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Effects of the use of battered piles on the dynamic response of structures supported by deep foundations

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1. Introduction – Inclined piles are frequently indicated in those cases in which foundations are expected to be subjected to important lateral loads. Nevertheless, the use of battered piles in seismically active regions has been considered detrimental and became highly discouraged in many codes (e.g. [1]) after a series of earthquakes in which deep foundations with raked piles showed a poor performance. 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 [2 – 6].

Up to the author's knowledge, only Gerolymos et al. [3] and Giannakou et al. [7] have analysed numerically the influence of using deep foundations with inclined piles on the dynamic response of the supported structures, while many authors have analysed the dynamic behaviour of the foundation itself. The influence of using inclined piles on the dynamic behaviour of the dynamic response of the superstructure remains a question that needs further research. Aiming at contributing to fill this gap, in this paper, a procedure based on a substructuring methodology [8] is used to obtain the response of the superstructure in terms of the effective period and the maximum shear force at the base of the structure per effective earthquake force unit for several configurations of 2 x 2 pile groups comprising inclined elements in direction of excitation.

2. Problem definition and methodology – This paper addresses an analysis of the effects of the variation of the rake angle of piles on the dynamic response of pile-supported linear shear structures. In this case, the system response can be approximated by that of a three-degrees-of-freedom (3DOF) system as the one depicted in Image 1, which is defined by the horizontal deflection u and the foundation horizontal displacement u^c and rocking φ^c. The parameters defining the dynamic behaviour of the structure are its fixed-base fundamental period T, the height of the resultant of the inertia forces for the first mode h, the mass participating in this mode m, its moment of inertia I and the viscous damping ratio ξ. On the other hand, m_o and I_o denote the pile-cap mass and its moment of inertia, respectively. Both the foundations mass and the structural mass are considered to be uniformly distributed over square areas. The columns of the structure are assumed to be massless and axially inextensible.

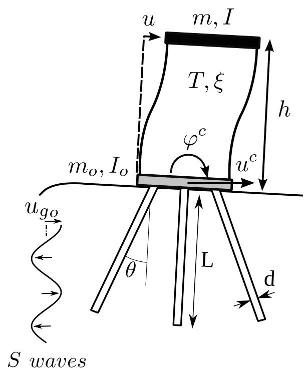

Image 1. Problem definition

A simple and accurate procedure, previously described and validated in [8], is used in this paper to determine the dynamic characteristics of an equivalent single-degree-of-freedom (SDOF) oscillator (Image 2b) which reproduces, as accurately as possible, the response of the 3DOF system shown in Image 2a within the range where the peak response occurs. The equivalent SDOF system can be defined by its damping ratio $\tilde{\xi}$ and its undamped natural period $\tilde{T}$. The structural dynamic response is expressed in terms of Q which represents the ratio of the shear force at the base of the structure to the effective earthquake force (see equation (1)).

$$Q = \left| \frac{\widetilde{\omega}_n^2 \, u}{\omega^2 u_{go}} \right| \tag{1}$$

where $\widetilde{\omega}_n^2 = 2\pi/\tilde{T}$.

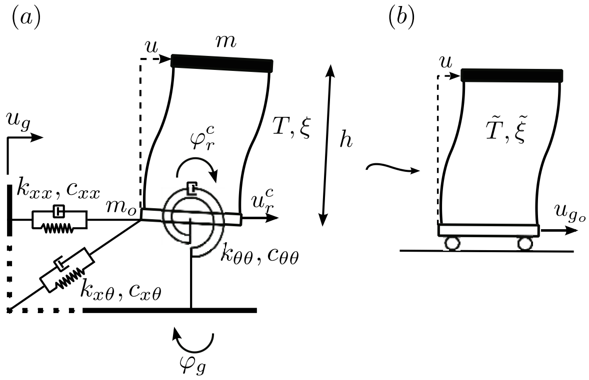

Image 2. (a) Substructure model of a one-storey structure and (b) equivalent single-degree-of freedom oscillator

The above mentioned procedure is based on a substructuring methodology [9] which allows to subdivide the whole system into *building-cap* structure and *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, represented by springs and dashpots in Image 2a. Thus, the solution can be broken into three steps: (1) determining kinematic interaction factors, (2) computing impedances and (3) obtaining the response of the structure supported on springs and subjected to the motion computed in step (1) at each frequency.

In this work, impedances and kinematic interaction factors of pile foundations are numerically obtained by using a boundary element (BEM) -finite element (FEM) coupling formulation [6, 10 – 12]. Several configurations of deep foundations are analysed in this paper. All configurations are symmetrical with respect to planes *xz* and *yz* and consist of square regular groups of identical piles embedded in a homogeneous, viscoelastic and isotropic halfspace. It is assumed that a rigid mass-less pile cap, which is not in contact with the ground surface, constrains the pile-head displacements through fixed-head connection conditions. The geometrical parameters characterizing each configuration are defined in Image 3 being L the pile length, d the pile diameter, θ the rake angle, b the foundation halfwidth and s the distance between centres of adjacent pile heads. In this figure, u_g and φ_g represent the horizontal and rocking motions at the pile cap level when the pile group is subjected to vertically incident plane S waves. Normalizing these values with the free-field motion at the surface u_{g_o} allows obtaining the translational and rotational kinematic interaction factors I_u and I_φ .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.

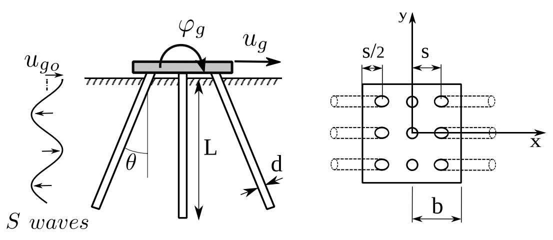

Image 3. Foundation geometry

Following earlier studies [13 – 16] and in order to characterize the soil-foundation-structure system, other dimensionless parameters, covering the main features of SSI problems, are 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 υ_s; and (8) damping ratio ξ_s of the soil. A hysteretic damping model of the type $\mu_s = Re[\mu_s](1 + 2i\xi_s)$ 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.

3. Results –The procedure proposed above is used in this section to study the influence of the rake angle of piles on the seismic response of the superstructure in terms of the maximum shear force at the base of the structure per effective earthquake force unit Q_m.

Different configurations of 2 x 2 pile groups with different values of the pile slenderness ratio ($L/d = 7.5, 15$ and 30) are analysed in the frequency range of interest for seismic loading. In the light of previous studies [8], an intermediate value of the embedment ratio $L/b = 2$ has been chosen as representative in this work. The varying values of the pile spacing ratio s/d are chosen in order to make the different results more comparable among each other by keeping the foundation halfwidth b constant for configurations with different number of piles.
It is assumed that $= 0.15$; $m_o/m = 0$; $0 < 1/\sigma < 0.5$; $h/b = 1, 10$; $\xi = 0.05$; $\xi_s = 0.05$ and $\upsilon_s = 0.4$. These values are representative for typical buildings and soils [16]. Moreover, $E_p/E_s = 10^3$ and $\rho_s/\rho_p = 0.7$. Four different rake angles have been considered: $\theta = 0^o$ (vertical piles), $10^o, 20^o\ y\ 30^o$.

Image 4 shows the impedances of the three different 2 x 2 pile group configurations under study. The stiffness values are represented with solid lines on the left axis, whereas the damping values are depicted with dashed lines to be read on the right axis. The values obtained for the translational and the rotational kinematic interaction factors corresponding to these configurations are provided in Images 5 and 6, respectively. Impedances and kinematic interaction factors are used to compute the maximum shear force at the base of the superstructure Q_m. Images 7 and 8 depict these results for non-slender ($h/b = 1$) and slender ($h/b = 10$) structures respectively.

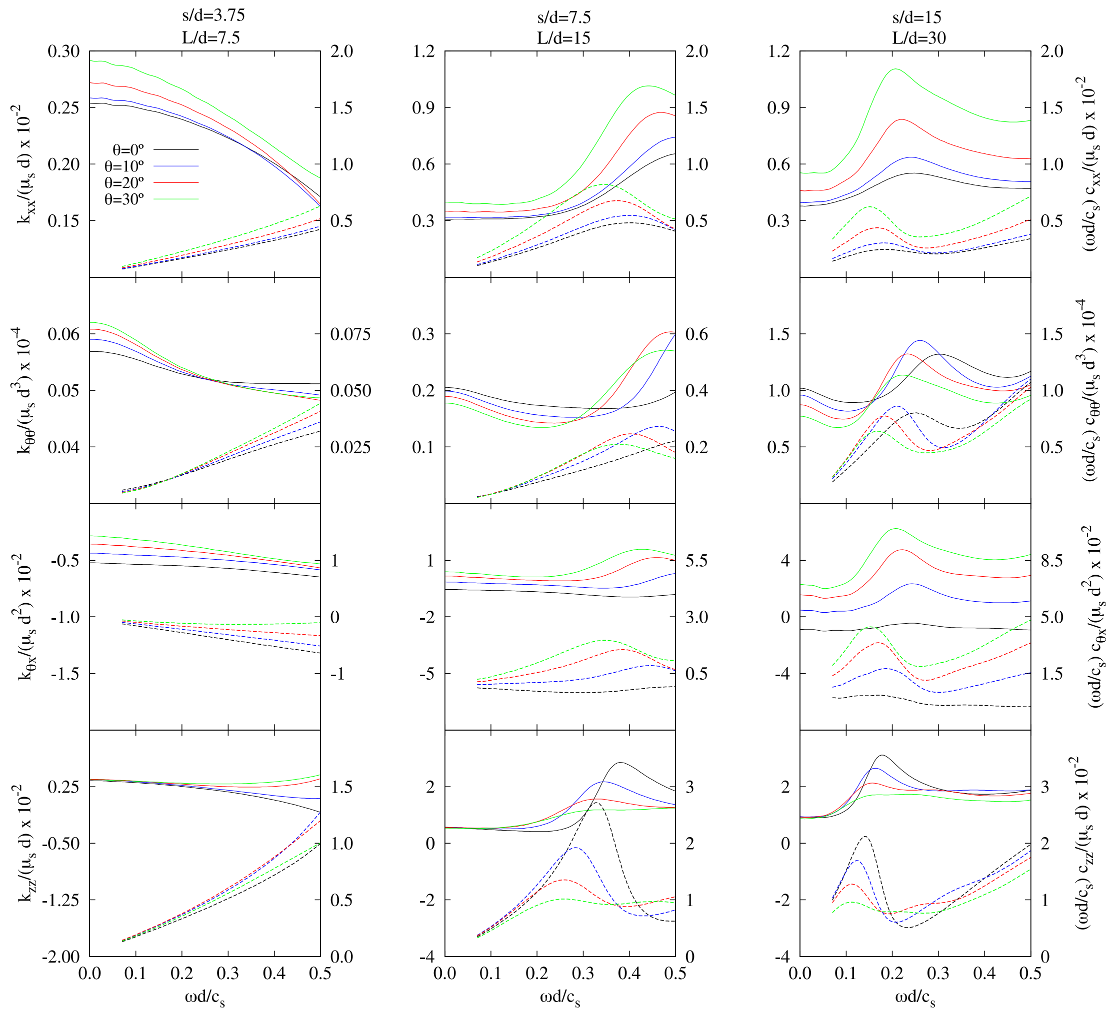

Image 4. Impedance functions of different 2 x 2 pile groups. $E_p/E_s = 10^3$ and $\xi_s = 0.05$. Solid lines to be read on left axis. Dashed lines to be read on right axis.

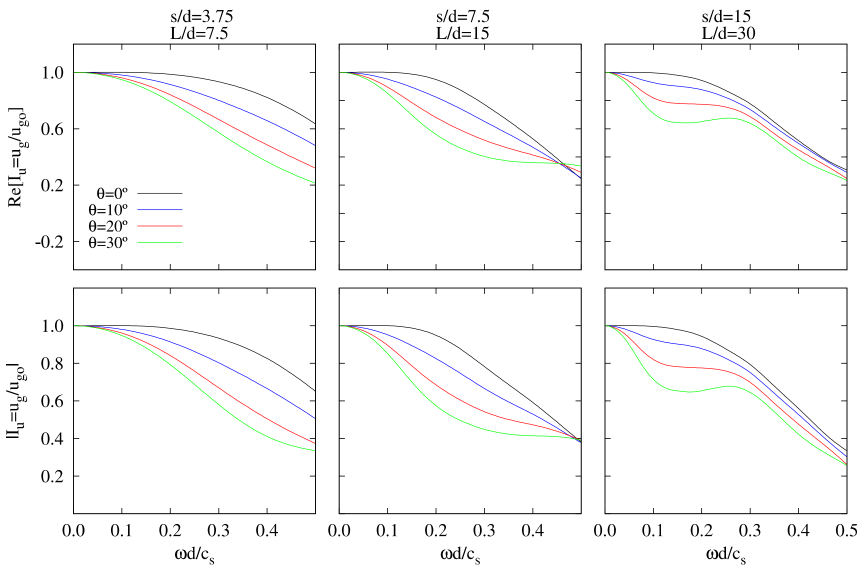

Image 5. Translational kinematic interaction factors of different 2 × 2 pile groups with $L/d = 7.5, 15$ *and* 30. $E_p/E_s = 10^3$ and $\xi_s = 0.05$.

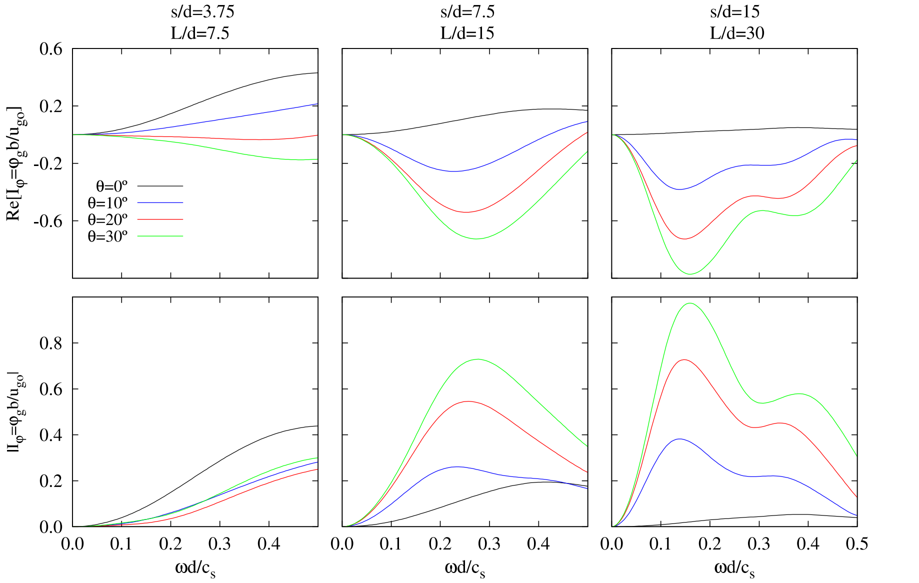

Image 6. Rotational kinematic interaction factors of different 2 × 2 pile groups with $L/d = 7.5, 15\ and\ 30$. $E_p/E_s = 10^3$ and $\xi_s = 0.05$.

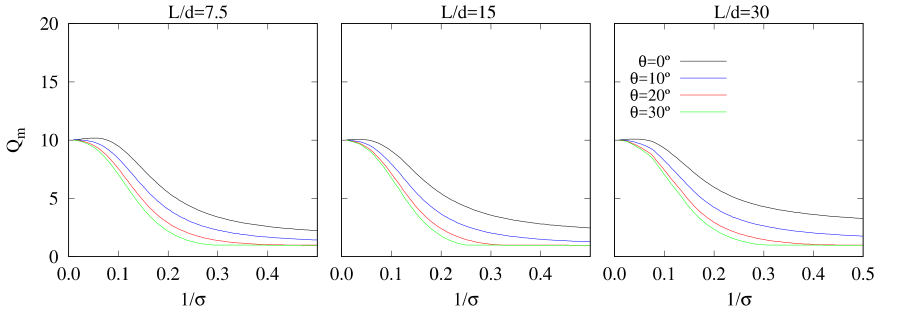

Image 7. Maximum structural response value for non-slender structures ($h/b = 1$) supported on different 2 x 2 pile groups with $L/d = 7.5, 15\ and\ 30$. $E_p/E_s = 10^3$ and $\xi_s = 0.05$.

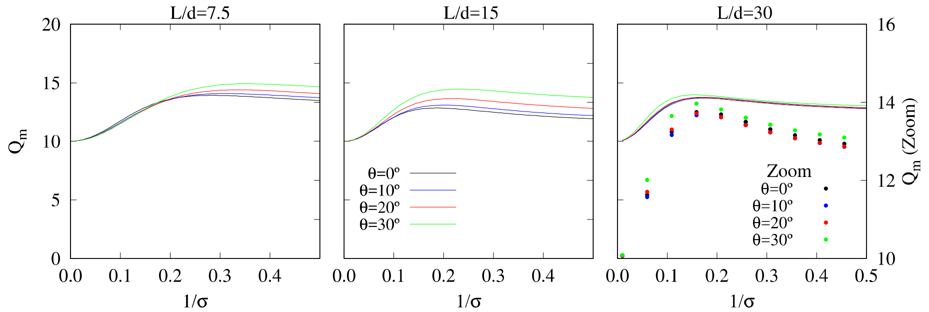

Image 8. Maximum structural response value for slender structures ($h/b = 10$) supported on different 2 x 2 pile groups with $L/d = 7.5, 15\ and\ 30$. $E_p/E_s = 10^3$ and $\xi_s = 0.05$.

4. Conclusions – This paper addresses an analysis of the influence of the rake angle on the dynamic response of structures supported by deep foundations comprising inclined piles. For this purpose, a simple and accurate procedure [8] based on a substructuring methodology is used to predict the maximum structural response of slender and non-slender structures supported by different pile group configurations. In this work, all impedance functions and kinematic interaction factors are computed using a boundary element method (BEM)–finite element method (FEM) coupling model [6, 10 – 12].

It is found that the beneficial or detrimental effect of battered piles on the maximum structural shear force depends on the structural slenderness ratio. For non-slender structures with $h/b = 1$ an increase of the rake angle results in a reduction of the structural response Q_m. Conversely, in the case of high buildings with $h/b = 10$, this trend is reversed.

5. Acknowledgements – This work was supported by the Subdirección General de Proyectos de Investigación of the Ministerio de Economía y Competitividad (MINECO) of Spain and FEDER through research project BIA2014-57640-R. The authors are grateful for this support.

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