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Influence of pile radius on the pile head kinematic bending strains of end-bearing pile groups

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ABSTRACT

An analytical solution is developed for the kinematic response of a group of end-bearing fixed-head cylindrical vertical piles embedded in a homogeneous elastic stratum subjected to vertically-propagating harmonic shear waves. Pile-soil interaction, incorporating group effects in a pile group, is represented through a simplified beam-on-dynamic-Winkler-foundation (BDWF) model with realistic frequency-dependent springs and dashpots. Expressions for interaction factors and curvature ratios atop the foundation are presented considering different boundary conditions at the tip of the piles. To investigate the fundamental characteristics of kinematic bending in end-bearing pile groups when kinematic interaction dominates, kinematic bending strains at the head of each pile are expressed in terms of the slenderness ratio. The methodology is verified by comparison against results of a coupled finite element-boundary element (FE-BE) model. Obtained results indicate that kinematic bending strains of end-bearing single piles and piles in a group follow the same trend, with values being almost coincident in the case of slender piles. In addition, boundary conditions at the pile tip markedly affect the kinematic bending at the pile head.

1. Introduction

During strong earthquakes, propagation of seismic waves through soil induces deformations in the soil that excite embedded piles by imposing a spatially-variable displacement field. Such displacement field will then generate, as the result of "kinematic interaction" [1–3], bending and shearing along the entire length of the pile. This is different from the bending and shearing generated by the inertial forces produced by the vibrating superstructure (as the result of "inertial interaction"). Kinematic response of piles has been a subject of research for over three decades [4–25], many of which are based on analytical formulations [4–7].

Previous earthquake events of Mexico City (Mexico) in 1985, Kobe (Japan) in 1995, and Chi Chi (Taiwan) in 1999 have highlighted the sensitivity of pile foundations to damage in dominance of kinematic interaction. Especially, under kinematic considerations, damages appear either at the pile head or deep down the pile where inertial forces are vanishingly small. The observed field data in the past in conjunction with theoretical studies have revealed three possibilities of damage due to kinematic bending along fixed head piles: (1) near the restraining pile cap; (2) at interfaces between soil layers; and (3) near the toe of the pile. In homogeneous soil layers, damage due to the kinematic bending occurs, generally, at the pile head. In this regard, kinematic bending moments at the head of a flexible vertical pile embedded in a soil deposit were investigated by Di Laora et al. [8]. They suggested that even in a homogeneous soil medium, kinematic bending moments can be important. Nikolaou et al. [9] performed a parametric investigation on the kinematic bending strains in a single pile embedded in both homogeneous and layered soil deposits subjected to steady-state harmonic shear waves. One of the conclusions from their analysis is that in most cases, the maximum bending strain occurs at the fundamental natural period of the soil deposit. The variation of kinematic bending strain with frequency follows, more or less, the amplification of the free-field acceleration. This signifies the influence of the first mode of vibration on the magnitude of bending strain. Murono [18] and Luo et al. [19] verified the dominant characteristics of the fundamental frequency and the corresponding 1st mode in kinematically loaded piles and reflected it to the present seismic design code in Railway Japan.

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Nomenclature

Latin symbols

a_0	dimensionless frequency
a_c	dimensionless cutoff frequency
A_p	pile cross section area
A^I, B^I, C^I, D^I	pile's internal force based integration constants
A^K, B^K, C^K, D^K	kinematic loading based integration constants
c_x	Winkler dashpot coefficient
d	pile diameter
E_p	pile Young's modulus
E_s, G_s	soil Young's modulus, soil shear modulus
H	soil stratum thickness
I_p	pile cross-sectional moment of inertia
L	pile length
K_0, K_1	modified Bessel's functions of first kind of order 0, 1
k_x	dynamic Winkler stiffness
k_x^*	complex-valued Winkler modulus
$K_x^{(1)}$	the dynamic stiffness of the single pile
m_p	mass per unit pile length
P_j	force amplitude at the head of pile j
$\{\overline{P_j}\}$	vector forces of pile group
S	axis-to-axis distance between the piles
u_s	horizontal soil displacement
u_0	top-active pile displacement due to pile's internal forces
u_{ff}	free-field displacement
u_{ff0}	free-field displacement amplitude
u_g	base displacement
u_{g0}	base displacement amplitude
u^I	displacement due to pile's internal forces
u^K	displacement due to kinematic loading
$U^{(G)}$	total horizontal displacement of the cap
$U^K{}_{jj}$	kinematic pile-top displacement of active pile j
V_s^*	complex-valued shear wave velocity of soil
z	vertical coordinate

Greek symbols

$\alpha^I{}_{ij}$	interaction factors due to internal forces in piles
$\alpha^K{}_{ij}$	interaction factors due to kinematic loading
β_{ij}^I	curvature ratios due to internal forces in piles
β_{ij}^K	curvature ratios due to kinematic loading
β_s	soil material damping coefficient
λ	Winkler wavenumber
δ	soil wavenumber
υ_s	soil Poisson's ratio
ρ_s, ρ_p	soil, pile mass density
ω_g	cyclic fundamental frequency of soil layer
Γ	dimensionless response coefficient
ξ_{uP}	diffraction dimensionless factor
$\psi_{ij}(s, \theta)$	attenuation function
γ_s	mean shear strain of soil
$\varepsilon_{pi}^K(0)$	kinematic bending strain of pile i
$\chi(z)$	shape function in lateral pile deformation
η_u	compressibility coefficient

The distributed soil deformation along the pile in soil layers subjected to earthquake ground motions presented in Luo et al. [19] proves the dominance of the first mode. Additionally, Saitoh [15] investigated the effect of pile radius on the kinematic bending strains at the head of a fixed-head pile embedded in a homogeneous elastic soil layer for the fundamental natural period of the soil layer. On the other hand, the possibility of damage, at the interface between soil layers in this case, will increase in layered soil media with strong discontinuities. A number of design-oriented researches [9–12] have contributed simple solutions allowing the estimation of kinematic pile moments at the interface between two consecutive layers with significantly differing stiffness. Studies indicate that the kinematic bending strains at these interfaces could exceed the bending strains at the head of the pile depending on the soil layers stiffness contrast, the pile-soil stiffness contrast, and the relative thickness of the soil layers with respect to the length of the pile. Di Laora and Rovithis [13] provided simple formulations for kinematic bending moments at the head of long pile embedded in a continuously inhomogeneous layer over rigid base. It has also been shown that both in homogeneous and layered soils, when the toe is strongly restrained, the kinematic bending strains may dominate [14].

In seismic design, pile radius plays an important role because it directly affects the bending stiffness of a pile (EI). In general, increasing the pile radius is often an appropriate measure in reducing the bending strains under the dominance of inertial interaction. However, under the dominance of kinematic interaction, specific techniques are needed to minimize the kinematic bending. Saitoh [15] proposed a technique in order to obtain the optimal pile radius (defined as the radius for which the bending strains in the pile are minimum) of a fixed-head cylindrical vertical single pile embedded in a homogeneous elastic soil layer and supported by a rotationally compliant bedrock. His theoretical model is identical to those described in Tajimi [16] and Ohira et al. [14], and the frequency of excitation is assumed to be equal to the fundamental frequency of the soil medium. In his research, variation in kinematic bending strains against the slenderness ratio (r/H) was also investigated. It was shown that the normalized kinematic bending strains approach zero when the slenderness ratio (r/H) tends to zero. The value of the kinematic bending strain increases approximately linearly up to the local maximum ($r/H \approx 0.1$), but gradually decreases afterwards. On the other hand, Di Laora et al. [17] inspected the role of pile diameter in seismically-induced bending for both steel and concrete piles in homogeneous soils as well as soils with stiffness increasing proportionally with depth. A number of closed-form expressions for kinematic and inertial bending moments were presented, based on which minimum and maximum admissible pile diameters for combined kinematic and inertial actions were defined. They suggested that geotechnical and geometrical properties appear to be more significant than the structural properties. Moreover, among all admissible diameters, an optimal pile radius that maximize safety against bending failure exists. This radius influences the design of piles in seismically prone areas.

On the contrary, and up to the authors' knowledge, in the case of pile groups where kinematic interaction dominates, there has been no investigation into the effects of the pile radius on the bending strains. In order to establish criteria for optimal pile radius for kinematically excited pile groups, it is essential to quantify variations of kinematic bending strains with respect to pile radius in a systematic way.

The present work focuses on obtaining a comprehensive relation between the pile radius and the kinematic bending strains at the head of an end-bearing cylindrical vertical pile group under kinematic loading. Piles are considered to be embedded in a homogeneous elastic stratum resting on a rigid bedrock, being the pile length identical to the thickness of the soil stratum. Two different constraint conditions are considered at the pile tip: (a) hinged-tip, and (b) fixed-tip. A similar study on the kinematic response of single pile in a homogenous soil under different boundary conditions at the pile head and the pile tip was carried out comprehensively by Anoyatis et al. [20]. In their research, closed-form analytical solutions were proposed for both kinematic response coefficient and curvature ratios between pile and soil at the pile