

SEISMIC RESPONSE OF DEEP FOUNDATIONS AND PILED STRUCTURES CONSIDERING INCLINED PILES

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Abstract. The beneficial or detrimental role of foundations including inclined piles remains an open question. This paper focuses on two aspects that need further research. One of them is related to the influence of inclined piles on the kinematic interaction factors of deep foundations. The other is the influence of the rake angle on the seismic response of the superstructure. Kinematic interaction factors corresponding to inclined single piles, and square 2 by 2 and 3 by 3 pile groups are presented in ready-to-use dimensionless graphs for different separation ratios. A significant dependence of the foundation kinematic response on the rake angle is shown. A reduction of the horizontal displacements is observed when inclining piles in the direction of the excitation. The response of the superstructure is also addressed in this paper through a procedure based on a substructuring methodology. It is shown that, in general, the rake angle tends to reduce the base shear forces induced at the base of non-slender superstructures, while this trend can be reversed for slender structures.

1 INTRODUCTION

Because of their larger horizontal stiffness, battered piles have been broadly used in foundations which are to be subjected to large horizontal loads. Despite this advantage, the use of inclined 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. Nevertheless, several authors [2, 3] have provided numerical results showing the potential benefits of using inclined piles on the seismic response of both the superstructure and the foundation. The influence of using inclined piles on the dynamic behaviour of the foundation as well as on the dynamic response of the superstructure remains a question that needs further research. Aiming at contributing to fill this gap, in this paper, a three-dimensional

boundary element (BEM)-finite element (FEM) coupling formulation [4, 5, 6] is used to obtain kinematic interaction factors corresponding to several configurations of deep foundations with inclined piles. The soil region is modeled as a homogeneous viscoelastic isotropic half-space by boundary elements. Piles are modeled by monodimensional finite elements as Euler-Bernoulli beams embedded in the soil. Coupling is performed by imposing equilibrium and compatibility conditions. The system is subjected to harmonic vertically-incident shear waves. Thus, kinematic interaction factors corresponding to inclined single piles, and square 2 by 2 and 3 by 3 pile groups are provided in ready-to-use dimensionless graphs for different separation ratios. Furthermore, a procedure based on a substructuring methodology [7] is used to obtain the response of the superstructure in each case which allows to study to which extent the rake angle influences its dynamic behaviour.

2 PROBLEM DEFINITION AND METHODOLOGY

The influence of the rake angle of piles on the kinematic response of several configurations of deep foundations is 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 the left side of Figure 1 being L the pile length, d the pile diameter, θ the rake angle, b the foundation halfwidth and s the distance between centers 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_0} allows to obtain the translational and rotational kinematic interaction factors I_u and I_ϕ .

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 [4, 5, 6]. The boundary element method is used to model the dynamic response of the soil region considering the internal loads arising from the pile-soil interaction. Finite elements are used later in order to introduce into the system the piles rigidity. The whole approach is depicted in Figure 1. Quadratic elements of triangular and quadrilateral shape with six and nine nodes, respectively, are used to discretize the boundary surface. On the other hand, piles are discretized using three-node beam elements. Imposing conditions of equilibrium and compatibility by correlating BEM load lines and FEM piles, a system of equations representing the soil-pile foundation problem can be obtained.

Once impedances and kinematic interaction factors are obtained for each foundation, a simple and accurate procedure [7] is used to analyse 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

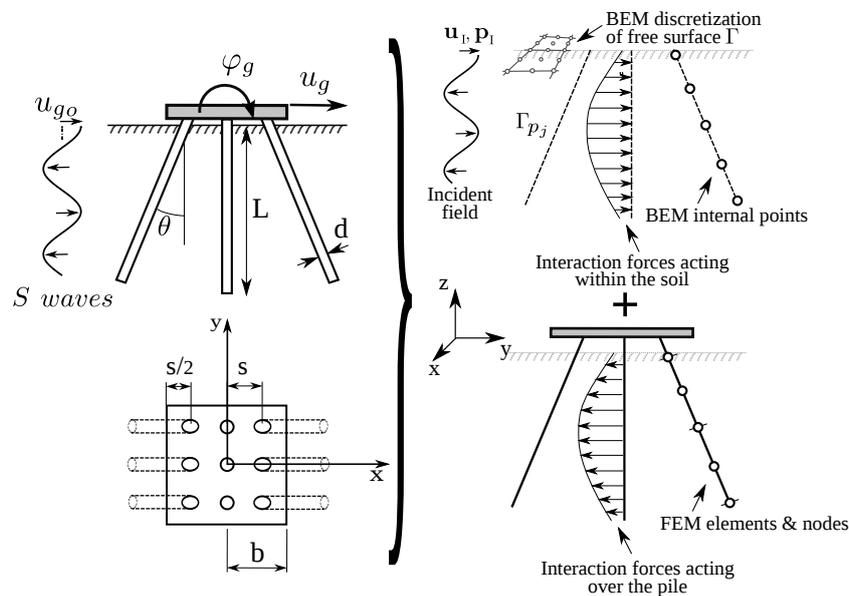


Figure 1: Foundation geometry and BEM-FEM model.

(3DOF) system as the one depicted in Figure 2, which is defined by the horizontal deflection u and the foundation horizontal displacement u^c and rocking φ^c . The above mentioned procedure is based on a substructuring methodology [8] which allows to subdivide the whole system into building-cap structure and soil-foundation stiffness and damping, represented by springs and dashpots in Figure 3a. 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.

The parameters defining the dynamic behaviour of the structure are depicted in Figure 2 being T its fixed-base fundamental period, h the height of the resultant of the inertia forces for the first mode, m the mass participating in this mode, I its moment of inertia and ξ the viscous damping ratio. 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.

Finally, the structural dynamic response is obtained by establishing, in the range where the peak response occurs, an equivalence between the 3DOF system under investigation and a replacement viscously damped single-degree-of-freedom (SDOF) oscillator in terms of Q which represents the ratio of the shear force at the base of the structure to the effective earthquake force.

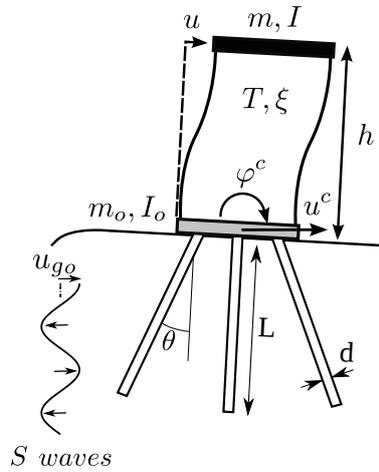


Figure 2: Soil-foundation-structure system.

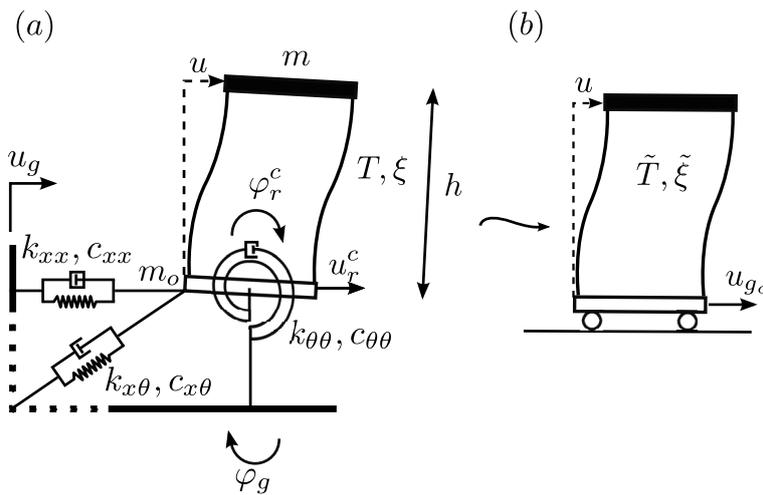


Figure 3: Substructuring model.

$$Q = \left| \frac{\omega_n^2 u}{\omega^2 u_{g_o}} \right| \quad (1)$$

where $\omega_n^2 = 2\pi/\tilde{T}$ being \tilde{T} the undamped natural period of the SDOF equivalent system.

A set of dimensionless parameters, which covers the main features of SSI problems, has been used in this work to characterize the soil-foundation-structure system. These are, among other, the soil Poisson's ratio ν_s , the soil internal hysteretic damping coefficient β_s , the soil-pile density ratio ρ_s/ρ_p , pile-soil Young's modulus ratio E_p/E_s , the pile spacing ratio s/d , the pile slenderness ratio L/d , the embedment ratio L/b , the structural

slenderness ratio h/b , the mass density ratio δ between structure and supporting soil, the wave parameter $\sigma = c_s T/h$ that measures the soil-structure relative stiffness, and the dimensionless excitation frequency $a_o = \omega d/c_s$. The excitation circular frequency is denoted by ω . c_s represents the speed of propagation of shear waves in the half-space.

3 RESULTS

Results for single inclined piles as well as for different configurations of 2×2 and 3×3 pile groups including elements inclined in the direction of excitation are presented in this section. Four different rake angles have been considered: $\theta = 0^\circ, 10^\circ, 20^\circ$ and 30° . The foundation halfwidth is defined as $b = d$ for single piles, $b = s$ for 2×2 pile groups, and $b = 3s/d$ for 3×3 pile groups.

The results presented in this study have been computed by considering that $m_o/m = 0$, $\xi = 0.05$, $h/b = 1, 10$, $\delta = 0.15$, $\beta_s = 0.05$, $\nu_s = 0.4$, $\rho_p/\rho_s = 0.7$, $E_p/E_s = 10^3$ and $0 < 1/\sigma > 0.5$.

3.1 Kinematic interaction factors

Figure 4 illustrates the influence of the rake angle on the kinematic interaction factors of a free-head single pile inclined parallel to the direction of excitation. It can be seen that, in the low-to-mid frequency range, lower values of the horizontal motion are reached as the rake angle increases. With regard to the rotational interaction factor, it slightly decreases with the rake angle for dimensionless frequencies lower than 0.5.

Figures 5 and 6 depict the kinematic interaction factors of 2×2 pile groups with pile spacing ratios $s/d = 3.75$ and $s/d = 7.5$, respectively. In both cases, it can be seen that inclining piles in the direction of excitation leads to lower values of the translational kinematic interaction factor I_u in the low-to-mid frequency range. As s/d decreases, the range of the dimensionless frequency where this effect occurs widens. It should be noticed that horizontal free-field ground motion and cap rotation become out of phase when inclining piles parallel to the direction of excitation. This effect can be observed for rake angle greater than 10° in the case of Figure 5 in which $s/d = 3.75$. However, for greater values of s/d , this effect occurs for lower values of the rake angle, as it can be seen in Figure 6. In this figure, an increase of rotation with the rake angle is shown.

Figures 7 and 8 show the influence of the rake angle on the kinematic interaction factors of 3×3 pile groups with pile spacing ratios $s/d = 2.5$ and $s/d = 5$, respectively. In these cases, some vertical piles are included to maintain symmetry with respect to planes xz and yz . Similar effects as those observed in Figures 5 and 6 can be seen.

3.2 Maximum structural response

Figure 9 shows how the maximum structural response Q_m of slender and non-slender structures supported by a 2×2 pile group is influenced by the variation of the rake angle of piles. For non-slender structures with $h/b = 1$, increasing rake angle θ lead to lower

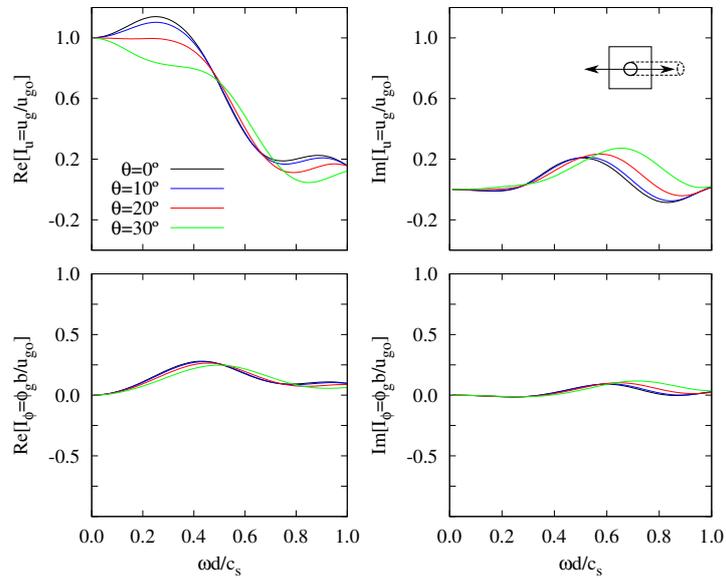


Figure 4: Kinematic interaction factors of a single pile inclined in the direction of excitation with several rake angles θ , $L/d = 15$, $L/b = 15$ and $E_p/E_s = 10^3$.

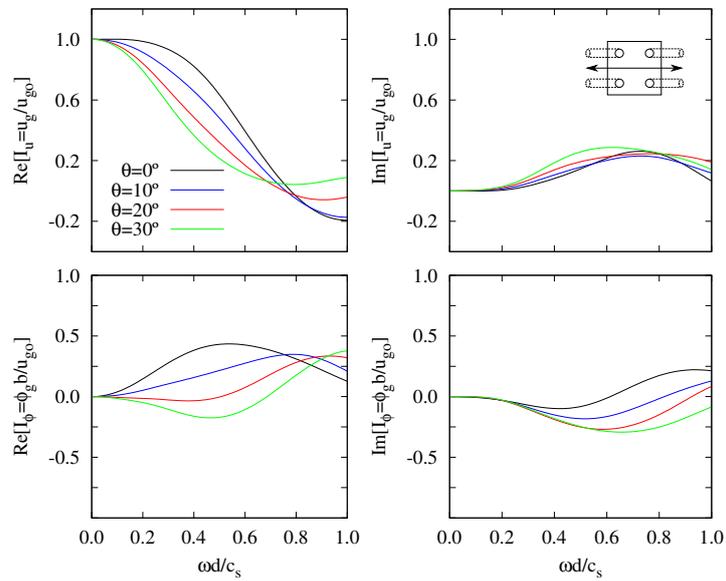


Figure 5: Kinematic interaction factors of 2×2 pile groups with piles inclined in the direction of excitation with several rake angles θ , $s/d = 3.75$, $L/d = 7.5$, $L/b = 2$ and $E_p/E_s = 10^3$.

values of Q_m due to the reduction of the translational kinematic interaction factor and the increased lateral stiffness (see first row in Figure 10). Nevertheless, for slender structures

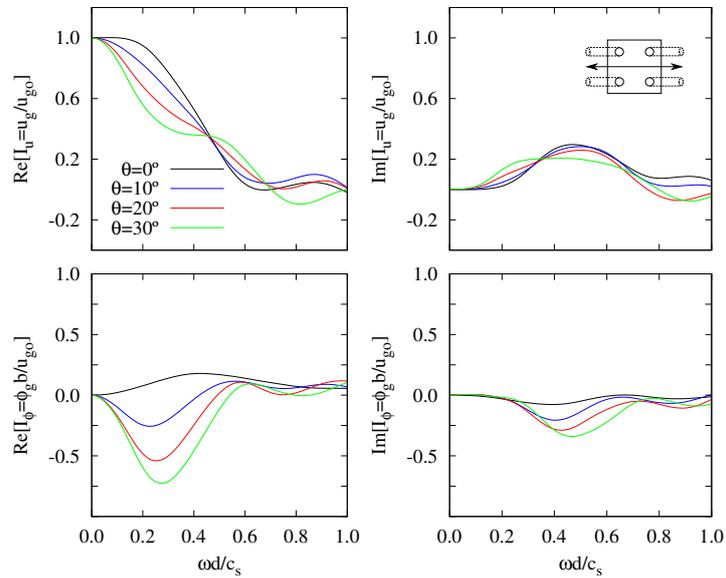


Figure 6: Kinematic interaction factors of 2×2 pile groups with piles inclined in the direction of excitation with several rake angles θ , $s/d = 7.5$, $L/d = 15$, $L/b = 2$ and $E_p/E_s = 10^3$.

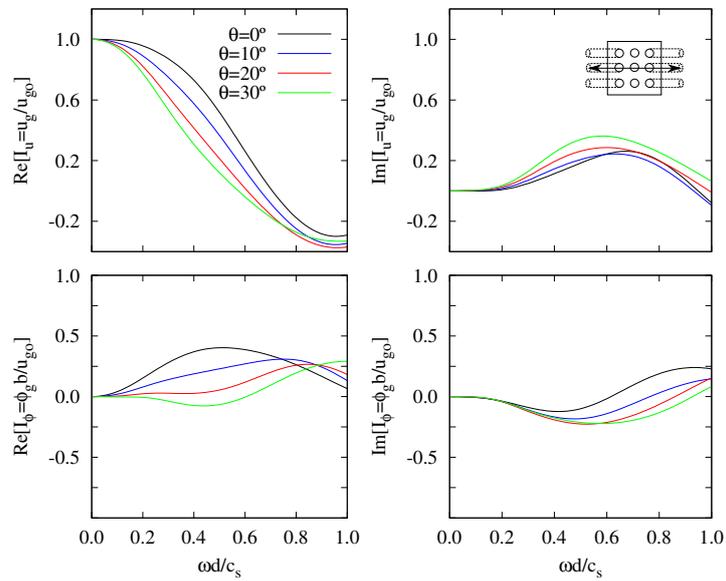


Figure 7: Kinematic interaction factors of 3×3 pile groups with piles inclined in the direction of excitation with several rake angles θ , $s/d = 2.5$, $L/d = 7.5$, $L/b = 2$ and $E_p/E_s = 10^3$.

with $h/b = 10$, higher values of Q_m are reached for increasing values of the rake angle θ . This effect is due to the increase of rotation with the rake angle, which is the controlling

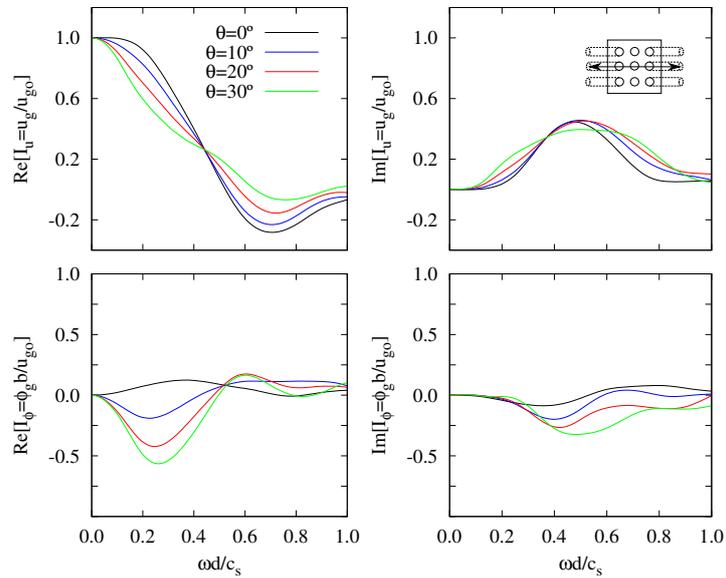


Figure 8: Kinematic interaction factors of 3×3 pile groups with piles inclined in the direction of excitation with several rake angles θ , $s/d = 5$, $L/d = 15$, $L/b = 2$ and $E_p/E_s = 10^3$.

factor in this case.

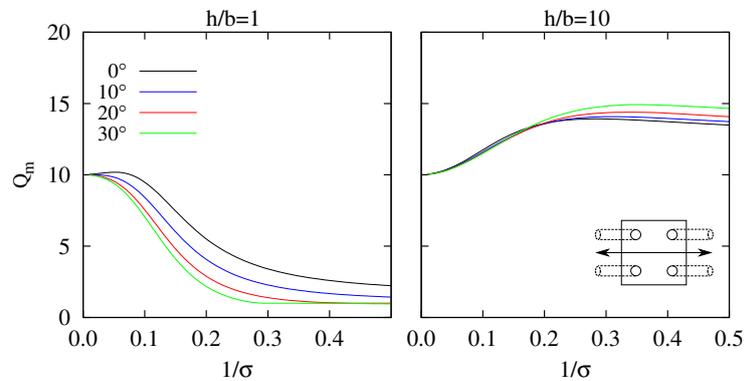


Figure 9: Maximum structural response value Q_m for 2×2 pile groups with piles inclined in the direction of excitation with several rake angles θ , $s/d = 3.75$, $L/d = 7.5$, $L/b = 2$ and $E_p/E_s = 10^3$.

4 CONCLUSIONS

This paper addresses an analysis of the influence of the rake angle on the seismic response of piled foundations as well as its effects on the dynamic behaviour of the structure

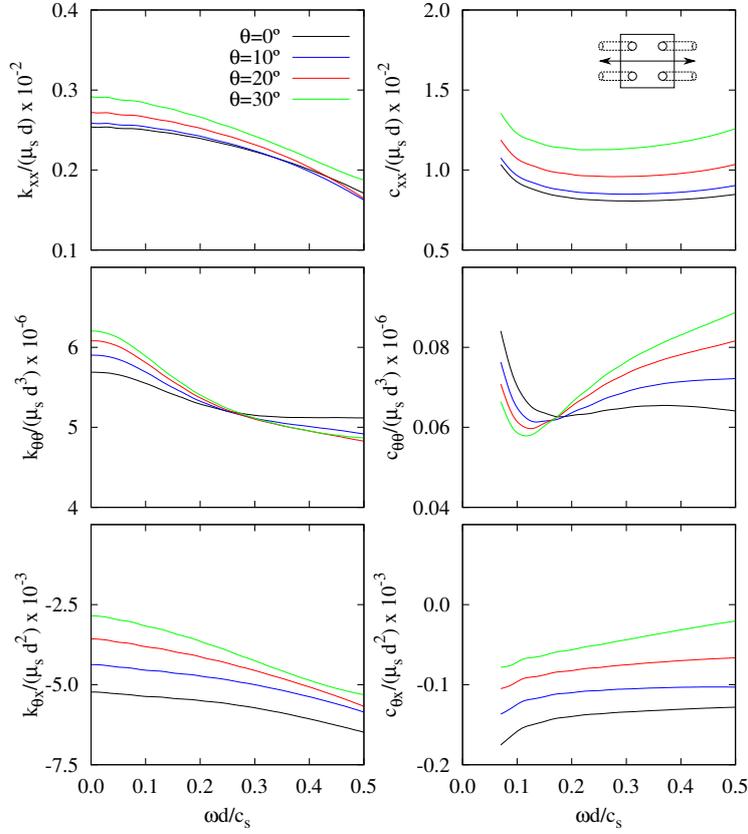


Figure 10: Impedances of 2×2 pile groups with piles inclined in the direction of excitation with several rake angles θ , $s/d = 3.75$, $L/d = 7.5$, $L/b = 2$ and $E_p/E_s = 10^3$.

supported on it. For this purpose, a BEM-FEM coupling model [4, 5, 6] is used to compute numerically the impedances and kinematic interaction factors of free-head single inclined piles and different configurations of 2×2 and 3×3 pile groups including battered elements. Furthermore, a simple and accurate procedure [7] based on a substructuring methodology is used to determine the maximum structural response of slender and non-slender structures supported by the different pile group configurations under investigation. A summary of the main conclusions drawn from the results presented in Section 3 is presented below.

- 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 Qm . Conversely, in the case of high buildings with $h/b = 10$, this trend is reversed.
- Inclining piles parallel to the direction of excitation results in lower values of the

horizontal displacement at the pile cap.

- Greater values of the rake angle of piles generally leads to an increase of the cap rotation. This could have a detrimental effect on the dynamic response of slender structures.
- Cap rotation becomes out of phase with the horizontal free-field ground motion as the rake angle increases.

Results of kinematic interaction factors for different configurations under study are provided in ready-to-use graphs in order to allow the determination, by means of a substructuring methodology, of the response of a superstructure.

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