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DYNAMIC CHARACTERISTICS OF STRUCTURES ON PILES AND FOOTINGS

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ABSTRACT

In this paper, novel analytical solutions are presented for single degree-of-freedom (SDOF) oscillators founded on footings and piles on compliant soil. *First*, exact formulas for the fundamental natural period of the above structures, encompassing the frequency dependence of the various impedance terms, are derived. *Second*, closed-form solutions for the corresponding damping coefficients are derived. It is shown that the common approximation of neglecting higher-order terms involving products of damping coefficients is unnecessary and potentially inaccurate for highly-damped soil-structure systems. To address the issue of coupled swaying-rocking oscillations at the pile head, the reference system is translated to the depth below the pile head where the resultant soil reaction to the pile is applied, to ensure a diagonal impedance matrix. *Third*, the amounts of radiation damping generated from a single pile and a footing are compared. To this end, the concept of statically and geometrically equivalent SSI systems is introduced. It is shown that a structure founded on a pile may generate twice the amount of radiation damping of a similar structure on a spread footing. Results are provided in ready-to-use graphs and charts that elucidate the salient features of the problem and can be directly implemented in design. The paper complements and extends the seminal studies in the subject by Parmelee, Veletsos, Bielak and their co-workers.

Keywords: Soil-structure interaction, piles, footings, natural period, radiation damping

INTRODUCTION

Knowledge on the subject of dynamic Soil-Structure Interaction (SSI) has been derived mainly from studies of structures on mat foundations during the last forty years. The seismic response of structures on pile foundations has received considerably less research attention. More importantly, the results of these efforts have not yet lead to established design methods and/or code provisions, such as the simple methods developed for structures on surface foundations (ATC-3, NEHRP-03, EC-8). Therefore much is yet to be learned on the subject before a comprehensive understanding is developed on the role of basic problem parameters on the seismic response of pile-supported systems.

The goals of this article are: (1) to review available methods on the subject with emphasis on the design-oriented solutions by Veletsos and co-workers (1974, 1975, 1977) and Wolf (1985), (2) to present a novel solution for determining the fundamental natural period and effective damping of a simple oscillator supported on a surface foundation, (3) to extend the solution to encompass pile foundations, (4) to present results for typical structural systems on compliant ground, and (5) to compare radiation damping generated from a surface foundation and a pile foundation.

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STRUCTURE ON SURFACE FOOTING

The classical approach for elastodynamic analysis of soil-structure interaction aims at replacing the actual structure by an equivalent simple oscillator supported on a set of frequency-dependent springs and dashpots accounting for the stiffness and damping of the soil medium. This model has been adopted by several researchers, including Parmelee (1967), Veletsos et al (1974, 1975, 1977), Jennings & Bielak (1973), Wolf (1985) and more recently Aviles et al (1996, 1998). A brief overview of available methods leading to closed-form solutions is presented below. Based on these procedures, a novel, accurate and straightforward scheme for analyzing the problem is presented.

Classical Solutions

The system studied is shown in Figure 1. It involves a simple oscillator on flexible base representing a single storey structure, or a multi storey structure after a pertinent reduction of its degrees-of-freedom (e.g., considering that the mass is concentrated at the point where the resultant inertial force acts).

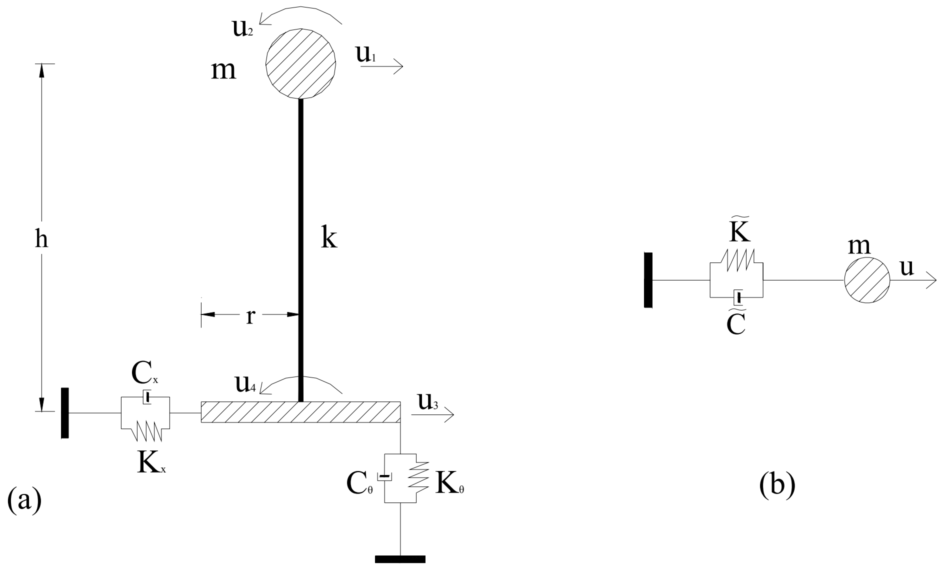


Figure 1. (a) Structure idealized by a stick model, (b) Reduced single degree-of-freedom model

The structure is described by its stiffness k, mass m, height h, and damping ratio ζ, which may be either viscous or linearly hysteretic. The foundation consists of a rigid surface circular footing of radius r resting on a homogeneous, linearly elastic, isotropic halfspace described by a shear modulus G_s, mass density ρ_s, Poisson's ratio ν_s, and hysteretic damping ratio ζ_s. Foundation stiffness is modeled by frequency-dependent springs K_x and K_θ representing stiffness in translational and rocking oscillations, respectively. Following Veletsos & Nair (1974) and to ensure uniform units in all stiffness terms, K_θ is expressed by a translational vertical spring acting at distance r from the center of the footing. Damping is modeled by a pair of dashpots C_x, C_θ, attached in parallel to the springs, representing energy loss due to hysteretic action and wave radiation in the soil medium. In the present formulation, the influence of foundation embedment and foundation mass is neglected.

The dynamic impedance $K^*(\omega)$ along any degree of freedom of the system is defined according to the formula

$$K^*(\omega) = K + i\omega C = K(1 + 2i\zeta) \tag{1}$$

in which K is the real part of the impedance, ωC is the corresponding imaginary part, ω is the cyclic excitation frequency, and i (= $\sqrt{-1}$) the imaginary unity. ζ is an energy loss parameter, which is analogous (yet not identical) to the viscous damping coefficient of a simple oscillator.

$$\zeta(\omega)=\frac{\mathrm{Im}(K^*)}{2\,\mathrm{Re}(K^*)}=\frac{\omega C}{2K} \tag{2}$$

For the model in Figure 1a, the foundation springs and dashpots can be expressed by the formulas proposed by Veletsos & Meek (1974):

$$K_x = a_x K, \qquad K_\theta = a_\theta K \tag{3}$$

$$C_x = \chi_x \frac{Kr}{V_s}, \qquad C_\theta = \chi_\theta \frac{Kr}{V_s} \tag{4}$$

where V_s denotes the propagation velocity of distortional waves in the halfspace and K is the static horizontal stiffness of the foundation defined by

$$K = \frac{8}{2-\nu_s} G_s r \tag{5}$$

α_x, α_θ, χ_x and χ_θ are dimensionless factors that depend on Poisson's ratio for the halfspace material, and the dimensionless frequency

$$\mathrm{a}_0 = \frac{\omega r}{V_s} \tag{6}$$

Under seismic excitation, the system displaces and deflects as shown in Figure 2. The translation of the mass relative to ground is composed of three parts: (1) horizontal translation due to swaying motion of footing u_x, (2) horizontal translation due to rocking motion of footing, u_θ and (3) horizontal deflection of the column, u_c. Based on these definitions, the impedance of the system is defined as:

$$\widetilde{K^*} \equiv \frac{P}{u_x + u_\theta h + u_c} = \widetilde{K}\left(1 + 2i\widetilde{\zeta}\right) \tag{7}$$

where $\widetilde{K}$ and $\widetilde{\zeta}$ denote the apparent stiffness and damping coefficients at elevation h.

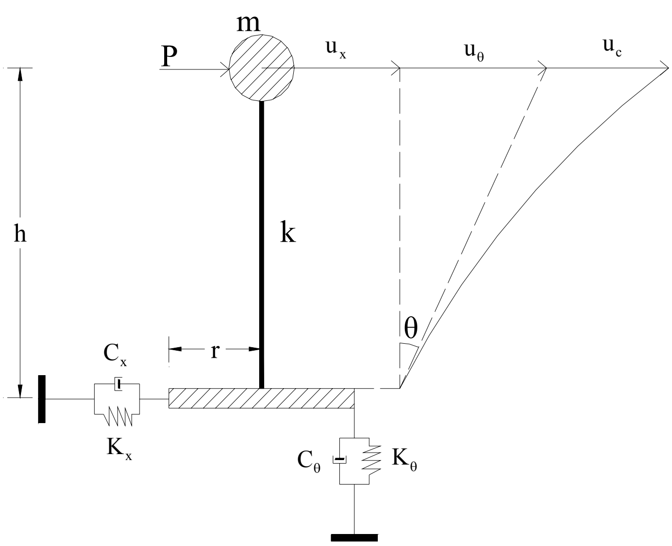


Figure 2. Deflection diagram for soil-structure system

The response of the soil-structure system depends on the mechanical properties of the foundation, the soil, the superstructure and the characteristics of the excitation. These are summarized in the following dimensionless parameters (Veletsos et al 1974, 1975, 1977):

(i) The wave parameter σ

$$\sigma = \frac{V_s}{f_c h} \tag{8}$$

where $f_c = \sqrt{k/m}/2\pi$ denotes the natural frequency of the fixed base structure.

(ii) The relative mass density for the structure and the soil γ

$$\gamma = \frac{m}{\pi \rho_s h r^2} \tag{9}$$

(iii) The damping ratio ζ of the structure for fixed base conditions.
(iv) The slenderness ratio (h/r).
(v) The Poisson's ratio ν_s of the soil.
(vi) The hysteretic damping ratio ζ_s of the soil.

Solution by Veletsos and co-workers (1974, 1975, 1977)

The aim of these solutions is to connect the properties of the soil-structure system ($\tilde{T}$, $\tilde{\zeta}$) with the properties of the fixed base structure (T, ζ), so that the influence of soil-structure interaction on the dynamic behavior of the structure can be elucidated. This connection is expressed by the following pair of equations (Veletsos 1977):

$$\tilde{T} = T\sqrt{1 + \frac{k}{K_x}\left(1 + \frac{K_x h^2}{K_\theta}\right)} = T\sqrt{1 + \left(\frac{2-\nu_s}{2}\right)\frac{\pi^3}{a_x}\frac{\gamma}{\sigma^2 \left(h/r\right)}\left[1 + 3\left(\frac{1-\nu_s}{2-\nu_s}\right)\frac{a_x}{a_\theta}\left(\frac{h}{r}\right)^2\right]} \tag{10}$$

$$\tilde{\zeta} = \tilde{\zeta}_0 + \left(\tilde{T}/T\right)^{-3}\zeta \tag{11}$$

where ζ represents the damping of the structure (assumed to be of viscous nature) and $\tilde{\zeta}_0$ the radiation damping of the footing. The latter is given by (Veletsos and Nair, 1975)

$$\tilde{\zeta}_0 = \frac{\pi^4}{2}\frac{\gamma}{\sigma^3}\left(\tilde{T}/T\right)^{-3}\left\|\left[\frac{(2-\nu_s)\chi_x}{a_x(a_x + i a_0 \chi_x)}\left(\frac{r}{h}\right)^2 + \frac{3(1-\nu_s)\chi_\theta}{a_\theta(a_\theta + i a_0 \chi_\theta)}\right]\right\| \tag{12}$$

The derivation is based on setting the resonant period and peak pseudo-acceleration of the actual elastodynamic system equal to that of an equivalent simple oscillator. More discussion is given below.

Solution by Wolf (1985)

The system considered by Wolf is identical to that shown in Figures 1 and 2. The main difference with the Veletsos approach is that frequency-independent moduli defined by the values $a_x = 1$, $\chi_x = 0.575$, $a_\theta = 0.15$, $\chi_\theta = 0.15$ are adopted for the foundation. Also, the response of the system is determined by directly solving a set of three simultaneous governing equations for degrees of freedom u_1, u_3, and u_4 shown in Figure 1.

The properties of the replacement oscillator in this solution are given by

$$\tilde{\omega}^2 = \omega_c^2 \left(1 + \frac{k}{K_x} + \frac{kh^2}{K_\theta}\right) \tag{13}$$

$$\tilde{\zeta} = \left(\frac{\tilde{\omega}}{\omega_c}\right)^2 \zeta + \left[1 - \left(\frac{\tilde{\omega}}{\omega_c}\right)^2\right] \zeta_s + \left(\frac{\tilde{\omega}}{\omega_x}\right)^2 \zeta_x + \left(\frac{\tilde{\omega}}{\omega_\theta}\right)^2 \zeta_\theta \tag{14}$$

In the above equations, $\omega_\theta = \sqrt{K_\theta r^2 / mh^2}$, $\omega_x = \sqrt{K_x / m}$, $\omega_c = \sqrt{k / m}$ define the uncoupled cyclic natural frequencies of the system under rocking oscillations of the base (superstructure assumed rigid), swaying oscillations of the base, and oscillations of the superstructure (foundation assumed rigid), respectively. Note the simpler form of Eqn (14) as compared to Eqn (12).

Notwithstanding the theoretical significance and practical appeal of the above methods, they both can be criticized on the following important aspects:

(a) Both methods neglect products of damping ratios ($\zeta_i \times \zeta_j$) – as negligible 'higher order' terms. This approximation is questionable for highly-damped soil-structure systems.
(b) The effective damping in the Veletsos approach arises from an approximate procedure leading to an expression containing imaginary terms (Eqn 12). This limits significantly its suitability for practical applications.
(c) Structural damping in the Veletsos solution is strictly of viscous nature.
(d) Frequency dependence of foundation springs and dashpots in the Wolf approach is neglected.
(e) Structural damping in the Wolf solution is strictly of hysteretic nature.
(f) Both solutions employ rather complex procedures involving either "equivalence" of responses of different dynamic systems (Veletsos), or solutions of simultaneous linear equations (Wolf).
(g) In both solutions, foundation mass and rotational inertia are neglected

Proposed exact procedure

In this section a simple exact solution to the problem shown in Figures 1 and 2 is presented. The solution contains no approximations in the derivation of the fundamental natural period and effective damping of the system. Furthermore, the exact frequency-varying foundation impedances may be employed.

Mention has already been made that the total horizontal deflection of the system can be decomposed as sum of the three modular displacements shown in Fig 2, i.e.,

$$u_t = u_c + u_x + u_\theta \tag{15}$$

This implies that the associated compliances can be viewed as complex springs attached in parallel and, thereby, the dynamic impedance of the system can be expressed through the well-known summation rule

$$\frac{1}{\tilde{K}^*} = \frac{1}{K_x^*} + \frac{1}{K_\theta^*}\left(\frac{h}{r}\right)^2 + \frac{1}{k^*} \tag{16}$$

in which the associated impedances are complex valued and frequency dependent. Substituting each complex impedance term in Eq. (16) by its representation according to Eq. (1) yields the exact damping and natural frequency of the system as (Maravas, 2006)

$$\tilde{\zeta} = \frac{\dfrac{\zeta_x}{\omega_x^2\left(1+4\zeta_x^2\right)} + \dfrac{\zeta_\theta}{\omega_\theta^2\left(1+4\zeta_\theta^2\right)} + \dfrac{\zeta}{\omega_c^2\left(1+4\zeta^2\right)}}{\dfrac{1}{\omega_x^2\left(1+4\zeta_x^2\right)} + \dfrac{1}{\omega_\theta^2\left(1+4\zeta_\theta^2\right)} + \dfrac{1}{\omega_c^2\left(1+4\zeta^2\right)}} \tag{17}$$

$$\tilde{\omega}^2 = \left[\frac{1+4\tilde{\zeta}^2}{\omega_x^2\left(1+4\zeta_x^2\right)} + \frac{1+4\tilde{\zeta}^2}{\omega_\theta^2\left(1+4\zeta_\theta^2\right)} + \frac{1+4\tilde{\zeta}^2}{\omega_c^2\left(1+4\zeta^2\right)}\right]^{-1} \tag{18}$$

The above solutions are exact in the sense that no approximations apart from those involved in numerically evaluating the foundation impedances are employed. Given the frequency-dependent nature of foundation impedances, an iterative procedure is generally required to determine ζ and ω from these solutions (Veletsos & Nair 1974). Note that omitting the products ζ_i^2, the above formulas duly reduce to those in Eqns (14) and (13), respectively.

Parametric analysis and comparisons with classical methods

Comparative graphs for the variation of the ratio $\tilde{T}/T$ (inverse of $\tilde{\omega}/\omega_c$) and the effective damping of the system $\tilde{\zeta}$ versus the slenderness ratio h/r are presented in Figure 3. Using the proposed exact procedure, the influence of the relative mass ratio γ and the material hysteretic damping ratio ζ_s on the period and effective damping of the soil-structure system is presented in Figure 4. For the parametric analysis, values of factors α_x, α_θ, χ_x and χ_θ correspond to a Poisson's ratio of 0.45.

It is evident from Figures 3(a,b) that the results from the method of Veletsos are in relative agreement with those obtained by the proposed exact procedure. Also in Figures 3(c,d), we observe that results from the method of Wolf are quite different from those of the proposed procedure. This is mainly due to the assumption of frequency-independent springs and dashpots adopted by Wolf.

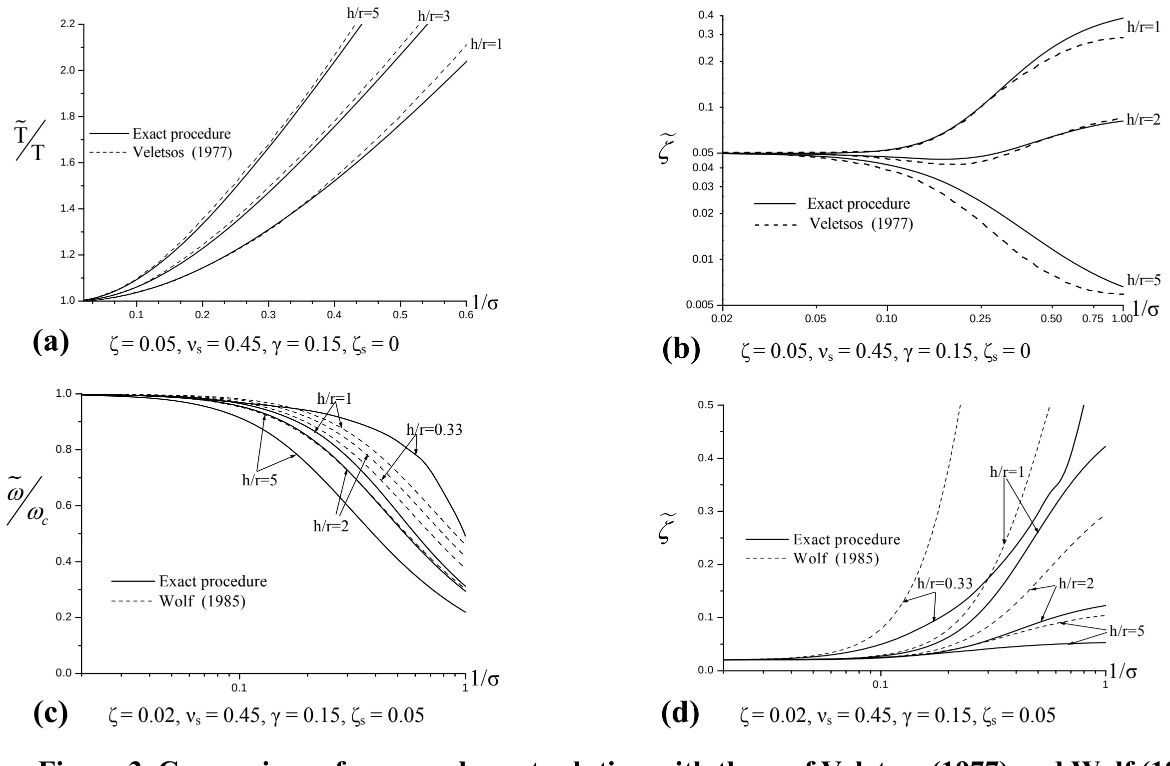


Figure 3. Comparison of proposed exact solution with those of Veletsos (1977) and Wolf (1985)

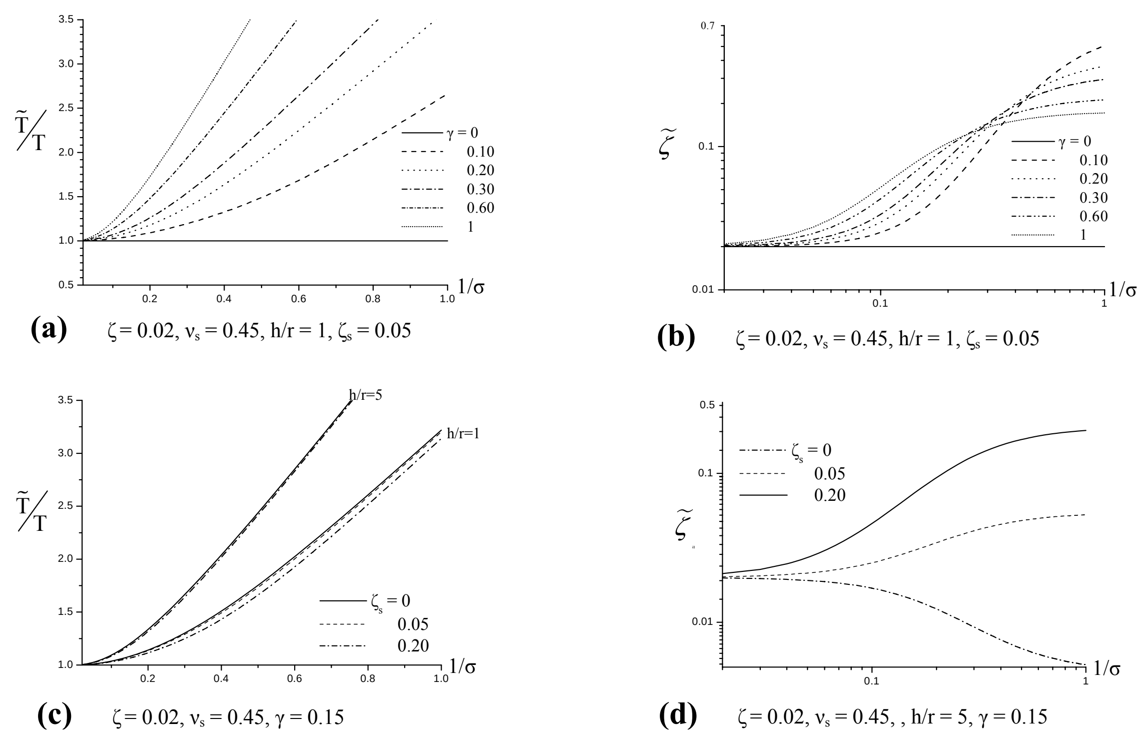


Figure 4. Parametric results using the proposed exact procedure. (a) Period of SSI system as function of γ, (b) Effective damping of SSI system as function of γ, (c) Period of SSI system as function of soil damping ratio ζ_s, (d) Effective damping of SSI system as function of ζ_s

The above observation is justified by the fact that for low values of ratio 1/σ (i.e., low values of ω_c) the results of the two methods are nearly identical. It is also apparent that the results obtained by Wolf lose accuracy with decreasing values of h/r.

Figures 4(a,b) show that the variation in relative mass ratio γ affects significantly the period and damping of the soil-structure system. More specifically, increasing γ leads to more flexible systems and higher values of damping ratio. The hysteretic damping ratio of soil ζ_s, does not affect much the system period, especially for tall structures (h/r=5), as shown in Figure 4(c). On the other hand, it affects considerably the effective damping of the system, as shown in Figure 4(d).

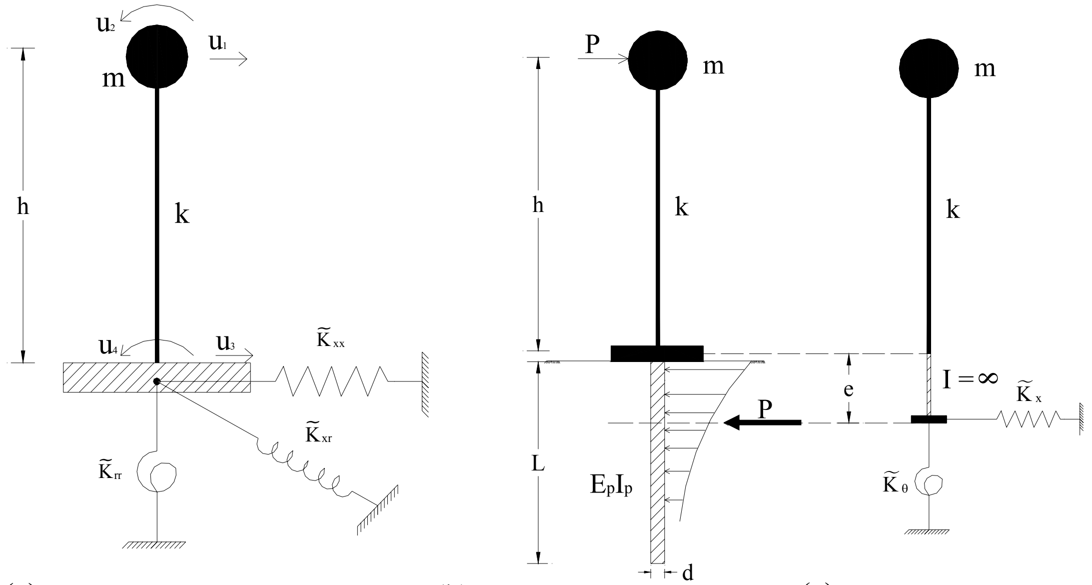
STRUCTURE ON PILE FOUNDATION

The case of a structure on a single pile foundation is investigated next. The problem is treated using a variance of the method for spread footings presented in the previous section. The amounts of energy radiated by a pile- or a footing-supported structure are compared via by the concept of "statically equivalent" SSI systems, introduced in this work

Soil-pile-structure system and method of analysis

The system studied is shown in Figure 5. It consists of the linear elastic SDOF structure described in previous section, founded on a single flexible, circular solid pile of Young's modulus E_p, diameter d, mass per unit length m_p, and length L, which is considered to be greater than the pile effective length L_e. Accordingly, the pile can be considered infinitely long. The soil is considered a linearly elastic homogeneous, isotropic halfspace, as described above.

Soil-pile system can be represented by three dynamic impedances K_{xx}^*, K_{rr}^*, and K_{xr}^*, corresponding to swaying, rocking, and cross-swaying-rocking of the pile head, respectively. In this study, analytical expressions for the dynamic impedances are used, as derived by Novak, (1974) and Mylonakis (1995)



(a) (b) (c)

Figure 5. (a) Model of pile-supported-structure, (b) Distribution of soil reactions due to horizontal loading, (c) Reduced model with two dynamic impedances

$$K_{xx}^* = 4E_pI_p\lambda^3, \quad K_{xr}^* = 2E_pI_p\lambda^2, \quad K_{rr}^* = 2E_pI_p\lambda \tag{19}$$

$$\lambda = \left[\frac{k_x - m_p\omega^2 + i\omega c_x}{4E_pI_p}\right]^{1/4} \tag{20}$$

where λ is a wave number parameter, I_p is the moment of inertia of the pile cross section, and k_x and c_x are the moduli of distributed springs and dashpots along the pile used to model soil reaction. The latter are given by

$$k_x = \delta E_s, \quad c_x = 6\mathrm{a}_{\mathrm{op}}^{-1/4}\rho_s V_s d + 2\frac{\zeta_s k_x}{\omega} \tag{21}$$

where $a_{op}=2a_o$ (where the footing radius r in Eq. (6) is replaced by the pile diameter d) and δ is the dimensionless Winkler factor, given as function of pile-soil stiffness ratio E_p/E_s (Dobry et al, 1982)

$$\delta = 1.67\left(\frac{E_p}{E_s}\right)^{-0.053} \tag{22}$$

Under horizontal loading the soil reacts in the manner shown in Figure 5(b). The resultant of the distributed reactions is applied at depth e below the pile head. Since the reference system is anchored at the pile head, a cross swaying-rocking impedance term $\widetilde{K}_{xr}$ is necessary for modeling the compliance of the foundation. This term is not compatible with the analysis of the spread footing presented earlier. In order to overcome this problem, the reference system can be translated to a depth e, where the total soil reaction is applied. In this manner, the cross impedance K_{xr}^* vanishes and the impedance matrix of the pile becomes diagonal, as shown in Figure 5(c). This transformation is approximate, as it requires the pile to be rigid between the depths z = 0 and z = e. However, this introduces little error, since e is usually small compared to the overall pile length. The transformed impedances K_{xxe}^* and K_{rre}^* are given by the expressions

$$K_{xxe}{}^{*} = K_{xx}{}^{*}, \quad K_{rre}{}^{*} = K_{rr}{}^{*} - 2K_{xr}{}^{*}\,e + K_{xx}{}^{*}\,e^{2}, \quad K_{xre}{}^{*} = 0 \tag{23}$$

where

$$e = \frac{K_{xr}{}^{*}}{K_{xx}{}^{*}} = \frac{1}{2\lambda} \tag{24}$$

is the aforementioned eccentricity.

The transformation shown in Figure 5(c) allows the usage using the exact procedure developed for the analysis of structures on surface footings. Thus, the natural frequencies ω_i of the soil-pile-structure system required by Eqs. (17) and (18)) are computed by Maravas (2006) as

$$\omega_x = \sqrt{\frac{K_{xx}}{m}}, \; \omega_\theta = \sqrt{\frac{K_{rr}}{m(h+e)^2}} \tag{25}$$

where

$$K_{xx} = \left(4E_p I_p\right)^{1/4} \left[\left(k_x - m_p\omega^2\right)^2 + \left(\omega c_x\right)^2\right]^{3/8} \cos\left(\frac{3}{4}\phi\right) \tag{26}$$

$$K_{rr} = \frac{1}{4}\left(4E_p I_p\right)^{3/4} \left[\left(k_x - m_p\omega^2\right)^2 + \left(\omega c_x\right)^2\right]^{1/8} \cos\left(\frac{1}{4}\phi\right) \tag{27}$$

$$\phi = Arc\tan\left(\frac{\omega c_x}{k_x - m_p\omega^2}\right) \tag{28}$$

The corresponding damping ratios ζ_i are given by the expressions (Maravas 2006)

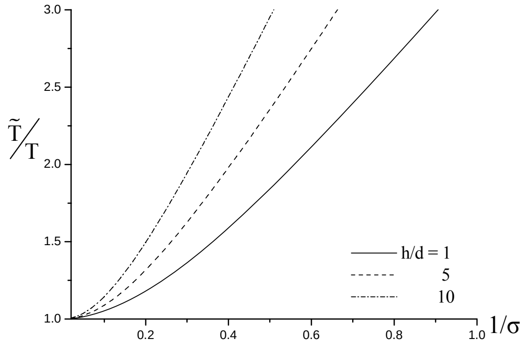
$$\zeta_x = \frac{1}{2}\tan\left(\frac{3}{4}\phi\right), \quad \zeta_\theta = \frac{1}{2}\tan\left(\frac{1}{4}\phi\right) \tag{29}$$

in which ϕ is defined by Eq. (28).

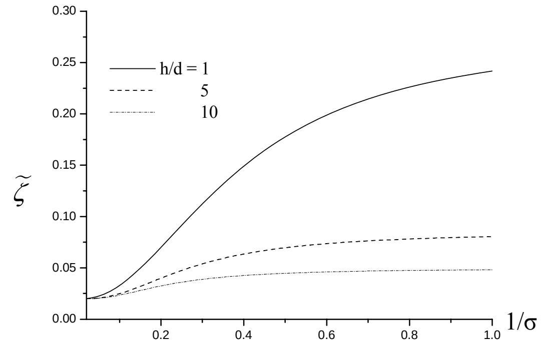
Results of Parametric Analyses

The response of the soil-pile-structure system depends on the properties of the pile, the supporting soil, the superstructure and the excitation. These properties are included in above dimensionless parameters, as in the case of the structure supported on surface footing.

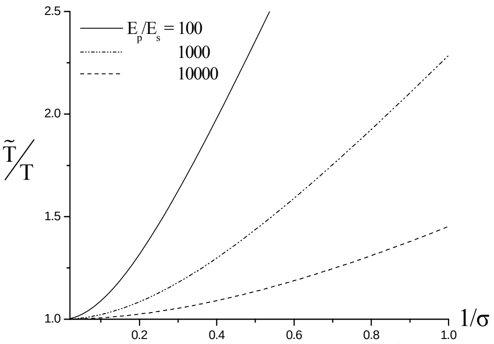
In Figure 6, results obtained with the use of the proposed exact procedure are presented. Specifically, Figure 6(a) presents the influence of the slenderness ratio (h/d) on the natural period of the interacting system. Evidently, the behavior is similar to the behavior of the soil-footing-structure system presented earlier. The same observation holds for the effective damping, as shown in Figure 6(b).
The influence of pile-soil stiffness ratio E_p/E_s, on the properties of the system is significant, as shown in Figures 6(c,d). For relatively flexible piles (low values of E_p/E_s), the soil-pile-structure system is more flexible and dissipates larger amounts of energy.



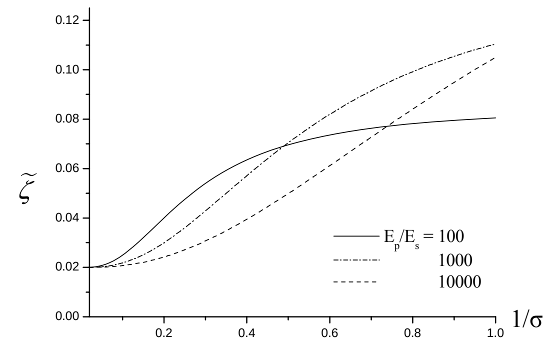
(a) $\zeta = 0.02$, $\nu_s = 0.45$, $\gamma = 0.15$, $\zeta_s = 0.05$, $\rho_p/\rho_s = 1.40$, $E_p/E_s = 100$



(b) $\zeta = 0.02$, $\nu_s = 0.45$, $\gamma = 0.15$, $\zeta_s = 0.05$, $\rho_p/\rho_s = 1.40$, $E_p/E_s = 100$



(c) $\zeta = 0.02$, $\nu_s = 0.45$, $\gamma = 0.15$, $\zeta_s = 0.05$, $\rho_p/\rho_s = 1.40$, $h/d = 5$



(d) $\zeta = 0.02$, $\nu_s = 0.45$, $\gamma = 0.15$, $\zeta_s = 0.05$, $\rho_p/\rho_s = 1.40$, $h/d = 5$

Figure 6. (a) System period as function of h/d, (b) System damping as function of h/d. (c) System period as function of E_p/E_s, (d) System damping as function of E_p/E_s

Comparison of the two SSI systems

In this section, the concept of statically and geometrically equivalent interacting systems is introduced, in an effort to compare the damping of systems on pile or surface footing foundations. To achieve this, the lateral stiffness of the two SSI systems should be comparable at the elevation of mass m. Accordingly, the two systems are geometrically equivalent, i.e., h/d=h/2r, if the ratio of Young's moduli for the soil (Maravas 2006):

$$\frac{E_s^{(f)}}{E_s^{(p)}} = \frac{1}{2}\left(\frac{\pi\delta^3}{16}\right)^{1/4}\left(\frac{E_p}{E_s^{(p)}}\right)^{1/4} \frac{(2-\nu_s)(1+\nu_s)\left[1+4\left(h/d\right)^2\right]}{1+\left[1+2\left(\frac{16\delta}{\pi}\right)^{1/4}\left(\frac{E_p}{E_s^{(p)}}\right)^{-1/4}\frac{h}{d}\right]} \tag{30}$$

In the above equation, symbol f denotes "footing" and symbol p "pile". Because a pile is much stiffer than a footing, the supporting soil of the footing must have a modulus of elasticity $E_s^{(f)}$ quite larger than the modulus of elasticity of the soil around a pile $E_s^{(p)}$.

Using the proposed exact procedure, the effective damping of the two SSI systems is compared for different ratios h/d and E_p/E_s, as shown in Figures 7a and 7b. Furthermore, comparative graphs of radiation damping for the two foundation types are presented in Figures 7c and 7d. It is obvious that a structure on a pile may experience as much as three times the amount of damping generated from the same structure on a spread footing (Figure 7a). This observation is justified in view of the tow-dimensional nature of wave propagation around a pile, which results to much higher energy dissipation.

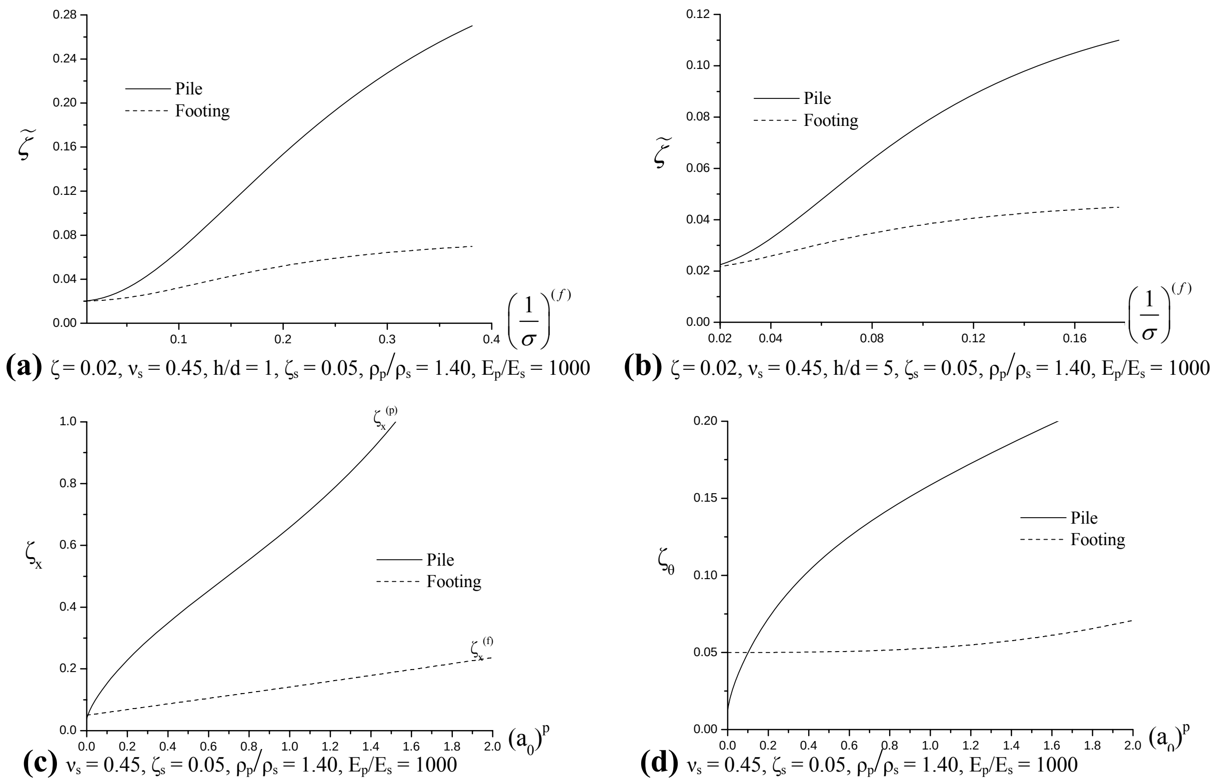


Figure 7. (a, b) Effective damping of a structure founded on pile and footing, (c) Radiation damping of a pile and footing due to translational oscillation, (d) Radiation damping of a pile and footing due to rocking oscillation

CONCLUSIONS

A novel analytical procedure for determining the dynamic characteristics of simple structures founded on surface footings and piles was presented. Using the proposed methodology, the influence of common assumptions on the computation of the mechanical properties of such systems was elucidated. Results were provided in ready-to-use graphs and charts that elucidate the salient features of the problem and can be directly implemented in design. By introducing the concept of statically and geometrically equivalent SSI systems, the amounts of radiation damping generated from a single pile and a footing were compared.

The main conclusions of the study are:

(1) The proposed solution is simpler, more accurate, and more general than the classical methods by Parmelee, Veletsos, Bielak, Wolf and co-workers.

(2) The common approximation of neglecting higher-order terms involving products of damping coefficients may be inaccurate for highly-damped SSI systems.

(3) The proposed analysis can easily incorporate embedded foundations, by translating the reference system to the depth below the surface where the resultant soil reaction is applied. This ensures a diagonal foundation impedance matrix and greatly simplifies calculations.

(4) A structure founded on a pile may generate 100% more radiation damping than a similar structure on a spread footing. The difference gets more pronounced with high-frequency, squatty structures on stiff soil.

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