NON-LINEAR SOIL-STRUCTURE INTERACTION ANALYSIS BASED ON A SUBSTRUCTURE METHOD INCORPORATING AN APPROXIMATE 3D APPROACH

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ABSTRACT

In this study, the time-history response of inelastic structure supported by soil-foundation systems is discussed, using some simple tools and considering a maximum number of parameters to best represent the nonlinear behavior of the soil-structure system. So, 1) based on the substructure method, an approximate 3D impedance function is evaluated through a computational model based on the 2D boundary element method (BEM) and a thin layer method (TLM) Green's function. Horizontal dashpots were incorporated into the soil in plane strain so as to represent the wave propagation toward the perpendicular direction from a slice of the soil. 2) In general, soil-foundation systems show various frequency-dependent impedance characteristics. For the sake of simplification, the lumped-parameter (L-P) model with frequency-independence is used to express the impedance functions in the time domain. The L-P model is usually composed of additional springs, dashpots and masses. 3) The building (superstructure and L-P model) is modelled by using commercial finite element method (FEM) software. The inelastic time-history response is obtained for the fixed base model and the soil structure system model for the sake of comparison.

Keywords: Boundary element method (BEM), Thin layer method (TLM), Lateral dashpots, Frequency-dependent impedance, Inelastic behavior of the soil-structure system.

1. INTRODUCTION

The design process of important structures, such as nuclear power plants and super high-rise buildings subject to seismic loading or offshore platforms subject to pseudo-monotonic cyclic loads due to swell, or even the foundations supporting vibrating machines, requires knowledge of the soil behavior under cyclic loading. The structural design required, on the one hand, the definition of the excitation (sources of vibration) and, on the other hand, the knowledge of the soil behavior supporting the structure. Once the latter two have been obtained, it would be possible to conduct the analysis considering soil-structure interaction. This interaction reflects the modification of the structural response, which is more or less, depending on the soil nature, the characteristics of the structure and the type of foundation. The results of this interaction may in some cases be determining criteria of the design process. The aim of this study is to develop greater understanding of dynamic soil-structure interaction considering both the nonlinearity of the soil and nonlinearity of the structure. The focus of study is on how to formulate a 3D impedance function based only on a 2D formula. Also, on how to deal with the frequency dependence of the impedance function for the purposes of conducting a nonlinear analysis. It is crucial to be able to account correctly for any soil-structure interaction when this kind of analysis is needed for seismic design.

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2. THE SUBSTRUCTURE METHOD: TIME HISTORY ANALYSIS

The methods that can be used to evaluate the soil-structure interaction, SSI effects can be categorized as direct approach and substructure approach. The direct approach consists of a modeling of the full system, mainly by finite elements, FEM. The analysis is done in a single step. The alternative approach is the substructure method, which partitions the solution into three steps, this approach was introduced firstly by Kausel et al. (1974). In this method, the first step includes the determination of rigid foundation movement due to the kinematic interaction. The foundation input motion is determined at this step. To accomplish this, a transfer function defined in frequency domain is typically used to convert free-field motions, which is an earthquake record that is taken from the surface of the soil for the absence of building. This is generally accomplished by carrying out analyses with a direct method where the foundation system is modeled with its inherent stiffness but without mass. The second step involves the evaluation of inertial interaction effects, that can be applied more simply by modeling the soil using a set of springs and dashpots, these later are better-known in the literature as “dynamic impedance function”, which represent the soil-foundation system's dynamic stiffness and radiation damping. The final step is comprised of the calculation of the response of the SSI system related to the previously solved impedance function and the kinematic interaction.

Usually, impedance functions show the following typical frequency-dependent characteristics a) cut-off frequency below which the damping is negligible and above which the damping increases rapidly, b) depending on the homogeneity of the soil and engineering bedrock depth, a slight or some important oscillations can be shown in the impedance function of a surface or embedded rigid foundation, c) multiple oscillations are typically exhibited in pile groups (Saitoh (2007)).

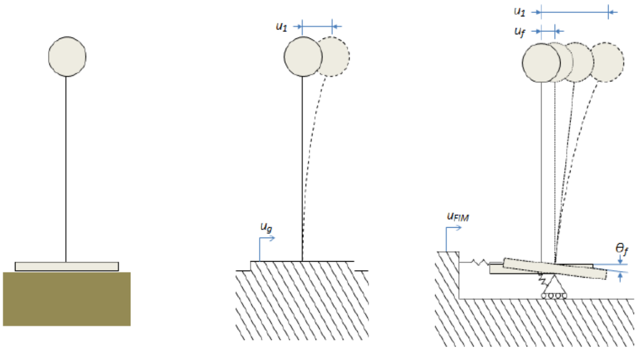
Several methods have been proposed based on time-domain transformations of frequency dependent dynamic impedance functions in order to perform a dynamic linear or nonlinear time-history analysis. These methods have been available in the literature for a number of years. Among the most famous existing methods in the literature we can cite: 1) Frequency domain solution, 2) Representative frequency solution, 3) Lumped parameter model (LPM), 4) Convolution-based solution, 5) Discrete-time filter method.

3. IMPLEMENTATION OF EXISTING METHODS

In this section, we consider the simplest soil- structure system as shown in Figure 1. The system consists of a single degree-of-freedom mass supported by a rigid disk that rests on a homogeneous half-space. The physical properties of the half space are presented in Table 1.

Table 1. Soil-Structure System Parameters.

	Soil		
ρ	Mass Density	1.7	t/m^3
V_S	Shear Wave Velocity	200	m/s
ν	Poisson's Ratio	0.45	-
	Structure		
m	Structure mass	1200	Tons
h	Structure Height	12	m
T	Structural Period	0.4	Sec
ξ	Critical damping Ratio	5	%
r	Foundation Radius	6.9	m



(a) Soil-Structure System (b) Fixed Base Model (c) Structural Model for Soil-Structure

Figure 1. A simple soil-foundation-structure system with fixed base and sub-structure models (Gash (2015)).

The ground motion used as an input base excitation for the fixed base structure and soil-structure system in the following examples will be the North-South surface motion recorded at JMA survey station, during the January 17th, 1995 Kobe Earthquake. The time history acceleration record of this event is plotted in Figure 2. It contains 2000 data points spaced at $\Delta t = 0.02$ seconds. During this event, the peak ground acceleration (PGA) recorded was 0.84g. The corresponding record's Fourier amplitude spectrum is displayed in Figure 3.

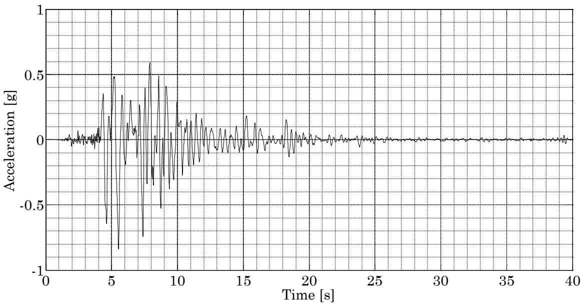


Figure 2. North-South ground acceleration recorded at the JMA survey during the January 17th, 1995 Kobe Earthquake.

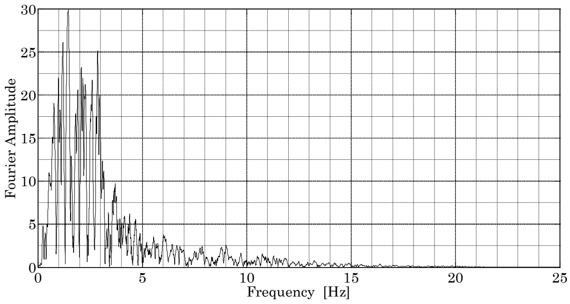


Figure 3. Fourier amplitude spectrum of North-South ground acceleration recorded at the JMA.

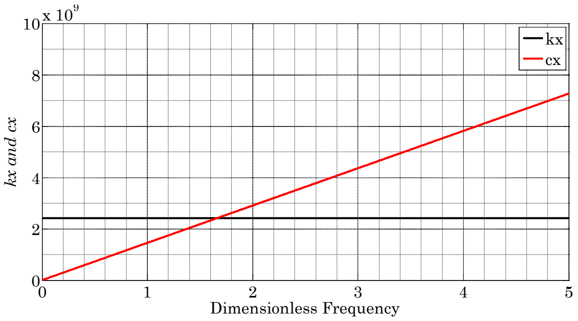


Figure 4. Horizontal component of the foundation impedance function stiffness and damping for disk resting on a homogeneous elastic half-space.

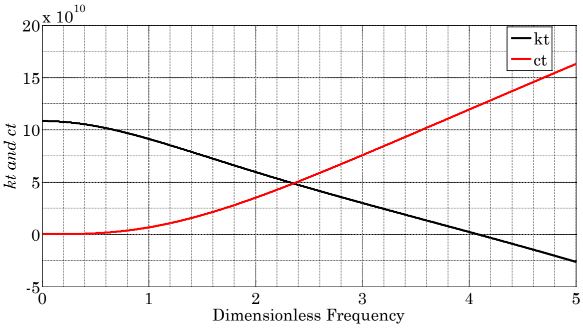


Figure 5. Rooking component of the impedance function stiffness and damping for disk resting on a homogeneous elastic half-space.

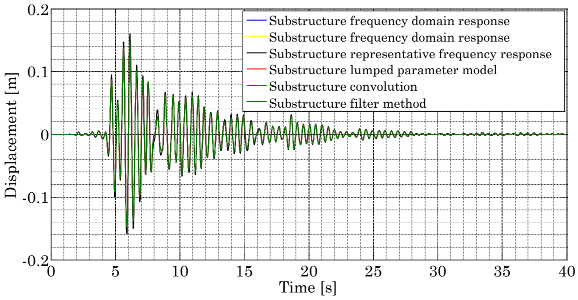


Figure 6. Comparison of displacement time-history response of the SSI system calculated by different methods.

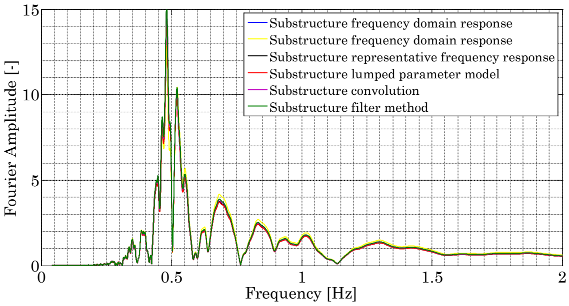


Figure 7. Fourier amplitude spectrum of the displacement time history for the SSI system calculated by different methods.

It can be concluded that all substructure methods yield the same period compared to the fixed base predominant period. All methods also yield nearly the same maximum structural displacement.

4. AN APPROXIMATIVE 3D IMPEDANCE FUNCTION

In this section, the effect of viscous forces introduced by Nakai et al. (1989) on the SSI is examined through the impedance functions and foundation input motions of rigid foundation which is embedded in a layered elastic half-space and layered stratum overlying a rigid rock. First, the Green's function for this problem is derived using a modified Thin Layer Method formulation (including additional term), then this Green's function is applied to the 2D formulation of the boundary element method, BEM. The effect of the dashpots on the SSI problem including the embedment, underlying bedrock is examined by comparing the results obtained by 2D approximated 3D and exact 3D analysis. The efficiency of the dashpot for a problem of rigid foundation in a half-space is recognized too. In order to validate the current formulation, an equivalent circular footing resting on a single layer over a stratum is studied. The stratum thickness was taken to the total width of the foundation (H/R=2). The stratum is divided into twelve equal sub-layers. The foundation was divided into ten equal elements. Figure 8 and Figure 9 shows the real and imaginary parts of the horizontal and rooking components of the impedance functions respectively. The results are compared with an exact 3D formulation presented by Tassoulas (1981).

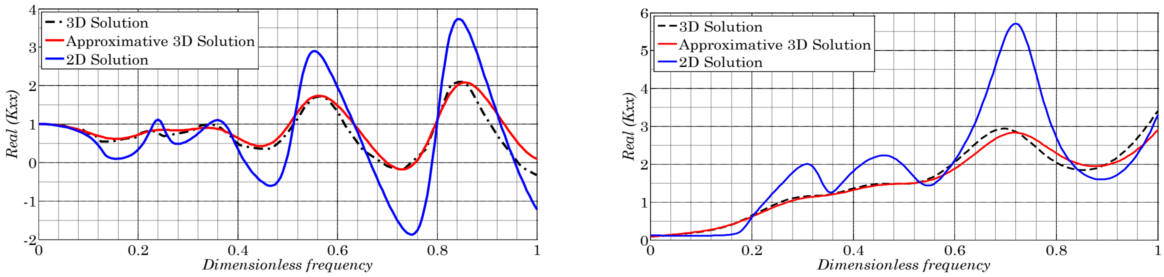


Figure 8. Horizontal component of the impedance function: (a) Real part, (b) Imaginary part.

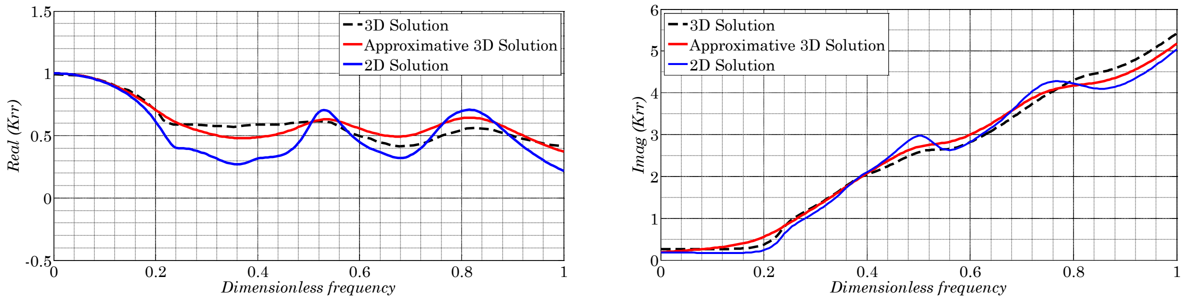


Figure 9. Rooking component of the impedance function: (a) Real part, (b) Imaginary part.

This formulation showed a good agreement with the exact 3D formulation using 3D Boundary Element Method formulation. Differences or errors were negligible from an engineering point of view.

5. INVESTIGATION OF SEISMIC SOIL-STRUCTURE INTERACTION CONSIDERING AN EQUIVQLENT LINEAR SOIL MODEL AND LINEAR STRUCTURAL MODEL

A structural analysis will be conducted, including the effect of the local geological conditions while also considering the soil structure interaction. Thus, first, the geotechnical and geophysical data relative to the site receiving the structure is analyzed in detail, which enables us to establish representative soil model of the study area. Once this is done, a one-dimensional wave propagation of the shear wave is conducted in order to estimate the acceleration time history at the surface of the soil. In the process of one-dimensional wave propagation, the nonlinearity of the soil will be considered by the simple equivalent linear model. Finally, two kinds of structural analysis will be conducted, one without considering the SSI effect, the second taking the SSI effect into consideration.

The frequency analysis of a 6-story RC building is conducted. For a fixed base structure, this analysis is of no practical value since the modal analysis provides all the necessary information concerning vibration modes and natural periods or natural frequencies of vibration. As the frequency analysis gives the same information, the latter serves as a baseline for comparison when we consider the SSI effect, that's because impedance functions are frequency dependent. Also, when the interaction is considered the classical modal analysis cannot be carried out easily, that's due to the presence of high damping value from the radiation damping induced by interaction, hence the interest of frequency analysis which is an alternative to modal analysis.

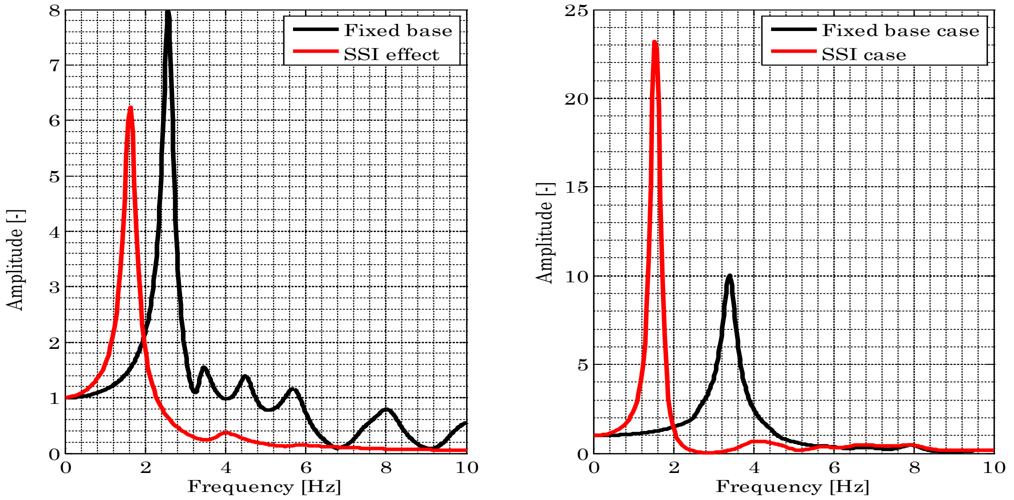


Figure 10. Normalized transfer function, X-direction (at the left), Y-direction phase (at the right).

Exactly as we expected the fundamental period in both directions increased. This can be easily remarkable through Figure 10, in which we can see the shifting of the peaks to the lowest frequencies range.

Concerning time domain analysis, the following figure shows a comparison of the lateral displacement of the structure in x and y directions for the fixed base structure and the structure considering SSI effect. The analysis was conducted for 3 couples of acceleration time history applied at the engineering bedrock level, these accelerograms were recorded during Boumerdes earthquake in 2003.

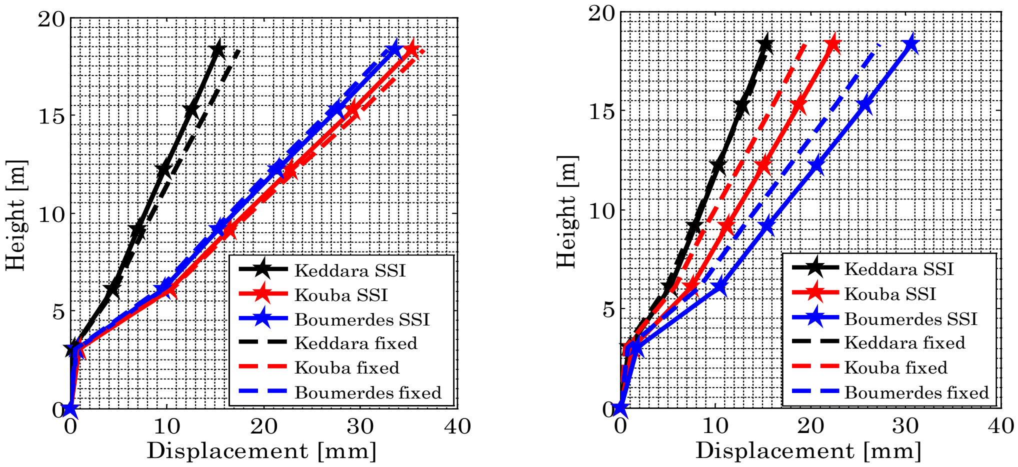


Figure 11. Comparison of the relative maximum lateral displacements of the fixed base structure and SSI system.

6. INVESTIGATION OF SEISMIC SOIL-STRUCTURE INTERACTION CONSIDERING AN EQUIVQLENT LINEAR SOIL MODEL AND NONLINEAR STRUCTURAL MODEL

The frequency-dependency of the impedance function is removed using a lumped parameter method, considering an additional internal degree of freedom. Figure 12 displayed a comparison of the lateral displacement at the top level of the SSI-system for the linear analysis and the nonlinear analysis cases.

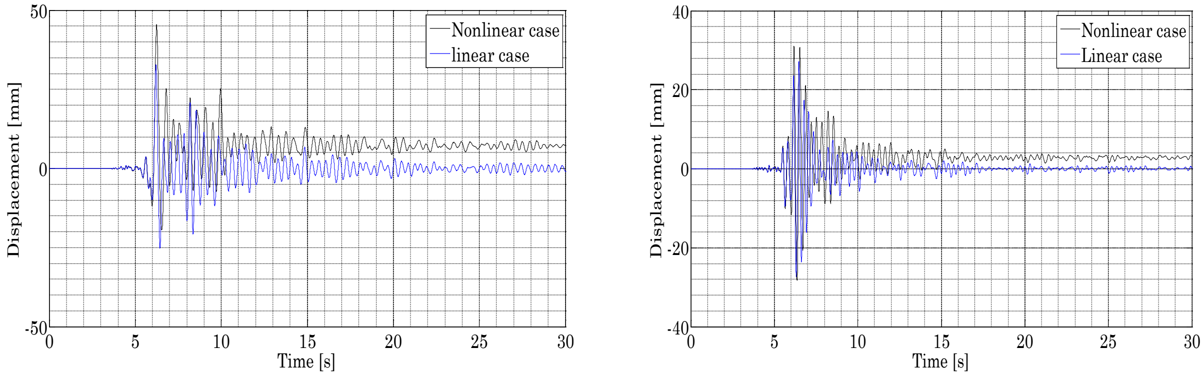


Figure 12. Comparison of the top displacement of the structure for X-direction (at the left), Y-direction (at the right) (Boumerdes acceleration).

7. CONCLUSION

The main objective of this research is to develop simple tools using simple, commonly available software used by engineers and structural designers to deal with the problem of “nonlinear soil-structure interaction”. The case study used a six-story building, and linear analyses were conducted with, and without consideration of the soil-structure interaction effect. Several findings and results were drawn from an in-depth analysis of the results, which were easy to interpret since it is always easy to link the input to the output in a linear analysis case. All the results were logical, and without contradiction. In the case of the non-linear analyses, several findings and results were also drawn from an in-depth analysis of the results. However, the difference was that the interpretation of the results is not straightforward, since the relationship between input and output was not explicitly defined. This was due to the mechanical characteristics of the system changing during dynamic loading (seismic). It is notable that the results did not contradict the general concept of non-linear analysis. Finally, this work is only a starting point for a variety of research options and practical applications, and it is far from complete, however the main lines of formulation and resolution of the soil-structure interaction problem were briefly discussed.

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