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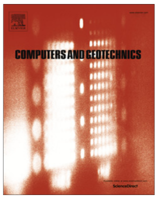

Research Paper

Assessing the dynamic stiffness of piled-raft foundations by means of a multiphase model

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ABSTRACT

The problem of evaluating the dynamic impedance of a vertically loaded piled raft foundation is investigated in this paper, based on the macroscopic description of the pile-strengthened soil as a two-phase linear elastic continuum. Conceived as an extension of the classical homogenization approach, this multiphase model incorporates elastic interaction laws between the soil and the reinforcing piles, which can easily be identified from the solution to a specific auxiliary problem. The equations of elastodynamics associated with this model can then be implemented into a dedicated finite element numerical code, the use of which makes it possible to produce reliable and accurate predictions for vertical impedance of large pile groups in a much easier and quicker way than with direct numerical simulations.

1. Introduction

Evaluating the dynamic stiffness of a foundation is a key ingredient to the analysis of soil–structure interaction effects [6,25]. The specific, but more and more frequently encountered case of piled raft or pile group foundations, has received increasing attention for a few decades, first through the vibration analysis and design of individual piles in the soil mass in the context for instance of pile driving techniques, then more recently in order to assess the improvement of the foundation dynamic performance to be expected from its reinforcement by a large number of piles placed under the footing.

Several engineering design methods are based on an extension to dynamics of the so called simplified Winkler model, widely employed in foundation engineering design [21]: see among others Novak [16], Novak and Sheta [17], Gazetas and Dobry [7], Mylonakis and Gazetas [14]. According to this model, the piles are schematized as one dimensional beams, interacting with the surrounding soil through continuous distributions of elementary springs and dashpots. More recently, Pacheco et al. [18] have extended the model in order to introduce inertia effects of the soil through "soil lumped masses". This kind of method can lead to analytical or semi-analytical formulations, at least for a small number of piles, but is facing two major difficulties. The first concerns the identification of the appropriate constitutive parameters to be assigned to the mass–spring–dashpot systems, whether this identification is being made from fitting model predictions with experimental or numerical (notably finite element and/or boundary element methods) results. It should be checked in such a case, that the identified parameters are really intrinsic and do not depend on each configuration. The second, and perhaps more fundamental criticism of the Winkler model is that the static as well as dynamic behavior of the soil mass as a loaded deformable continuum is not considered in such analyses, the mass–spring–dashpot systems behaving independently from each other.

A more rigorous and comprehensive approach to the design of piled raft foundation under dynamic loading would consist in resorting to full numerical methods, such as the finite element and/or boundary element techniques, both the soil and the reinforcing piles being treated as continuous media in mutual interaction with one another through contact surfaces. Some examples of such simulations may be found in Kaynia and Kausel [11], Wu and Finn [26], Maeso et al. [13], Padron et al. [19, 20], Giannakou et al. [8]. Unfortunately, since such numerical methods prove to be highly computational time consuming as the number of piles increases, their use is most often limited to designing large projects and cannot therefore form the basis of a practical engineering design tool.

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Making an intensive use of coupled finite element–boundary element methods, Taherzadeh et al. [24] have provided numerical evaluations for the dynamic stiffness of pile group foundations under dynamic combined loadings. They established simple user-friendly analytical formulas, the coefficients of which were identified from the previously determined numerical database. The range of applicability of such formulas is however restricted to the particular configuration of a rectangular group of end-bearing or floating piles with homogeneous soil characteristics.

This contribution advocates the use of an alternative approach based on the general concept of macroscopic behavior of the pile-reinforced soil, which more specifically pertains to the case when a relatively large number of identically oriented and evenly spaced piles is involved in the design of the foundation. Implementing this basic idea, the paper is organized as follows. Starting from a direct fem-based simulation of a piled raft foundation subject to harmonic vertical loading (Section 3), an alternative homogenization method is first proposed in which the reinforced soil is modelled as an anisotropic linear elastic medium (Section 4), resulting in a considerable reduction of the computational effort needed for evaluating the impedance of the foundation.

Pointing out the limitations of such a homogenization procedure, which tends to overestimate the foundation dynamic stiffness, a multiphase model, already successfully developed for piled raft foundations under static loading conditions [2], is presented in Section 5 in the context of a linear elastic dynamic behavior. It is characterized by the introduction of two soil–pile interaction stiffness parameters which can be easily identified from the solution of a static auxiliary problem (Section 6). The implementation of this model in a finite element code is finally applied to an illustrative example in Section 7. This application gives clear evidence of the good performance of the so obtained numerical tool based on the multiphase model, in that it is able to provide accurate and reliable estimates for the foundation vertical impedance with dramatically reduced computational times as compared with direct numerical simulations.

2. Problem statement

The problem to be investigated is that of a rigid square footing of side B acting upon a homogenous elastic soil layer of depth H, which has been preliminary (that is before the installation of the raft footing) reinforced by a group of periodically distributed vertical “floating” piles of length L ($<H$) placed beneath the footing as sketched in Fig. 1. In order to evaluate the vertical dynamic stiffness (or impedance) of such a reinforced structure, a harmonic uniform vertical rigid body translation of the form:

$$\delta(t)\underline{e}_x = \delta_0 \exp(i\omega t)\underline{e}_x \tag{1}$$

where δ_0 is the displacement amplitude and ω the angular frequency, is classically prescribed to the footing, as shown in Fig. 1.

The global response of the structure is expressed through the evolution with time of the vertical resultant force exerted by the footing on the reinforced ground, equal to:

$$\underline{F}(t) = F(t)\underline{e}_x \quad \text{with} \quad F(t) = \int_S \sigma_{xx}(y,z;t)\mathrm{d}S \tag{2}$$

where S is the area of contact between the footing and the reinforced ground. As soon as the harmonic regime is established, this resultant force is varying with the same frequency as the prescribed footing motion:

$$F(t) = F_0 \exp[i(\omega t + \phi)] \tag{3}$$

Under such conditions, the vertical impedance (or dynamic stiffness) of the foundation is classically introduced, defined as:

$$K = \frac{F}{\delta} = \frac{F_0}{\delta_0}\exp(i\phi) = K_0(\omega)\exp(i\phi(\omega)) \tag{4}$$

The dynamic structural stiffness K_0 and out-of phase angle ϕ, which both characterize the overall steady state response of the piled group foundation under vertical harmonic loading, will now be computed as functions of the angular frequency ω on the basis of the following set of hypotheses and data.

The soil is modelled as an isotropic linear elastic medium with the following typical characteristics: $E_s = 45$ MPa, $\nu_s = 0.3$, while the reinforcing piles are made of a much stiffer linear elastic material (concrete, metal): $E_p = 20{,}000$ MPa, $\nu_p = 0.2$. Perfect bonding (*i.e.* no slip condition) is assumed between the piles and the surrounding soil mass, as well as between the rigid raft and the reinforced ground, so that (1) represents a displacement-prescribed boundary condition on top of the pile group.

Three different configurations will be considered as regards the distribution of piles, the length of which is always kept fixed equal to $L = 16$ m, whereas their spacing s and radius ρ are varied proportionally, so that the reinforcement volume fraction defined as:

$$\eta = \pi\frac{\rho^2}{s^2} \tag{5}$$

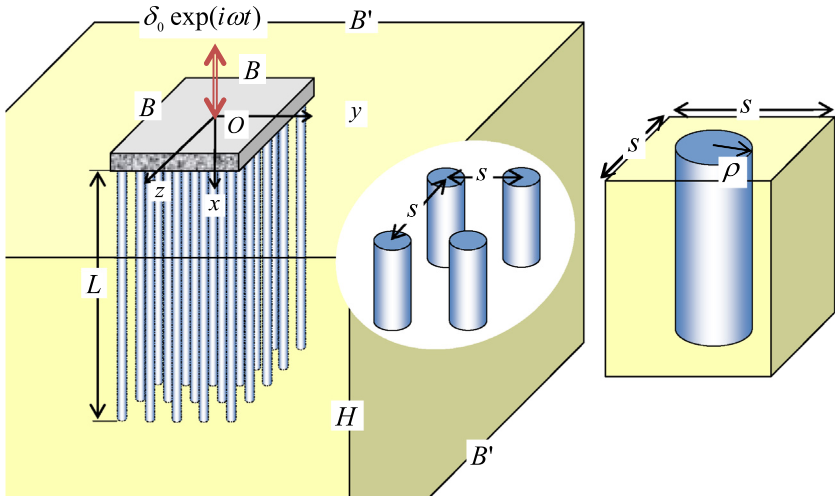

Fig. 1. Square piled raft footing under vertical dynamic loading.