Coupled Systems Mechanics, *Vol. 13, No. 4 (2024) 293-310*
https://doi.org/10.12989/csm.2024.13.4.293

Effect of static and dynamic impedance functions on the parametric analysis of SSI system

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(Received July 17, 2022, Revised May 2, 2024, Accepted June 4, 2024)

Abstract. This paper investigates the dynamic response of structures during earthquakes and provides a clear understanding of soil-structure interaction phenomena. It analyses various parameters, comprising ground shear wave velocity and structure properties. The effect of soil impedance function form on the structural response of the system through the use of springs and dashpots with two frequency cases: independent and dependent frequencies. The superstructure and the ground were modeled linearly. Using the substructure method, two different approaches are used in this study. The first is an analytical formulation based on the dynamic equilibrium of the soil-structure system modeled by an analog model with three degrees of freedom. The second is a numerical analysis generated with 2D finite element modeling using ABAQUS software. The superstructure is represented as a SDOF system in all the SSI models assessed. This analysis establishes the key parameters affecting the soil-structure interaction and their effects. The different results obtained from the analysis are compared for each studied case (frequency-independent and frequency-dependent impedance functions). The achieved results confirm the sensitivity of buildings to soil-structure interaction and highlight the various factors and effects, such as soil and structure properties, specifically the shear wave velocity, the height and mass of the structure. Excitation frequency, and the foundation anchoring height, also has a significant impact on the fundamental parameters and the response of the coupled system at the same time. On the other hand, it have been demonstrated that the impedance function forms play a critical role in the accurate evaluation of structural behavior during seismic excitation. As a result, the evaluation of SSI effects on structural response must take into account the dynamic properties of the structure and soil accordingly.

Keywords: impedance function; seismic response; soil-structure interaction (SSI); viscoelastic model

1. Introduction

In the 19th and early 20th centuries, innovations in structural engineering and structural analysis emerged and developed rapidly. Currently, structures are becoming higher and larger, and several factors can affect their seismic response. Many of these things are still ignored by engineers and building standards, even though several research have proven their importance and impact. Soil-structure interaction is one of these factors that can cause many complex implications. The structure, the foundation, and the soil underlying and surrounding, influence the response of

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http://www.techno-press.org/?journal=csm&subpage=8 ISSN: 2234-2184 (Print), 2234-2192 (Online)

the structure when an earthquake occurs. However, it is still common for an SSI influence to be completely ignored when designing a structure, assuming that integrating SSI results in a conservative design (Abdel Raheem *et al.* 2015). Despite its effect, which can be favorable or prejudicial (Abate and Massimino 2017, Mylonakis and Gazetas 2000), it is still a controversial subject (Renzi *et al.* 2013). However, in both cases, it should be considered because it could give a significant overestimation of the design response spectra for buildings (Guellil *et al.* 2020), as a result of uneconomical designs, it is imperative to encourage the studies of coupled soil-structure systems, because, without them, a risk of rough and inaccurate evaluation of the seismic response of the structure (Massimino *et al.* 2019).

Many analytical, numerical, and experimental studies have been conducted on the subject, especially: soil-structure interaction, highlighting its important role in the analysis of structure. Among these studies, the influence of soil-structure interaction on the behavior and the dynamic response of structures such as the work of Worku (2014) which demonstrates the importance of SSI in increasing the total lateral deformation of buildings and its beneficial effect in reducing design spectral values or basic shear in most building structures. Gao *et al.* (2020) studied using the response spectrum method (RSM), the effect of the seismic soil-structure interaction (SSI) on a structure with a shallow foundation. Other studies that investigate the effect of SSI on the dynamic properties/response of the base-isolated structure, Abdeddaim *et al.* (2022), Spyrakos *et al.* (2009), Karabork *et al.* (2014), analyzed using the computer program SAP2000 the dynamic behavior of multi-story structures with an isolated base under the influence of three different types of earthquakes with and without SSI. The results indicated that SSI is an important factor that must be taken into account when selecting the appropriate isolator for isolated base structures in soft soils. Other research focuses on the influence of SSI on fragility curves and the seismic vulnerability assessment of structures (Karapetrou *et al.* 2015, Rajeev and Tesfamariam 2012).

The soil-structure interaction includes two parts: the kinematic interaction and the inertial interaction. The kinematic interaction results from the difference in stiffness between the ground and the foundation, which prevents it from following the movements imposed by the ground and causes the movements of the foundation to deviate from the movements of the free field. The induced motion of the foundation develops oscillations of the superstructure and therefore gives rise to inertial forces which are retransmitted to the foundation in the form of forces and moments, which is known as inertial interaction. The direct method and the substructure method are the most widely used methods for dynamic SSI. The direct method deals with the problem of soil-structure interaction in its entirety to obtain the response of the soil and the structure simultaneously, and it directly solves the equation of motion in the entire soil-structure system. The different parts of the system (structure, foundation, and soil) are considered with their behavior and contact conditions in the same analysis. the calculation is performed in one step (Jaya and Meher Prasad 2002). While, the method where the soil-structure system is divided into two substructures i.e., a structure with a rigid foundation and a massless rigid foundation-soil system, is known as the substructure method. Several steps in this method are easier to deal with compared to the global problem, where the kinematic and inertial analysis are decoupled and the superposition principle is used (Chen and Shi 2013). The calculation of the interaction force-displacement relationship (dynamic stiffness) is the key step in the analysis of soil-structure interaction. An important concept for evaluating the dynamic response of the foundation is the impedance function which provides valuable means to couple the two mutually interacting subdomains, the unbounded soil domain and the structure (Harichane *et al.* 2018, Sbartai 2018, Belkhir *et al.* 2022, Lagaguine and Sbartai 2023).

It is well demonstrated that the nature of the soil-structure interaction depends essentially on frequency (Saitoh 2007, Wolf and Preisig 2003) and as such, the dynamic impedance functions are affected by the frequency content of the seismic motion input. However, due to various difficulties of numerical analysis, the simplified hypotheses were adopted. The frequency-independent representation of the soil-structure interaction in a structure can lead under certain circumstances to a structural behavior that is very different from the actual behavior, and therefore it can cause misdirection in the setting process engineer's decision. As Lesgidis *et al.* (2017) investigated the impact of the frequency dependence of the soil-structure interaction on the fragility of RC bridges by comparing the predicted vulnerability of a reference bridge using both a conventional, frequency-independent Kelvin-Voigt model and the lumped parameter formulation developed by the same authors. various studies noticed that the simplified, frequency-independent approach can both underestimate and overestimate the actual fragility curves of a bridge, and thus the latter may lead to a structural behavior significantly diverging from the actual one. According to Betti *et al.* (1993), the outcome of the structure's response to seismic excitation depends on the characteristics of the ground motion and the dynamic properties of the structure and the underlying ground and these influencing factors should be sufficiently considered to correctly estimate the behavior of the structure under seismic loading.

The underlying goal of the present study is to examine and analyze the dynamic response of structures during earthquakes, considering the effect of soil-structure interaction. To this end, two different analyzes are conducted in this work to obtain the seismic response of the chosen structure. The first is an analytical formulation based on the dynamic equilibrium of the soil-structure system modeled by an analog model with three degrees of freedom. The second is a numerical analysis generated with 2D finite element modeling using ABAQUS software. To explore the sensitivity of the response of a soil-structure system to different soil and structure parameters, this paper investigates the impact of adopting different impedance function forms on the structural response of the soil-structure system by using springs and dashpots with two frequency cases: independent and dependent frequencies. Different other parameters were analyzed, such as ground shear wave velocity and structure properties. The superstructure and the ground were modeled linearly. The obtained results show the sensibility of the buildings to the interaction of the soil structure and highlight the various influences of different factors.

2. System and method of analysis

The model of the influence of soil-structure interaction on the response of a structure shown in Fig. 1 is well suited to identify the key parameters affecting soil-structure interaction and to study their effects. This can be illustrated using a simplified rheological model. The structure is treated as a mass m, a lateral stiffness with a spring coefficient K, and a damper with a coefficient C placed at a height h of a rigid bar above the foundation. A rigid base achieves the connection between the structure and the soil. The foundation rests on the ground and the interaction between them is modeled through the impedance functions. The latter consists of a spring and a damper that represents the radiated and dissipated energy in the ground, the coefficients are denoted K_h and C_h in the horizontal direction and K_r and C_r in the rotational direction. the influence of the mass m_0 and the mass moment of inertia I_0 associated with the base are neglected. The system is subject to a horizontal displacement of the ground support of pulsation ω and an amplitude u_g (g for ground). The frequency of the fixed base structure is denoted as ω_s, and ξ the damping

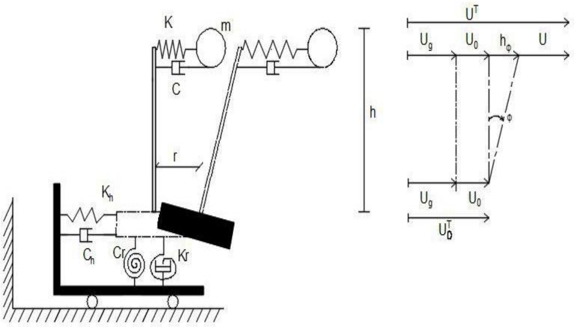


Fig. 1 Simplified model of soil-structure interaction (for a structure with a single degree of freedom)

coefficient of the structure are given as follows (Wolf 1985).

$$\omega_s^2 = \frac{K}{m} \tag{1}$$

$$C = \frac{2K\xi}{\omega} \tag{2}$$

although the system has three degrees of freedom, The total lateral displacements of the mass with amplitude u^t and the base of the structure u_0^t can be divided into individual components as follows

$$u^t = u_g + u_0 + h\phi + u \tag{3}$$

$$u_0^t = u_g + u_0 \tag{4}$$

Where

u_g: Amplitude of horizontal excitation or free-field motion.

u: Amplitude of the relative displacement of the mass which is equal to the structural distortion.

u_0: Amplitude of horizontal displacement of the foundation relative to the free-field motion.

ϕ: Amplitude of the rotation of the foundation around a horizontal axis.

P_h and M_r : The horizontal-force amplitude and the moment amplitude of the soil respectively are formulated as

$$P_h = K_h u_0 + C_h \dot{u}_0 \tag{5}$$

$$M_r = K_r \phi + C_r \dot{\phi} \tag{6}$$

The forces result only from the movement of the base relative to that of the ground. For a soil without material damping, the corresponding equation is written as

$$P_x = K_x u_0 + C_x \dot{u}_0 \tag{7}$$

for a harmonic excitation

$$\dot{\mathrm{u}}_0 = \mathrm{i}\omega\mathrm{u}_0 \tag{8}$$

substituting Eq. (8) in Eq. (7) leads to

$$P_x = K_x(1 + i\omega \frac{C_x}{K_x})u_0 = K_x(1 + i2\xi_x)u_0 \tag{9}$$

Where, ξ_x is the ratio of the viscous radiation damping in the horizontal direction.

The material damping of the soil is introduced roughly by multiplying the spring K_x (for frequency ω) with the factor $(1 + i2\xi_g)$ where ξ_g is the hysteretic damping ratio. This results in

$$P_h = K_x\left(1 + i2\xi_x + i2\xi_g\right)u_0 \tag{10}$$

Analogously, for the rocking degree of freedom, the moment amplitude of the soil is formulated as

$$M_r = K_\phi(1 + i2\xi_\phi + i2\xi_g)\phi \tag{11}$$

The subscript "*x*" indicates the horizontal direction, while "ϕ" denotes the rocking direction of undamped soil.

Starting from scratch, formulating the dynamic equilibrium of the mass point and the horizontal and rocking equilibrium equations of the total system (see Fig. 1) can be established to obtain the equations of motion for this structure with a rigid basement by using Eqs. (10)-(11). Introducing the following critical depreciation percentages leads to

$$\xi = \frac{\omega C}{2K}, \xi_x = \frac{\omega\, C_x}{2\, K_x}, \xi_\phi = \frac{\omega\, C_\phi}{2\, K_\phi} \tag{12}$$

$$C_h = C_x + \frac{2}{\omega}\xi_g K_x, \qquad C_r = C_\phi + \frac{2}{\omega}\xi_g K_\phi \tag{13}$$

$$\begin{cases} -\omega^2 m(u_0 + h\phi + u) + k(1 + 2\xi i)u = m\omega^2 u_g \\ -\omega^2 m(u_0 + h\phi + u) + k_h\left(1 + 2\xi_x i + 2\xi_g i\right)u_0 = m\omega^2 u_g \\ -\omega^2 mh(u_0 + h\phi + u) + k_r\left(1 + 2\xi_\phi i + 2\xi_g i\right)\phi = mh\omega^2 u_g \end{cases} \tag{14}$$

By introducing the following notations

$$m\omega_s^2 = k \qquad m\omega_h^2 = k_h \qquad mh^2\omega_\phi^2 = k_\phi \tag{15}$$

Moreover, by eliminating u_0 and ϕ from the three previous equations, it comes

$$\left(1 + 2\xi i - \frac{\omega^2}{\omega_s^2} - \frac{\omega^2}{\omega_h^2}\frac{1 + 2\xi i}{1 + 2\xi_x i + 2\xi_g i} - \frac{\omega^2}{\omega_r^2}\frac{1 + 2\xi i}{1 + 2\xi_\phi i + 2\xi_g i}\right) u = \frac{\omega^2}{\omega_s^2} u_g \tag{16}$$

Now, consider a simple oscillator with one degree of freedom, having the same mass m, its own pulsation $\tilde{\omega}$, and damping $\tilde{\xi}$, subjected to a harmonic displacement $\tilde{u}_g$ at its base with a pulsation ω (case of the structure embedded at its base).

The response of the oscillator is

$$\left(1 + 2\tilde{\xi} i - \frac{\omega^2}{\tilde{\omega}^2}\right) u = \frac{\omega^2}{\tilde{\omega}^2}\tilde{u}_g \tag{17}$$

The equivalent oscillator will have the same response as the structure of Fig. 1 if the following equation is satisfied

$$\frac{1}{\tilde{\omega}^2}=\frac{1}{\omega_s^2}+\frac{1}{\omega_h^2}+\frac{1}{\omega_r^2} \Rightarrow \tilde{\omega}^2=\frac{\omega_s^2}{1+{}^{k}/_{k_h}+{}^{kh^2}/_{k_r}} \tag{18}$$

It follows that the fixed-base frequency ω_s is always bigger than the fundamental frequency of the soil-structure system, from the Eqs. (16), (17) and (18) and with resonance $\tilde{\omega}=\omega$ the equivalent damping ratio comes

$$\tilde{\xi}=\frac{\tilde{\omega}^2}{\omega_s^2}\,\xi+(1-\frac{\tilde{\omega}^2}{\omega_s^2})\xi_g+\frac{\tilde{\omega}^2}{\omega_h^2}\xi_x+\frac{\tilde{\omega}^2}{\omega_r^2}\xi_\phi \tag{19}$$

And

$$\tilde{u}_g=\frac{\tilde{\omega}^2}{\omega_s^2}u_g \tag{20}$$

$$u_0+h\phi+u=\omega_s^2\left(\frac{1}{\tilde{\omega}^2}+2(\xi-\xi_g)i\left(\frac{1}{\tilde{\omega}^2}-\frac{1}{\omega_s^2}\right)-\frac{2\xi_x i}{\omega_h^2}-\frac{2\xi_\phi i}{\omega_r^2}\right)u \tag{21}$$

The dimensionless parameters given in Eq. (22) can be used to generalize the results obtained and better assess the effect of soil-structure interaction, where c_s is the shear wave velocity of the soil, r is the radius of the foundation, ρ is the mass density and $G(=\rho c_s^2)$ is the shear modulus.

$$\bar{s}=\frac{\omega_s h}{c_s},\bar{h}=\frac{h}{r},\bar{m}=\frac{m}{\rho r^3} \tag{22}$$

This work presents the study of the seismic response of structures by considering and ignoring the SSI. Two expressions will be used to estimate the soil stiffness and damping parameters (static parameters, “frequency independent”, dynamic parameters, “frequency-dependent”). This aims to determine if the properties of these expressions affect the response.

One crucial aspect to address is the judicious estimation of the impedance functions. In real conditions, the stiffness and damping coefficient of the foundation depend on the frequency. To illustrate the effect of SSI and the influence of the expression forms used to estimate the stiffness and damping parameters of the soil, the following frequency-independent and frequency-dependent approximate expressions can be employed to estimate the stiffness and damping coefficient of a rigid circular base with a radius of r.

2.1 Case of frequency independent expressions

The following expressions which are frequency-independent (pseudo-static), are used as a crude approximation for the undamped soil to calculate the properties of the equivalent dynamic one-degree-of-freedom system

$$K_x^s=\frac{8Gr}{2-\nu} \tag{23}$$

$$C_x=\frac{4.6}{2-\nu}\rho c_s r^2 \tag{24}$$

$$K_{\phi}^{s}=\frac{8Gr^{3}}{3(1-\nu)} \tag{25}$$

$$C_{\phi}=\frac{0.4}{1-\nu}\rho c_{s}r^{4} \tag{26}$$

The expression of the frequency $\tilde{\omega}$ and the equivalent damping coefficient $\tilde{\xi}$ calculated in the Eq. (18) and the Eq. (19) of a rigid base using the dimensionless parameters mentioned above for the case of a surface rigid base $(D=0)$ leads to

$$\frac{\tilde{\omega}^{2}}{\omega_{s}^{2}}=\frac{1}{1+\frac{\bar{m}\bar{s}^{2}}{8}[\frac{2-\nu}{\bar{h}^{2}}+3(1-\nu)]} \tag{27}$$

$$\tilde{\xi}=\frac{\tilde{\omega}^{2}}{\omega_{s}^{2}}\,\xi+(1-\frac{\tilde{\omega}^{2}}{\omega_{s}^{2}})\xi_{g}+\frac{\tilde{\omega}^{3}}{\omega_{s}^{3}}\frac{\bar{s}^{3}\bar{m}}{\bar{h}}\left[0.036\frac{2-\nu}{\bar{h}^{2}}+0.028(1-\nu)\right] \tag{28}$$

2.2 Case of frequency-dependent expressions

In the Case of frequency-dependent expressions (pseudo-dynamic), stiffness K^{d} is now expressed in terms of a static part, K^{s} (see Eqs. (23) and (25)), times a dynamic modifier, k, the radiation dashpot coefficient is similarly expressed in terms of static stiffness and the product of a dimensionless frequency $a_{0}(={}^{\omega r}/_{c_{s}})$, times a dynamic modifier, c. The dimensionless spring and damping coefficients k_{x}, c_{x}, k_{ϕ} and c_{ϕ} are functions of a_{0} evaluated at the frequency $\tilde{\omega}=\omega$ (Pais *et al.* 1988).

$$K^{d}=K^{s}(k+ia_{0}c) \tag{29}$$

$$k_{x}(\omega)=1 \tag{30}$$

$$c_{x}(\omega)=\frac{\pi[1+(1+\alpha)\,{}^{D}/_{r}]}{{}^{K_{x}^{s}}/_{Gr}} \tag{31}$$

$$k_{\phi}(\omega)=1-\frac{0.35\,a_{0}^{2}}{1+a_{0}^{2}} \tag{32}$$

$$c_{\phi}(\omega)=\frac{\pi\left[\frac{\alpha}{4}+{}^{D}/_{r}+\left(\frac{1+\alpha}{2}\right)\frac{2}{3}\left({}^{D}/_{r}\right)^{3}\right]\frac{a_{0}^{2}}{b+a_{0}^{2}}+0.84(1+\alpha)\left({}^{D}/_{r}\right)^{2.5}\frac{b}{b+a_{0}^{2}}}{{}^{K_{\phi}^{s}}/_{Gr^{3}}} \tag{33}$$

The same dimensionless parameters are again used to describe the key parameters of this coupled system (neglecting the influence of m_{0} and I_{0}), which has three dynamic degrees-of-freedom: the stiffness ratio of the structure and the soil $\bar{s}$, the mass ratio $\bar{m}$ and the slenderness ratio $\bar{h}$.

It follows from Eq. (18) that the frequency $\tilde{\omega}$ of the soil-structure interaction system equals

$$\frac{\tilde{\omega}^2}{\omega_s^2}=\frac{1}{1+\frac{\bar{m}\bar{s}^2}{8}[\frac{2-\nu}{\bar{h}^2k_x(1+D)}+\frac{3(1-\nu)}{k_\phi(1+2.3D+0.58D^3)}]} \tag{34}$$

the equivalent damping ratio $\tilde{\xi}$ (Eq. (19)) is specified by

$$\tilde{\xi}=\frac{\tilde{\omega}^2}{\omega_s^2}\,\xi+(1-\frac{\tilde{\omega}^2}{\omega_s^2})\xi_g+\frac{\tilde{\omega}^3}{\omega_s^3}\frac{\bar{s}^3\bar{m}c_s}{128\bar{h}r}\left[\frac{(2-\nu)^2}{\bar{h}^2k_x^2(1+\mathrm{D})^2}c_x+\frac{9(1-\nu)^2}{k_\phi^2(1+2.3D+0.58D^3)^2}c_\phi\right] \tag{35}$$

$*D=\frac{E}{r}$: the degree of embedment.

With $b=\frac{2}{1+D}=2$ for the case of a surface rigid base $(D=0)$, $\alpha=\frac{c_p}{c_s}$ and ν is the Poisson's ratio of the soil.

Eqs. (34) and (35) are the new analytical formulas that we propose, which allow for calculating the equivalent frequency and the

equivalent damping of the soil-structure system based on impedance functions dependent on the frequency.

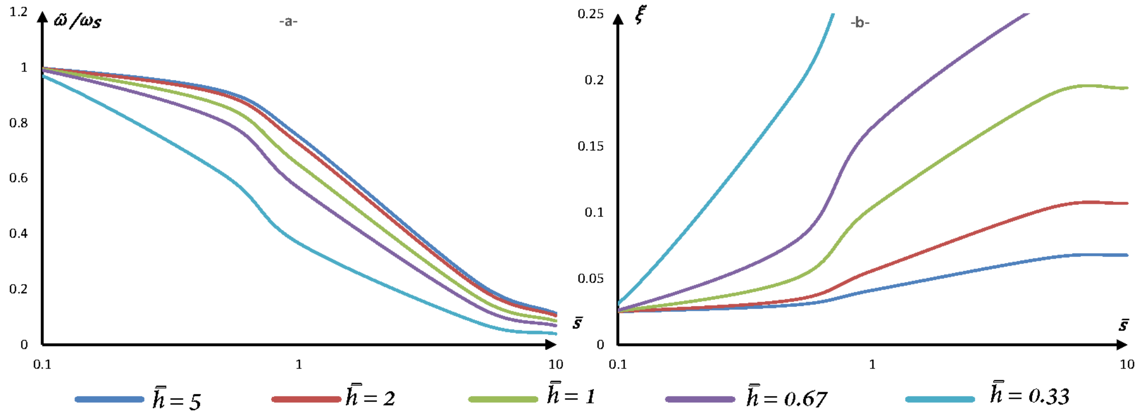
3. Parametric analysis and results

The problem considered in this work consists of a structure $(\xi=0.025)$ on a half-space represented in a simplified way as an SDOF system in all of the SSI models. Soil properties are described by Poisson's ratio $\nu=0.33$ and material damping $\xi_g=0.05$. The superstructure and the ground were modeled linearly. This work aims to evaluate the influence of considering and neglecting the SSI and the effect of impedance function form on the structural response of the soil-structure system by using springs and dashpots with two frequencies cases: independent (static impedance function) and dependent frequencies (dynamic impedance function). The slenderness ratio, the mass ratio, the shear wave velocity of the soil, and several other parameters are the essential parameters that are considered in this parametric analysis (Wolf 1985).

3.1 Natural frequency and damping of the soil-structure system

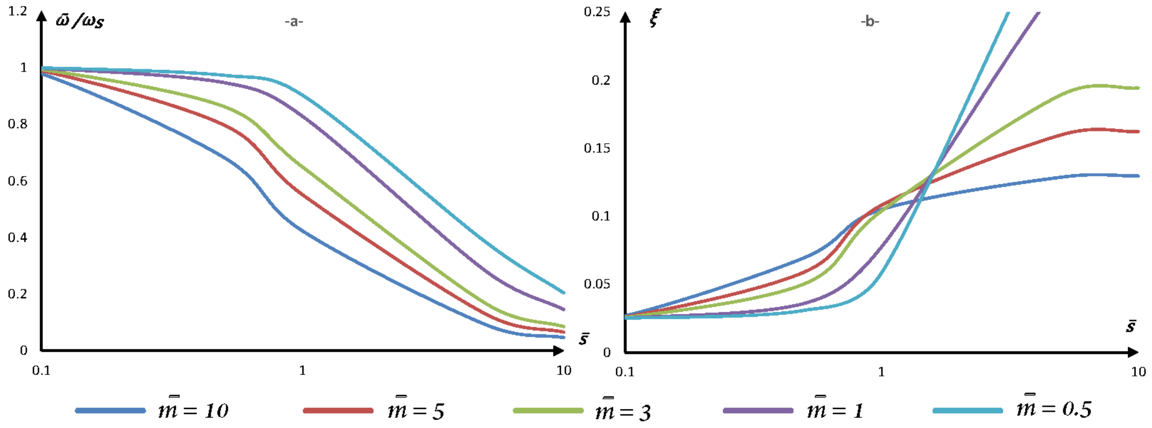
3.1.1 Case of frequency-Independent expression

The proprieties of the equivalent one-degree-of-freedom system $\tilde{\omega}/\omega_s$ and $\tilde{\xi}$ are plotted in Figs. 2-3 as a function of $\bar{s}$ (=0.1, …,10), while varying the slenderness ratio ($\bar{h}$) and the mass ratio ($\bar{m}$). It is noted that the ratio $\tilde{\omega}/\omega_s$ (Figs. 2-3(a)) decrease monotonically with the decrease of $\bar{h}$ and the increase of both $\bar{s}$ and $\bar{m}$. Regarding the effective damping ratio (Fig. 2(b)), an apparent increase is observed with the increasing value of $\bar{s}$ due to the effect of a large amount of radiation damping (mainly in the horizontal direction) applied over the entire range. it is found that $\tilde{\xi}$ is larger for squat structures (small $\bar{h}$) than for slender structures (large $\bar{h}$). Interestingly, contrary to the variation of $\bar{h}$, in the variation of $\bar{m}$, (Fig. 3(b)), at the lower frequency ratio range $(\bar{s}<1)$, the magnitude of $\tilde{\xi}$ increases with increasing mass ratio ($\bar{m}$), and at the higher frequency ratio $(\bar{s}>1)$ (softer soil), $\tilde{\xi}$ increases with increasing mass ratio ($\bar{m}$), while at the higher frequency ratio $(\bar{s}>$



(a) natural frequency (b) damping

Fig. 2 Properties of equivalent one degree of freedom system ($\bar{m}$=3, ν=0.33, ξ=0.025, ξ_g=0.05), varying slenderness ratio $\bar{h}$



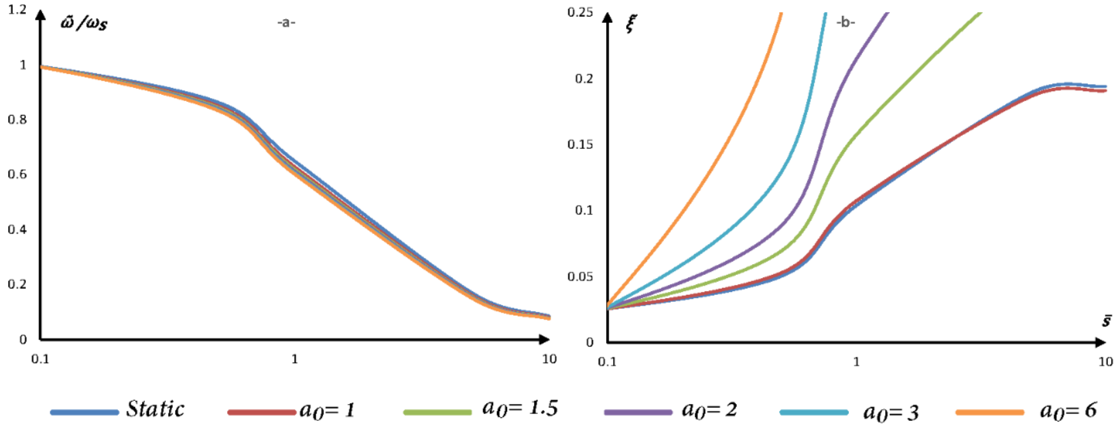
(a) natural frequency (b) damping

Fig. 3 Properties of equivalent one degree of freedom system ($\bar{h}$=1, ν=0.33, ξ=0.025, ξ_g=0.05), varying mass ratio $\bar{m}$

1) (softer soil), $\tilde{\xi}$ increases with decreasing the mass ratio ($\bar{m}$) (the prevalent role of the soil), (Lin *et al*. 2008).

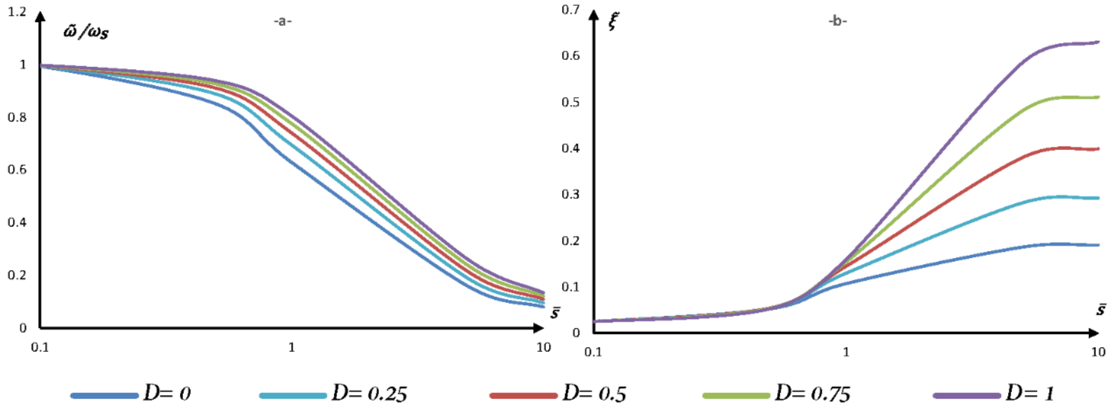
3.1.2 Case of frequency-dependent expressions

Similarly, for frequency-dependent expressions, equivalent system parameters are plotted as $\tilde{\omega}/_{\omega_s}$ and $\tilde{\xi}$ for $\bar{s} = (^{\omega_s h}/_{c_s})$, in Fig. 4, we varied the dimensionless circular frequency a_0(=1, 1.5, 2, 3, 6) too. We observe that SSI effects and frequency-dependent impedance functions combined lead to an increased value of change in results compared to the static case (the frequency-independent parameters). We note that the dimensionless circular frequency a_0 greatly influences the equivalent-damping coefficient of the soil- structure system, but has little influence on the equivalent natural frequency of the system. However, similar trends are observed compared



(a) natural frequency (b) damping

Fig. 4 Properties of equivalent one degree of freedom system ($\bar{h}$=1, $\bar{m}$ =3, ν=0.33, D=0, ξ=0.025, ξ_g=0.05), varying the dimensionless circular frequency a_0



(a) natural frequency (b) damping

Fig. 5 Properties of equivalent one degree of freedom system ($\bar{h}$=1, $\bar{m}$=3, ν=0.33, ξ=0.025, ξ_g=0.05, a_0 = 1), varying the anchoring height D

to the case of the frequency-independent expression (static impedance function) with different values, this resemblance was due to the prevalent role of the soil in the structure response (Çelebi *et al.* 2012).

The influence of the foundation anchoring height D on the properties of the equivalent system was also considered (see Fig. 5). We find that the anchoring height of the foundation D significantly influences the equivalent damping ratio and the equivalent natural frequency of the system (i.e., the structure and the soil). Wherewith its increase (D) we note an increase in the equivalent damping coefficient and a decrease in the equivalent natural frequency of the system compared to the case of a surface rigid base ($D = 0$). This is due to the increase in the contact surface between the foundation and the ground, where the embedment enhances the stiffness of the foundation substantially. results are similar to those obtained by Ahmad and Rupani (1999) when studying the dynamic response to horizontal excitation of a rigid square footing in a two-layer soil profile by using an advanced BEM algorithm, where they find that when the embedment ratio, $^{D}/_{B}$, and the sidewalls to soil contact ratio, $^{d}/_{D}$, are both raised, the horizontal impedance increases in general.

On other hand, it has been shown that in all cases, the increase in adimensional frequency $\bar{s}$ (c_s small, soft soil) (Fay 2010) also significantly affects the two equivalent parameters ($^{\tilde{\omega}}/_{\omega_s}$ and $\tilde{\xi}$). We notice a clear decrease in the frequency ratio, often departs from the unit value and a clear increase in the equivalent-damping ratio. The nonzero value of the latter at a very low value of stiffness ratio of the soil ($\bar{s}$=0.1) denotes the presence of hysteretic dissipation of the structure (assumed to be 2.5%), and for a significant soil-structure-interaction effect, the ratio $\tilde{\xi}$ essentially converges to the material damping ratio of the soil $\xi_g = 0.05$. The few small undulations observed in the curves are the result of resonance phenomena in the soil-structure system.

Based on the above results, the effect of SSI in this part is summarized by shifting the fundamental frequency of the system to lower frequencies (resulting in an increase in the natural period) and by increasing the dissipation energy in the ground compared to the fixed base structure, especially as the ground becomes softer (Farghaly and Ahmed 2013, Sobhi and Far 2021). Additionally, it is noted that the characteristics and parameters of both the soil and structure, have a very important influence on this phenomenon. These results are in agreement with those described in the literature on the SSI effect (Crouse and McGuire 2001, Forcellini *et al.* 2022) and in major design codes (FEMA 440, ATC-3-06). On the other hand, as widely observed by many researchers (Guellil *et al.* 2017, Maria Rossella Massimino *et al.* 2019, Veletsos and Meek 1974), who are interested in the study of the effects of soil-structure interaction on impedance functions and structural response of the soil-foundation-structure (SSFS) system, soil characteristics and structural parameters, particularly shear wave velocity and layer thickness, structure height, and foundation radius, have a considerable impact on the impedance functions and, at the same time, the response of the coupled system.

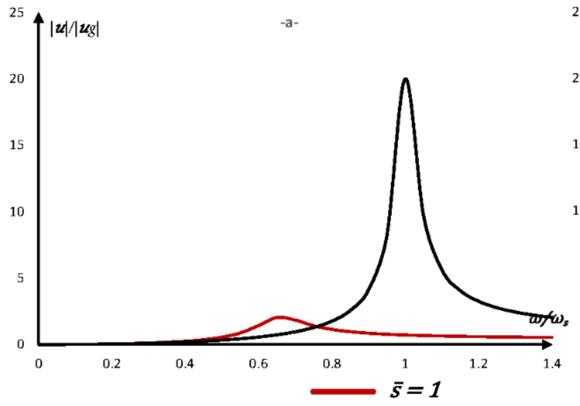
As a consequence, the alteration of the structure's fundamental dynamic characteristics due to the SSI effect must be taken into consideration during structural design to avoid resonance effects, thus making the analysis more realistic.

3.2 Relative and absolute displacement of the structure

In Figs. 6-8 below, the variations in structure displacement (not dimensioned with u_g) are illustrated for $\bar{s} = 1$ and $\bar{s} = 0$ relative to the dimensionless excitation frequency $^{\omega}/_{\omega_s}$(= 0 … 1.4). This is derived from Eq. (17), Eq. (20), and Eq. (21) employing two approximations, one frequency-independent and the other frequency-dependent, for the visco-linear behavior of the soil at rigidity $\bar{\mathrm{s}} = 0$ (rigid ground, $\mathrm{c_s} = \infty$). Essentially, this pertains to a scenario of a structure with a fixed base (or $\tilde{\xi} = \xi$, $\tilde{\omega} = \omega_s$ and $\tilde{u}_g = u_g$). Notably, the response considering soil-structure interaction ($\bar{s} = 1$) always differs from that of the same structure on rigid soil.

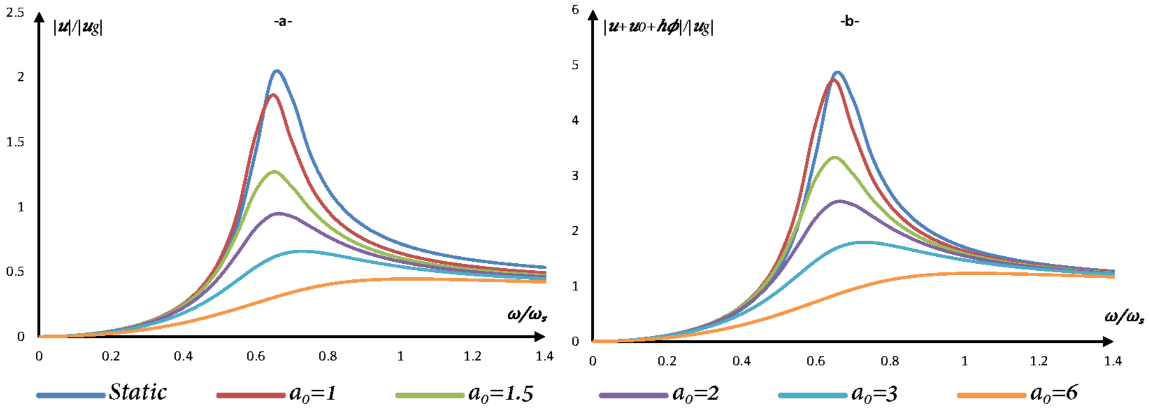
3.2.1 Case of frequency independent expressions

It is very interesting to observe how the displacement of the structure was strongly influenced by the presence of the soil, where SSI had a beneficial effect because it reduces the maximum response (Veletsos and Damodaran Nair 1974). Naturally, this is attributable to an increase in the effective damping of the whole system related to the effect of soil-structure interaction. This leads



(a) structural distortion (b) displacement of mass relative to free field

Fig. 6 influence of soil-structure interaction as a function of excitation frequency ($\bar{m}$ =3, $\bar{h}$=1, ν=0.33, D=0, ξ=0.025, ξ_g=0.05)



(a) structural distortion (b) displacement of mass relative to free field

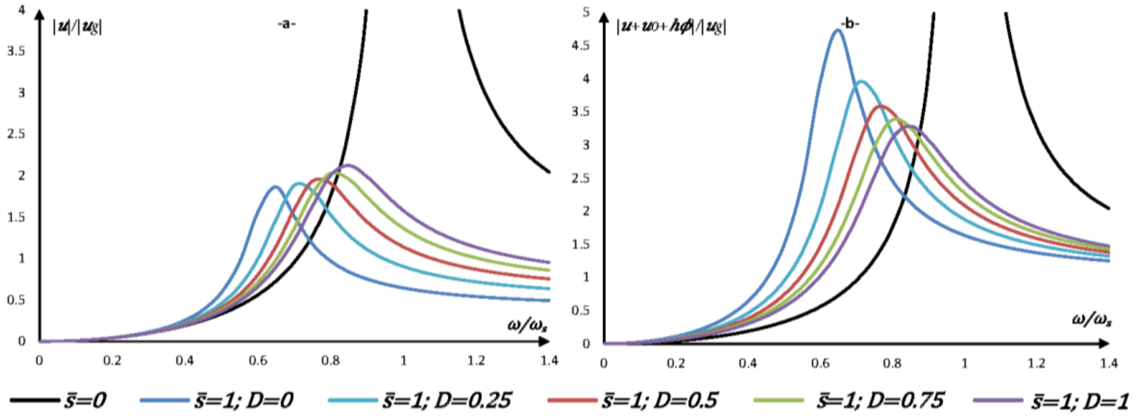
Fig. 7 Influence of soil-structure interaction as a function of excitation frequency ($\bar{m}$ =3, $\bar{h}$=1, ν=0.33, D=0, ξ=0.025, ξ_g=0.05), varying a_0

us back to the soil's fundamental function. However, it is important to stress that in several cases SSI has been shown to have a detrimental effect (Karatzetzou and Pitilakis 2018, Rovithis *et al.* 2017). From Fig. 6 its clear that the interaction effect is negligible for extremely small and very large $^{\omega}/_{\omega_s}$ ratios.

3.2.2 Case of frequency dependent expressions

In Figs. 7-8, we have calculated the displacements with the form of frequency-dependent expression, where we have varied the adimensional circular frequency $a_0 = (1, 1.5, 2, 3, 6)$ (see Fig. 7) and the anchoring height D of the foundation (Fig. 8) as a function of the excitation frequency $^{\omega}/_{\omega_s}$ for $\bar{s} = 1$.

We note that increasing the foundation anchoring height, D, not only reduces the structural distortion or increases the mass displacement (Moghaddasi *et al.* 2011), but also shifts the



(a) structural distortion (b) displacement of mass relative to free field

Fig. 8 Influence of soil-structure interaction as a function of excitation frequency ($\bar{m}$ =3, $\bar{h}$=1, ν=0.33, ξ=0.025, ξ_g=0.05 a_0=1, c_s=1), varying the anchoring height D

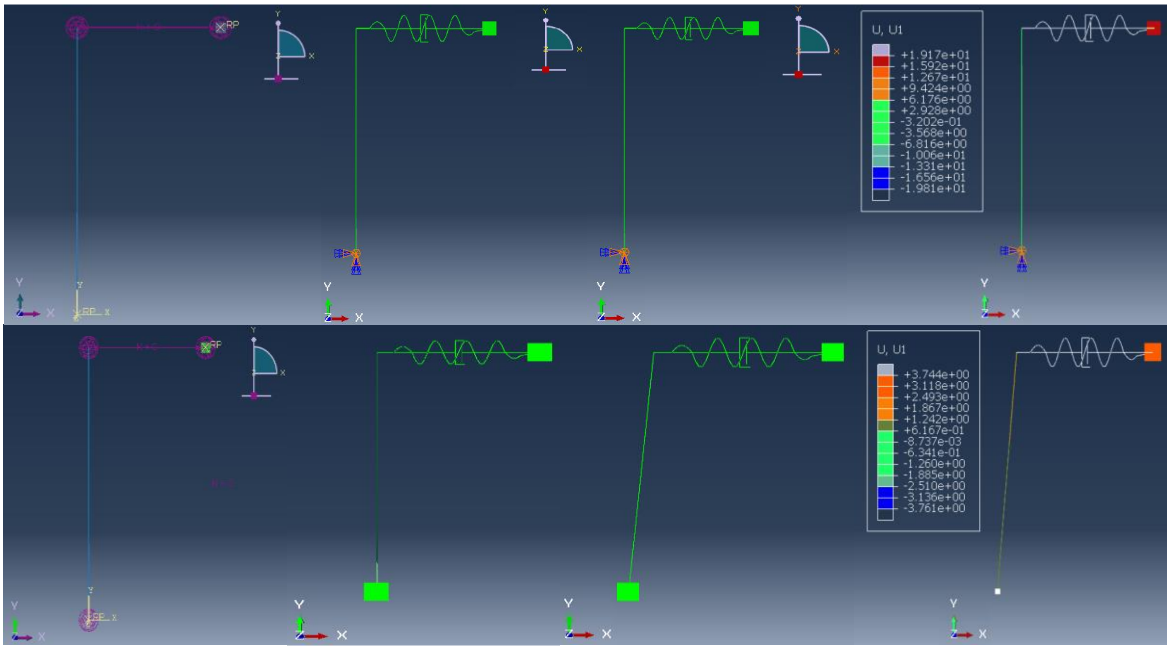
frequency to the right. However, the effect of the adimensional circular frequency, a_0, is larger than that of the foundation anchoring height, it decreases the structural distortion and the displacement of the mass with its increase, and expands the frequency content. This general pattern is typical of infinite domains and applies to them as well. As the frequency rises, K^d decreases and C increases, which explains the decrease in displacements (Wen *et al.* 2002).

Furthermore, the frequency-dependent expressions seem to mainly affect the amplitude of the dynamic response of the structure compared to the case of the frequency-independent expressions (static impedance function), while the shape of the curves remains the same and the peak is at the same frequency. In other words, the damping in the system is larger when a frequency-dependent impedance function is considered (Far and Flint 2017, Maheshwari and Sarkar 2011, Zhang and Tang 2009). However, in the low-frequency range, the structural distortion and the displacement of the mass do not deviate from the static case.

3.3 Comparative study/ comparison between the analytical and numerical results

In addition to the analytical results that we have carried out in this paper to study the effect of the soil-structure interaction on the dynamic response of structures to earthquake excitation, we also carried out a numerical analysis, where we have simulated numerically the dynamic response of a full-coupled soil-structure system by 2D finite element modeling using ABAQUS software. considering and neglecting the SSI by using two different expression forms to estimate the stiffness and damping parameters of the soil (Static parameters “Frequency independent impedance function”, Dynamic parameters “Dependent frequency impedance function”). The structure is modeled as a mass, a spring, and a rigid bar, and the soil-foundation compliance is modeled using appropriate elastic springs and dashpot elements.

The comparisons of the numerical data (dotted line) (see Fig. 9) with the predictions obtained by an analytical formulation based on the dynamic equilibrium of the soil-structure system modeled by an analog model with three degrees of freedom showed in general a very good agreement between the analytical and numerical results. A slight deviation is observed at some



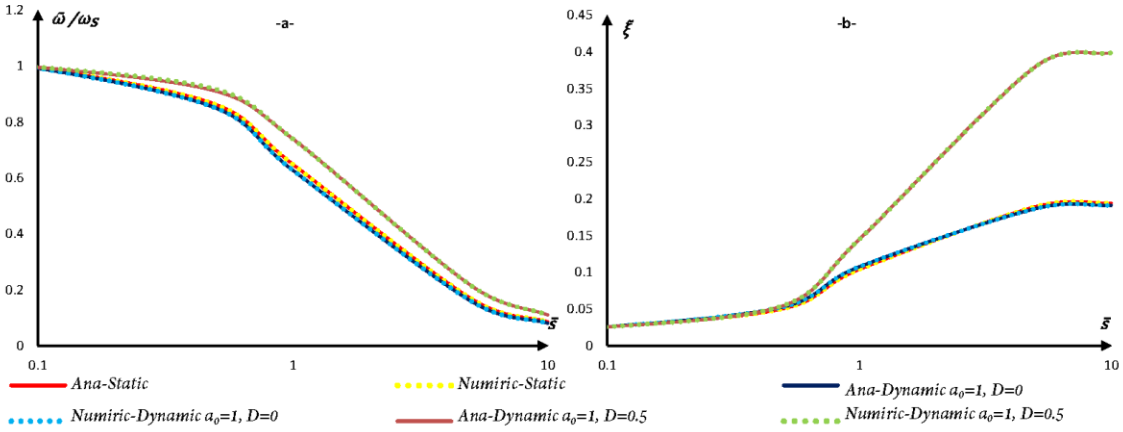
Representation of Abaqus model

frequency which may be related to the computational approximation. However, the differences found were very small, this is a significant computational advantage for the designer who wishes to take into account the interaction of the ground, without adopting long and difficult procedures. The numerical results obtained in this part and the comparisons between all the various cases studied show good agreement with most of the results in the literature (Bolisetti 2015, Farghaly and Ahmed 2013, Raychowdhury 2009, Chaker *et al.* 2017, 2018, 2024).

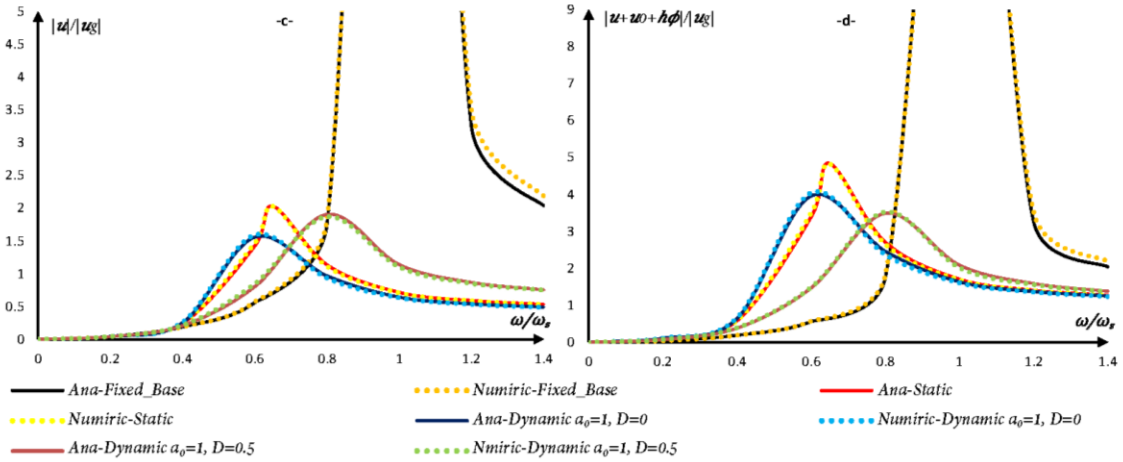
4. Conclusions

The objective of this work is to present an effort towards a comprehensive and systematic investigation of the effects of SSI on the seismic response of structures, and to highlight the different parameters that affect this phenomenon. Two different approaches are used in this study: the first one is an analytical formulation based on the dynamic equilibrium of the soil-structure system, and the second is a numerical analysis generated with 2D finite element modeling using ABAQUS software. The key findings from these analyses can be summarized as follows:

- The presence of soil has clearly altered the dynamic characteristics and seismic response of the structure, and this effect is entirely dependent on the damping radiation of the soil.
- From the observations just mentioned, it is evident that the dynamic response of a structure under a seismic movement, with the consideration of soil-structure interaction, can strongly depend on various factors: the type of soil (c_s), characteristic of structure itself (massive, slender, etc.), the foundation anchoring height D, and frequency of the excitation movement (a_0).



(a) natural frequency (b) damping



(c) structural distortion (d) displacement of mass relative to free field

Fig. 9 Comparative study between the analytical and numerical analysis

*It should be noted that on the following graphs we denote by:

Ana: analytical results (solid line)

Numiric: numerical results (dotted line)

Static: results using the frequency-independent springs and dashpots of the soil

Dynamic: results using the frequency-dependent springs and dashpots of the soil

- For massive and/or taller structures, soft soil, and the frequency content of the excitation, the impact of SSI is more pronounced.
- This document illustrates the differences arising from the form of the impedance function (static or dynamic).
- The incorporation of soil-structure interaction into the structural analysis in this work demonstrates a significant adverse effect on the response and displacement performance of the structure. This effect is characterized by an overestimation of the structure's displacement and a strong dependence on the properties of the soil and the structure.

In conclusion, neglecting the soil-structure interaction effect and/or using approximate representations of impedance functions or different parameters in structural analyses can, in certain circumstances, lead to behavior that diverges significantly from reality. This can consequently misguide engineers' decision-making processes and potentially compromise the seismic safety of buildings.

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