DYNAMIC BEHAVIOR OF PILE GROUP CONSIDERING SOIL-PILE-CAP INTERACTION

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ABSTRACT :

It is well known that the earthquake response of a pile-supported structure is strongly affected by the dynamic soil-pile interaction. In the case of weak soils or severe ground motions, group piles are often the suitable solution. In most practical cases the pile cap is sitting on the ground as well as the piles in the group. The contact between the pile cap and supporting pile is simply neglected in practice. However, with advent of fast computers, geotechnical researchers would like to reach precise and rigorous solutions. Therefore, in this research, a finite element model to take into account soil-pile-cap interaction for dynamic loads is developed. The proposed model for the soil-pile-cap (SPC) system consists of structural elements to represents piles and concrete cap, brick elements representing the soil and interface element to model the contact surfaces between soil-pile and soil-cap. Seismic response of the system is found using an explicit successive-coupling incremental solution scheme. Material nonlinearity of soil is also introduced into the model. Proper absorbing boundary conditions, simulating radiation effects are used. Developing a comprehensive study, a series of numerical analyses using dynamic finite element method are conducted to investigate affecting parameters on dynamic behavior of group-pile foundation. Along with the effect of pile-soil-cap interaction, the piles slenderness, type of piles, piles space and embedment of the pile cap is also studied. The results showed that neglecting the pile-soil-cap interaction in dynamic analysis of pile groups could lead to non-exact results in terms of the pile group response.

KEYWORDS: pile groups, soil-pile-cap interaction, dynamic behavior

1. INTRODUCTION

For the last three decades, a large of number of studies has been conducted on dynamic soil-pile group interaction. Dynamic behavior of soil-pile group systems in dynamic loading processes is highly affected by nonlinear behavior of soil, soil plasticity and also gapping and sliding during extreme excitations. This highlights the necessity of conducting more precise analysis. With advent of fast computers, focus of researchers is increasing towards rigorous soil-pile-structure interaction analyses. The most prominent developed methods for dynamic analysis of single piles can be listed as Winkler model, empirical non-linear "p-y", "t-z" curve models, analytical and semi-analytical formulations (Novak' plane-strain approach) and Finite-element formulations. In these methods, it has been found that the most affecting parameters on response of singles piles are: soil-pile stiffness ratio, the pile slenderness, type of pile, soil shear modulus and the pile head boundary condition. For the pile groups, since each pile's response is affected not only by its own load, but also by the load and deflection of the neighboring piles, therefore the dynamic response of the group pile should be evaluated accounting for the frequency dependent pile-to-pile interaction phenomenon. A variety of numerical and analytical methods have been developed to compute the dynamic response of pile groups. Wolf and Von Arx (1978) employed an axisymmetric finite element formulation to establish the dynamic displacement field due to ring loads. Wass and Hartmann (1981) formulated an efficient semi-analytical method, which uses ring loads and was well suited for layered media for near field. Kaynia and Kausel (1982) further improved the accuracy by combining the cylindrical loads with the consistent stiffness matrix of layered media using a boundary element formulation. He introduced the dynamic interaction factors, which are complex and frequency dependent. The pile group response to earthquake excitations not only is depended to the main affecting dynamic parameters of single piles but also is influenced by relative distances of piles due to pile-to pile interaction effect.

The soil nonlinear behavior can play an important role in both single pile response and pile-to-pile interaction resulting more deformation to the group pile. Heavy damage reported on pile foundations during recent earthquakes (e.g. Chi-Chi 1999 and Kocaeli 1999) showed a need to take into account the nonlinear behavior of soil for designing pile-supported structures. To adequately account for the soil non-linearity, dynamic analysis should be performed in the time domain. Nogami [6] introduced material and geometrical non-linearities in the analysis using discrete systems of mass, spring and dashpots. However, proper representation of damping and inertia effects of continuous soil media is difficult with such discrete systems. The inclusion of material non-linearity due to soil plasticity requires the analysis to be performed using finite element approach. Wu and Finn (1997) presented a quasi-3D method for the analysis of nonlinear pile response. Bentley and El Naggar (2000) investigated the kinematic response of single piles to account for the soil plasticity using the Drucker–Prager soil model and gapping at the soil–pile interface. No work hardening for soil media was taken into account. Cai et al. included soil plasticity with the work hardening in a finite element model for single piles. However, they assumed fixed boundary conditions and neglected damping in the foundation subsystem. Using the hierarchical single surface (HiSS) soil model, Maheshwari et al. (2003) examined the effects of material non-linearity of soil on the free field response as well as on the kinematic response of single piles. Maheshwari et al. (2004) extended it for pile groups.

The pile cap may affect the kinematic and inertial dynamic response of pile-supported structures. In some cases of pile groups, pile caps could be resting on the ground surface or may be even embedded. In both cases, an interaction between the flexible cap, pile and supporting soil is anticipated. Furthermore, embedded caps could provide an excessive stiffness and damping during the dynamic excitation as the embedded shallow foundations do. To clarify the significance of the dynamic soil-pile cap interaction effects in non-linear seismic group pile responses a 3D nonlinear model was developed. In this paper, the effect of pile-soil-cap interaction along with the other mentioned affecting parameters on seismic response of a group with shallow and embedded cap are investigated. The model was subjected to transient excitation.

2. SOIL-PILE SYSTEM

In this study three soil-pile systems are considered. One involves a 2 x 2 pile group shown in Figure 1. having the pile cap located above the ground surface (Figure 2a). The other two systems are using the same configuration and geometry of piles referred as the reference model (Figure 1) but having the pile cap rested on the ground surface (Figure 2b) and embedded in a soil side layer (Figure 2c). The diameter and length of piles in the reference model are 0.4m and 5m, respectively. The pile cap in all three systems is having 2m x 2m x 0.5m dimensions.

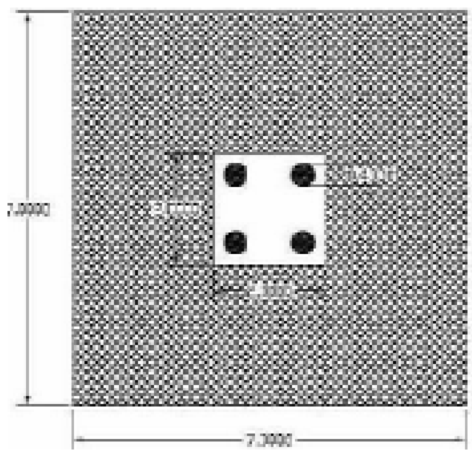

Figure 1. The reference pile group plan

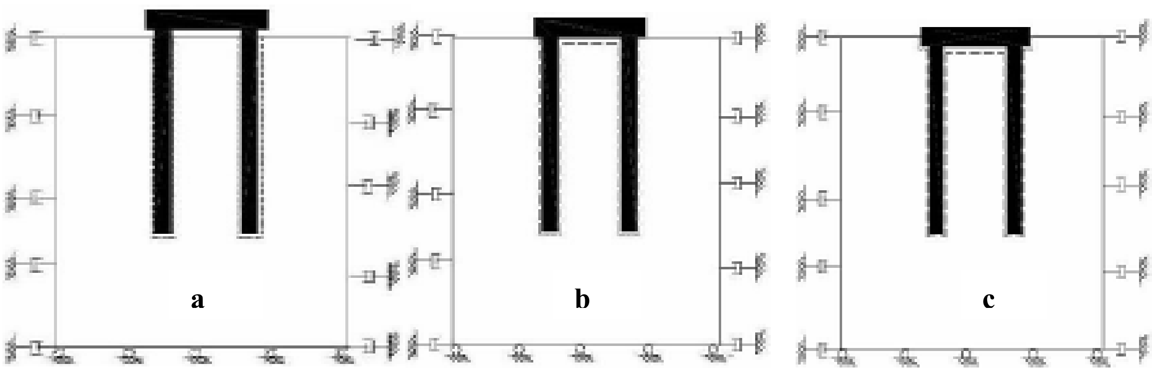

Figure 2. Three pile-soil-cap systems

Full three-dimensional finite element models are developed to represent the soil-pile-cap systems. The soil and piles are modeled using eight-node brick elements with each node having three translation degrees of freedom. Viscous boundaries as artificial transmitting boundaries are attached in all three directions along the model boundaries (Figure 3) in order to model the far field conditions and allow for wave propagation. The coefficients of the dashpots are derived separately for the horizontal and vertical directions based on soil shear and compression velocities (V_s, V_p). For computational reasons, soil material damping is taken as a Raleigh damping. Therefore, the material damping is assumed to be proportional to stiffness and mass matrices. The coefficients of the linear combination are obtained using two natural frequencies of the soil-pile-cap model, provided that the corresponding damping coefficients are given as:

$$\xi_i = \alpha / 2\omega_i + \beta\omega_i / 2 \tag{1}$$

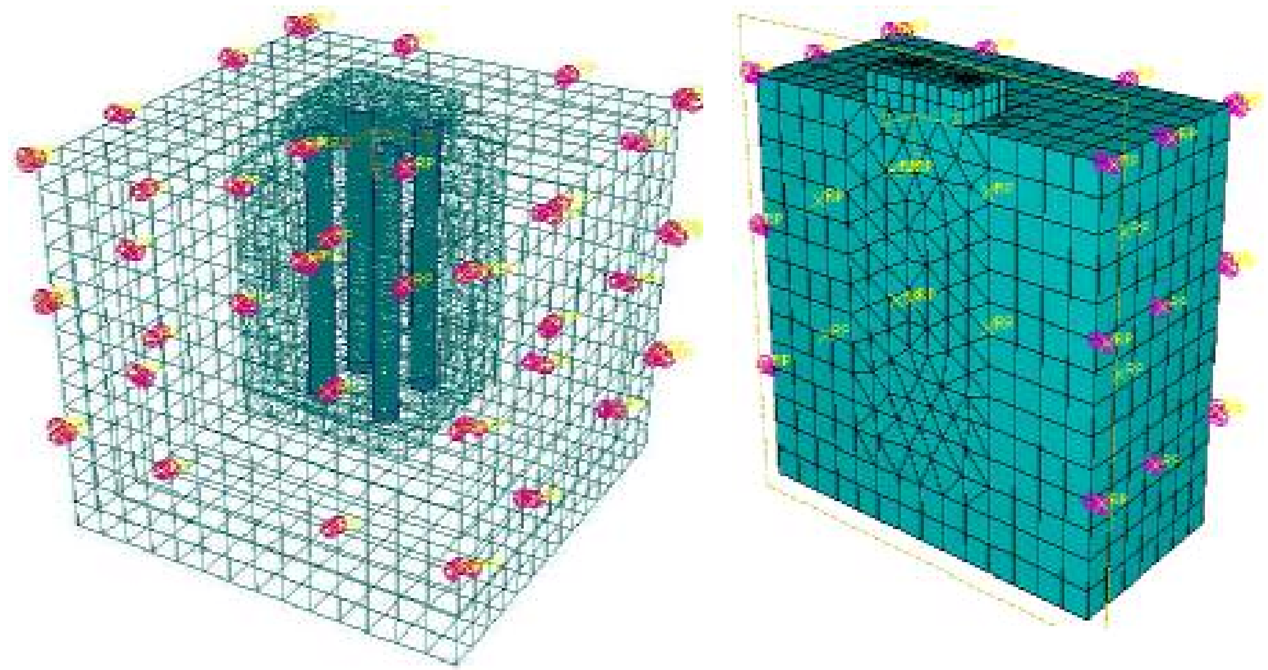

Figure 3. Finite element model for the pile group system: (a) 3D (b) cross section

where α, β are the mass proportional and stiffness proportional coefficients of the damping matrix. Also ω_i, is the natural frequency of the i^{th} mode of the system. In the plastic zone the Drucker-Prager failure constitutive model was adopted where the failure envelope is based on Mohr-Coulomb criteria. According to this theory, failure along a plane in the soil occurs by a critical combination of normal and shear stresses and not by normal or shear stress alone. Using the Drucker-Prager criteria, the yield function can be defined as:

$$F(\boldsymbol{\sigma}', \mathbf{k}) = J_2 - \left(\frac{c'}{\tan\varphi'} + p' \right) M_{JP} = 0 \tag{2}$$

In the present analysis, the soil-pile and soil-cap interfaces are modeled using an interface element. In the interface element, it is assumed that separation occurs in the direction of loading only and the soil and pile are

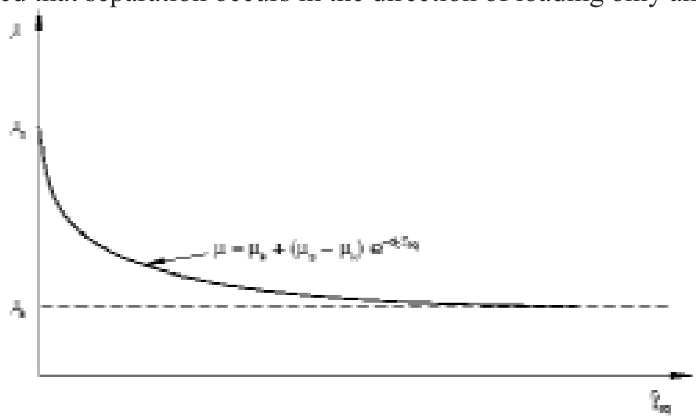

Figure 4. The friction coefficient variation versus sliding rate

still in contact in the other horizontal direction. For the normal direction to the cap-soil interface surface and base of end-bearing piles hard contact is used. Friction at the soil–pile and soil-cap interfaces is considered using tangential kinematics interaction algorithm. In this definition, due to developing the interaction forces the friction coefficient of the interface surfaces decreases from a constant static value to a dynamic limit value. Figure 4 shows the variation of this coefficient with respect of surface sliding rate. In this figure μ_s, μ_k are the static and dynamic interaction coefficients chosen in this research as 0.40 and 0.2, respectively.

3. EQUATIONS OF MOTIONS AND SOLVING ALGORITHM

As the transient loading is represented in the time incremental form, therefore, the governing equation of motion at time
$t+\Delta t$ can be written as:

$$[M]\{\ddot{u}\}^{t+\Delta t} + [C]^{t+\Delta t}\{\dot{u}\}^{t+\Delta t} + [K]^{t+\Delta t}\{u\}^{t+\Delta t} = R^{t+\Delta t} \quad (3)$$

in which [M] is the mass matrix of the soil-pile-cap system. [C] and [K] are the total damping matrix including both material damping and lumped boundary damping due to radiation effect and stiffness matrix determined assuming full coupling in all three directions of motion containing material non-linearity due to soil plasticity. $\{u\}^{t+\Delta t}$, $\{\dot{u}\}^{t+\Delta t}$, $\{\ddot{u}\}^{t+\Delta t}$ are relative nodal displacement, velocity and acceleration, respectively at $t+\Delta t$ due to seismic excitation. $R^{t+\Delta t}$ is the external load at the time step $t+\Delta t$ and is calculated as:

$$R^{t+\Delta t} = -[M][R_F]^{t+\Delta t}\{\ddot{u}_g\} \quad (4)$$

where $[R_F]^{t+\Delta t}$ is the pseudo-static response influence coefficients matrix that is updated at each step of time for the nonlinear soil model; and $\{\ddot{u}_g\}$ is the bedrock acceleration vector. In this study, the explicit approach as a computational efficient approach was adopted to solve the governing equations. The static material non-linear analysis under the static situation is essential as a starting point for the non-linear seismic analysis using explicit algorithm, taking the initial conditions at rest for the soil and accounting the initial induced strains to the pile system. The explicit central-difference operator satisfies the dynamic equilibrium equations at the beginning of the increment, t; The accelerations calculated at time t are used to advance the velocity solution to time $t+\frac{\Delta t}{2}$ and the displacement solution to time $t+\Delta t$ as

$$\{\dot{u}\}^N_{i+\frac{1}{2}} = \{\dot{u}\}^N_{i-\frac{1}{2}} + \frac{\Delta t_{i+1} + \Delta t_i}{2}\{\ddot{u}\}^N_i \quad (5)$$

$$\{u\}^N_{i+1} = \{u\}^N_i + \Delta t_{i+1}\{\dot{u}\}^N_{i+\frac{1}{2}} \quad (6)$$

The subscript i refers to the increment number in an explicit dynamics step. $\{u\}^N$ is the displacement vector, $\{\dot{u}\}^N$ is the velocity vector and $\{\ddot{u}\}^N$ is the acceleration vector, where N is the number of degrees of freedom in the model. The explicit integration rule is quite simple but by itself does not provide the computational efficiency associated with the explicit dynamics procedure. The accelerations at the beginning of the time increment using D'Alambert's principle are computed by

$$\{\ddot{u}\}^N_i = [M]^{-1\,NJ}(\{P\}^J_i - \{I\}^J_i) \quad (7)$$

where $[M]^{-1\,NJ}$ is the inverse mass matrix, $\{P\}^J_i$ is the applied load vector, and $\{I\}^J_i$ is the internal force vector including stiffness and damping forces and J is a numerator. A lumped mass matrix is used because its inverse is simple to compute and because the vector multiplication of the mass inverse by the inertial force requires only N operations. The explicit procedure requires no iterations and no tangent stiffness matrix. The internal force vector, $\{I\}_i^J$ is assembled from contributions from the individual elements such that a global stiffness matrix need not be formed. The explicit procedure integrates through time by using many small time increments. The central-difference operator is conditionally stable, and the stability limit for the operator with damping is given in terms of the highest frequency of the system as

$$\Delta t \leq \frac{2}{\omega_{max}}(\sqrt{1+\zeta_{max}^{2}}-\zeta_{max}) \tag{8}$$

where ω_{max} is the highest natural frequency and ζ_{max} is the fraction of critical damping in the mode with the highest frequency.

4. NUMERICAL RESULTS

The soil-pile-cap systems were subjected to the El Centro excitation and the response of the pile cap is evaluated. In this study, the non-linear analyses of pile-soil-cap systems are carried out accounting for soil plasticity. The effects of interaction between cap, soil and piles, soil stiffness, pile's slenderness and cap's flexibility and embedment on the response of pile group are investigated in detail in a form of series of analyses. In each analysis only the effect of one parameter is investigated, while the remaining parameters are kept constant.

a) Pile-soil-cap interaction

As the main aim of this study, the effect of dynamic interaction between soil, cap and pile on the response of piles' head is considered. To achieve this important goal, models (a) and (b) are used to calculate the response of a pile group with and without the effect of pile-soil-cap interaction. In both models, the piles are assumed to be end bearing-floating piles. The pile spacing ratio (S/D) and the slenderness ratio (L/R) is taken equal to 3 and 25, respectively. A flexible cap with thickness of 50 cm connects all the pile-heads. Figure 5 shows a comparison of the piles head response for the models with and without cap interaction. It is seen that the response of piles, in general, increases as the pile-soil-cap interaction is neglected.

b) Pile-spacing ratio

To consider the effect of pile-spacing ratio on the response of the pile group when the pile-soil-cap interaction is taken into account, model (b) is assumed to have two different pile-spacing ratios equal to 3 and 3.5. Figure 6

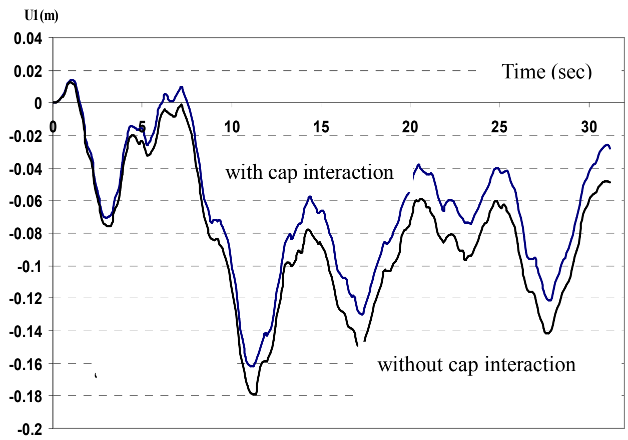

Figure 5. Time histories of piles head with and without cap interaction

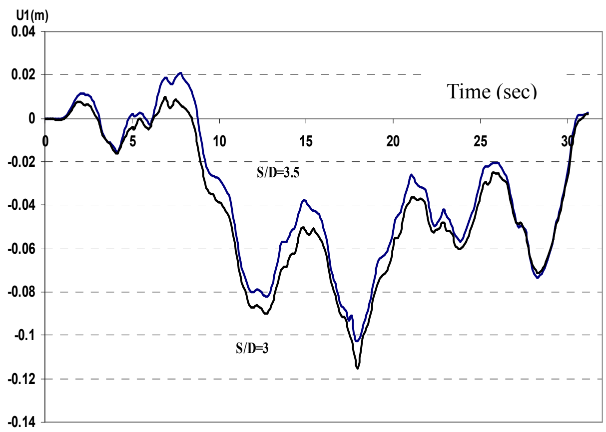

Figure 6. Time histories of piles head with cap interaction for two pile spacing ratios

shows the comparison between the piles head responses. It can be noted that the pile spacing ratio makes not a remarkable difference (less than 15 percent) on lateral displacement of the pile group system. Depends of the piles type this parameter could affect differently.

c) Soil stiffness

It has been found that dynamic response of pile groups depend primarily on the type and stiffness of the soil profile. The soil shear modulus of elasticity affects not only on the kinematic response factors of semi-infinite soil medium but also on viscous constants of FEM boundaries. In this study, two values for soil shear wave velocities, 100 and 150 m/sec are used. Figure 7 shows the lateral response of model (b) using two different mentioned soil stiffnesses when the soil-pile-cap is taken into account. As it can be seen more soil stiffness results less lateral piles displacements.

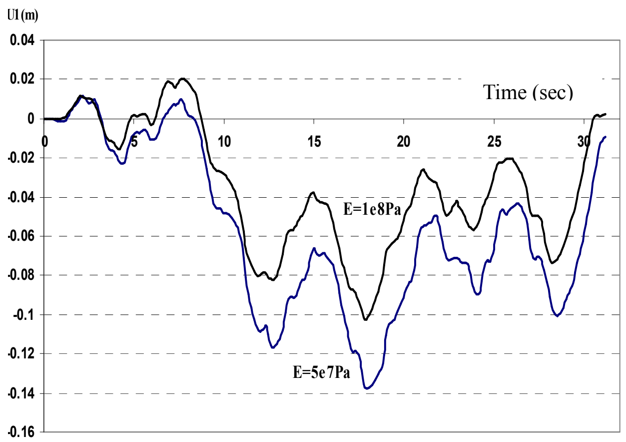

Figure 7. Time histories of piles head with cap interaction for two soil stiffnesses

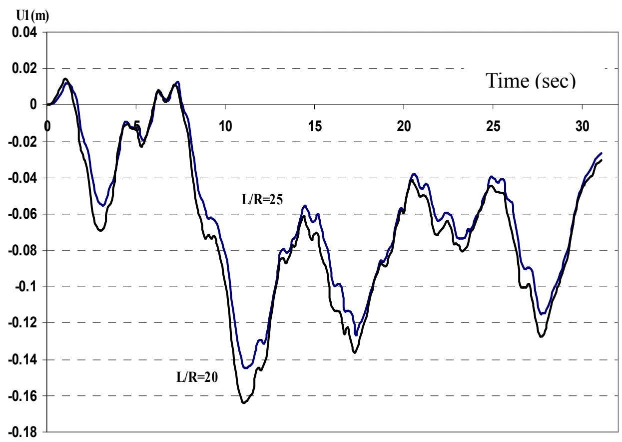

Figure 8. Time histories of piles head with cap interaction for two slenderness ratios

d) Pile slenderness ratio

The model (b) was analyzed with two different slenderness ratios (L/R=20 and 25) to examine the effect pile slenderness along with soil-pile-cap interaction on lateral dynamic response of pile groups. The results are illustrated in Figure 8. It is shown that the slenderness is among the less significant parameters affecting the total response of pile groups accounting for soil-pile-cap interaction.

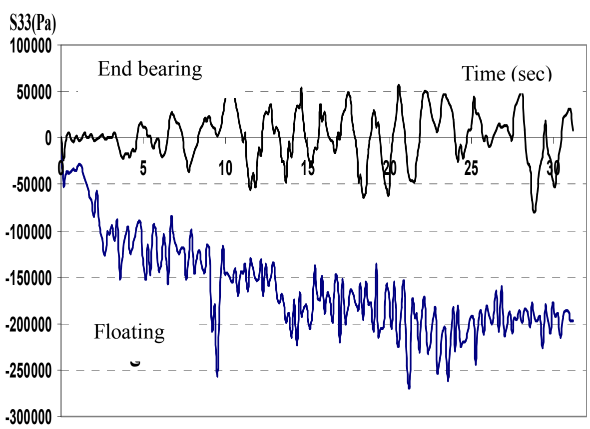

Figure 9. Time histories of pile cap's induced principal stress with cap interaction

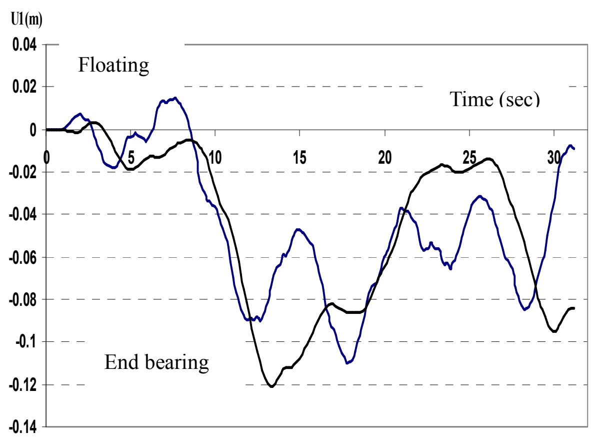

Figure 10. Time histories of piles head with cap interaction for two type of piles

e) Type of pile

Pile Group dynamic behavior also depends on the piles properties with the depth. Assuming two sets of piles (end-bearing and floating) model (b) was subjected to the given transient ground motion. The time histories of the principle stress induced to the pile cap and time histories of lateral displacement of piles head, assuming the soil-pile-cap is taken into account, for two different cases are shown in Figures 9 and 10, respectively. Results showed that the floating piles induce more stress into the pile cap. This could be due to more nonlinear behavior of soil adjacent to piles in floating piles resulting some torsional moments at the piles head.

f) Cap flexibility

The cap flexibility is examined using two different thicknesses for the pile cap (40 cm and 50 cm) in model B. Accounting for soil-pile-cap interaction, the results of piles head displacements are shown in Figures 11 and 12 for two sets of end bearing and floating piles, respectively. Rotation of piles in the group depends on the cap's rigidity. Rotation to the piles head results reduction to the induced stresses and increasing to the piles head displacements. The results obtained from Figures 11 and 12 illustrate that the effect of this parameter is more pronounced for floating piles than end bearing piles.

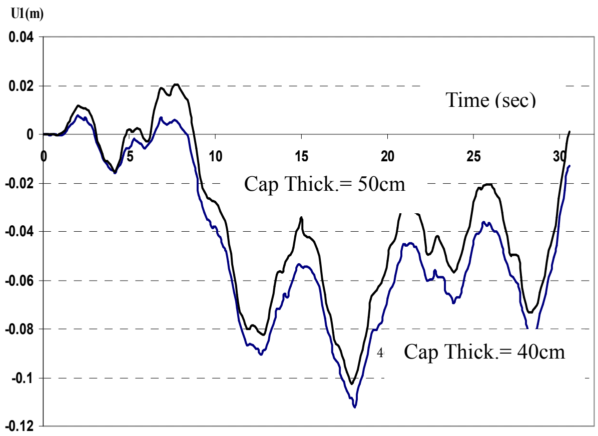

Figure 11. Time histories of pile's head displacement with cap interaction for end bearing piles

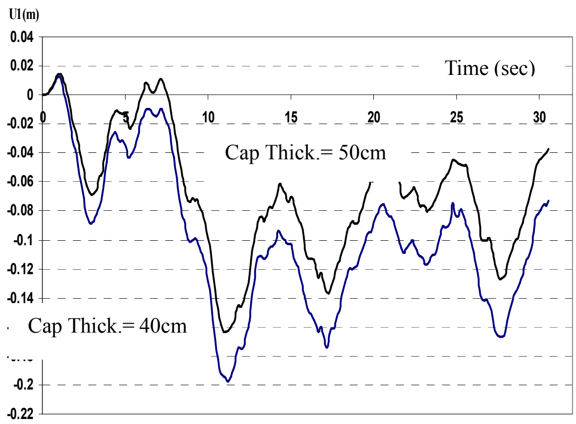

Figure 12. Time histories of pile's head displacement with cap interaction for floating piles

g) Cap embedment effect

Some pile caps do not rest on the surface of the soil and are partly embedded. Embedment is known to increase

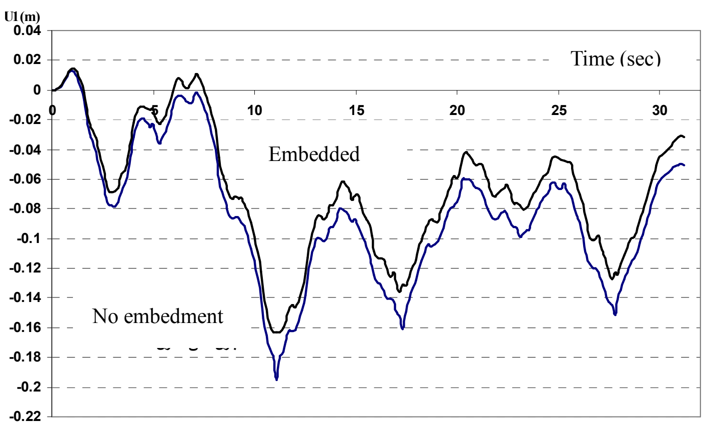

Figure 13. Time histories of pile's head displacement with cap interaction and embedment effect

both stiffness and damping but the increase in damping is more significant. These effects of embedment are observed in Figure 13, when the effect of soil-pile-cap interaction in model (c) is considered. The results showed the embedment effect could also decrease the pile group response up to 10 percent.

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