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Influence of pile inclination angle on the dynamic properties and seismic response of piled structures

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ABSTRACT

This paper aims to contribute to clarify whether the use of battered piles has a positive or a negative influence on the dynamic response of deep foundations and superstructures. For this purpose, the dynamic response of slender and non-slender structures supported on several configurations of 2×2 and 3×3 pile groups including battered elements is obtained through a procedure based on a substructuring model assuming a linear elastic response and taking soil–structure interaction into account. Results are expressed in terms of flexible-base period and maximum shear force at the base of the structure. Moreover, modified response spectra considering soil–structure interaction effects are provided for different rake angles. It is shown that an increment of the rake angle can result in beneficial or detrimental effects depending on the structural slenderness ratio.

1. Introduction

The dynamic behaviour of buildings is affected by kinematic and inertial effects associated with soil–structure interaction (SSI), with these effects being important mainly for stiff structures founded on soft soil deposits. Their influence on the fundamental period and damping of soil–structure systems have been broadly investigated for shallow foundations [1–6] as well as for embedded foundations, either considering only inertial interaction (e.g. [7,8]) or taking also into account the modified foundation input motion defined by kinematic interaction [9–13]. A few studies [14–23] analysing the effects of SSI on the dynamic characteristics of pile-supported structures can also be found in the scientific literature. The virtues and drawbacks of using piled foundations including battered elements have been analysed in pioneering works [24–28], which suggest that further research needs to be undertaken to better understand the behaviour of this type of foundations. Furthermore, up to the author's knowledge, only Gerolymos et al. [29] and Giannakou et al. [30] have analysed the influence of using deep foundations with inclined piles on the dynamic response of the supported structures.

In recent years, inclined piles have recovered their popularity. Indeed, several studies have shown the beneficial role of battered piles on the seismic response of the structure [29,31–33]. However, further research is needed to be able to elucidate in which cases the presence of raked piles is beneficial or detrimental.

The aim of this work is to evaluate the influence of the rake angle on the dynamic response of shear structures founded on square pile groups comprising inclined piles and embedded in homogeneous viscoelastic half-spaces subjected to vertically incident S waves. The analysis is addressed through a simple and accurate procedure, previously described and validated in [23], based on a substructuring model in the frequency domain that takes into account kinematic and inertial interaction effects. A boundary element–finite element (BEM–FEM) formulation [34–36] has been used to compute the impedance functions and the kinematic interaction factors.

Results for several configurations of 2×2 and 3×3 pile groups including battered elements are obtained. The seismic response of the superstructure is presented in terms of the effective period and the maximum shear force at the base of the structure per effective earthquake force unit Q_m [2,37]. Moreover, results in terms of effective period and damping are used to build modified response spectra for different values of the rake angle.

2. Methodology

The dynamic behaviour of linear shear structures supported on pile groups and subjected to vertically incident plane S waves is analysed in this paper by using a three-degree-of-freedom (3DOF)

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system as the one depicted in Fig. 1a. This system is defined by the foundation horizontal displacement u^c and rocking φ^c, together with the structural horizontal deflection u.

The structure is considered to be founded on a square regular group of piles embedded in a homogeneous, viscoelastic and isotropic halfspace. Pile heads are constrained to a rigid square cap of negligible thickness and mass m_o, which is free of contact with the ground surface. The moment of inertia of this pile cap is denoted by I_o. All piles have identical geometrical properties defined by length L and sectional diameter d. Several configurations of pile groups have been considered in this study. Each one of them is defined by number of piles, foundation halfwidth b, centre-to-centre spacing between adjacent piles s and rake angle of piles θ. It is worth noting that some vertical piles are included in 3×3 pile groups for the purpose of maintaining symmetry with respect to planes xz and yz.

The superstructure consists of massless and axially inextensible columns that support the structural mass m, which is situated at the height h of the resultant of the inertia forces for the mode of vibration under study. The moment of inertia of the vibrating mass, which is distributed over a square area, is denoted by I. Its dynamic behaviour, corresponding to fixed-base condition, is characterized by the structural stiffness k, fundamental period T and viscous damping ratio ξ.

The 3DOF system dynamic response, considering kinematic and inertial interaction effects, is studied through a substructuring model in the frequency domain such as that represented in Fig. 1b. This model consists of a *building-cap* structure supported on springs and dashpots representing the *soil-foundation* stiffness and damping in the horizontal (k_{xx}, c_{xx}), rocking $(k_{\theta\theta}, c_{\theta\theta})$ and cross-coupled horizontal-rocking $(k_{x\theta}, c_{x\theta})$ vibration modes respectively. The whole system is subjected to the horizontal (u_g) and rocking (φ_g) motions measured at the massless pile cap level when subjected to free-field motion at the surface u_{g_o}.

In this paper, a BEM–FEM coupling model [33–36] is used to compute translational $I_u = u_g/u_{g_o}$ and rotational $I_\varphi = \varphi_g b/u_{g_o}$ kinematic interaction factors, as well as impedance functions at each frequency a_o, which are usually written as $K_{ij} = k_{ij} + \mathrm{i}a_o c_{ij}$, where k_{ij} and c_{ij} are the mentioned frequency-dependent dynamic stiffness and damping coefficients, respectively, $i=\sqrt{-1}$ is the imaginary unit. The dimensionless excitation frequency is defined as $a_o = \omega b/c_s$, with ω being the excitation circular frequency, $c_s = \sqrt{\mu_s/\rho_s}$ the speed of propagation of shear waves in the halfspace, and μ_s and ρ_s the soil shear modulus of elasticity and mass density, respectively.

Following earlier studies [2,3,8,12] and in order to characterize the soil–foundation–structure system, other dimensionless parameters, covering the main features of SSI problems, have been used. These are (1) structural slenderness ratio h/b; (2) fixed-base structure damping ratio ξ; (3) dimensionless fixed-base natural frequency of the structure $\lambda = \omega_n/\omega$; (4) foundation–structure mass ratio m_o/m; (5) wave parameter $\sigma = c_s T/h$ (that measures the soil–structure relative stiffness); (6) mass density ratio $\delta = m/(4\rho_s b^2 h)$ between structure and supporting soil; (7) Poisson's ratio ν_s; and (8) damping ratio ξ_s of the soil. A hysteretic damping model of the type $\mu_s = \mathrm{Re}[\mu_s](1+2\mathrm{i}\xi_s)$ is considered in this study for the soil material.

The dimensionless parameters used to characterize the pile foundation are pile spacing ratio s/d, pile–soil Young's modulus ratio E_p/E_s, size of the square pile group, embedment ratio L/b, pile slenderness ratio L/d, dimensionless frequency a_o, soil–pile densities ratio ρ_s/ρ_p and rake angle θ.

A simple and accurate procedure, previously described and validated in [23], is used in this paper to determine the dynamic characteristics of an equivalent single-degree-of-freedom (SDOF) oscillator (Fig. 1c) which reproduces, as accurately as possible, the response of the 3DOF system shown in Fig. 1b within the range where the peak response occurs. This response is expressed in terms of $Q = |\omega_n^2 u/(\omega^2 u_{g_o})|$, which represents the ratio of the shear force at the base of the structure to the effective earthquake force. The equivalent SDOF system can be defined by its damping ratio $\tilde{\xi}$ and its undamped natural period $\tilde{T}$.

The effective period $\tilde{T}/T = \tilde{\lambda} = \omega_n/\tilde{\omega}_n$ can be found as the root of Eq. (1), with $\tilde{\omega}_n$ being the undamped natural frequency of the

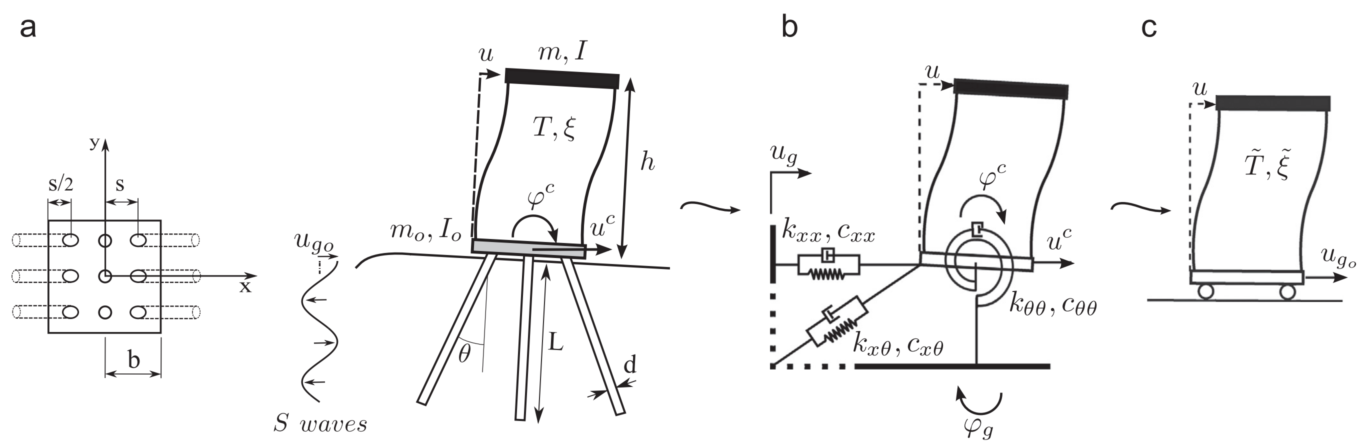

Fig. 1. (a) Problem definition, (b) substructure model of a one-storey structure and (c) equivalent single-degree-of-freedom oscillator.

Table 1
Values for the dimensionless parameters in the cases under investigation.

ν_s	ξ_s	E_p/E_s	ρ_p/ρ_s	L/b	L/d	s/d		ξ	δ	$1/\sigma$	m_o/m	h/b
						2×2	3×3					
					7.5	3.75	2.5					
0.4	0.05	10^3	0.7	2	15	7.5	5	0.05	0.15	0–0.5	0	1,2,5,10
					30	15	10					