Soil Dynamics and Earthquake Engineering 97 (2017) 424–438

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

An analytical solution for the rotational component of the Foundation Input Motion induced by a pile group

Raffaele Di Laora[a,*], Yado Grossi[b], Luca de Sanctis[c], Giulia M.B. Viggiani[b]

[a] Università della Campania “Luigi Vanvitelli”, Italy
[b] Università degli Studi di Roma “Tor Vergata”, Italy
[c] Università degli Studi di Napoli “Parthenope”, Italy

ARTICLE INFO

Keywords:
Kinematic interaction
Piled foundations
Rotational component

ABSTRACT

This work investigates the effect of the rotational component of input motion induced by the kinematic interaction between a pile group and the surrounding soil on the seismic behaviour of a structure. To this end, a simple analytical model is developed by deriving the pile group behaviour from the seismic response of a single pile, taking into account equilibrium and compatibility of displacements at piles' heads. Closed-form solutions in the frequency domain are provided for both the translational and the rotational motion of a group of unevenly distributed identical piles, rigidly connected at the top and displaced by the surrounding soil, which is subjected to purely translational oscillations. The proposed solutions, applicable to any subsoil conditions, highlight that pile group layout is the crucial parameter governing the magnitude of the foundation rotation. Further, new transfer functions from the soil surface in free field conditions to the top of a SDOF system are introduced, which take into account the translational and/or rotational kinematic effects. An application of the above concepts to a case study is presented, highlighting that the rotational component of input motion may be important for tall structures on small pile groups.

1. Introduction

The seismic analysis of a coupled soil-foundation-structure system can be conveniently carried out through the well-known substructure method [9,12,18,22,37], consisting of three consecutive steps: (i) calculation of the seismic motion at foundation level, or the Foundation Input Motion (FIM), neglecting the mass of the superstructure; (ii) computation of the dynamic impedances (‘springs’ and ‘dashpots’) associated with swaying, vertical, rocking and cross swaying-rocking oscillation of the foundation; (iii) evaluation of the response of the superstructure supported on springs and dashpots determined in step (ii) and subjected to the FIM calculated in step (i).

The substructure method is most commonly adopted in practice by assuming that the foundation motion is equal to the free-field seismic input. For a piled foundation, this suggests that the effect of piles on the seismic motion imposed on the supported structure is not accounted for, even if the horizontal displacements at the piles' head may differ substantially from the free-field motion. Such an effect may be important especially for soft soils, where piles are frequently employed to increase bearing capacity and/or reduce foundation settlement [11,28,31,32,36]. In this regard, available evidence [9,15,25,35] demonstrates that piles may modify substantially the amplitude of the free-field ground acceleration, as high frequency components of the free-field motion are filtered out by pile-soil interaction. In addition to the above effects, soil-structure interaction induces a rotational component in the input motion, which does not exist in the corresponding free-field motion.

The kinematic response coefficient, defined as the ratio of the horizontal pile displacement over that of the free-field, was originally introduced by Blaney et al. [3], who investigated the effect of a free-head pile on the motion at the free surface of an homogeneous soil deposit using the consistent boundary matrix method developed by Kausel et al. [13]. Since then, literature on pile-soil kinematic interaction effects concentrated primarily on the evaluation of the horizontal displacements and the rotation of a single pile, while a few works dealt with the rocking motion of pile groups. The early contribution on the problem of the rocking motion induced by kinematic interaction dates back to Wolf and von Arx [38], who examined the kinematic response of groups of piles connected by a rigid mat using a continuum model with hysteretic and radiation damping. Results of the above study obtained in the frequency domain by the FEM showed that the rocking motion at foundation level may be important, especially in the case of

---

* Correspondence to: Dipartimento di Ingegneria Civile Design Edilizia e Ambiente, Università della Campania “Luigi Vanvitelli”, via Roma, 29, 81031 Aversa, CE, Italy.
E-mail address: raffaele.dilaora@unina2.it (R. Di Laora).

http://dx.doi.org/10.1016/j.soildyn.2017.03.027
Received 7 October 2016; Received in revised form 19 March 2017; Accepted 21 March 2017

Nomenclature

a_0, a_λ	dimensionless frequency parameters
a_b	horizontal acceleration at the base of the SDOF
a_{ff}	free-field acceleration
a_G	pile group acceleration
a_r	acceleration at bedrock level
a_{SK}	absolute structural acceleration considering kinematic interaction
a_{Sff}	absolute structural acceleration neglecting kinematic interaction (*i.e.* a_b=a_{ff} and θ_b=0)
B	distance between the two external piles in a row
c_S	viscous damping coefficient of a SDOF system
d	pile diameter
E_p	pile Young's modulus
E_s	soil Young's modulus
$f(n)$	dimensionless function of number of piles
h	height of a SDOF system
H	horizontal force at the pile head
$H(\omega)$, $F(\omega)$	transfer functions of the SDOF system
I_p	cross-sectional moment of inertia of pile
I_u, I_{uX}, I_{uY}	horizontal kinematic interaction factors of the foundation
I_{uR}	horizontal kinematic interaction factor of the fixed-head pile
I_{uS}	horizontal kinematic interaction factor of the free-head pile
$I_{\theta S}$, $I_{\theta S\lambda}$	rotational kinematic interaction factors of the single pile
L	pile length
I_θ, $I_{\theta G}$, $I_{\theta X}$, $I_{\theta Y}$	rotational kinematic interaction factors of the foundation
J_a	ratio of the mass acceleration generated by kinematic interaction over that of free-field
k	Winkler modulus
k_S	stiffness of a SDOF system
K_V, K_{HH}, K_{HM}, K_{MM}	axial, swaying, cross-swaying and rotational stiffness of single pile
M, M_Y	restraint moments at the pile head
m, n, p	number of piles
m_S	mass of a SDOF system
N, N_i	axial loads on piles
s	pile spacing
T_{st}	oscillation period of the fixed-base building
u, u_X, u_Y	horizontal displacements of the foundation
u_b	horizontal displacement at the base of the SDOF
u_{ff}	free-field horizontal displacement
u_M, u_{MX}	single pile horizontal displacements due to moment restraint
u_R	fixed-head single pile horizontal displacement
u_S	free-head single pile horizontal displacement
u_Z, u_{Zi}	vertical displacements of piles
V_s	shear wave propagation velocity in the soil
x_G, y_G	centre of pile group vertical stiffness
x_i, y_i	coordinates of *i*-th pile
β_s	soil damping ratio
θ, θ_G, θ_Y	pile cap rotations
θ_M, θ_{MY}	single pile rotation due to restraint moment
θ_s	single pile rotation
θ_b, $\ddot{\theta}_b$	rotation and rotational acceleration at the base of the SDOF
λ	Winkler wavenumber
ξ	dimensionless factor for a pair of piles
ξ_X, ξ_Y	dimensionless factors for a group of piles
χ	dimensionless factor for a row of piles
ω	excitation frequency

small groups of piles and high frequency content of the base excitation, while for large group of piles this component may be neglected. Gazetas [9] applied the consistent boundary matrix method developed by Kausel et al. [13] and later used by Blaney et al. [3] to study the influence of a number of factors on the kinematic rotation of a single pile, including pile-soil stiffness ratio, soil inhomogeneity, soil damping ratio, and pile slenderness. Mamoon and Banerjee [19] implemented a hybrid boundary element method to study the problem of pile-soil kinematic interaction; their rotational kinematic interaction factors compare well with those obtained by Gazetas [9]. Fan et al. [8] studied the kinematic behaviour of groups of vertical floating piles connected by a rigid massless cap. Pile-soil and pile-pile interaction were modelled rigorously, using the formulation by Kaynia and Kausel [16]. The results of their study indicate that the number of piles and their layout do not affect the horizontal component of the cap motion, *i.e.* that group effects are negligible for lateral displacements, while they affect significantly the rotation of the pile cap. This is always smaller than the rotation of the single pile, reduces with increasing spacing, and is affected only by the number of piles and their relative spacing parallel to the direction of the seismic excitation. Nikolaou et al. [24] derived a closed form solution for the rotation of a long pile in a homogeneous soil by using the classical dynamic Winkler formulation. Mylonakis et al. [23] applied the analytical solution by Nikolaou et al. [24] to examine the seismic response of a single-span bridge supported by piers extended into the ground in the form of long-drilled shafts (single piles), concluding that the rocking motion caused by kinematic interaction may increase the seismic response of tall piers. Following Nikolaou et al. [24], Anoyatis et al. [2] provided analytical solutions for the rotation of a single pile embedded in a homogeneous soil layer using the classical Winkler formulation with different boundary conditions. Finally, Sextos et al. [33] investigated the seismic performance of bridge piers supported by groups of 2×2 piles embedded in a homogeneous soil layer with shear wave velocities of V_s=360 m/s or 180 m/s. The kinematic response of the foundation was analysed by placing the individual piles on uniformly distributed frequency-dependent springs and dashpots along the pile length. Results of this study showed that, in case of soft soil, the rotational component induced by piles may lead to an increase of the deck displacement ranging between 1.2 and 1.7.

Besides these results, and despite the fact that the Eurocodes [7] prescribe that potential negative consequences of the rocking motion of the foundation should be taken into account, to the knowledge of the Authors, no analytical solutions have been developed to quantify the kinematic rotational motion of a pile group and evaluate its consequences on the structural behaviour.

As a contribution to this topic, this work aims at: (i) offering insight into the mechanism of kinematically induced rotation of a group of piles connected by a cap; (ii) developing a simple closed-form solution for the rotational component of the FIM to be applied at the base of a structure founded on piles; and (iii) providing guidelines to evaluate the importance of the rotational component of the FIM.

2. Problem statement

Fig. 1 shows the problem under investigation in the realm of the substructure approach. The acceleration applied at the bedrock, a_r, is transferred to the ground surface in free-field conditions as a_{ff}; due to the kinematic interaction between the pile group and the soil, the foundation seismic motion has a horizontal component, a_G, and a rotational component, $\ddot{\theta}_G$, generated by the rigid connection between