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THE EFFECT OF SEISMIC SOIL-STRUCTURE INTERACTION ON THE DYNAMIC CHARACTERISTICS OF STRUCTURAL SYSTEMS ON SHALLOW FOUNDATIONS

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ABSTRACT

The natural frequency and the damping factor of a structure are key dynamic parameters that influence the structure response under dynamic loads. It is a common practice among engineers to model the structure alone ignoring the surrounding sub-soil. If soil-structure interaction is to be accounted for in the analysis of a structure without modeling the surrounding sub-soil, then it is paramount to modify the dynamic characteristics of this superstructure. The objective of this study is to introduce modified dynamic characteristics (natural frequency and damping) of the whole structural system taking into consideration the soil-structure interaction effect. These modified dynamic characteristics can be used by practicing engineers to account for the SSI effects if they decide to use the common practice of modeling the structure alone ignoring the surrounding sub-soil.

This research presents two simple equations to predict the natural frequency and damping factor of structural systems on shallow foundations. A database of modified dynamic characteristics in terms of the influencing parameters were generated using ProShake. The proposed equations are found to be capable of predicting the modified natural frequency and damping factor of the whole structural system with a high degree of accuracy. The proposed equation for predicting the modified natural frequency was compared with experimental results found in the literature.

INTRODUCTION

In spite of the significance of considering the soil-structure interaction (SSI) in the seismic analysis of different structures, performing an analysis considering SSI is computationally uneconomical for conventional design tasks. It is a common practice to model the structure alone, ignoring the sub-soil, and to apply the boundary conditions at its interface with the sub-soil at the foundation level (i.e. fixed supporting of the structure).

If a structure is analyzed alone under seismic loads assuming fixed supporting and ignoring the presence of the sub-soil, the real behaviour of the structure might considerably be different from what the analysis produces. This difference is due to the fact that the response of a structure during an earthquake depends not only on the properties of the structure itself, but also on the characteristics of the ground motion and the sub-soil conditions.

The assumption that a certain structure is fixed-supported at its interface with the sub-soil ignores the interaction effects that result from the scattering of waves when reaching the foundation surface and the energy radiated from the structure during its vibration. These interaction effects lead to dynamic responses that may differ considerably in amplitude and frequency content from what is obtained when a fixed supporting is assumed [1].

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When the damping factor of the interaction system is estimated, a large amount of attention should be paid to the radiation damping due to the radiating waves from the structure to the extensive ground. On the other hand, artificial boundaries must be introduced when the finite element method is used to analyze the dynamic behaviour of a semi-infinite region such as ground, because the analyzed region must be finite. The waves which should propagate to infinite distance are reflected by the artificial boundaries, and this may nullify computed results. In order to solve this problem, many boundary treatment methods have been proposed and they could be grouped into three categories. These categories are: (i) the energy transmitting boundary [2,3], (ii) the superimposing boundary [4], and (iii) the viscous boundary [5,6]. Each of these methods has advantages and disadvantages. The suitability of each method depends on the nature of the problem to be solved.

Extensive studies have been conducted on dynamic soil-structure interaction problems in addition to the studies listed above and many valuable results have been obtained. In general, except for special structures, these results are not reflected on the seismic design of structures. The reason is that these results are not summarized in formulas or guidelines which can be easily applied to the design.

The objective of this study is to introduce modified dynamic characteristics (natural frequency and damping) of the whole structural system taking into consideration the soil-structure interaction effect. These modified dynamic characteristics can be used by practicing engineers to account for the SSI effects if they decide to use the common practice of modeling the structure alone ignoring the surrounding sub-soil.

NONLINEAR ANALYSIS MODEL FOR SEISMIC SSI SYSTEMS

The viscous boundary method was implemented in this study as ProShake [6] was the program used to perform the analysis. ProShake calculations starts from the surface (i.e. surface motion is given; for each other layer the motion is calculated together with equivalent soil properties); this case is called "deconvolution". This procedure is schematically shown in Figure 1. Let Point A be a point at the base of the structure foundation and Point B be a point at the top of basal layer. First, the acceleration at Point B, b(t) is obtained from the accelerogram at the base of the structure, f(t), by using the frequency domain analysis, i.e. by deconvolution. Then, the dynamic analysis of the ground is performed for which the input accelerogram is b(t). The goal is to obtain f '(t) from f (t). Throughout this study ProShake was used to obtained f \(t) by using frequency and time domain analysis.

The response of a soil-structure interaction system is affected by different types of nonlinearities which strongly depend on the soil constitutive relationships and strength, strength of interface between the structure and the ground, characteristics of excitation. These sources of nonlinearities were considered in this study as they implemented in ProShake. The superstructure was modeled as a lumped mass with its associated dynamic characteristics.

The dynamic response of a horizontal soil layer bed depends on: (i) the soil stiffness; and (ii) the material damping in the soil. The stiffness of a certain soil element depends on the void ratio and confining pressure to which it is subjected. In case of a saturated soil layer bed, the stiffness also depends on the excess pore pressure generated during an earthquake ground motion. The material damping in the soil will have two components: (i) hysteretic damping in the soil skeleton; and (ii) viscous damping in the pore fluid.

The most significant soil parameter in determining the magnitude of soil natural frequency is the shear wave velocity. The natural frequency of any dry soil layer is a function of the shear wave velocity in that soil layer. If 'Vs' is the shear wave velocity in soil, then the soil natural frequency (*fg*) may be obtained as follows [7]:

$$fg = \frac{(n+\frac{1}{2})\,\pi\, V_S}{H} \tag{1}$$

Where *fg* is the soil natural frequency in the nth mode (only the first mode is considered herein) and H is the soil layer depth. In case of a soil bed, the shear wave velocity, Vs, depends on the small strain shear modulus (G), and the saturated density of soil, (γ). The shear wave velocity can be obtained from the following relationship [7]:

$$V_S = \sqrt{\frac{G}{\gamma}} \qquad (2)$$

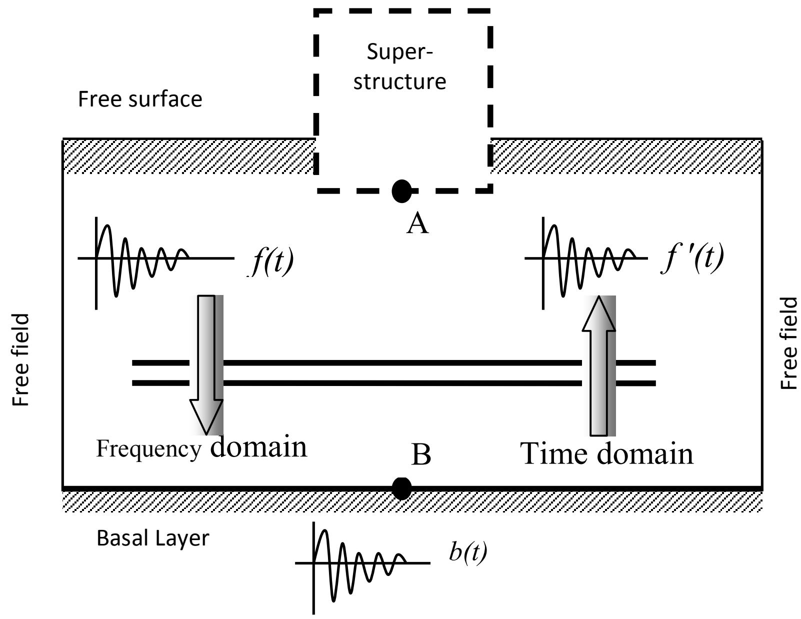

Figure 1. Schematic representation of the transformation of input acceleration to the basal layer.

EQUATIONS OF MOTION

A typical soil-structure interaction system surrounded by a basal layer and a free field is illustrated in Figures 1 and 2. The equation of motion for this system, Equation 1, can be obtained by adding the terms which include the virtual works done by radiating waves to the basal layer, radiating waves to the side free field, and free field ground motion [8,9,10].

$$[M] = \{X\} + ([C] + [C_b] + [C_L] + [C_R])\{X\} + [K]\{X\} =$$
$$\{f\} + ([C_L] + [G_{CL}])\{X_L\} + ([C_R] + [G_{CR}])\{X_R\} + [G_L]\{X_L\} + [G_R]\{X_R\}$$
(3)

Where:

$[M]$,$[C]$ and $[K]$ are the mass, damping and stiffness matrices of the entire system; respectively,

$\{X\}$ is the nodal displacement vector,

$\{f\}$ is the external force vector,

$[C_b]$ is the viscous boundary matrix for the basal boundary,

$[C_L]$ and $[C_R]$ are the viscous boundary matrices for the left and right free fields; respectively,

$[G_L]$ and $[G_R]$ are the left and right boundary stiffness matrices associated with the displacements of the free field, respectively;

$[G_{CL}]$ and $[G_{CR}]$ are the left and right boundary damping matrices associated with the velocities of the free field; respectively.

$\{X_L\}$ and $\{X_R\}$ are the left and right displacement vectors of the free fields.
$\{X_L\}$ and $\{X_R\}$ are the left and right velocity vectors of the free fields.

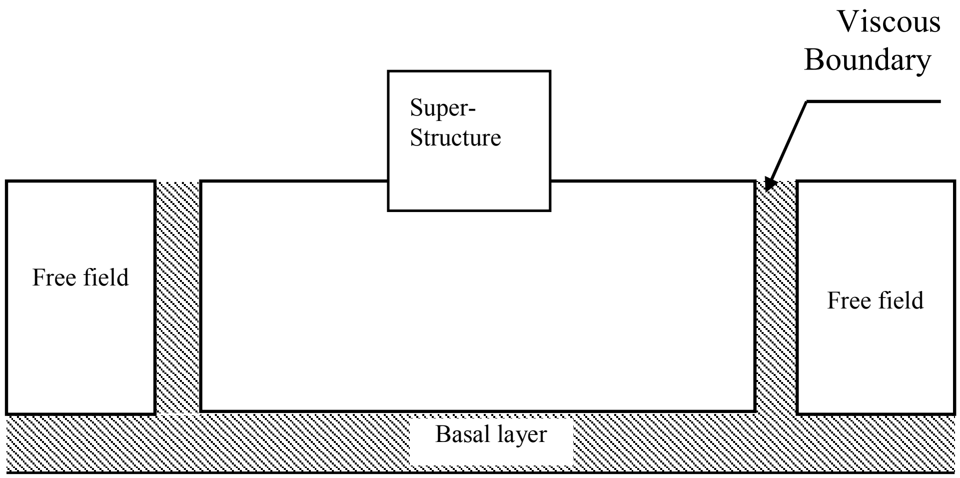

Figure 2. Typical Soil-structure interaction system surrounded by a basal layer and a free field.

Referring to Figure 3, the viscous boundary matrix for each boundary element, $[C_b]$, $[C_L]$ and $[C_R]$ is given as follows:

$$[C] = \frac{\rho X}{2}\begin{bmatrix} V_H & 0 & 0 & 0 \\ 0 & V_V & 0 & 0 \\ 0 & 0 & V_H & 0 \\ 0 & 0 & 0 & V_V \end{bmatrix}$$

(4)

Where:
$V_H = V_S \cos\theta + V_P \sin\theta$ and $V_V = V_P \cos\theta + V_S \sin\theta$

V_P and V_S are the P-wave and S-wave velocities, respectively; and ρ is the density of the outer region.

The boundary stiffness matrices $[G_L]$ and $[G_R]$ are given as follows:

$$[G] = \frac{1}{2}\begin{bmatrix} 0 & -\lambda & 0 & \lambda \\ -\mu & 0 & \mu & 0 \\ 0 & -\lambda & 0 & \lambda \\ -\mu & 0 & \mu & 0 \end{bmatrix}$$

(5)

Where λ and μ are Lame's constants. The boundary damping matrices, $[G_{CL}]$ and $[G_{CR}]$, are given as follows assuming Rayleigh's damping:

$$[G_C] = a.[G]$$

(6)

a = $\frac{h}{\pi f}$ where h is the damping factor at frequency *f*.

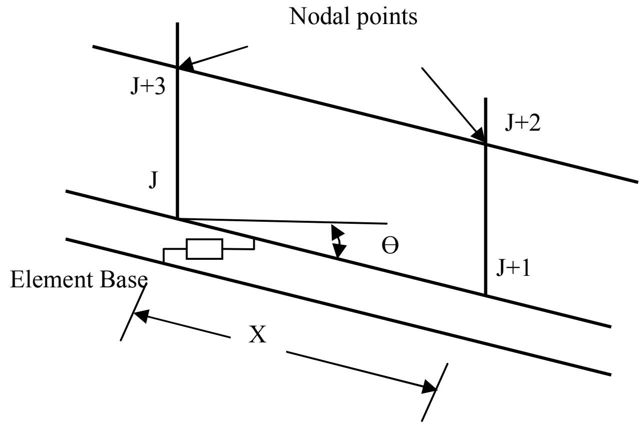

Figure 3. Notation of a viscous boundary element.

FREE FIELD GROUND MOTION

To solve Equation 1, the free field ground motions $\{X_f\}$ and $\{X_f\}$ (f = L or R) are required. These free field ground motions could be obtained by solving the following equation of motion for one-dimensional shear vibration.

$$[M_f]\{X_f\}+[C_f])\{X_f\}+[K_f]\{X_f\}=-[M_f]\{Z\} \qquad (7)$$

Where the matrices $[M_f],[C_f]$, and $[K_f]$ are constructed by adding the sub-matrices, $[m_f],[c_f]$, and $[k_f]$

$$[m_f]=\frac{\rho H}{6}\begin{bmatrix}2 & 1\\ 1 & 2\end{bmatrix} \qquad (8)$$

$$[c_f]=\frac{h}{\pi f}[K_f] \qquad (9)$$

$$[k_f]=\frac{\mu}{H}\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix} \qquad (10)$$

As Equation 1 is nonlinear, the solution must be obtained using the time-step method. To treat the nonlinearity, Newmark's β-method is adopted and the load transfer method is employed.

As soil is considerably nonlinear, Schnabel et al. [11] suggested a special method to describe the seismic response of horizontally-layered soil to the vertically propagating free-field seismic waves by equivalent linear model. Parameters of this model are obtained in iterative calculations, as modules and damping in each layer are strain dependent. This method is implemented in ProShakE. ProShakE calculations start from the surface (i.e. surface motion is given; for each other layer the motion is to be calculated together with equivalent soil properties); this case is called “deconvolution”. Usually, about 7-8 iterations are enough to get an error less than one percent.

FINITE ELEMENT MODELS

The soil-structure interaction system used in this study and the corresponding ProShake finite element models are shown in Figures 4 and 5, respectively. The surrounding ground is assumed to consist of two layers. The depths of the top and bottom layers are 25.0 m and 60.0 m; respectively. The foundation level is assumed to be at the surface level. The size of the surrounding sub-soil considered in the model was 20.0 m × 20.0 m. The element size in the top layer was 0.5 m length × 0.5 m width × 0.5 m height while the element size in the bottom layer 0.5 m length × 0.5 m width × 1.0 m height.

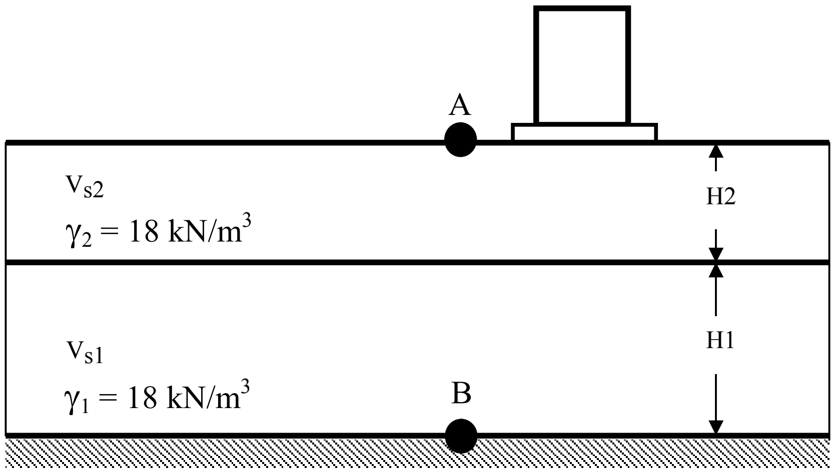

Figure 4. Soil profile used in the finite element model.

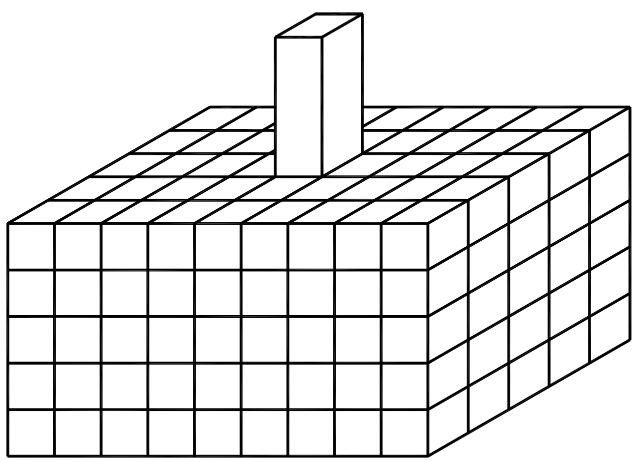

Figure 5. Schematic representation of the finite element model.

The earthquake excitations considered in this study to estimate the natural frequency and damping factor for seismic soil-structure interaction systems are the El Centro earthquake (1940), the Northridge earthquake (1994) and the Loma Prieta earthquake (1989). Figure 6 presents the acceleration response spectrum and mean spectrum for the above mentioned three earthquakes.

Figures 7 to 9 show the effect of the soil-structure interaction on the real time-history of the three earthquake considered in this study for the case where the soil layer depth of the top and bottom layers be 25.0 m and 60.0 m, respectively, and the shear wave velocity of the top and bottom layers are 200 m/s and 400 m/sec, respectively. In soil-structure interaction problems energy is dissipated through friction and nonlinear behavior and in the soil through nonlinear behavior and radiation. To arrive at an effective value of damping for the complete system it is necessary to combine these different contributions.

Figure 10 presents the shear strain percentage versus the time period of ground motions for all used earthquakes. In general, a wide range of nonlinearities can be described by strain-dependent properties. However, these properties should be transient, i.e. it should vary from one time point to another during one seismic event. In the Seed's approach [12], these properties in each soil layer are established once for the whole event duration (changing not from time to time, but from one linear run to another one). So, in fact soil properties depend not on the instant transient strains, but on some "effective" strains (in practice - on some portion of the maximal strain over the duration) [7].

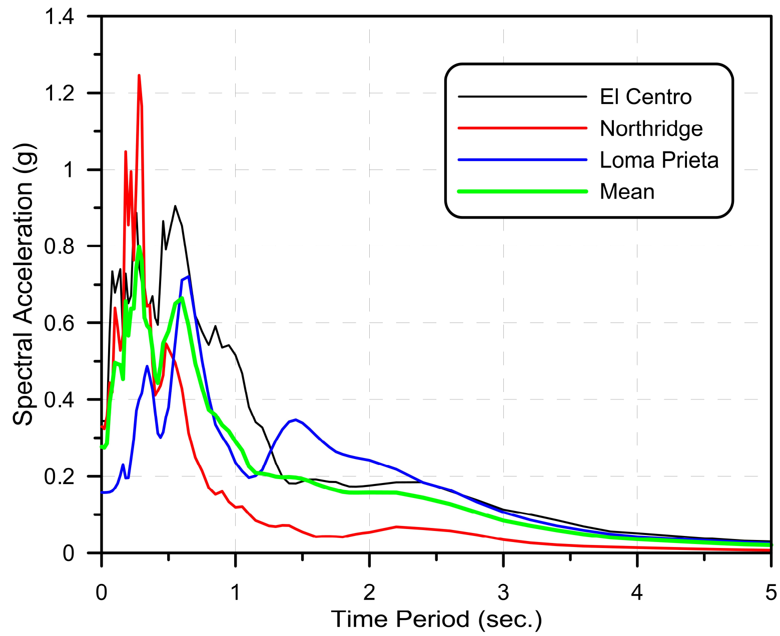

Figure 6. Acceleration response spectrums of different earthquakes and their mean.

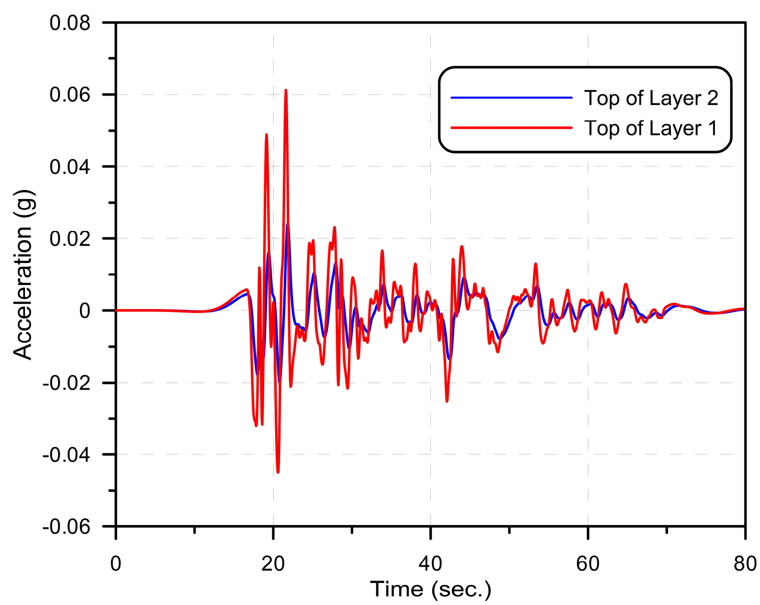

Figure 7. Modified acceleration time-history of El Centro earthquake due to SSI effect.

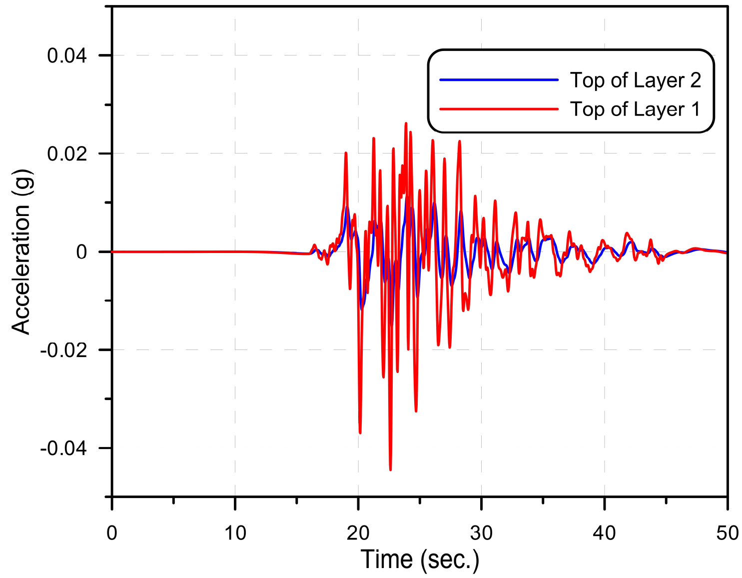

Figure 8. Modified acceleration time-history of Northridge earthquake due to SSI effect.

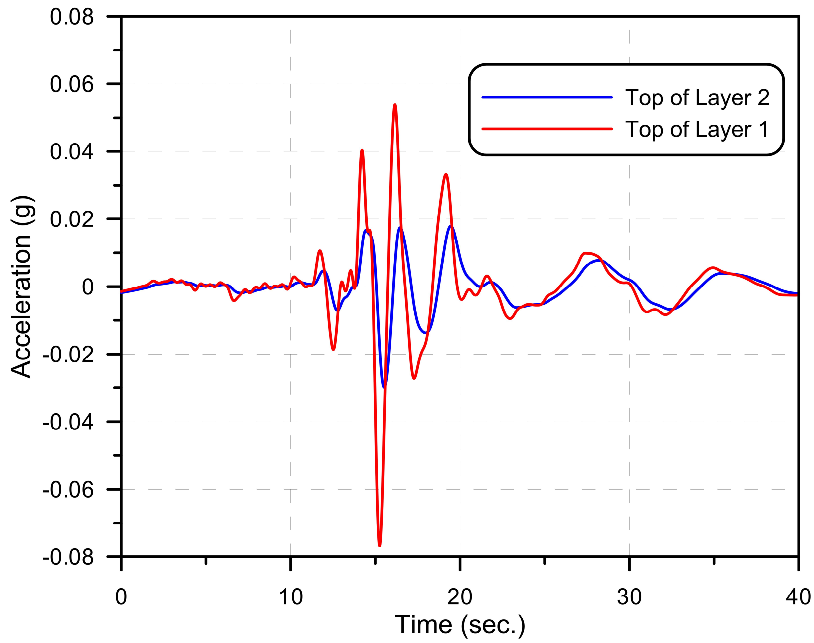

Figure 9. Modified acceleration time-history of El Centro earthquake due to SSI effect.

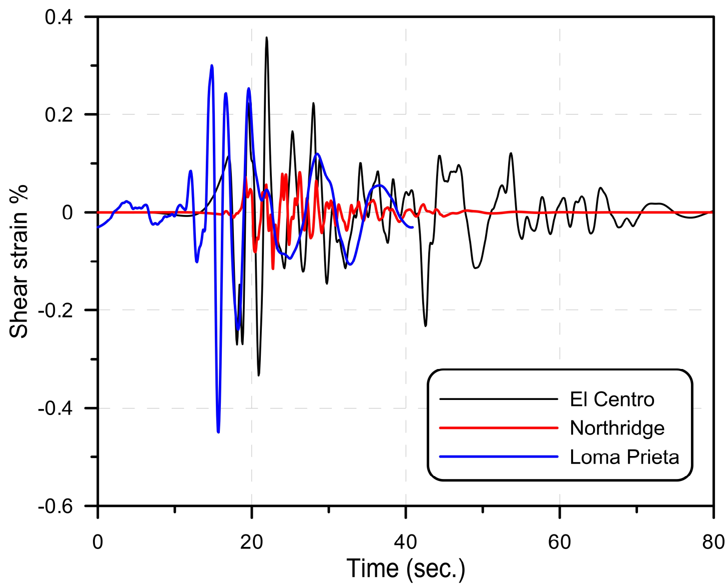

Figure 10. Shear strain percentage for different earthquakes due to SSI effect at the top of the bottom layer.

Figure 11 shows the peak ground acceleration values versus the depth of soil for the three earthquakes. The peak acceleration values in the upper layers are less than the values in the lower layers. The increase of the peak acceleration values in the lower layers is the result of the internal viscous damping in the soil-structure interaction system. The internal viscous damping combined with the damping of the super structure results in the increased damping value for the whole system. The internal soil damping is normally considered using linear hysteretic damping with analyses in the frequency domain. For time domain analyses it is common to use Rayleigh damping attempting to maintain it nearly constant and close to the desired value over the range of frequencies of interest.

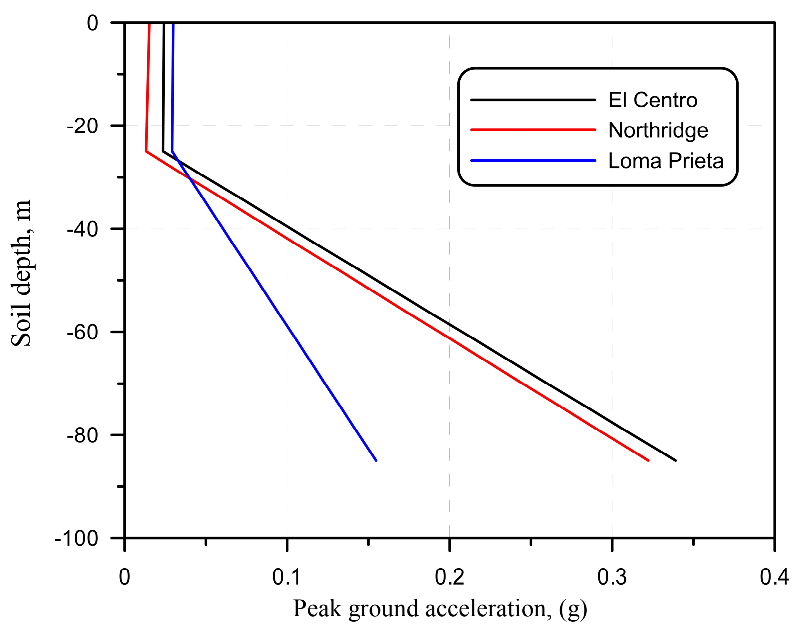

Figure 11. Peak ground acceleration versus soil depth.

MODIFIED DYNAMIC CHARACTERISTICS

ProShake was used to generate a comprehensive database of modified dynamic characteristics (natural frequency and damping) of the whole structural system shown in Figure 4 and 5 taking into consideration the soil-structure interaction effects. A database of about 286 records of modified dynamic characteristics as a function of different influencing parameters was obtained through an extensive parametric study carried out in this research.

From the parametric study it was clear that modified dynamic characteristics (natural frequency and damping) of the whole structural system shown in Figure 4 is governed by the following parameters: (i) frequency of the superstructure, (ii) the natural frequency of the ground, and (iii) the ratio between the shear wave velocity of the top layer to that of the bottom layer. It was decided to use El Centro Earthquake record for the generation of the database as the type of earthquake record was found to have an insignificant effect on the modified dynamic characteristics (natural frequency and damping) of the whole structural system. Throughout this study, the unit weight and Poisson's ratio of soil were taken as 18 kN/m3 and 0.4; respectively. The damping of the superstructure was taken as 5%.

Two empirical equations were developed using statistical methods to obtain the best fit for the data obtained from the database. These empirical equations are applicable for the following range of parameters: (i) superstructure frequency, fS, of 0.55 to 1.67 Hz, (ii) ground natural frequency, fg, of 2 to 8 Hz, (iii) a shear wave velocity of the top layer of 100 to 600 m/s, (iv) a ratio between the shear wave velocity of the top layer to that of the bottom layer of 0.25 to 1, and (v) the soil damping ratio is 5%.

The modified dynamic characteristics (natural frequency and damping) of the whole structural system shown in Figure 4 can be predicted using the following empirical equation:

$$f_{SM} = 0.114 f_S + 0.743 f_g - \frac{0.209 f_g}{f_S + \frac{V_1}{V_2}} \tag{11}$$

$$\xi = \frac{V_1}{V_2} \cdot \frac{(5.24 f_g - 2.48 f_S)}{(20.0 f_g + 75.7 f_S)} \tag{12}$$

Where f_{SM} is the modified natural frequency and ξ is the modified damping of the whole system.

As could be noticed, Equations 11 and 12 are simple and suitable for hand calculations. The maximum error between modified natural frequencies predicted using Equation 11 and Proshake results is 0.05%. This indicates that Equation 11 was successful in capturing the relationship between the modified natural frequency of the superstructure and the influencing parameters with a high level of accuracy. The R-squared goodness of fit is 0.9999. The maximum error between modified damping predicted using Equation 12 and Proshake results is 4.15% and the R-squared goodness of fit is 0.9996.

VERIFICATION OF THE PROPOSED FORMULAS

In this section, the experimental findings reported by Geneş et al. [13] shall be used in order to verify the accuracy of the Equation 11 proposed to estimate the overall natural frequency of structural systems taking into consideration SSI effect.

In the study by Geneş et al. [13], the effect of soil-structure interaction on two reinforced concrete buildings which were instrumented by building monitoring systems was detected and identified. The dominant frequency recorded for a building subjected to SSI is always smaller than the dominant frequencies of the fixed-based building and of the foundation when no building is present. The identification of SSI referred to extracting natural frequencies of the fixed-based building and the foundation from records of the foundation and upper stories. This interaction could be identified easily from the dynamic characteristics of the structure obtained by using seismic vibration records on the structures and, if in addition to the records from the building, there are also free-field surface records available from nearby locations that are not influenced by building's vibrations.

Geneş et al. [13] investigated two RC framed buildings using the method mentioned above to identify the SSI by using strong motion data. For each building, two earthquake records were used and the results are compared with each other. For the first building (Antakya Hospital) the SSI was identified during the both earthquakes, and in both directions. For the second building (H. Ozbugday High School) SSI was identified during both earthquakes, dominantly in E-W direction. The effects of SSI may considerably vary, and therefore the dynamic characteristics of the buildings are not always the same from all recordings.

Tables 1 and 2 show a comparison between the experimental natural frequency of the two RC buildings accounting for the SSI effect and the natural frequency computed using Equation 11. As could be noted from Tables 1 and 2, the proposed equation predicted the natural frequency of the structure accounting for effects of the soil-structure interaction with a reasonable degree of accuracy.

Table 1. A comparison between the experimental results reported by Geneş et al. [13] and the results of Equation 11 for estimating the natural frequency of Antakya Hospital.

	Direction	Experimental Natural Frequency, with SSI (Hz)	Estimated Natural Frequency, Fi, Using Proposed Equation 11.	Error (%)
Oct. 9, 2006	N-S	3.09	2.91	-5.80
	E-W	2.97	2.88	-3.03
Jun. 17, 2009	N-S	2.44	2.53	3.69
	E-W	2.54	2.46	-3.15

Table 2. A comparison between the experimental results reported by Geneş et al. [13] and the results of Equation 11 for estimating the natural frequency of Huseyin Ozbugday High School.

	Direction	Experimental Natural Frequency, with SSI (Hz)	Estimated Natural Frequency, Fi, Using Proposed Equation 11.	Error (%)
Oct. 9, 2006	N-S	3.12	2.98	-4.49
	E-W	3.21	3.11	-3.16
Jun. 17, 2009	N-S	5.12	4.84	-5.47
	E-W	5.64	5.36	-4.96

CONCLUSIONS

The effect of seismic soil-structure interaction on the dynamic characteristics of structural systems on shallow foundation was investigated. A database of 286 records of modified dynamic characteristics (natural frequency and damping factor) as a function of different influencing parameters was generated using ProShake. The generated database account for the radiation damping and viscous boundary. Two simple equations suitable for hand calculations are presented to predict the modified natural frequency and damping factor of the superstructure. These modified dynamic characteristics can be used by practicing engineers to account for the SSI effects if they decide to use the common practice of modeling the superstructure alone ignoring the surrounding sub-soil. The following could be concluded from this study:

1. The natural frequency of the super structure and shear wave velocity of the surrounding soil are the most significant factors affecting the modified natural frequency and damping factor of the whole system.
2. The proposed Equations are capable of predicting the modified natural frequency and damping factor of the whole structural system with a high degree of accuracy.

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