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KINEMATIC RESPONSE OF GROUPS WITH INCLINED PILES

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ABSTRACT

3D finite element analyses are performed to investigate the dynamic response of pile group configurations which contain batter piles. Three simple groups of two piles are studied: (a) one comprising a vertical pile and a pile inclined at 25^o, (b) one consisting of two piles symmetrically inclined at 25^o and (c) a group of two vertical piles. The latter is used as a reference, in assessing the beneficial or detrimental role of pile inclination to seismic behavior. Two pile–to–cap connections, fixed and hinged, are analysed.The soil shear modulus increases linearly with depth. The role of the inclined piles as well as of pile group configuration on kinematic response is investigated. The influence of the key parameters is analysed and non-dimensional diagrams are presented to illustrate the role of raked piles on pile group response.

Keywords: inclined piles, kinematic response, pile groups

INTRODUCTION

It is well known that seismically loaded piles tend to "resist" and, hence, modify soil deformations generated by the passage of propagating seismic waves (S-waves). As a result, bending, axial, and shear strains develop in the piles, and the motion at the base of the pile-supported structure differs from the free-field motion and may generally include both translational and rotational components. This type of pile distress is called '*kinematic*' in order to be distinguished from the loading generated by the inertial forces of the superstructure. The importance of this type of loading has been explicitly recognised in Eurocode 8. Analyses of the kinematic seismic response of single vertical piles and pile groups have been reported by several researchers including Flores-Berrones & Whitman (1982), Kaynia & Kausel (1982), Dobry & O' Rourke (1983), Harada et al (1981), Gazetas (1984), Fan et al (1991), Kavvadas & Gazetas (1993), Mylonakis et al (1997), Takewaki & Kishida (2005).

Little attention has been paid to the kinematic response of pile group configurations containing inclined (also called raked or batter) piles. Such piles find frequent use in foundations when substantial lateral stiffness is required. However for years, the seismic behavior of inclined piles has been considered detrimental, and many codes require that such piles be avoided. In recent years evidence has been accumulating that inclined piles may, at least in certain cases and if properly designed, be beneficial rather than detrimental both for the structure they support and the piles themselves. (Gazetas and Mylonakis, 1998). Recent research (Guin, 1997) has shown that the response of a typical bridge type structure to representative seismic excitation may improve in many respects when supported by inclined piles. The Edgecumbe 1987 case history offers some support, although indirect, to such findings. In addition, field evidence has been accumulating revealing the successful performance of inclined piles. Characteristic examples include the Maya Warf (Kobe earthquake 1995), the Ohba Ohashi bridge in Japan (1984) and the Landing Road bridge (New Zealand) in the Edgecumbe

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earthquake. Sadek & Shahrour (2006) studied the seismic response of inclined micropiles, and showed that, for kinematic loading, a group of four symmetrically inclined micropiles exhibits lower values of lateral acceleration at the cap level and larger values of internal forces in the piles compared to a group of vertical micropiles.

In this article 3D finite element analyses are performed for the kinematic response of three simple pile group configurations which contain batter piles, embedded in a non-homogenous soil: (a) a group comprising of a vertical and a 25^{o} inclined pile, (b) one of two piles inclined at 25^{o}, and (c) one of two vertical piles. The latter is used as a reference for comparison with the batter pile groups for detecting the beneficial or detrimental role of pile inclination to the seismic behaviour of the foundation.

PROBLEM DEFINITION AND MODEL DESCRIPTION

Figure 1 shows the analysed pile group configurations. All piles of Young's modulus E_p, diameter d, length L, and cross-sectional moment of inertia I_p, are considered to be linear elastic.

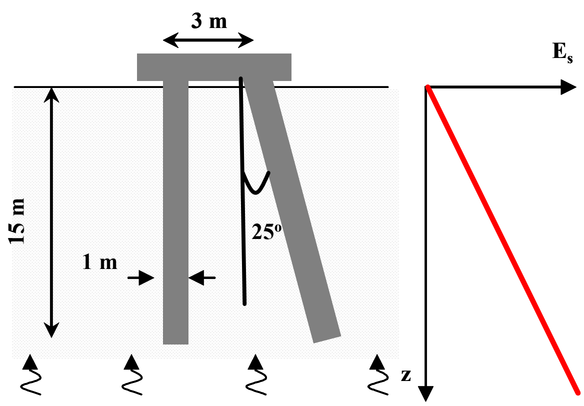

Figure 1. Problem geometry and soil Young's modulus profile

The center-to-center distance between the piles at the pile head level, s, is 3 m. The piles are embedded in a soil deposit whose Young's modulus, E_s, is assumed to vary linearly with depth according to the following equation:

$$E_S = E_O\left(\frac{z}{d}\right) \tag{1}$$

where E_o = 30 MPa is the Young's modulus at depth z = d. It is noted that non-homogenous profiles with E_s linearly increasing with depth are a reasonable assumption for normally consolidated clays (Velez et al, 1983).

The problem is analyzed in 3-D, making use of the Finite Element (FE) method. Both the pile and the soil are assumed to be linear elastic materials. Soil and pile are modelled with eight-noded brick elements. Due to symmetry, only one half of the model is analyzed, thus significantly reducing computation time. Figure 2 depicts the finite element discretization for the three pile group configurations studied. Two pile-to-cap fixity conditions are considered, namely fixed-head and hinged-head piles. Rayleigh damping is used to model material damping, taken equal to 5% for the range of frequencies between the eigenfrequency of the soil deposit and the dominant frequency of the earthquake. Appropriate kinematic constraints are imposed to the lateral edges of the model allowing the latter to move as a laminar box.

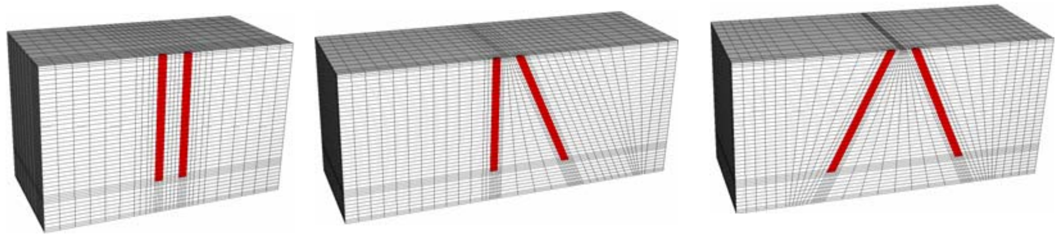

Figure 2. Finite element discretization of the three pile group configurations analyzed

First, the kinematic response of the three pile group configurations to vertically propagating harmonic waves is investigated, and the displacements and rotations at the pile-cap are compared with the free-field displacements for a wide frequency range. At a further step, the pile groups are subjected to three real acceleration time histories: (i) Lefkada record (Gazetas et al, 2005), PGA = 0.42g, from the Lefkada 2003 earthquake (M = 6.4), (ii) Aegion–rock outcrop motion (Gazetas et al, 2005), PGA = 0.39 g from the Aegion 1995 earthquake (M = 6.2), and (iii) JMA record, PGA = 0.83 g, from the Kobe 1995 earthquake (M = 7.2).

OBSERVED TRENDS FROM HARMONIC EXCITATION

In the case where harmonic waves are used as base excitation, the effects of soil-pile group interaction are portrayed in the form of two kinematic response factors (Fan et al. 1991):

$$I_u = \frac{\left|U_p\right|}{U_{ff}} \qquad \text{and} \qquad I_\phi = \frac{\left|\Phi_p\right| d}{U_{ff}} \tag{2}$$

where U_p is the horizontal displacement amplitude of the pile cap, Φ_p is the rotation amplitude of the pile cap , and U_{ff} is the associated displacement amplitude of the free field. The variation of these two factors is illustrated in Figure 3 for the three pile groups studied and for both pile-to-cap fixity conditions considered as a function of the frequency factor α_0:

$$a_0 = \frac{\omega d}{V_s} \tag{3}$$

where ω is the circular frequency of the harmonic excitation, and V_s is the shear wave velocity of the soil.

For the groups containing inclined piles with respect to the vertical pile group the following trends are observed:

(a) There is a low-frequency region $0< \alpha_0< \alpha_{01}$, where $I_u \approx 1$, an intermediate-frequency region $\alpha_{01}< \alpha_0< \alpha_{02}$, where I_u decreases rapidly with frequency, and a high-frequency region $\alpha_0> \alpha_{02}$, in which I_u fluctuates with frequency. However, the limits of these three distinct regions vary with pile group configuration.

(b) Pile groups containing inclined piles (configurations "b" and "c") filter the free field motion more than the vertical pile group, even at very low frequencies, due to the increased lateral stiffness of the batter piles.

(c) For the pile group configurations "b" and "c", the frequency at which I_u reaches its lowest value, α_{02}, is smaller than that for the vertical pile group. Moreover, I_u decreases more rapidly with increasing values of a_0 in the range of (a_{01}, a_{02}). At the high frequency region the fluctuation with frequency of I_u is suppressed in configurations "b" and "c" and an increase is only observed close to α_0= 0.5. As expected, the stiffer pile groups are more effective in restraining seismic soil movements, and, therefore, their kinematic response is characterized by smaller values of α_{01} and α_{02} compared to the more flexible vertical pile group.

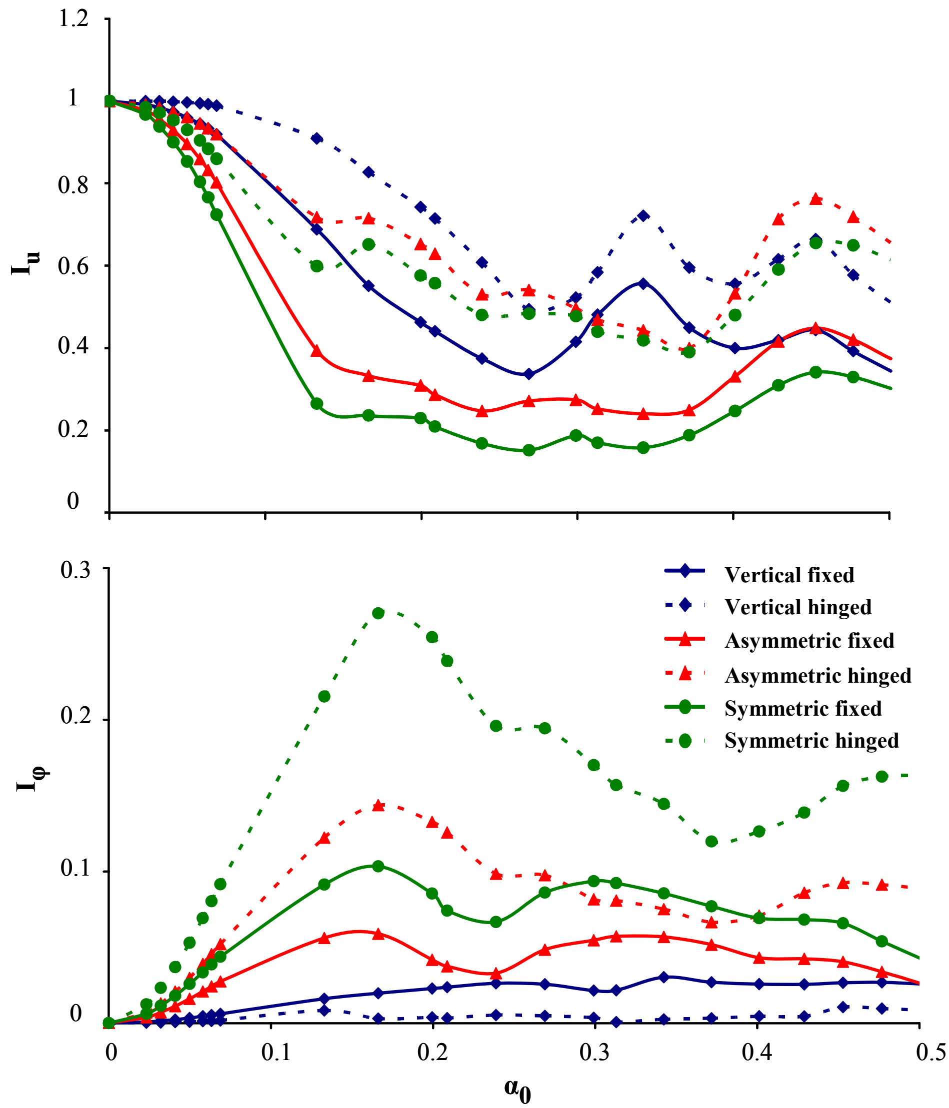

Figure 3. Effect of pile group configuration and pile head fixity condition on kinematic interaction of pile groups in non-homogenous soil

(d) It is important to note that pile groups experience cap rotations due to seismic excitation. These rotations are more significant for the groups containing batter piles. More specifically, the greater the pile group stiffness due to the presence of inclined piles, the more significant the cap rotation is. This means that while batter piles tend to decrease the translational component of the "effective" pile-cap input motion, their presence leads to large cap rotation which may be of importance for slender superstructures.

(e) The decrease of the degree of fixity between pile and pile-cap (from fixed- to hinged-head piles) makes the "effective" pile-cap input motion more severe in terms of both displacement and rotation. Moreover, the resistance of inclined pile groups to soil displacements decreases and the differences between vertical and inclined pile group displacements become less pronounced in the case of hinged-head piles.

RESULTS FROM EXCITATION WITH ACCELERATION TIME HISTORIES

Results from the analyses using three real acceleration time histories as excitation at the base of the models are presented herein. Distributions of displacements and internal forces for the Lefkada (2003) record are only presented in this paper due to space limitations, but the observed trends and conclusions are valid for all earthquake records used in this study. Moreover, the maximum kinematic response of the configurations to all three acceleration time histories utilised as base excitation is presented in Figure 7. All results are normalized by the corresponding response of the fixed-head vertical pile group, since this is the type of pile foundation that is commonly used in practice.

(a) Response Spectra

The response spectra at pile-cap level normalized by the peak ground acceleration of the free-field are depicted in Figure 4. For fixed pile-to-cap conditions, configurations with inclined piles tend to produce lower spectral accelerations at the pile-head compared to those of the vertical group, especially in the lower period range (0<T<1), which is the range of interest for most earthquakes. This observation is in agreement with the fact that inclined piles reduce the translational components of the "effective" pile-cap input motion with respect to the group with vertical piles. However, changing the degree of fixity from fixed- to hinged-head condition the beneficial role of inclined piles in the reduction of the "effective" input motion attenuates significantly.

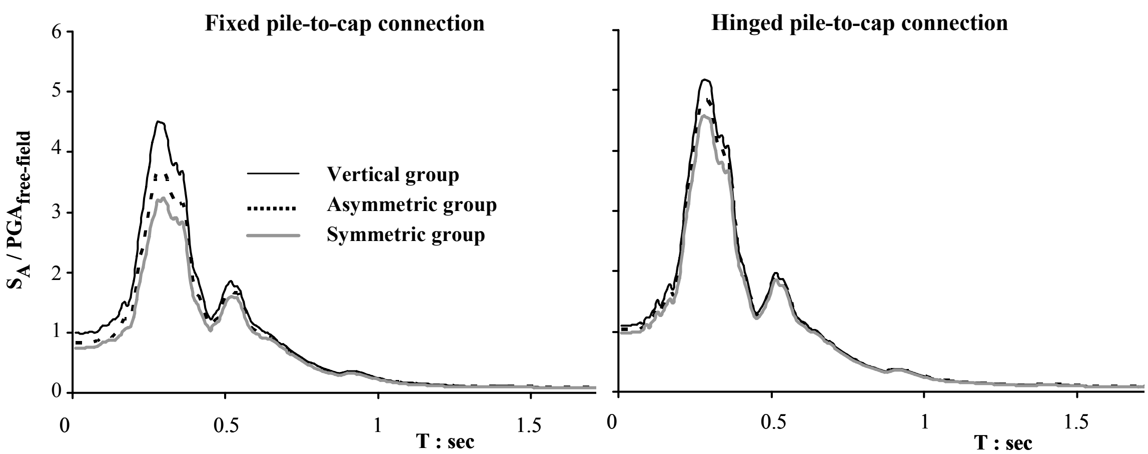

Figure 4. Normalized response spectra of the three pile configurations for fixed, and hinged pile-to-pile-cap connection (Lefkada record)

(b) Displacements

The great advantage of the group configurations containing batter piles is that the maximum lateral displacement at the pile-cap is smaller than that of the vertical pile group, as is portrayed in Figure 5. The maximum horizontal displacement of the piles for three recordings is illustrated in Figure 7. Particularly in the case of the group with two inclined piles the displacements are up to 40% less than in the case of the group of vertical fixed-head piles. This observation matches well the frequently observed behavior of the inclined piles in the field under conditions of extensive soil movements (such as liquefaction and lateral spreading). For the group of hinged-head inclined piles the displacement at the pile-cap is only 20% less than that of the group with fixed-head vertical piles.

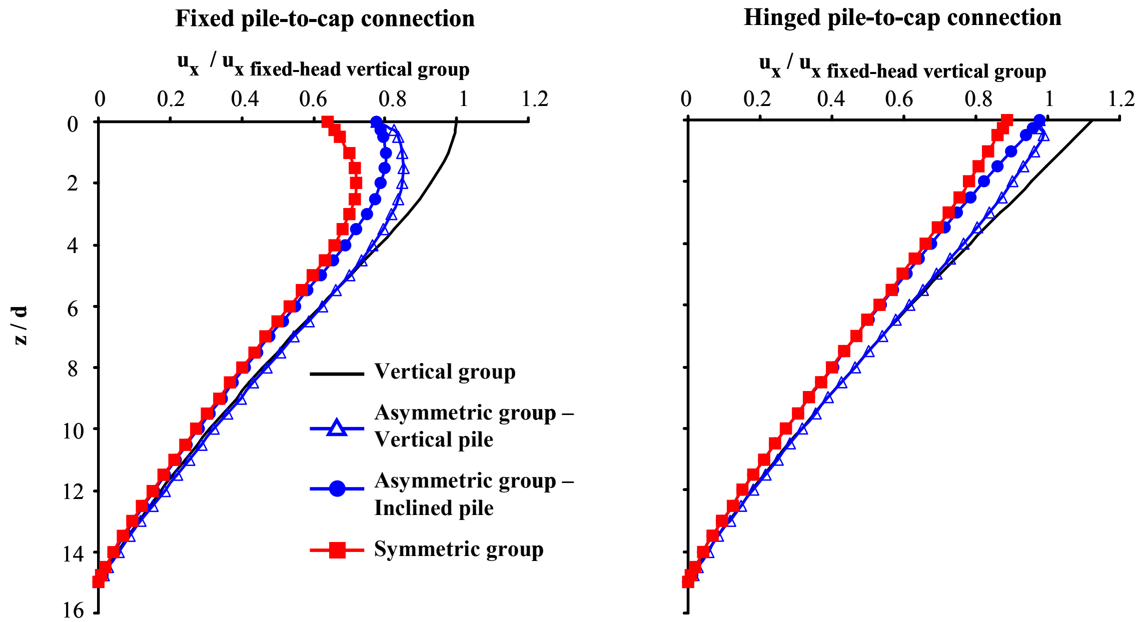

Figure 5. Distibution of horizontal displacements at the time when the maximum occurs (Lefkada record)

(c) Internal Forces

The distributions of the internal forces (bending moments, shear and axial forces) along the piles at the time when the maximum occurs normalized by the maximum value of the internal force of the vertical fixed-head pile group are presented in Figure 6. The maximum value of the bending moment and axial force developed on the piles for all the records used as excitation in the analyses are presented in Figure 7.

Notice that the asymmetric configuration "b" exhibits systematically greater bending moments at the connection with the cap than the piles of the other two groups, mainly due to the asymmetry of the foundation. As a result, the inclined pile, which is stiffer than the vertical one, resists more the soil movement and, hence, greater bending moments are developed, as depicted in Figure 7 for all records utilized herein. The inclined pile in the symmetric group configuration exhibits similar behavior with the vertical pile in the asymmetric pile group configuration, and both develop their maximum bending moment two diameters below the ground surface. When the piles are hinged to the cap, the bending moments at the pile-head become zero, while the inclined piles in configuration "c" develop their maximum bending moment at a greater depth (in the order of 6 pile diameters), and is smaller than the maximum bending moment of the vertical pile group

For fixed pile-cap conditions, the vertical pile in configuration "b" develops greater shear force than that of the inclined pile in the same group and exhibits similar behavior to the inclined pile in configuration "c". However, when the degree of fixity decreases, the maximum shear force in configuration B becomes significantly larger than that in the group of vertical fixed-head piles. On the contrary, configuration "c" with hinged pile-to-cap connection develops significantly smaller shear force than the group of fixed-head vertical piles.

Inclined piles in both configurations "b" and "c" develop significantly larger (in the order of 4) axial force than that of the vertical group for both fixed and hinged pile-head conditions. This force, however, occurs at a depth of approximately 10 pile diameters.

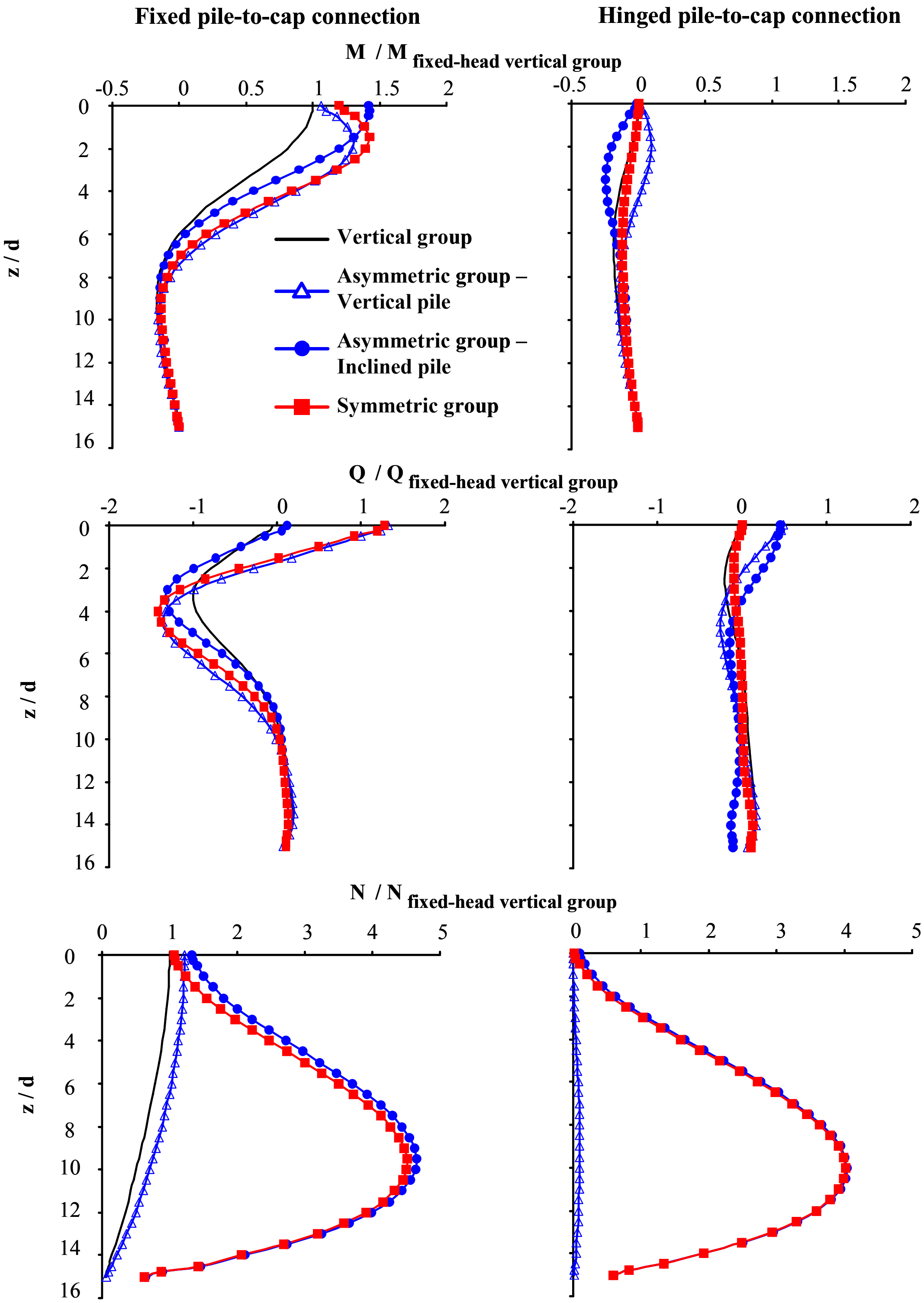

Figure 6. Distibution of bending moments, shear forces, and axial forces at the time when the maximum occurs (Lefkada record)

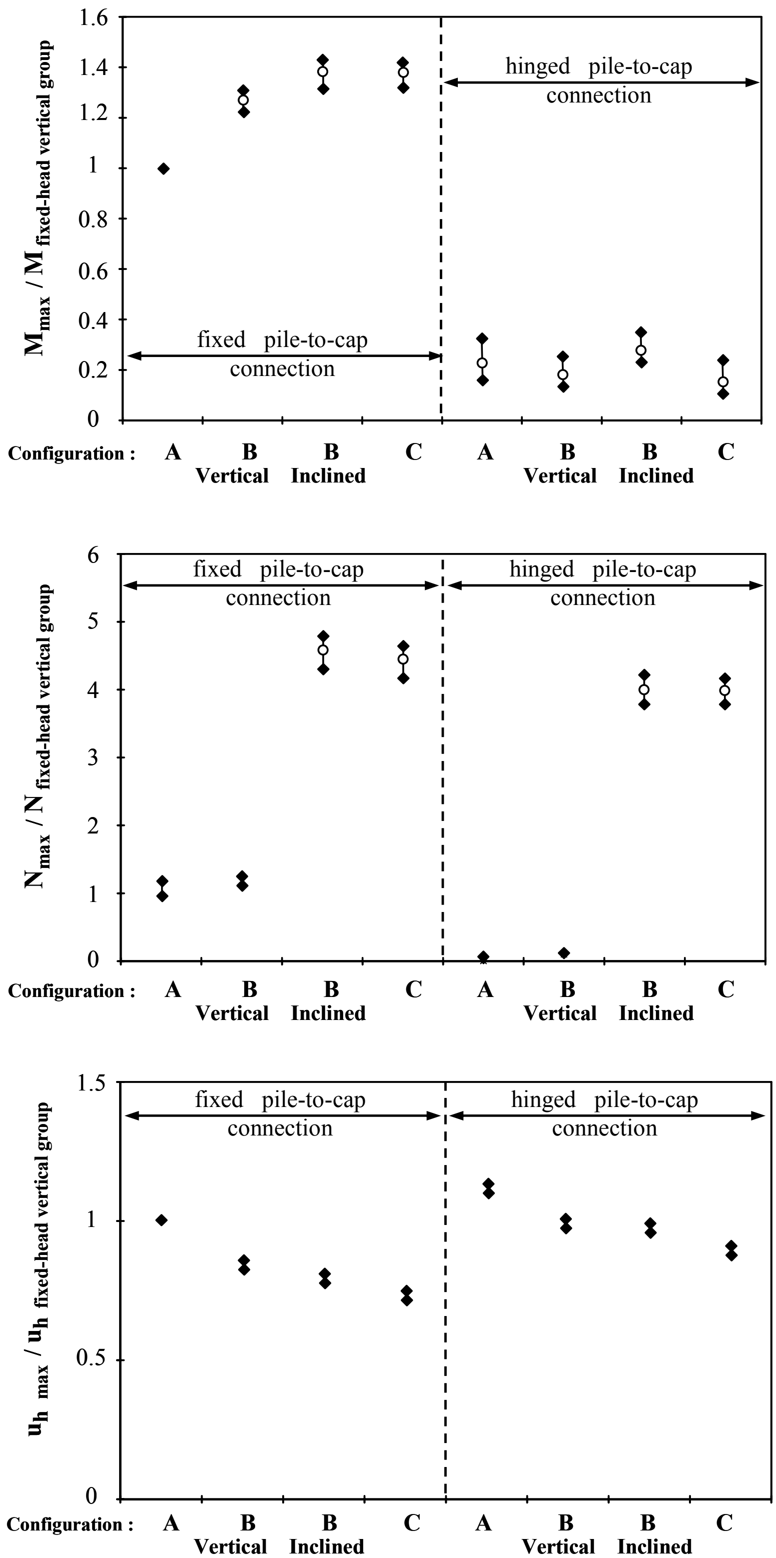

Figure 7. Foundation maximum response to kinematic loading with Aegion–rock outcrop (1995), Lefkada (2003), and JMA (1995) acceleration records

CONCLUSIONS

The results of the kinematic response of pile group configurations containing batter piles are presented in this paper. Dimensionless graphs are produced for dynamic horizontal displacements and rotations of the pile–cap for three simple groups embedded in a non-homogenous soil profile. Two pile–to–cap connections, fixed and hinged, are studied. These graphs provide insight on the role of inclined piles on the "effective" pile–cap input motion at the base of the superstructure. The response Analyses with real earthquake time histories are performed, and acceleration response spectra, displacement and internal force distributions normalized by the corresponding ones of the group with vertical fixed-head piles are provided to elucidate the role of inclined piles in response of the foundation. The different pile group configurations modify the seismic excitation leading to different maximum response at the pile–cap level. The internal forces that develop near the pile-cap are greater when the group contains an inclined pile and, hence, attention should be drawn on the detailing of the pile–to–cap connection.

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REFERENCES

Dobry R. & O' Rourke M. J. Discussion on "Seismic response of end-bearing piles" by Flores-Berrones R. & Whitman R. V., Journal of Geotechnical Engineering Division, ASCE, p 109, 1983

Fan K., Gazetas G., Kaynia A., Kausel E. and Ahmad S. "Kinematic seismic response of single piles and pile groups," Journal of Geotechnical Engineering, 117, 1860-1879, 1991

Flores-Berrones R. & Whitman R. V. "Seismic response of end-bearing piles," Journal of Geotechnical Engineering Division, ASCE, 108, 554-569, 1982

Gazetas G. "Seismic response of end-bearing piles," Soil Dynamics and Earthquake Engineering, Vol. 3, 89–93, 1984

Gazetas G. and Mylonakis G. "Seismic soil-structure interaction: new evidence and emerging issues, " Geotechnical Earthquake Engineering and Soil Dynamics III, ASCE, 2, Geotechnical Special Publication, 75, 1119-1174, 1998

Gazetas G., Anastasopoulos I., and Dakoulas P. "Failure of harbor quaywalls in the Lefkada 2003 earthquake," Proceedings of Geotechnical Earthquake Engineering Satellite Conference, Osaka, Japan, 62-69, 2005

Guin J. "Advances in soil-pile-structure interaction and non-linear pile behavior," PhD thesis, State University of New York at Buffalo, 1997

Harada T., Kubo K., and Katayama T. "Dynamic soil-structure interaction by continuum formulation method," Report, Institute of Industrial Science, Tokyo, 29 (5), 1981

Kavvadas M. and Gazetas G. "Kinematic seismic response of free-head piles in layered soil," Geotechnique, 43, 207-222, 1993

Kaynia A. M. & Kausel E. "Dynamic stiffness and seismic response of pile groups," Research report R82-03, Massachusetts Institute of Technology, 1982

Sadek M. & Shahrour I. "Influence of the head and tip connection on the seismic performance of micropiles," Soil Dynamics and Earthquake Engineering, 26, 461-468, 2006

Takewaki I. & Kishida A. "Efficient analysis of pile-group effect on seismic stiffness and strength design of buildings," Soil Dynamics and Earthquake Engineering, 25, 355-367, 2005

Velez A., Gazetas G., and Krishnan R. "Lateral dynamic response of constrained-head piles," Journal of Geotechnical Engineering, ASCE, 109, 1983