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Dynamic pile impedances for fixed-tip piles

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ABSTRACT

The behavior of a laterally loaded pile with fixed-tip boundary condition (i.e., displacement and rotation, are perfectly restrained) is evaluated using a recently proposed, improved Tajimi-type model. The model performance in both, static and dynamic regime is first validated against rigorous finite element solutions and subsequently compared with Winkler model results for a selected range of pile-soil system parameters. In addition, pile impedances for fixed-tip piles are compared with previously proposed impedance expressions for hinged-tip piles. Results indicate that pile tip fixity has moderate impact on the pile stiffness in rotation but show stronger influence for pile stiffness in swaying and cross-swaying. The effect of tip fixity on pile impedances diminishes when piles are longer than approximately ten pile diameters. The proposed expressions for damping were evaluated across a wide range of frequencies, and damping was found to be most pronounced in rotation across the entire spectrum of pile-soil stiffness ratios examined. Winkler based formulations from literature almost exclusively over-predict damping for fixed tip piles.

1. Introduction

The consideration of dynamic soil-structure-interaction (SSI) is crucial to correctly assess the seismic vulnerability of a structure. The traditional assumption of a fixed-base condition at the foundation level is known to misrepresent the effects of SSI on the structural response by altering the period and damping of the system. Contrarily, the implementation of soil-foundation compliance leads to correct understanding of structural stiffness and damping; however, the significant increase of computational time and costs associated with complex SSI analyses poses considerable disadvantages. Therefore, simpler computational tools that provide the engineer with the capability to assess potential SSI effects on the structural response are beneficial.

For structures resting on pile foundations, approximate three-dimensional Tajimi-type formulations can be implemented to evaluate analytically soil-structure interaction resulting from lateral loading via closed form expressions. These formulations can yield results for pile impedances [dynamic pile head stiffness in swaying, rotation and cross swaying-rotation (K_{hh}, K_{rr}, K_{hr}) and corresponding damping ratios (ζ_{hh}, ζ_{rr}, ζ_{hr})] to be readily implemented in subsequent superstructure analyses. Pile impedances depend on the pile boundary conditions and therefore the consideration of pile tip fixity may be of importance, especially for "short" piles. While elastodynamic models published in the literature provide rigorous solutions for piles embedded in a half-space, these models do not account for the structural fixity condition at the pile tip (e.g. [1,2]).

Several researchers have proposed simple expressions for pile impedance functions for a variety of pile boundary conditions. Static pile impedances (pile head stiffnesses K) have been presented by Gazetas [3] and Syngros [4] through curve fitting of finite element (FE) results of piles embedded in a homogeneous half space. Specifically, Gazetas and Syngros proposed relationships for static swaying (K_{hh}), rotation (K_{rr}), and cross swaying-rotation (K_{hr}) as a function of the pile-soil stiffness ratio. Yet, similarly to rigorous elastic solutions described earlier, these expressions [3,4] fall short in their ability to accurately capture the dynamic response and are limited in their applications to "long piles" (i.e., no effect of tip fixity is considered). The performance of the Syngros and Gazetas expressions has been tested in Anoyatis and Lemnitzer [5] where an extensive parametric analysis for static pile impedances was conducted for the case of hinged-tip piles.

In dynamic regime, simple frequency-dependent expressions, have been introduced by Dobry et al. [6] and Roesset and Angelides [7] based on results from FE analyses. Dobry et al. presented expressions for frequency-dependent pile stiffness in swaying and corresponding frequency-dependent pile damping. Roesset and Angelides proposed frequency-dependent expressions for dynamic pile stiffnesses K_{hh}, K_{rr}, K_{hr} (yet not for pile damping). In both research efforts, expressions for

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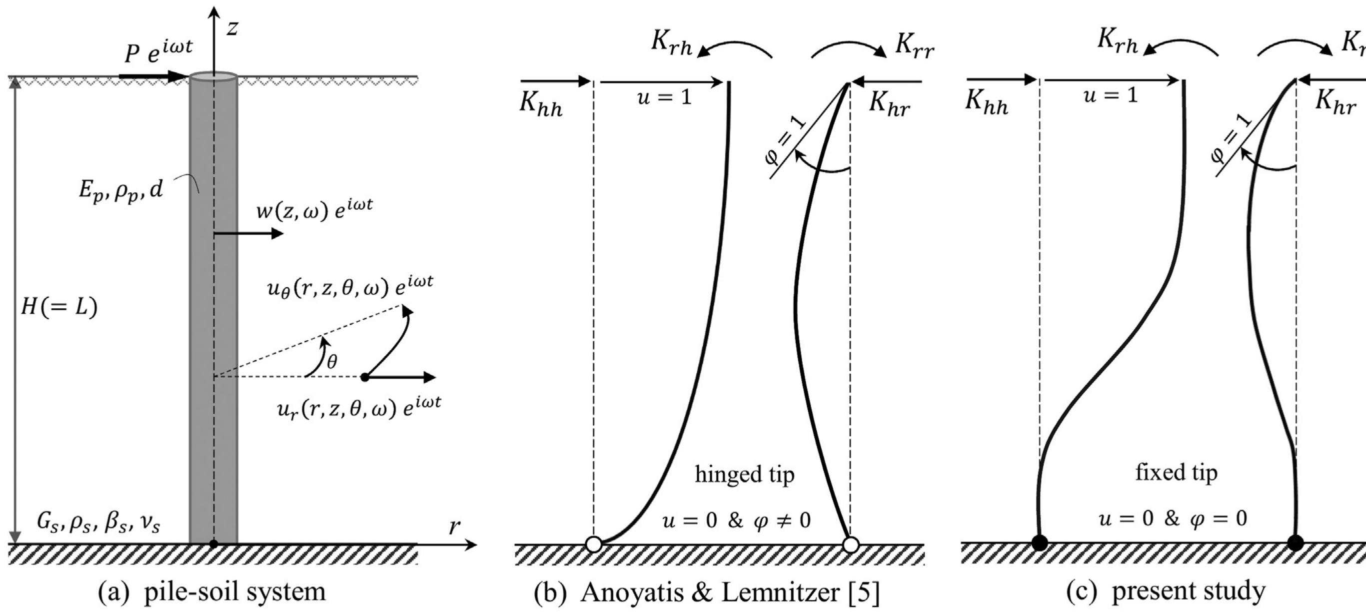

Fig. 1. Problem considered: (a) pile-soil system, and (b), (c) deformed pile shape and pile impedances based on different fixity conditions at the tip.

stiffnesses are a function of the Winkler modulus. This indicates that their performance strongly depends on the selection of a proper value for the modulus. Using frequency independent ("static") expressions for the Winkler springs (e.g. [8]), pile stiffnesses will not be able to account for resonant effects (significant "drop" in K_{hh}, K_{rr}, K_{hr} at resonance) and will exhibit a monotonic variation with excitation frequency. Note that the expression for pile damping in swaying presented by Dobry et al. [6] accounts for resonant effects through a two-part equation (i.e., manually), by separating the expression into a "before" resonance and "after" resonance term which accounts for the "jump" in damping by including a Winkler dashpot.

Closed-form expression for dynamic pile impedances are available in the literature through a simple Winkler model (e.g. [9]). The accuracy of these expressions, along with the expressions from Dobry et al. [6] and Roesset and Angelides [7] previously discussed, strongly depends on the selections of proper values/expressions for the Winkler moduli [dynamic stiffness k and dashpots c (or damping ratio β)]. Note that a thorough discussion on the effect of existing Winkler moduli [dynamic stiffness k and dashpots c (or damping ratio β)] on dynamic pile impedances is presented in Anoyatis and Lemnitzer [5], where new expressions for k and β were presented. The majority of moduli available in the literature were either frequency- or resonance- independent and fell short in yielding realistic results for dynamic pile impedances, especially at frequencies close to the first resonance of the soil-pile system.

Alternatively, simple Winkler models can treat the problem of a pile embedded in a soil layer overlying rock and consider pile tip restraints. However, existing expressions for Winkler springs and dashpots are not calibrated for fixed tip conditions. Therefore, a need for closed-form expressions to accurately evaluate pile stiffness and damping for piles socketed in shallow rock, emerges. Previously, effects of tip fixity on pile impedances have been recognized by Novak and Nogami [10], however, pertinent expressions have not been published and are not available for users.

In this paper, stiffness and damping of tip-restrained piles is investigated through an improved, analytical model, recently presented in detail by Anoyatis and Lemnitzer [5]. The improvement of the model lies in a better prediction of soil response which ultimately yields more accurate results for pile impedances. In the ensuing, closed–form solutions for static and dynamic pile impedances (pile head stiffness and damping ratios) are presented in terms of infinite Fourier series, and validated against rigorous FE solutions. The primary objective of this investigation is to study the influence of tip fixity on pile stiffness and damping ratios using selected pile-soil configurations, and compare results of fixed-tip piles against such for hinged-tip piles. Hereafter, the capability of existing Winkler formulations to predict damping is assessed through comparison with the results obtained from the proposed model. Note that the ability of the model to accurately predict damping is of particular importance when performing SSI analyses (Maravas et al. [11], Bilotta et al. [12]). Substantial benefits in terms of reduction of structural accelerations may be achieved when the structural frequency is larger than the fundamental frequency of the soil as shown in ensuing graphs.

The current study assumes an idealized configuration in which the pile tip is perfectly fixed at the elevation of the bedrock. The Authors acknowledge that in situ conditions encountered in engineering design practice may vary, as the level of tip fixity depends on the strength and condition of the rock, which is often approximated. The Authors further acknowledge that the degree of fixity intrinsically influences the ability of the pile to rotate within the embedment socket (e.g., if rock is weathered). With the assumption of a perfectly fixed tip and the solution provided in Anoyatis and Lemnitzer [5], who investigated the condition of the pile with a hinged tip, the pile response at both ends of the pile tip boundary spectrum is fully described.

2. Pile-soil configuration

The pile-soil configuration examined in this study is depicted in Fig. 1(a): a cylindrical pile of diameter d and length L is embedded in a homogenous soil layer of thickness H (=L) and fixed in a medium with infinite stiffness. The pile is modelled as a vertical cylindrical beam in the framework of the strength-of-materials solution [5,10] and is described by its Young's Modulus E_p and mass density ρ_p. The soil is characterized by a mass density ρ_s and Poisson ratio ν_s. The hysteretic damping β_s is implemented in the analysis through a complex-valued shear modulus $G_s^* = G_s(1 + 2i\beta_s)$. The pile is subjected to the following loading: (i) a harmonic horizontal load $Pe^{i\omega t}$ applied at the pile head which generates horizontal harmonic oscillations of the form $w(z, \omega)e^{i\omega t}$, as well as (ii) a static load P which generates static displacements in the form of $w(z)$. In the aforementioned formulations, z represents the space variable in vertical direction; t represents time; ω describes the cyclic excitation frequency; and i is the imaginary number. As a result of the applied loading, the soil surrounding the pile undergoes harmonic motion or static displacements which will be