desai and Christian 1997).

Earthquake ground surface response, transferred motion to the surface, is obtained either as a transferred surface acceleration or as surface response spectrum. This procedure is followed in a step-by-step process in which transfer functions are used successively and recursively. It means further that the input motion record is first transferred to frequency domain using Fast Fourier Transform (FFT). This is mainly because the transfer functions developed are essentially frequency dependent. After applying transfer function, the response obtained in frequency domain is transferred back to time domain using an inverse of FFT (IFFT). The whole process described above is referred to as Hybrid Frequency Time Domain procedure (HFTD).

The procedure described above is limited to linear analysis in which shear modulus of soil is assumed constant and independent of shear strain. Shear modulus is usually obtained using empirical relations. For simplicity and practical purposes, a generally acceptable empirical relation in the form of $G_{\max} = f(e, \sigma_0)$ is adopted. σ_0 and e are respectively the mean stress and porosity of the soil. For a layered soil system, such as one that will be analyzed later in this paper, $G_{\max}$ is obtained for each layer which, in turn, is based on the above typical relation. To extend the analysis to nonlinear behavior of soil, an internal loop in the procedure described above should be introduced in which some iteration are made successively in order to reach convergence of the soils' shear modulus with corresponding strain. This procedure, however, will be described in detail in part II of this paper.

2.1 Development of transfer function for surcharged soil layers

In developing transfer functions for soil formations which are overlained by a mass surcharge, a solid, equivalent rigid soil layer is assumed to replace the surcharge at the surface of top layer. This layer is defined and characterized by equivalent parameters. For example, as also seen in Fig. 1, d is a key parameter which, in fact, defines the equivalent thickness of the imaginary layer imposed on the surface. No deformation is assumed within this equivalent extra soil layer since the surcharge mass is virtually solid. When surcharge exist, boundary conditions should be defined according to real condition; that is the shear stress on the surface layer is developed by inertial force which is due to acceleration of mass. It should be noted that when no surcharge exists on the top, no extra inertial forces and no such shear stress develops and, hence, the problem reduces to an ordinary seismic ground response analysis.

Fig. 1 depicts the methodology behind the current approach and graphically shows the position of equivalent extra layer on the surface. If soil formation is a layered media, calculation of the site response involves a successive, or recursive, procedure in which the response of each layer is related to responses of the corresponding adjacent upper and lower layers.

The simple schematic diagram in Fig. 2 shows the geometrical and physical / mechanical properties of a multilayer soil media and the actual mass surcharge (M) as well as the scheme of equivalent layer positioned at the top of the layers which represents an equivalent of the surcharge.

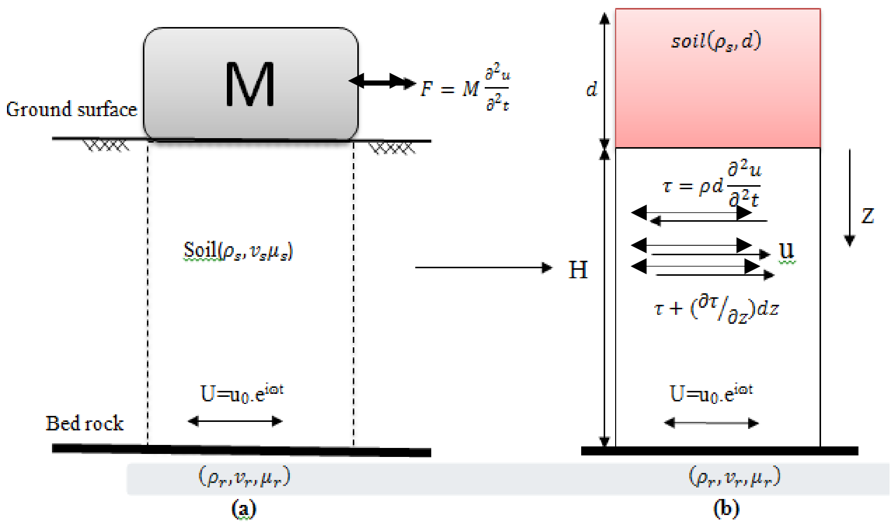

Fig. 1 (a) Surcharge on top of a single layer soil system; and (b) Shear stresses developed at boundaries and equivalent of surcharge

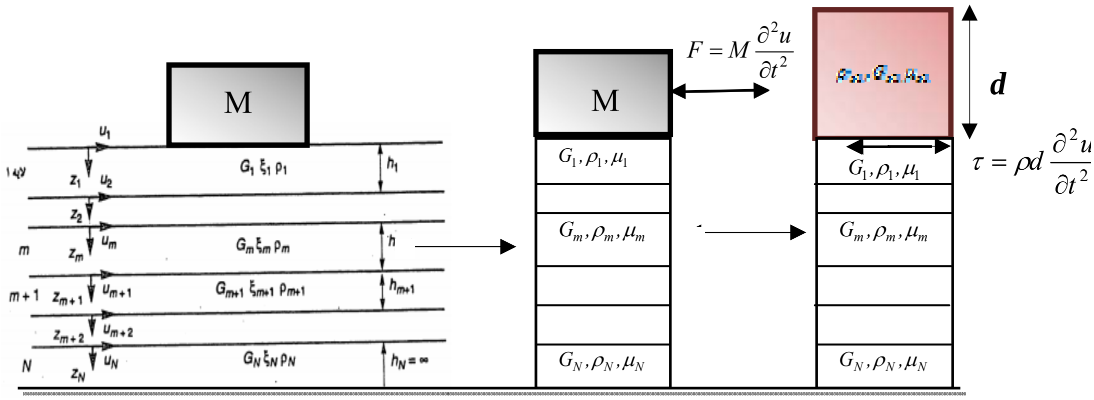

Fig. 2 A surcharged multilayer soil system and equivalent to the surcharge mass

As can be seen from Fig. 2, a multilayered soil media is characterized by m sub layers having different geometrical (thickness; *H*) and mechanical (shear modulus, damping ratio, density; *G, μ, ρ*) properties all overlain the bedrock. An incident earthquake shear wave travels from bedrock to the surface. It is also assumed that *u* is the horizontal displacement in the soil layers. The differential equation of motion for any soil element is subsequently is developed and it is presumed that the soil behave as a visco-elastic material and to follow Kelvin-Voigt rheological model. The equation of motion is, therefore, described as follows

$$\rho \frac{\partial^2 u}{\partial z^2} = G \frac{\partial^2 u}{\partial t^2} + c \frac{\partial 3u}{\partial z^2 \partial t} \tag{1}$$

In which *G, ρ, c* are respectively the density, the shear modulus, and the equivalent viscosity of the soil material. Solution of Eq. (1) for *u* requires assumption of a harmonic wave with frequency (*ω*) travelling upward and downward through the soil layers which is described by the following relation

$$u(z,t) = E_m e^{i(k_m^* z + \omega t)} + F_m e^{i(k_m^* z - \omega t)} \tag{2}$$

In which $k_m^* = \omega / v_m^*$ is referred to as complex wave number v_m^* and is the complex shear wave velocity in the m^{th} layer. The complex shear wave velocity is further described by the relation $v_s^* = v_s\,(1 + i\mu)$ that μ is damping ratio. E_m and F_m are amplitudes of harmonic shear waves related to the waves travelling upward and reflected one (travelling downward) respectively in the m^{th} layer. In order to determine these amplitudes, boundary condition should be applied to Eqs. (1) and (2).

In classical solutions provided for this equation, a stress-free boundary is defined for the surface of the layered soil media. However, in particular condition considered in this study, which accounts for presence of a surcharge mass on top layer, assumption of stress-free boundary is no longer valid. As mentioned before, the surcharge mass induce forces (and hence shear stress) on the boundary between the surface of top layer and the bottom of the surcharge mass. Therefore, such condition necessitates defining new following relations (Verruijt 1996).

$$\begin{cases} z = h \rightarrow u = u_0 e^{i\omega t} \\ z = 0 \rightarrow \rho d \dfrac{\partial^2 u}{\partial t^2} = \tau = G \dfrac{\partial u}{\partial z} \end{cases} \tag{3}$$

Considering Eq. (2) and applying boundary conditions, shear stress at the ground level *(z*=0) due to the surcharge mass is defined in the following relations

$$\tau(z_m, t) = G_m \frac{\partial u}{\partial z} \rightarrow \tau(z_m, t) = ik_m^* G_m (E_m e^{i(k_m^* z)} - F_m e^{-i(k_m^* z)}) \tag{4}$$

$$\tau(0,t) = ik_m^* G_m^* (E_1 - F_1) e^{i\omega t} = \rho d \frac{\partial^2 u}{\partial t^2} \tag{5}$$

Solution Eq. (4) and (5) results in

$$\frac{(E_1 - F_1)}{(E_1 + F_1)} = -\frac{ik_m^* G_m}{\omega^2} \rightarrow \frac{F_1}{E_1} = \frac{i + d.k_1^*}{i - d.k_1^*} = R \tag{6}$$

Further calculations are necessary to define the amplitude of the travelling shear waves in each layer and the resulting shear stresses. In order to facilitate these calculations, a non-dimensional parameter known as E_1/F_1 is introduced which defines ratio of the amplitude of reflected shear wave to that of input shear wave. Compatibility of the displacement at the boundary of each inter layer also necessitates defining the following relations

$$\tau(z_m = h) = \tau(z_{m+1} = 0) \tag{7}$$

$$u(z_m = h) = u(z_{m+1} = 0) \tag{8}$$

Considering Eq. (7)and (8) and in a recursive process, one obtains

$$(E_{m+1} + F_{m+1}) = E_m e^{i(k_m^* h_m)} + F_m e^{-i(k_m^* h_m)} \tag{9}$$

$$(E_{m+1} - F_{m+1}) = \frac{k_m^* G_m}{k_{m+1}^* G_{m+1}} (E_m e^{i(k_m^* h_m)} - F_m e^{-i(k_m^* h_m)}) \tag{10}$$

In which α_z is defined as impedance ratio which relates the properties of two neighboring layers and is, therefore, described by the following equation (Kramer 1996).

$$\alpha_z = \frac{v_m^* \rho_m}{v_{m+1}^* \rho_{m+1}} = \frac{k_m^* G_m}{k_{m+1}^* G_{m+1}} \tag{11}$$

The transfer function for elastic bedrock which relates the amplitude of displacement in layer m to that in layer $m+1$ is finally described by the following equation

$$A(\omega) = \frac{u_m}{u_{m+1}} = \frac{E_m}{E_{m+1}} \tag{12}$$

Once non-dimensional parameter $A_m(\omega)$ is calculated by Eq. (12), a recursive process is started in which amplitudes of shear wave are calculated for all layers from bottom to the top.

It is of note that the dimensionless factor R reflects the ratio of amplitude of the ground surface wave to that of incident at bed rock. In special case where $R = 1$, then the free field ground motion at surface is obtained. Other assumption considered in the current approach includes rigidity of the surcharge mass and the propagation of SH waves towards ground surface as well as representation of the surcharge mass with an equal soil layer at top of the soil layers.

Considering relations developed in preceding paragraphs, the transfer function for a uniform and single soil layer with a thickness H is defined by the following relation

$$A(\omega) = \frac{2}{e^{i(k^*H)} + \mathrm{Re}^{-i(k^*H)}} \tag{13}$$

And if the bedrock behaves elastically and exhibits deformations, then

$$A(\omega) = \frac{2}{(1+\alpha_z).e^{i(k^*H)} + (1-\alpha_z).\mathrm{Re}^{-i(k^*H)}} \tag{14}$$

In Eqs. (13) and (14), k^* requires that the shear wave is introduced as complex value (i.e., $v_s^* = v_s\ (1 + i\mu)$). Hence all other related parameters have to be defined in complex notation, including $G^* = G\ (1 + 2i\mu)$. In particular and to maintain compatibility, R is also denoted as complex and all relevant calculations are proceed with complex notations. Considering Fig. 3 and noting that the factor R is, in fact, a complex and non-dimensional value, the range for variation of the real part is seen as -1 to 1. In reality such variation from -1 to 1 reflects the difference between the seismic responses of a surcharged soil layer with that of soil layer with no surcharge. In the extreme value of 1 for R, the value of d reduces correspondingly to zero which reflects a soil layer with no surcharge. It is also of note that the damping ratio has little effect on factor R. In order to investigate the effect of damping ratio on the transfer functions, a uniform soil layer having thickness H is considered. Effect of the ratio d/H is also investigated here.

In Fig. 4, it is deduced that increase in the height of surcharge, d, causes an increase in the

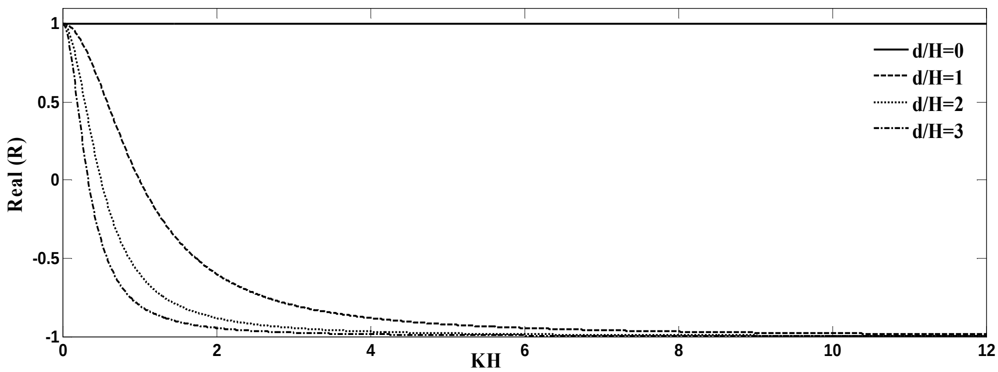

Fig. 3 Variation of the ratio R vs. KH for various d/H values

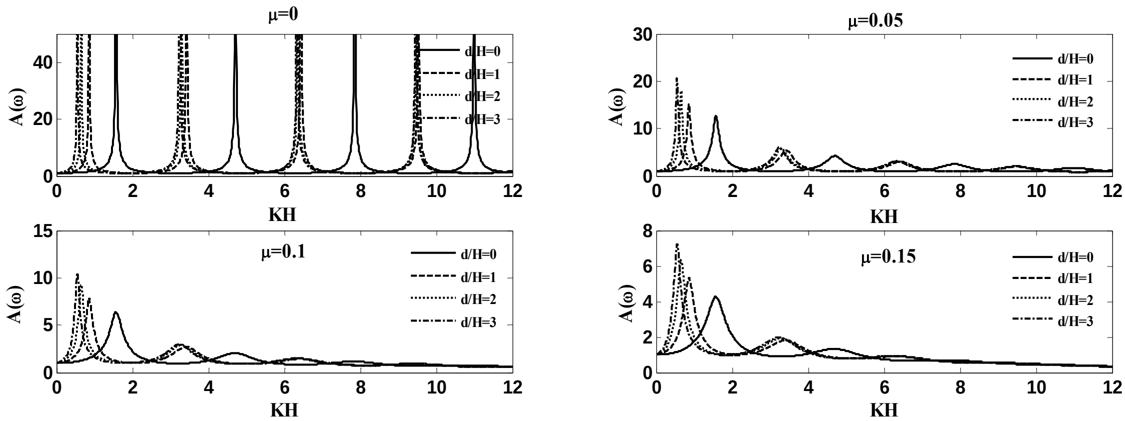

Fig. 4 Effect of damping ratio (μ) on transfer function for various d/H values

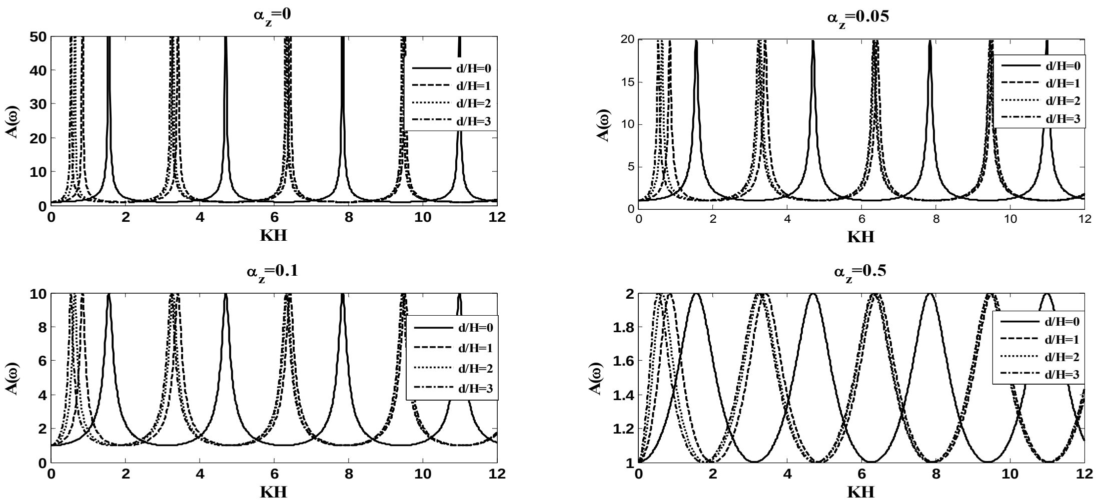

Fig. 5 Effect of impedance ratio (α_z) on transfer function of undamped soil for various d/H values

transfer function and a decrease in its frequency of occurrence. Fig. 5 presents a similar trend as that observed in Fig. 4. This figure also shows that as the impedance ratio of two adjacent layers increases, the maximum value of the transfer function is inversely reduced.

3. Computer program developed

A computer program has been developed in this study in order to carry site response analysis of surcharged soil media. The program is based on an algorithm developed on the basis of the relations described earlier in previous section. The program has been written, in fact, in MATLAB environment. For the sake of comparison and validating the results given by program, a simple site response problem is primarily solved and analyzed. The problem chosen is related to a soil medium without surcharge mass. This natural choice allows comparison of results given by the computer program developed with those provided by available and classic softwares. Analysis of surcharged layered soils is provided in the following section.

DEEPSOIL V.5 software was used to analyze a sample problem related to a specific site known as Loma Prieta for which an acceleration time history of an earthquake recorded in 1989 is

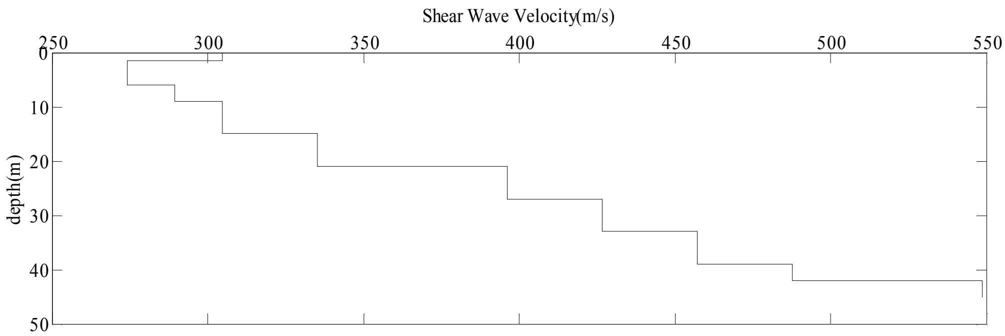

Fig. 6 Variation of shear wave velocities of soil layers investigated at Loma Prieta site (Asgari 2009)

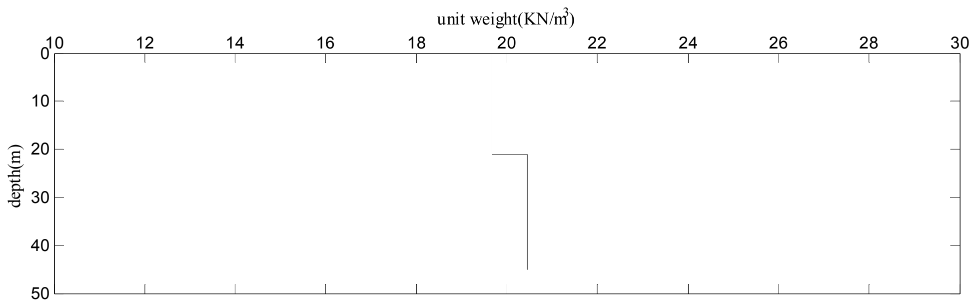

Fig. 7 Variation of density of soil layers investigated at Loma Prieta site (Asgari 2009)

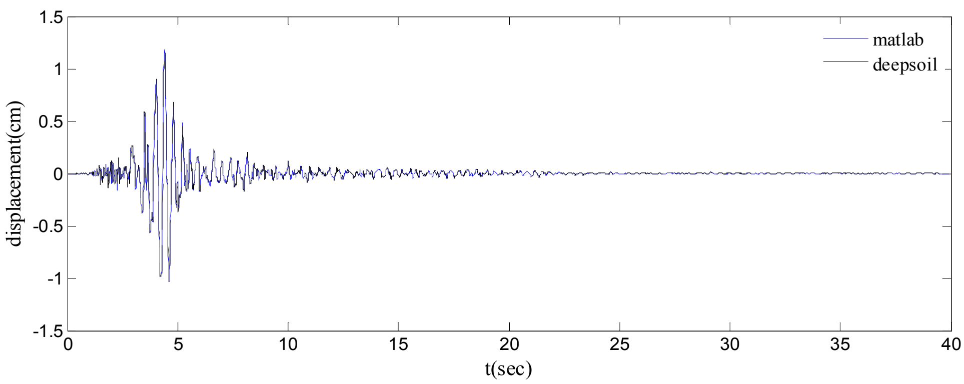

Fig. 8 Acceleration time history of the ground surface calculated by current approach and by DEEPSOIL

available and to compare results. The layered soil media also includes 10 sub layers investigated at site. Variation of shear wave velocities and the unit weight of each soil layer are shown in Figs. 6 and 7 respectively (Asgari 2009). Damping coefficient of all soil layers are assumed equal to %5 ($\mu_s = 0.05$) and that of the elastic bedrock is considered as small as %2 ($\mu_f = 0.02$).

Fig. 8 shows the acceleration time history of the earthquake at surface of the Loma Prieta site calculated by DEEPSOIL and also by current approach.

Comparison of graphs shown in Fig. 8 shows good agreement between results calculated by DEEPSOIL software and those given by the program developed in this study. This further implies on the validity of the results given by program developed here and hence on the accuracy of the current approach.

4. Effect of surcharge and mechanical properties of soil layers on transfer function

In this section, response of layered soil is investigated considering effect of surcharge mass placed on the ground surface. As mentioned earlier, large structures such as concrete dams or large spread footings may behave as a relatively solid and non-deformable surcharge mass when compared with soft soil layers.

Response calculated is based on relations described by Eqs. (6) through (12). Considering these equations, parameters affecting on the response are: (a) thickness of layers; (b) shear wave velocity of layers; (c) damping of each layer; (d) height of surcharge; and (e) impedance ratios.

A representative layered soil system with 10 meters equivalent of surcharge height (d) is adopted to study these effects. Results are graphically shown in Figs. 9 to 13. In Fig. 9, effect of layers' thickness on the transfer function is shown. It can be deduced from this figure that increase in thickness of layer does not have significant effect on the transfer function in low frequencies. However, in higher frequencies of earthquake loading, increase in thickness of layers cause considerable reduction in response. On the other hand, peaks in transfer functions are shifted rightward (toward higher frequencies) when thickness of soil layers (H) decreases.

Effect of damping ratios of soil layers is investigated through Fig. 10. It is shown, in this figure, that as damping in soil layers increases, transfer functions decreases. However, rate of decrease in

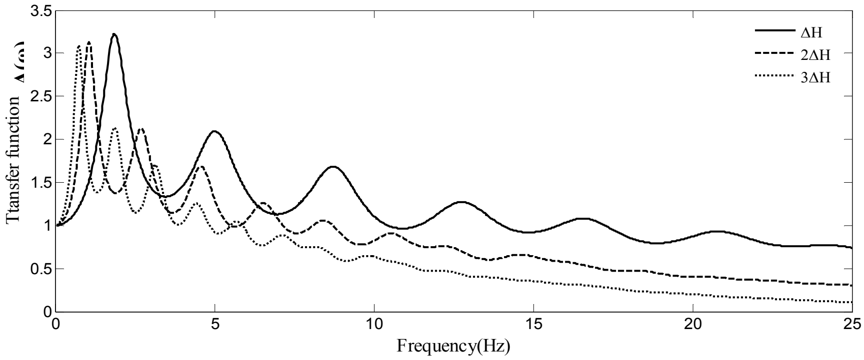

Fig. 9 Effect of increase in thickness of soil layers (1 to 3 times) on transfer function

transfer function increases as the frequency of the earthquake loading increases. This phenomenon seen is exactly the same as vibrational behavior of a 1-D mass-spring system subjected to harmonic loadings.

Fig. 11 presents variation of transfer function vs. frequency of earthquake loading for various shear wave velocities of soil layers which are taken from Figs. 6 and 7. These two figures show variation of Vs vs. depth. To generalize the results and to extend the conclusion to any case studies, shear wave velocities at any depth adopted in Figs. 6 and 7 are correspondingly double or tripled. It is seen, in the figure, that as shear wave velocities increase, transfer function generally decreases. The rate of decrease is much higher in low frequencies than is in higher frequencies. Such a behavior may be attributed to the change in stiffness of soil layers since behavior of soil layer can be approximated by simple mass-spring-dashpot systems.

Fig. 12 shows effect of impedance ratio of two adjacent soil layers, represented by α_z, on the transfer function values. It can be seen from this figure that as α_z increases, transfer functions drastically reduce especially in lower range of earthquake loading frequencies. It further means that if frequency of earthquake loading increase, effect of α_z on the transfer functions relatively decreases.

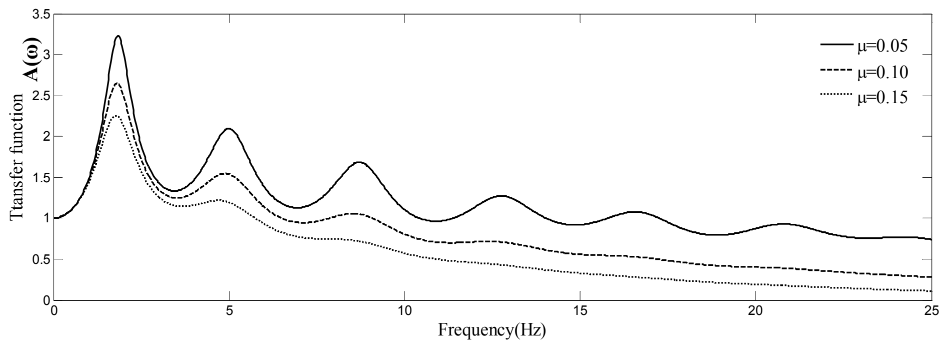

Fig. 10 Effect of change in damping ratios of soil layers (1 to 3 times) on transfer function

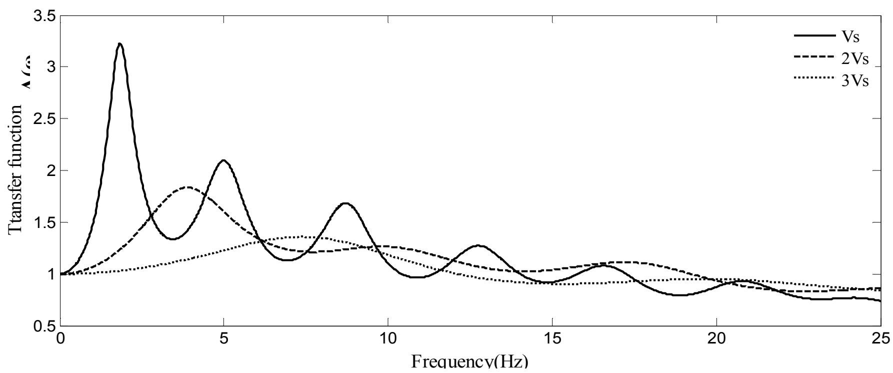

Fig. 11 Effect of change in shear wave velocity of soil layers (1to 3 times) on transfer function

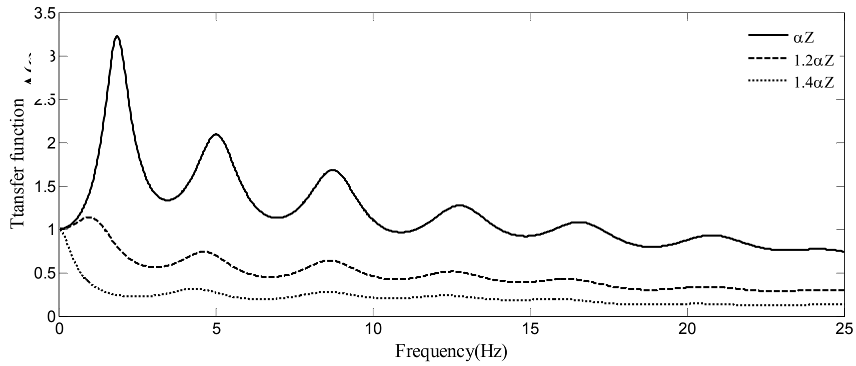

Fig. 12 Effect of increase in impedance ratio (α_z) of two adjacent soil layers on transfer function

Finally, Fig. 13 presents effect of the equivalent surcharge height on the transfer function for various frequencies of earthquake loading. It can be seen from this figure that height of the surcharge mass does not have considerable effect on the transfer function especially at higher frequencies of earthquake loading.

Table 1 presents maximum acceleration and displacements as well as their frequency of occurrence calculated for seismic response analysis of soil layer shown in Figs. 6 and 7 considering effect of surcharge mass with different equivalent surcharge heights and subjected to 3 different acceleration records. These records are related to Loma Prieta earthquake of 1989, Kobe earthquake of 1995 and Imperial Valley earthquake of 1940. It can be seen, from the results summarized in table 1, that for Kobe earthquake of 1995 increase in PGA is directly related to increase in height of surcharge mass. However, when height of surcharge mass approaches 80 m, PGA reduces relatively.

A reverse phenomenon occurs in Loma Prieta earthquake of 1989 since the results show that increase in height of surcharge mass cause PGA to decrease.

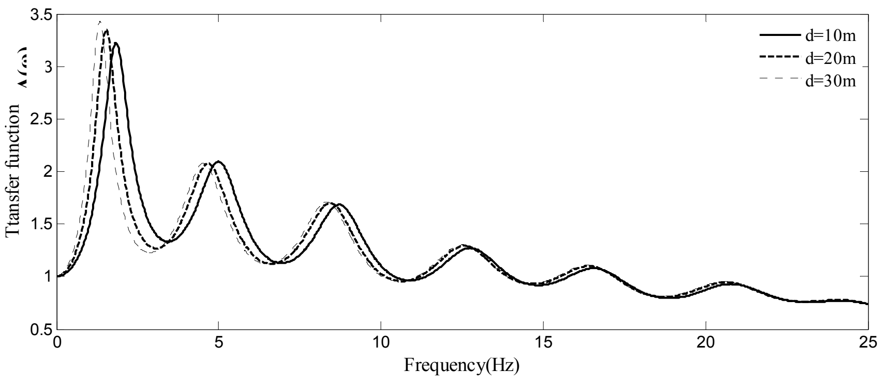

Fig. 13 Effect of increase in height of surcharge on transfer function

Table 1 Maximum acceleration, displacement, and corresponding frequency of occurrence calculated for various surcharge height subjected to 3 different earthquakes

d(m)	Kobe (1995)			Loma Prieta (1989)			Imperial valley (1940)		
	PGA	Max *u* (cm)	*f* (Hz)	PGA	Max *u* (cm)	*f* (Hz)	PGA	Max *u* (cm)	*f* (Hz)
0	1.2304	22.46	2.085	1.1846	8.882	2.679	0.3471	4.932	2.354
20	1.4691	27.69	1.459	0.7801	9.416	2.679	0.3121	5.349	1.647
40	1.8406	36.58	1.209	0.6799	11.242	2.679	0.6293	5.280	1.585
60	1.9367	38.26	0.98	0.6935	12.692	2.679	0.2598	5.337	1.647
80	1.8610	36.96	0.98	0.9890	13.911	2.679	0.2590	8.329	0.861

It can be generally deduced that earthquake response is affected by parameters such as, frequency content of earthquake record, peak ground acceleration, and even duration of earthquake as well as by geological and mechanical properties of the soil media. For example, if the dominant frequency of earthquake record (obtained by FFT approach) is close to fundamental frequency of the site, a resonance may occur. In such case, it can be seen that increase in height of surcharge leads to increase in response and the conclusion is applicable. Three earthquake records adopted in this study may present a broad range of earthquake characteristics and hence the results obtained appears to be applicable to other similar earthquakes as well.

5. Conclusions

Effect of geometrical and mechanical properties of soil layers as well as the impact of the surcharge mass placed at the surface of soil layers on the earthquake ground response analysis were studied in this part. Compared with the conventional site response analysis, in which effect of surcharge mass is neglected, equation of motion includes particular and amended boundary conditions. Equation of motion was solved using these amended boundary conditions and transfer functions were derived in frequency domain. Computer program was developed which, when properly run and necessary parameters are input, automatically calculates the results and output them.

It was observed that increase in thickness of soil layers inversely effect on the amplification ratios (transfer functions). Damping ratio has a similar effect on transfer function especially in low frequency contents of earthquake loading. Since increase in shear wave velocities of soil layers directly affect on the stiffness of layers, therefore, increase in shear wave velocities, cause decrease in amplification ratios (transfer function values) especially at lower frequencies of earthquake loading. Increase in height of surcharge mass has significant effect on the values of transfer functions especially at lower frequency of earthquake loading.

It was also shown that despite existing small difference in impedance ratio, considerable gap is developed in transfer functions at corresponding frequencies. Considering effect of equivalent surcharge height, it was schematically shown that as height of surcharge is twice or even tripled, there is no significant change developed in transfer functions especially at higher range of earthquake loading frequencies. Other parameters may have impacts with intensities in between the effect of impedance and height of surcharge.

Part II of this paper, as mentioned earlier, provides details on the extension of the current approach to nonlinear analysis and on the results obtained in some worked examples.

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