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Dynamic torsional response of an elastic pile in a radially inhomogeneous soil

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ABSTRACT

Surrounding soil may be weakened or strengthened due to construction disturbance of the pile, resulting in soil properties varying gradually in the radial direction. In this paper, an analytical solution is developed to investigate the torsional vibration of an elastic pile embedded in a radially inhomogeneous soil and subjected to a time-harmonic torsional loading. The radially inhomogeneous soil is subdivided into many thin concentric annular sub-zones, with each having constant complex shear modulus in radial direction. The dynamic equilibrium equation of each sub-zone of the soil is then solved and the circumferential displacement and shear stress along the pile-soil interface are obtained by a newly developed method that enforces the continuity conditions between the two adjacent sub-zones. By virtue of the boundary and continuity conditions of the pile-soil system, the torsional impedance at the pile head is derived in an exact closed form in the frequency domain. Some numerical results are presented to study the influence of the soil layer rigidities on the vibration characteristic of the pile-soil system.

1. Introduction

Pile foundations of machines and structures are often subjected to dynamic loadings. In most cases, torsional loading commonly occurs in typical pile foundations including those of machinery, bridges, pylons, towers and lighting posts due to eccentricity of applied lateral dynamic loads. The frequency and time-domain torsional response of piles embedded in soil deposits can provide valuable guidelines for the design of dynamic foundations and nondestructive testing of piles. In the pile-soil system, the reaction of the surrounding soil is also important and is the subject of intensive research. For example, Pak and Abedzadeh [1] dealt with the stress analysis of an elastic half-space with an open cylindrical cavity of finite dimension subjected to torsional shear tractions. Eskandari-Ghadi et al. [2] and Ardeshir-Behrestaghi et al. [3] investigated, respectively, the dynamic torsional response of a transversely isotropic half-space and two-layer transversely isotropic half-space containing a finite cylindrical cavity. Various theoretical methods were also proposed to study the vibration of piles or foundations in single-phase soils [4–13] or saturated poroelastic soils [14–18].

It is noted that in most previous works the soil medium was assumed to be homogeneous in the radial direction. However, when the pile is installed into the soil, the soil in the vicinity of the pile would experience a change in its properties, due to, for instance, the disturbance and remolding from the construction operation, compacting from the pile driving into the soil, and strengthening of the surrounding soil using new construction techniques. In these cases, the soil becomes inhomogeneous in the radial direction. To solve this type of problems, Masoumi et al. [19] presented a non-linear finite element–boundary element coupling method for the prediction of the free-field vibrations due to vibratory and impact pile driving. The surrounding soil was approximated as a bounded plastic soil domain and an unbounded exterior linear soil domain during the pile driving process. Shi et al. [20] investigated the compacting effect caused by the construction of jacked piles via the finite element method, which showed that both the shear modulus of the surrounding soil and the load bearing capacity of a single jacked pile increase with increasing lateral compact. Liu et al. [21] studied the influence of different construction methods of piles on the properties of the surrounding soil by virtue of model test, and found that installation effects would lead to the increase of physical and mechanical parameters of soil around SDS (soil displacement screw) piles. Zhou et al. [22] investigated the bearing capacity and load transfer mechanism of a static drill rooted nodular pile consisting of precast nodular pile and the surrounding cemented soil. Their study showed that the bearing capacity of a static drill rooted nodular pile is higher than the bored pile due to the strengthening of surrounding cemented soil.

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Nomenclature

G_0	shear modulus of the soil layer at the outer zone
G_m	shear modulus of the soil layer at the pile-soil interface
ρ_0	density of the soil layer at the outer zone
ρ_m	density of the soil layer at the pile-soil interface
V_0	shear wave velocity in the soil layer at the outer zone
V_m	shear wave velocity in the soil layer at the pile-soil interface
D_0	material damping coefficient of the soil layer at the outer zone
D_m	material damping coefficient of the soil layer at the pile-soil interface
$u_{\theta j}(r, z)$	amplitude of circumferential displacement of the jth soil zone
ρ_j	density of the jth soil zone
G_j^*	complex shear modulus of the jth soil zone
V_j	shear wave velocity in the jth soil zone
D_j	material damping coefficient of the jth soil zone
f	excited frequency
G_p	shear modulus of the pile
ρ_p	density of the pile
r_0	radius of the pile
H	height of the pile
$\phi(z)$	twist angle amplitude at depth z of the pile
$f(z)$	amplitude of the circumferential contact traction along pile-soil interface
T_0	torque applied on the pile head
G_s	shear modulus of the substratum
S_{w1}	non-dimensional real stiffness part of the soil reaction
S_{w2}	non-dimensional damping part of the soil reaction
k_T	non-dimensional torsional impedance at the pile head
H'_θ	non-dimensional twist angle at the pile head
t_m	radial width of disturbed zone
η	ratio of shear wave velocity of the inner disturbed zone to that of the outer undisturbed zone

The influence of the relaxing or compacting effect due to the construction on the dynamic response of a pile was investigated by many researchers using different analytical methods. Novak and Sheta [23] proposed a weakened annular boundary zone adjacent to the foundation based on the simplified continuum method. The mass in the boundary zone was assumed to be zero, thus neglecting its inertia effects. Veletsos and Dotson [24] took the mass of the boundary zone into account and derived the analytical expression for the torsional impedance of the weakened or softening soil. Dotson and Veletsos [25] further proposed a boundary zone model for the weakened soil and derived an analytical solution of the torsional impedance of the soil where the shear modulus and the boundary zone were fixed. In light of the limitation of Dotson and Veletsos' solution, Han and Sabin [26] developed a boundary zone model in which the soil shear modulus changes in a parabolic fashion. El Naggar [27] then developed a discrete boundary zone model and studied the effect of soil strengthening on dynamic impedances. The impedance of the composite soil layer was obtained by evaluating the stiffness of each annular zone separately and then joining them with a number of springs in series. Owing to the fact that the stiffness represented by springs in series cannot authentically reflect the dynamic interaction of the adjacent soil zones, Wang et al. [28] proposed a complex stiffness transfer model and derived an analytical solution for the vertical impedance of the radially inhomogeneous soil. Using a similar method, Wu et al. [29] investigated the dynamic response of a tapered pile embedded in a radially inhomogeneous soil.

In these previous studies, the surrounding soil was generally treated as a simplified continuum model (e.g., the plane strain soil model). The soil was assumed to be composed of a set of independent infinitesimally thin layers that extend to infinity and the gradient of displacement and stress in the vertical direction were neglected. As a result, the wave in soils can only propagate horizontally, which does not simulate correctly the mechanism of pile-soil dynamic interaction. Therefore, the main objective of this article is to develop a more rigorous and comprehensive analytical solution to assess the influence of radial inhomogeneity of the soil due to construction effects on the torsional vibration behavior of the pile. The accuracy of the proposed method is further demonstrated by comparing the numerical results with those based on the other theories. A parametric study is also conducted with the corresponding results being discussed for possible future applications.

2. Mechanical model of pile-soil system

2.1. Geometry of the pile-soil system and basic assumptions

The geometry of the pile-soil interaction is presented in Fig. 1 where H and r_0 denote the height and radius of the pile, respectively. $T_0 e^{i\omega t}$ is the time-harmonic torsional load acting on the pile top, in which ω and t are the circular frequency of excitation and time variable, respectively. Furthermore, the following fundamental assumptions are adopted in this analysis:

(1) The pile–soil system is subjected to small deformation during the vibration. The circumferential displacement of the surrounding soil is considered, but the vertical and radial displacements are neglected.
(2) The pile is elastic and vertically with a uniform circular cross-section. It remains in perfect contact with the surrounding soil. The interaction of the pile and pile-end soil is assumed to be elastic.
(3) The surrounding soil is linear viscoelastic isotropic with hysteretic-type damping which is independent of frequency. The surface of the soil is free with no normal/shear tractions, and the support at the bottom of the soil is assumed to be elastic.

2.2. Description of the radially inhomogeneous soil

The geometry of the surrounding soil model examined is similar to that employed by El Naggar [27]. As shown in Fig. 1, an elastic pile is embedded in the viscoelastic soil medium consisting of two annular zones, an outer semi-infinite undisturbed zone and an inner annular zone of disturbed material with width t_m. The outer zone medium is homogeneous and viscoelastic isotropic with frequency-independent material damping. The properties of the soil medium in each zone are defined by the complex shear modulus as:

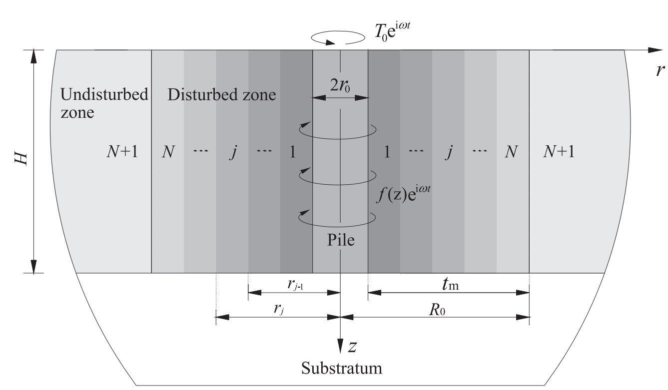

Fig. 1. Geometry of pile-soil interaction.