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Simplified discrete systems for dynamic analysis of structures on footings and piles

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ABSTRACT

A simplified discrete system in the form of a simple oscillator is developed to simulate the dynamic behavior of a structure founded through footings or piles on compliant ground, under harmonic excitation. Exact analytical expressions for the fundamental natural period and the corresponding damping coefficients of the above system are derived, as function of geometry and the frequency-dependent foundation impedances. In an effort to quantify the coupling between swaying and rocking oscillations in embedded foundations such as piles, the reference system is translated from the footing–soil interface to the depth where the resultant soil reaction is applied, to ensure a diagonal impedance matrix. The resulting eccentricity is a measure of the coupling effect between the two oscillation modes. The amounts of radiation damping generated from a single pile and a surface footing are evaluated. In order to compare the damping of a structure on a surface footing and a pile, the notion of static and geometric equivalence is introduced. It is shown that a pile may generate significantly higher radiation damping than an equivalent footing, thus acting as an elementary protective system against seismic action.

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1. Introduction

During the last fifty years, the problem of dynamic soil–structure interaction (SSI) has received considerable research attention. Knowledge on the subject has been derived mainly from studies on the dynamic behavior of structures resting on surface foundations. Some of these studies have become standard references in the area of foundation dynamics, e.g., Richart et al. [1], Parmelee [2], Bielak [3], Veletsos and Wei [4], Veletsos and Verbic [5], Veletsos [6], Luco and Westmann [7,8], Vaish and Chopra [9], Luco [10], Wong and Luco [11,12] and Wolf [13]. It is established that SSI causes significant alterations to the dynamic response of structures supported on deformable soils in comparison to the response of the same structures when considered fixed at their base, mainly by increasing the natural period and damping of the fundamental mode [6,13,14].

The analysis of soil–foundation–structure interaction can be accomplished by various methods, depending on the part of the system that is analyzed. These methods can be classified as: (a) analytical, which usually refer to simple foundation geometries lying on elastic half-space, e.g., Triantafyllidis [15], (b) semi-analytical, that combine analytical formulations for the half-space with numerical procedures e.g., the subdivision of the soil–foundation contact area for solving the mixed boundary value problem by integration of the corresponding surface-to-surface Green's functions used by Vrettos [16] to determine the vertical and rocking response of rigid foundations resting on a non-homogeneous half-space, or usually Finite Element Methods (FEM) for the discretization of the foundation and the structure, e.g., Wong and Luco [12], (c) numerical, usually FEM, e.g., Lysmer et al. [17], Boundary Element Methods (BEM) e.g., Ahmad and Banerjee [18] or a combination of FEM and BEM, e.g., Karabalis and Beskos [19], Gaitanaros and Karabalis [20] employed for the discretization of the soil medium, the foundation and the structure, and (d) simplified discrete models, which allow fast calculation of the foundation–soil–structure system properties, e.g., Veletsos and Meek [21], Dobry and Gazetas [22]. More information on the subject can be found in various sources, e.g., Gazetas [23,24], Karabalis [25], Beskos [26], Wolf [27,28], Mylonakis et al. [29], Stewart et al. [30,31], among others.

This work is focused on the development and use of discrete models, for estimating the dynamic behavior of simple structures resting on an elastic half-space. Discrete models for the analysis of soil–foundation–structure system have been developed by various researchers. One of the earliest such attempts is the one by Lysmer and Richart [32] who derived a single-degree-of-freedom model for computing the vertical dynamic response of foundations connected to an elastic half-space. Luco [10] derived analytical expressions for the dynamic stiffness of circular, long strip and square foundations laying on the surface of a layered elastic half-space. Parmelee [2], Veletsos

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Nomenclature

A. Latin symbols

k	stiffness of structure
m	mass of structure
h	height of structure
f_c	natural frequency of structure in fixed-base condition
T	natural period of structure in fixed-base condition
r	radius of surface footing
V_s	soil shear wave propagation velocity
G_s	soil shear modulus
K_j^*	dynamic impedance of footing along the j^{th} degree of freedom
K_j	real part of dynamic impedance of footing along the j^{th} degree of freedom
C_j	dashpot coefficient representing energy loss due to wave radiation along the j^{th} degree of freedom
a_0	dimensionless frequency parameter ($a_0 = \omega r / V_s$ for footing, $a_0^p = (\omega d / V_s)$ for pile)
$\tilde{K}^*$	overall dynamic impedance of soil–structure system
$\tilde{K}$	overall stiffness of soil–structure system
$\tilde{T}$	natural period of soil–structure system
K_{ij}	real part of dynamic impedance-pile foundation stiffness
E_p	pile Young's modulus of elasticity
I_p	pile cross-sectional moment of inertia
L	pile length
L_e	effective pile length
d	pile diameter
k_x	modulus of distributed Winkler springs
c_x	modulus of distributed Winkler dashpots

B. Greek symbols

$\tilde{\zeta}$	damping of soil–structure system
ζ_j	energy loss parameter
ρ_s	soil mass density
ν_s	soil Poisson's ratio
ζ_s	soil hysteretic damping
ω	circular excitation frequency
ω_x	fictitious uncoupled circular natural frequency under swaying oscillations
ω_θ	fictitious uncoupled circular natural frequency under rocking oscillations
ω_c	circular natural frequency of structure in its fixed-base condition
$\tilde{\omega}$	circular natural frequency of soil–structure system
λ	pile wave-number parameter
δ	dimensionless Winkler factor
ζ	damping ratio of the structure
σ	dimensionless wave parameter
γ	mass density ratio

and Meek [21] and Veletsos [6] analyzed a simple structure founded on rigid circular surface footing, and were the first to clearly demonstrate the need of taking into account the effect of SSI in structural design. Dobry and Gazetas [22] developed expressions for calculating the stiffness and damping of arbitrarily shaped foundations. Aviles and Perez-Rocha [33,34] used a discrete model to determine the influence of SSI on the period and damping of a structure as a function of foundation embedment and the overall depth of the soil. Mulliken and Karabalis [35] developed a discrete model for the calculation of the dynamic through-the-soil interaction between adjacent rigid, surface foundations supported by an elastic half-space using frequency-independent springs and dashpots. Aviles and Suarez [36] used a discrete model to calculate the period and damping of a soil–structure system taking into account the influence of seismic waves for various cases of structures mounted on a soil layer over bedrock.

The dynamic response of structures on pile foundations has received less research attention, e.g., Bielak and Palencia [37], Wolf et al. [38], Gazetas et al. [39], Mylonakis [40], Mylonakis et al. [41] and Kappos and Sextos [42]. More importantly, the results of these efforts have not yet led to established design methods, such as the simple code provisions developed for structures on surface foundations [43,44]. The main research effort has been focused on the dynamic behavior of the piles themselves. Various numerical techniques have been used to this end: Kaynia and Kausel [45] computed the dynamic response of pile groups using BEM in frequency domain; Rajapakse and Shah [46], Kaynia and Kausel [47], Gazetas et al. [48], Kaynia and Novak [49] and Padron et al. [50] used combinations of BEM and FEM for the dynamic analysis of pile groups.

One of the earliest efforts to develop discrete models for the dynamic analysis of pile foundations was undertaken by Novak [51]. In his study, the restraining action of soil is simulated by distributed springs and dashpots which ultimately resulted in estimates of dynamic impedances for a single pile foundation. Wolf and Von Arx [52] used a discrete model to analyze the response of vertical pile groups. Gazetas and Dobry [53] presented a simplified procedure for calculating radiation damping of pile foundations, Mylonakis and Gazetas [54] used frequency-dependent spring and dashpots to calculate axial stiffness and radiation damping of pile groups in layered soil medium, under harmonic excitation. Mylonakis [55] and Gazetas and Mylonakis [56] presented a simplified discrete model to calculate the pile response to horizontal and vertical seismic excitation in a layered soil medium.

In this paper a simplified discrete system is developed to simulate the dynamic behavior of a structure founded on footings or piles under harmonic dynamic excitation. Classical methods regarding solutions of SSI problems are reviewed with emphasis on the design-oriented solutions by Veletsos and co-workers [5,6,21] and Wolf [13]. Exact analytical expressions for the fundamental natural period and the corresponding damping coefficients of a structure on a surface footing are presented and compared with the previous methods. These analytical expressions are then modified to encompass structures on pile foundations by transferring the reference system from the footing–soil interface to the depth where the resultant soil reaction is applied, to ensure a diagonal impedance matrix. The resulting eccentricity is a measure of the coupling effect between swaying and rocking oscillations in embedded foundations. Using the above modification the fundamental period and damping of structures founded on a single pile can be determined in a straightforward way. The amounts of radiation damping generated from a single pile and a surface footing are evaluated and compared using the notions of statically-equivalent and geometrically-equivalent SSI systems. Results for typical configurations are provided in ready-to-use graphs and charts.

2. Problem definition and classical solutions

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

The structure is described by its stiffness k, mass m, height h, and damping ratio ζ, which may be either linearly viscous (i.e.,

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