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EVALUATION OF DIFFERENT LEVELS OF EXCITATION ON KINEMATIC INTERACTION

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ABSTRACT

Although it is known that the performance of piled foundations is better than that of shallow foundations under earthquake loads, reports about damaged piles are often encountered in literature.

The objective of this paper is to lay emphasis on the effect of relative difference in the level of seismic excitations on kinematic response of single piles. To this end, an idealized simple model consisting of three layered soil medium into which a single pile with fixed head is studied employing 3D nonlinear dynamic FE analyses regarding material nonlinearity. For simplicity, the round-shaped piles are simulated with square-shaped elements in the finite element analyses, making sure that the bending stiffness EI of the representative one is to the actual shape. Frequencies of seismic excitations as input motion are generated assuming equal to the natural frequency of upper soft soil layer, natural frequency of lower stiff soil layer, and fundamental frequency of lower and upper soil layers together. It is aimed to find out the maximum peak displacement or acceleration, which will cause failure. To overcome this problem the best is to use an artificial input motion in such a manner that it can give maximum peaks in soil-pile system. Numerical results are outlined within graphs showing the variation of bending moments and shear forces along pile for each seismic excitation, separately.

As a conclusion, the kinematic effects on pile foundation are more significant and depend on the frequency of the excitation and the fundamental period of surface ground layer.

Keywords: Kinematic interaction, 3D nonlinear dynamic FEA, Seismic excitation, bending moment

INTRODUCTION

Seismic soil-structure interaction analysis involving pile foundations is one of the more complex problems in geotechnical earthquake engineering. There are two parts in calculating the response of piled structures subjected to earthquake excitation; the kinematic part, which incorporates the effects of seismic waves due to free-field ground motion on the piles without the superstructure; and the inertial part , which is directly related to the extent of shaking to which the structure is subjected.

As the inertial and kinematic interaction effects have to be regarded simultaneously in rather soft soils, many research attempts to assess these effects together are implemented. However this type of analysis may not be feasible in engineering practice. Thus, various approximate analysis methods such as pseudo-static type of analysis are used. In most seismic design codes, pile foundations are designed merely against inertial force. The pseudo-static type of analysis neglects some of the effects of seismic shaking of the foundation soils on pile response including kinematic interaction. However, soil

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deformation caused by seismic waves generates curvature of piles and subsequently a bending moment along their whole length (Mylonakis and et al., 1997).

Numerous research results have been published exposing the extent of the damage to pile foundations due to recent devastating earthquakes (Mylonakis and et al., 2006; Miwa and et al., 2006; Koyamada and et al., 2006; Maki and Mutsuyoshi, 2004; Luo and et al., 2002).

Piles undergo especially shear and bending failures due to relative displacements at the boundaries of soil layers with significant stiffness contrast (Aydınoğlu and et al., 2000).

The analyses were carried out using a full three-dimensional finite element analysis technique with a commercial finite element program, LUSAS (FEA Ltd, 2001).

STATEMENT OF THE PROBLEM

Analyses were performed using structural model shown in Figure 1. The representative model used consists of massless raft and a constrained-head square pile. The height of the raft above ground level is 1.00 m. The reinforced concrete pile of 20.00 m in length is capped with the raft having dimensions of 5.00×5.00 m in plan. The pile cap is restrained against rotations, while the translations in all directions are allowed. The representative model is analyzed using three different input motions with three layered soil profile exhibiting significant stiffness contrast.

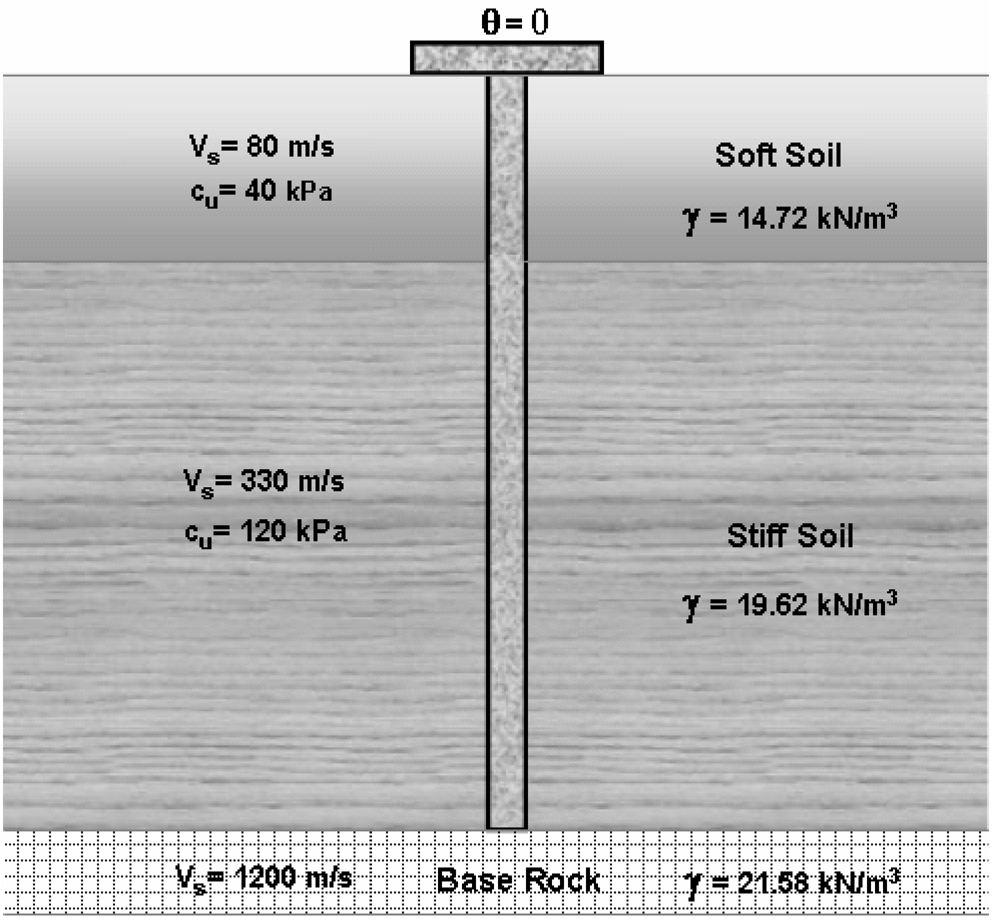

Figure 1. Model of soil-pile system

Finite Element Model

As the maximum dimensions of the elements are controlled by the frequency range of interest, minimizing the number of elements usually becomes a matter of minimizing the size of the discretized region. The mesh was refined near the pile, with a gradual transition to coarser mesh away from the pile in the horizontal X and Y directions. The vertical Z direction to allow for even distribution of vertically propagating SH waves. The maximum element size is less than one-fifth to one-eight the shortest wavelength to ensure accuracy following the approach proposed by Bentley and El Naggar (2000). The whole system shown in Figure 2 is idealized by 8688 elements with a number of 30381 degrees of freedom, 26800 nodal points.

To abstain from the reflected waves resulting from inappropriately defined boundary conditions in time-domain analysis, various methods, such as proposed by Sadek and Shahrour (2002), Zheng and Takeda (1995), are reported in literature. In this study, setting lateral boundaries in y direction equal to the thickness of the soil below the pile cap and in x direction 240 m away from the foundation, as proposed by Ordu (2005), gave reasonable results. The bottom of the mesh is completely fixed.

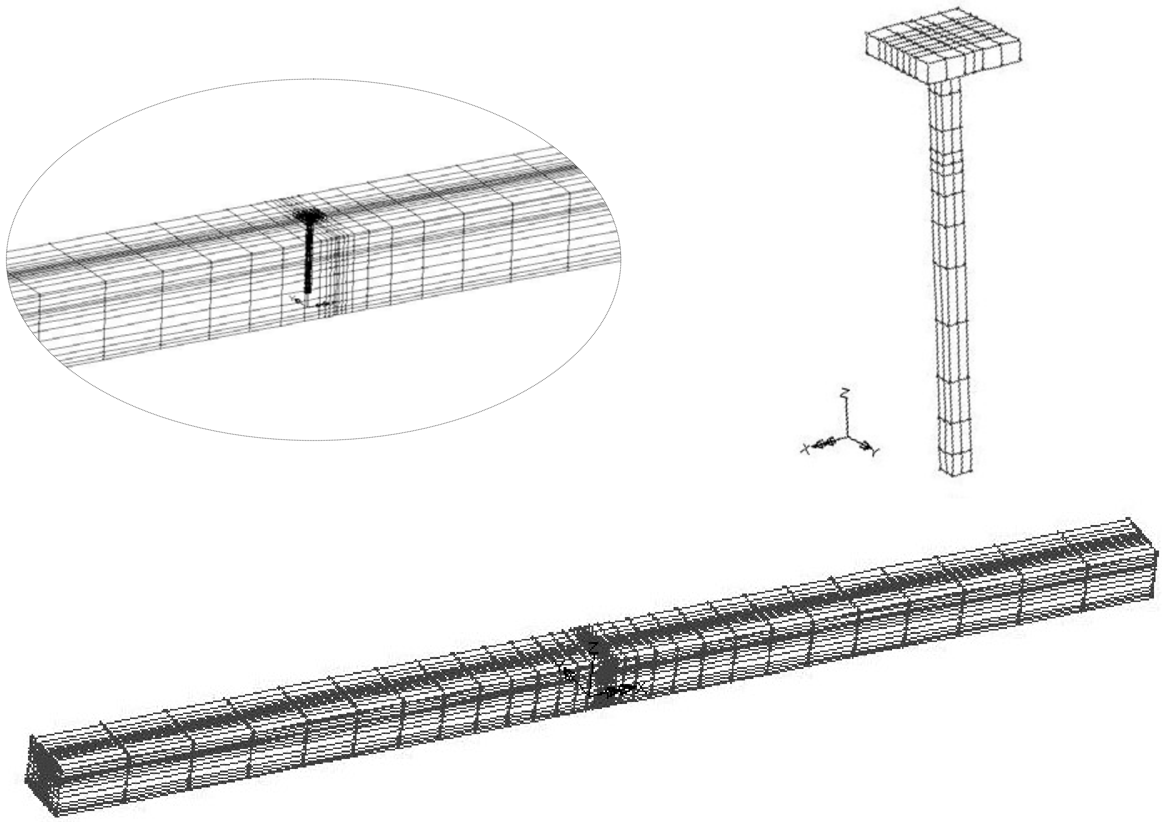

Figure 2. Isometric view of three-dimensional finite element mesh of the full system.

Soil Profile

The ground is composed of three layers. The profile shown in Figure 1 consists of 15.00 m thick stiff soil underlain by a soft soil as surficial layer 5.00 m in thickness, with bedrock of 1.00 m at the bottom. The bottom layer of the ground is supposed to be an elastic material in the numerical analyses.

Material Properties

Nonlinear dynamic analyses using nonlinear material model is necessary for obtaining accurate results. In material nonlinearity, when the stresses exceed a certain point yielding occur and the internal forces are transferred surrounding elements. To evaluate the soil nonlinearity, soil is modelled as an elasto - plastic material using the Drucker-Prager failure criterion. Structural elements were assumed to be linear elastic. As the interface elements employed for representing the pile-soil interface make the solutions inconceivable, interface elements were not used.

Material parameters for the ground layers used in the study can be summarized in Table 1. In the finite element analyses, the pile and the raft are assumed to be linearly elastic. The Young's modulus and the Poisson's ratio of the structural parts, consisted of single pile and raft are 2.50×10^7 kN/m^2 and 0.25, respectively.

Table 1. Material parameters of soils

Material Type	Shear Wave Velocity (m/s)	Unit Weigtht (kN/m^3)	Poisson's Ratio	Cohesion c_u (kN/m^2)	Damping Coefficient (%)
Soft Soil	80	14.72	0.45	40	5
Stiff Soil	330	19.62	0.35	120	5
Base-Rock	1200	21.58	0.25	elastic	5

TYPES OF ANALYSES

To simulate nonlinear dynamic behaviour of soil-pile-structure system, three phases of analyses are conducted.

Static Analysis

To take the state of stress in the full system under in situ conditions into consideration, calculations are carried out by applying a global gravitational acceleration, *g*, regarding also the existence of the pile. Stresses resulting from the applied body forces are then applied to all of the elements forming the mesh.

Eigenvalue Analysis

A Rayleigh type of damping is adopted and the damping factors of the structural parts and the soils are assumed as 2 % and 5 % respectively in the dynamic analysis of the full system. Although the stiffness of the ground and the pile may change because of the nonlinearity of these materials, the viscous matrix which is calculated from the Rayleigh type of attenuation is assumed to be constant, in spite of the changes in the stiffness matrix.

Different procedures are applied in determining the viscous matrix to ensure reasonable values for damping ratios all the modes contributing significantly to the response. In order to calculate the viscous matrix, an eigenvalue analysis for the full system is conducted to evaluate the first and fourth eigenvalues as proposed by Chopra (2000). As the damping ratio for the second and third modes will be somewhat smaller than modal damping ratio and for the fifth mode it will be somewhat larger than the modal damping ratio. The damping ratio for modes higher than the fifth will increase monotonically with frequency and the corresponding modal responses will be essentially eliminated because of their high damping. The eigenvalue analysis has shown that the first and fourth eigen periods are 0.3095 and 0.3064 sec., respectively. The eigenvalue analysis is conducted with a hybrid of Jacobian and subspace methods.

Dynamic Analysis

Dynamic analyses, to study the response of full system to seismic loading, are carried out in the time domain. Due to material and geometry nonlinearities, the computational cost increases dramatically. Therefore, one of the dynamic finite element analyses under seismic loading with direct integration method using Hilber-Hughes method takes approximately 140 hours of computer time in this study on a Pentium III, 675 MHz with 512 Mb RAM. The Hilber-Hughes integration scheme is adopted in the present study to perform the direct time integration of the equations of motion which can be written in the form as in equation 1.

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\} = F(t) \tag{1}$$

In this equation, F(t) is the external load vector, [M], [C], [K] are the mass, damping and stiffness matrices; while $\{\ddot{u}\}$, $\{\dot{u}\}$, $\{u\}$ are the acceleration, velocity and displacement vectors of the finite element assemblage, respectively. The accuracy and stability of Hilber-Hughes integration scheme is provided using $\alpha=0.25$, $\beta=(1-\alpha^2)/4=0.25$, $\gamma=(1-2\alpha)/2=0.5$ (where α, β and γ are integration constants).

Seismic Excitation

Three input motions with amplitude of 0.3 g are considered to investigate the relative difference in the level of excitation. Frequencies of seismic excitations as input motion are generated assuming equal to the natural frequency of upper soft soil layer, natural frequency of lower stiff soil layer, and fundamental frequency of lower and upper soil layers together, 4 Hz (0.25 sec), 8 Hz (0.125 sec), and 3.33 Hz (0.3 sec), respectively.

If the first fundamental period of the upper soft soil layer is (t) which is 0.25 sec, then according to Veletsos and Meek (1974), in half cycle impulse displacement curve (Figure 3) an input motion can be generated and the applied total model.

The maximum time step for a nonlinear dynamic analysis should be between t/30 to t/10. Since the first natural frequency of upper soil layer is 4 Hz or a period of 0.25 sec, the duration of artificial input motion should be at least four times of this value (4 x 0.25= 1 sec, see Figure 3). This 1-second interval of cyclic load curve can be extended to four times the value needed, thus time reaches to 4 seconds, totally. Other input motions are generated in a similar manner above.

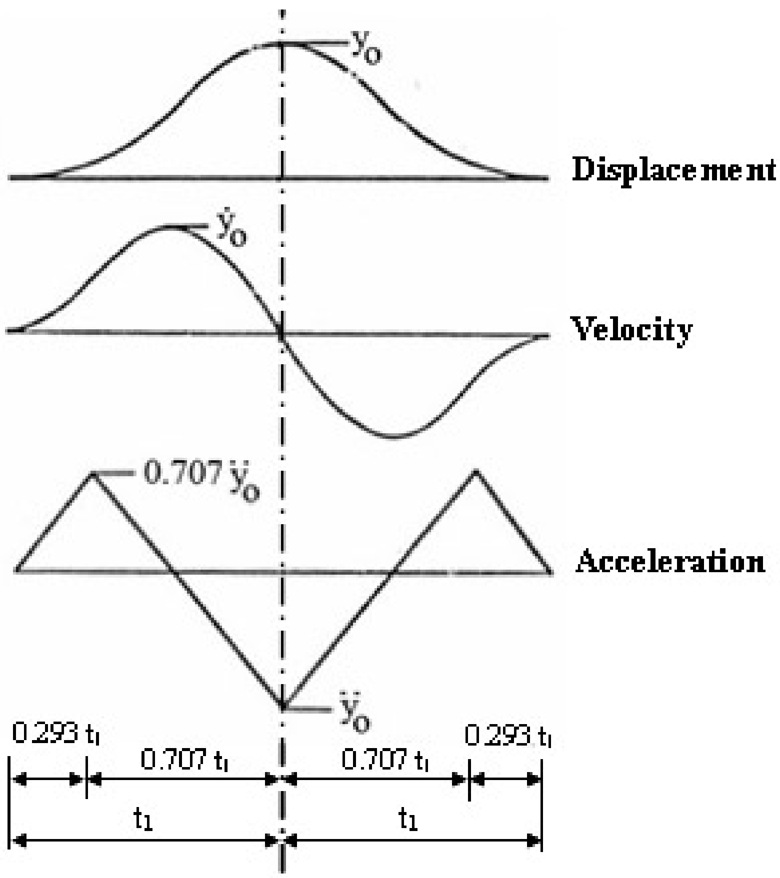

Figure 3. Half cycle displacement impulsive curve

OUTLINE OF RESULTS

In order to define shear forces and bending moments along pile, cross-sections are first taken through three-dimensional solid pile elements at selected depths using LUSAS parametric command language. The section cuts allow us to get resultant forces and moments acting at each slice through the pile within each time step. On the other hand, the displacement values along the pile can be found through the translation of nodes at the centre of the pile at each time step. Then, the obtained displacement, shear force and bending moment results versus time in seconds are plotted into graphs. The profiles of positive and negative displacement, shear force and bending moment along pile are formed using maximum and minimum values in the time domain. Eventually, the profiles providing absolute maximum values are selected for subsequent figures.

Figure 4 shows the maximum displacements of the pile corresponding to the three incident motions. The distribution of pile deflections under different seismic excitations changes sharply for lower level of excitation when compared to higher level of excitations.

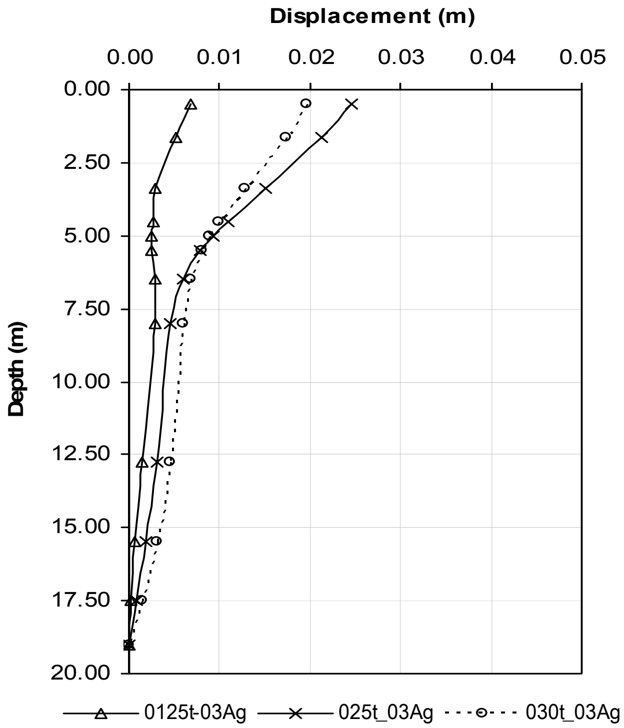

Figure 4. Displacements of the pile

Figure 5and 6 show a comparison of the variation of the shear forces and bending moments along the pile obtained from the analyses for three different seismic excitations.

Both the maximum shear force and bending moment in piles, are obtained in case of input motion with a period of 0.25 sec, and occurred at the interface of soft and stiff soil layers.

Since the analyses were conducted with the assumption that the pile head is fixed against rotation, much larger shear forces and bending moments still occur at the pile head. Therefore, realistic values of rotational stiffness at the pile head should be included in any seismic response analysis.

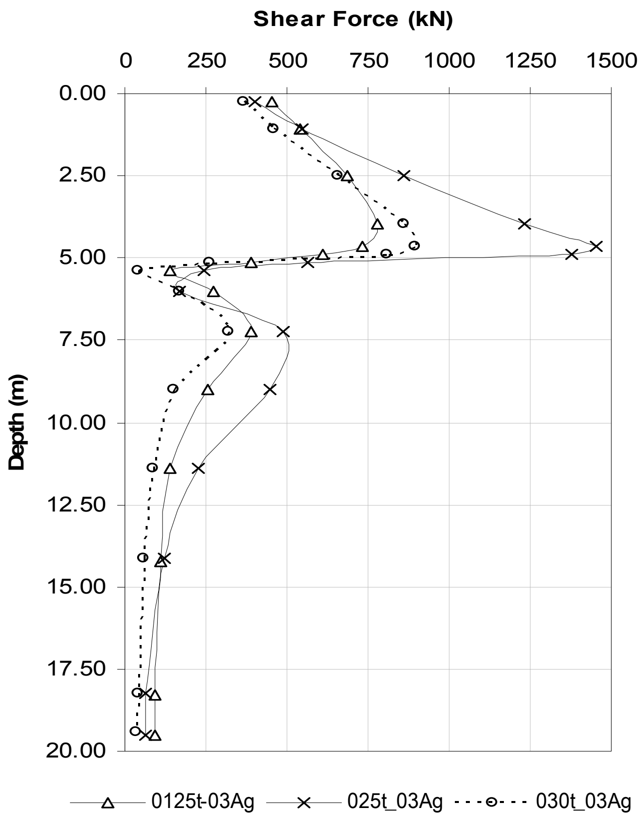

Figure 5. Distribution of shear force along pile

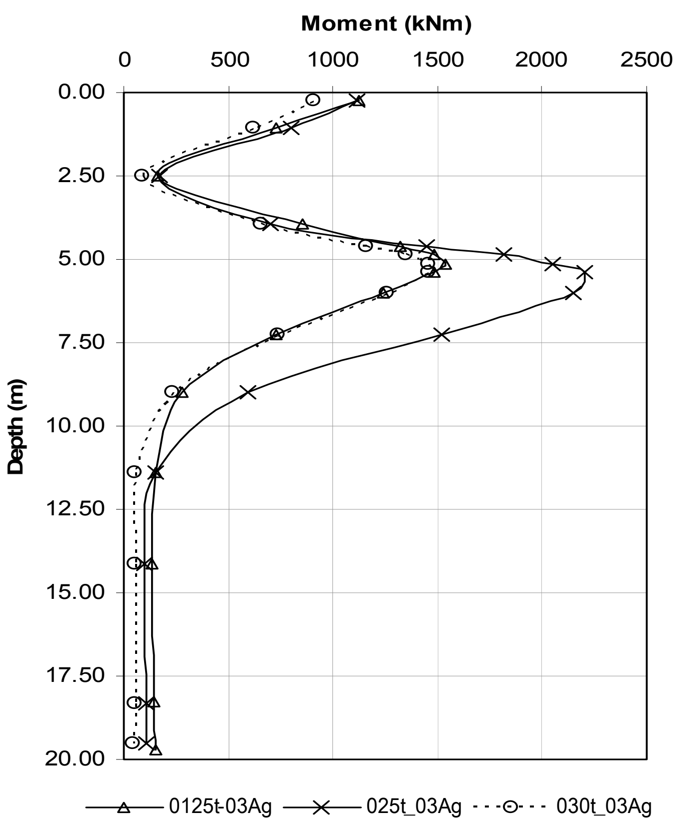

Figure 6. Distribution of bending moment along pile

CONCLUSIONS

This paper gives a general overview of the important factors that affect the seismic design of piles to resist earthquake loading.

3D finite element analyses are performed to investigate the dynamic response of piled foundations under input motions with different frequency content excitations. The analyses consider kinematic interaction on the pile foundation response including the effects of material nonlinearity of soil, the coupling effect of soil-pile interaction and the effects of layered soil.

It has been shown that the material nonlinearity of the soil makes it possible to accurately evaluate the interaction of the soil-pile system. Thus, the damages of piles in seismic events can be predicted more precisely resulting from residual displacement or plastic strain.

The result of the analyses demonstrates that the kinematic effect mainly depends on the frequency content of the excitation and the fundamental period of surface ground layer.

The main results of this study can be summarized as follows:

- The seismic shear forces and bending moments in a pile are larger not only at the pile-heads, but also at the boundaries of soil layer where the stiffness varies significantly.
- The results demonstrate the importance of ground response effects in the seismic design of piles.
- The results show the inadequacy of the present design practice that directly accounts for the superstructure inertia effects alone.
- It may be possible to evaluate the nonlinear response of a soil-pile-structure system by a 3D finite element method provided the necessary parameters are selected to adequately represent the dynamic characteristics of the ground.

Therefore, it is worth emphasizing that the influence of the deformation of ground on the piles must be taken into consideration.

Such parametric studies using input motions with different frequency content would allow the reliability of the representative pile design concept to be evaluated properly. Generalization of these results, however, may require more analyses with different soil and pile parameters.

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REFERENCES

Aydınoğlu, M.N., Berilgen, M., and Özaydın, K., "Dynamic soil-pile interaction under earthquake," Zemin Mekaniği ve Temel Mühendisliği 8nci Ulusal Kongresi, 427-436, 2000 (in Turkish).

Bentley, K.J., El Naggar, M.H., "Numerical analysis of kinematic response of single piles," Canadian Geotechnical Journal, 37, 1368-1382, 2000.

Chopra, A.K., Dynamics of Structures, Prentice Hall, 2nd edition, 844 p, 2000.

FEA Ltd, LUSAS Finite Element System, UK, 2001.

Koyamada, K., Miyamoto, Y., and Tokimatsu, K., "Field investigation and analysis study of damaged pile foundation during the 2003 Tokachi-oki Earthquake," Geotechnical Special Publication, 145, 97-108, 2006.

Luo, X., Murono, Y., and Nishimura, A., "Verifying adequacy of the seismic deformation method by using real examples of earthquake damage," Soil Dynamics and Earthquake Engineering, 22, Issue 1, 17-28, 2002.

Maki T and Mutsuyoshi H., "Seismic behavior of reinforced concrete piles under ground," Journal of Advanced Concrete Technology, 2, Issue 1, 37-47, 2004.

Miwa, S., Ikeda, T., and Sato, T., "Damage process of pile foundation in liquefied ground during strong ground motion," Soil Dynamics and Earthquake Engineering, 26, Issue 2, 325-336, 2006.

Mylonakis, G., Nikolaou, A., Gazetas, G., "Soil-pile-bridge seismic interaction: Kinematic and inertial effects. Part I: Soft soil," Earthquake Engineering and Structural Dynamics, 26, Issue 3, 337-359, 1997.

Mylonakis, G., Syngros, C., Gazetas, G., and Tazoh, T., "The role of soil in the collapse of 18 piers of Hanshin Expressway in the Kobe Earthquake," Earthquake Engineering and Structural Dynamics, 35, Issue 5, 547-575, 2006.

Ordu, E., "An investigation on the nonlinear seismic response of the pile foundation analysis in the layered soils," Ph.D. thesis submitted to ITU in Turkey, 2005 (in Turkish).

Sadek , M., and Shahrour, I., "Three-dimensional finite element analysis of the seismic behavior of inclined micropiles," Numerical Methods in Geotechnical Engineering, Mestat(ed.), Presses de l'ENPC/LCPC, 2002.

Veletsos, A. S. and Meek, J. W., "Dynamic behavior of building-foundation systems," Journal of Earthquake Engineering and Structural Dynamics, 3, Issue 2, 121-138, 1974.

Zheng, J. and Takeda, T., "Effects of soil-structure interaction on seismic response of PC cable-stayed bridge," Soil Dynamics and Earthquake Engineering, 14, Issue 6, 427-437, 1995.