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EFFECTS OF PILE FOUNDATION CONFIGURATIONS IN SEISMIC SOIL-PILE-STRUCTURE INTERACTION

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SUMMARY

Soil-Pile-Structure Interaction (SPSI) has an important effect in the dynamic analysis and seismic design of massive or stiff structures and pile foundations. Because of soil stiffness degradation under earthquake excitations, pile foundation configurations affect the seismic response of soil-pile-structure systems. This paper develops an efficient computational method to quantify seismic response of a soil-pile foundation system. A comprehensive study is presented to consider the effects of pile foundation configurations on the seismic soil-pile-structure interaction (SPSI). Using a three-dimensional finite element model of a soil-pile foundation system, both linear and nonlinear analyses are performed in the time domain to provide a method for assessing the seismic performance of the soil-pile system with different pile foundation configurations included. An infinite element boundary condition is used to simulate radiation damping. Both harmonic and specific seismic excitations are considered.

Material nonlinearity is represented by Drucker-Prager soil plasticity model and the nonlinear dynamic analysis of the soil-pile foundation system is performed using ABAQUS, a general purpose finite element analysis package. The effects of pile spacing to diameter ratios and pile-soil stiffness ratios on the seismic responses of the soil-pile system are studied. The proposed model is validated against experimental data and existing results of numerical analyses. The proposed method reliably predicts the essential features of seismic responses and provides insight into the nonlinear response characteristics. This study shows that soil properties affect seismic interaction of the soil-pile system greatly and the effects of pile spacing ratios on pile head responses are not significant. A systematic research is suggested to study the effects of number of piles on seismic performance of the soil-pile system.

INTRODUCTION

Pile foundations are widely used to support buildings and structures on soft soil. A typical dynamic load on a soil-pile-structure system is earthquake vibrations and analysis of performance of the structure-foundation system is important in the seismic assessment and design of existing and new structures. It is

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common that piles are damaged due to earthquake excitations, as revealed by some researchers. Mizuno [1] investigated pile damages during earthquakes in Japan from 1923 to 1983 and Tokimatsu et al. [2] reported pile damages in Kobe earthquake of 1995. Pile damages are also observed in earthquakes such as Alaska earthquake (1964), Mexico earthquake (1985) and Loma Prieta earthquake (1989) [3]. Soil-Pile-Structure Interaction (SPSI) plays an important role in seismic responses of the soil-pile-structure system. As indicated by Kramer [4], SPSI usually elongates the period of the structure and tends to reduce its peak seismic response by increasing the damping of a pile-supported structure due to energy dissipation in the soil. As a result, structural seismic "demand" is often mitigated with the consideration of SPSI in conventional seismic design practice. However, spectral values can also be increased by a lengthening period due to the consideration of SPSI. The performance of structure-foundation systems in Mexico City earthquake (1985) provided sufficient reason to believe that SPSI effects should be investigated with greater rigor and precision. The mechanism of pile damages needs to be further examined in order to have a more reliable seismic design of pile foundations and superstructures.

The effects of SPSI on the seismic performance of soil-pile-structure systems are composed of kinematic interaction and inertial interaction. Kinematic interaction accounts for the effects of the pile foundation on free-field ground motion, which refers to the motion at the level of the foundation without presence of the foundation. Inertial interaction represents the transmission of inertial loads from the superstructure to the pile foundation. Due to the characteristics of unbounded domain of soil, radiation damping plays a critical role in seismic soil-pile-structure interaction analysis. Appropriate boundary conditions are required to represent the energy dissipated by the propagating waves in the soil field. [5]

STATE OF THE ART

Seismic SPSI is one of the most complex problems in geotechnical engineering and many fundamental aspects of SPSI remains to be examined. Substantial research has been focused on studying and simulating the dynamic behaviour of piles and pile groups subjected to seismic excitations since the early 1980s. Significant progress has been made on the development of analytical methods for the lateral response of pile foundations under dynamic loading. Methods of analyzing seismic soil-pile-structure interaction can be divided into three categories: elastic continuum method, nonlinear Winkler foundation method and finite element method.

Based on Mindlin's solution for point loads to a semi-infinite domain, the elastic continuum method was first used to analyze a dynamic soil-pile interaction problem by Tajimi in 1966. Various researchers modified this method gradually to consider inertial effects of superstructures, degradation of soil resistance, layered soil, material damping, etc. Subgrade reaction method proposed by Swane and Poulos in 1984 considered soil-pile gapping and bilinear elastic-plastic springs.

Nonlinear Winkler foundation method assumes a linear elastic beam-column representing the pile linked to fully nonlinear p-y springs and dashpots representing the surrounding soil. Matlock et al. [6] first implemented an uncoupled approach to perform dynamic analysis of offshore structures. Subsequently, numerous researchers have studied soil-pile-superstructure dynamic responses using a similar approach. First, site response analysis is employed to calculate the "free-field" acceleration time histories. Then, the corresponding displacement time histories are applied to the nonlinear p-y springs to analyze the dynamic responses of the pile-superstructure system. The site response calculations are a greater source of uncertainty than the dynamic p-y calculations in the prediction of superstructure responses, according to Boulanger et al. [7].

Although the nonlinear Winkler foundation model is effective and popular in design codes, this method ignores three-dimensional interaction effects of soil-pile contact by using a two-dimensional simulation. And numerical errors might be introduced by double integrating the free-field motion in the uncoupled formulation.

The Finite Element Method (FEM) is capable of performing a 2-D or 3-D fully coupled analysis with the simulation of any soil-pile-structure configurations easily. FEM includes substructure methods and direct methods. In the substructure method, the structure, pile foundation, and geometrically irregular and materially non-homogenous soil form finite element region. The infinite soil is modeled as a regular layered homogeneous semi-infinite domain and is considered by a rigorous interaction force-displacement relationship. Integration of this interaction force-displacement relationship of the unbounded domain into equations of motion of the structure constructs the dynamic analysis of soil-pile-structure systems. In the direct method, the finite element region contains the structure, pile foundation and soil profile up to the artificial boundary. The semi-infinite half-space, soil, is represented by artificial boundary conditions, simulating the wave propagation and energy dissipation so that no wave reflection exists from the outwardly propagating waves.

The substructure method is generally formulated in the frequency domain, so this approach does not include the nonlinear seismic responses of soil-pile-structure systems and can not be used in a nonlinear SPSI analysis. The direct method considers the nonlinearity of the near-site soil domain and involves a large number of degrees of freedom due to a much larger finite element region than that in the substructure method. Therefore, this approach requires large computational efforts, but is popular in nonlinear SPSI analysis due to its direct time solution.

ANALYTICAL MODEL

Model Description

This research focuses on the kinematic interaction due to different pile foundation configurations, so a system composed of soil and pile foundation is studied. The analytical model of a soil-single pile is illustrated in Figure 1. The soil-pile system with dimensions of 40m*30m*18m is modeled as eight-node hexahedral three-dimensional finite elements for the soil with embedded 1m*1m pile. The far-field soil is represented by infinite elements to account for the energy absorption from the unbounded soil domain.

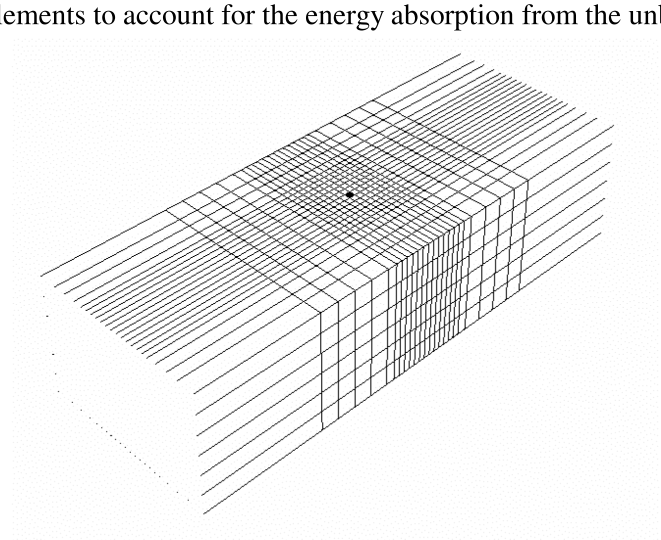
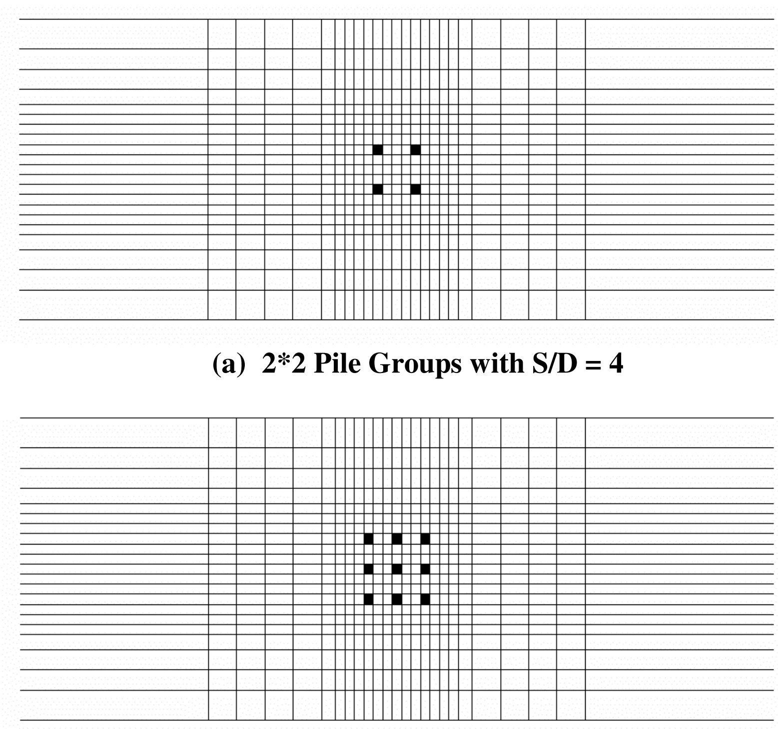


Figure 1. Finite Element Model of a Soil-Single Pile Foundation System

As suggested by Kuhlemeyer and Lysmer [8] and Lysmer et al. [9], the maximum dimension of mesh depends on the shortest wavelength λ in the wave propagation problems and should be smaller than (1/8~1/5)λ. The soil is discretized as different size meshes for near-site soil and far-site soil considering computational efficiency. The soil mesh size in this analysis is 1m*1m in plan for elements near the pile. As the distance from the pile increases, the soil mesh size becomes larger. The maximum dimension of mesh is 3m in plan for finite elements on the boundary between finite elements and infinite elements. Considering the even distribution of wave propagation in vertical direction, mesh size is 3m in depth for all finite and infinite elements. The proposed model consists of 2898 finite elements and 252 infinite elements.

The length of the pile is the same as the depth of the soil media. The concrete pile is modeled with three-dimensional eight node hexahedral finite elements and is assumed to be linear behavior with Young's modulus of 2.58×10^{10} Pa and Poisson's ratio of 0.15. The bottom of the soil and the single pile are fixed with either harmonic or seismic excitation in one direction.

Similarly, plans of soil-pile foundation systems for 2*2 and 3*3 pile groups are illustrated in Figure 2(a) and Figure 2(b), respectively. To study the effects of pile foundation configurations on soil-pile kinematic interaction, different pile spacing to diameter ratios (S/D) are considered in this research.



(a) 2*2 Pile Groups with S/D = 4

(b) 3*3 Pile Groups with S/D = 3

Figure 2. Finite Element Model of Soil-Pile Foundation Systems

Drucker-Prager Soil Model

Material nonlinearity of the soil has significant effects on the seismic response of a soil-pile-structure system, as suggested by Bentley and Naggar [10] and Maheshwari et al. [11]. Bentley and Naggar investigated the effects of soil plasticity on the kinematic response of single piles using a perfectly plastic Drucker-Prager soil model. The Drucker-Prager plastic soil model is employed in this study and soft clay is assumed with a Young's modulus of 2×10^7 Pa and Poisson's ratio of 0.3. Associated flow rule of the Drucker-Prager model is considered with work-hardening behavior.

Radiation Damping

Radiation damping is defined as the energy dissipated from the finite element region of a soil-pile system by outwardly propagating waves. Since radiation damping plays a critical role in seismic soil-pile-structure interaction analysis, appropriate boundary conditions are required to simulate this energy dissipation. Lysmer and Kuhlemyer [12] presented a frequency independent viscous dashpot boundary to consider radiation damping in a finite element analysis of unbounded domain. Chu and Truman [5] compared the dynamic response of a soil-pile foundation system using a frequency independent viscous dashpot boundary and an infinite element boundary, respectively. It was found that dynamic responses using an infinite element boundary agree with existing results of elastic analyses. Thus an infinite element boundary is considered in this study to represent the energy absorption by the far-field soil to avoid reflection of dilatational and shear wave energy back into the finite element model. The infinite elements are assumed to have linear behavior.

Model Validation

The proposed three-dimensional soil-single pile model is validated by comparing elastic results under static axial loading with existing data. Using an axial load of 2,500 kN acting at the pile head, the head settlement is 1.72 cm in the elastic three-dimensional finite element analysis presented in this study, while the corresponding settlement is 1.7 cm as in the charts provided by Poulos and Davis [13]. Compared with 0.51 cm pile head horizontal deflection for a 200 kN lateral loading acting at the pile head given by Maheshwari [14], the elastic analysis in this study is 0.48 cm.

For a harmonic excitation of 1 m/s^2 amplitude and 1 Hz acting at the bottom of the soil and pile, free field response (without the presence of the pile) in present study is 1.12, while the soil amplification is 1.25 using one dimensional frequency domain analysis given by Gazetas [15]. The pile head acceleration in a soil-single pile system due to amplitude of 1 m/s^2 and 2 Hz harmonic excitation is computed to be 1.55 m/s^2, as compared with the linear time domain response 1.4 m/s^2 by Maheshwari et al. [12].

After validating the proposed analytical model against pile head settlement and lateral deflection in static analyses as well as free field response and pile head response in dynamic analyses, a parametric study is performed using the above finite element model to study the effects of pile group configurations on kinematic interaction between the soil and pile.

PARAMETRIC STUDY

To study the effects of pile group configurations on seismic soil-pile kinematic interaction, this research investigates both 2*2 pile groups and 3*3 pile groups with different soil properties and pile spacing ratios included. First, natural frequency extraction is performed in order to study the dynamic characteristics of both 2*2 and 3*3 pile foundation systems. Then, effects of soil properties and pile spacing to diameter ratios (S/D) on kinematic interaction are studied in nonlinear analyses of soil-pile foundation systems under a harmonic excitation. Finally, El Centro earthquake motion is employed to consider effects of the number of piles on seismic responses of soil-pile systems.

Dynamic Characteristics

The fundamental frequencies of 2*2 and 3*3 pile foundation systems with varying soil Young's Moduli and pile spacing ratios are given in Tables 1 and 2, respectively. As shown in Table 1, effects of soil Young's Modulus on natural frequency of the soil-pile systems are large, from 1.168 Hz for Es=2×10^7 Pa to 0.8401 Hz for Es=1×10^7 Pa (28.1% decrease) and 1.6311 Hz for Es=4×10^7 Pa (39.6% increase) in 2*2 pile foundation systems, while the effects of pile spacing ratios are insignificant, from 1.168 Hz to 1.1785 Hz (0.9% increase) corresponding to S/D=2 and S/D=8. This can be explained by the small contribution of pile groups to the stiffness of the soil-pile systems considering the 1m*1m pile embedded in the 40m*30m*18m soil media.

The effects of soil properties on natural frequencies are significant in 3*3 pile foundation systems as well. As shown in Table 2, natural frequency decreases by 27.3% for softer soil (Es=1×10^7 Pa) and increases by 38.5% for stiffer soil (Es=4×10^7 Pa). Compared to 2*2 pile foundation systems, the effects of pile spacing ratios on natural frequencies are larger, from 1.2074 Hz to 1.2227 Hz (1.3% increase) corresponding to S/D=2 and S/D=4 due to a larger stiffness contribution of pile groups in 3*3 pile foundation systems.

Table 1. Frequencies of 2*2 pile foundation systems

Soil Young's Modulus Es (Pa)	Pile Spacing Ratio (S/D)	Natural Frequency (Hz)
1.00E+07	2	0.8401
2.00E+07	2	1.168
4.00E+07	2	1.6311
2.00E+07	2	1.168
2.00E+07	4	1.1728
2.00E+07	6	1.1764
2.00E+07	8	1.1785

Table 2. Frequencies of 3*3 pile foundation systems

Soil Young's Modulus Es (Pa)	Pile Spacing Ratio (S/D)	Natural Frequency (Hz)
1.00E+07	2	0.8777
2.00E+07	2	1.2074
4.00E+07	2	1.6726
2.00E+07	2	1.2074
2.00E+07	3	1.2151
2.00E+07	4	1.2227

Effects of Soil Properties

As suggested by the natural frequency extraction analyses, it is expected that soil properties play an important role in seismic soil-pile-structure interaction. For a harmonic excitation of 1 m/s^2 amplitude and 1 Hz acting at the bottom of the soil and pile in a 2*2 pile foundation system, pile head acceleration and displacement corresponding to Es = (1, 2, 4) $\times10^7$ Pa are displayed in Figure 3. It is found that pile head responses are smaller when the soil is stiffer.

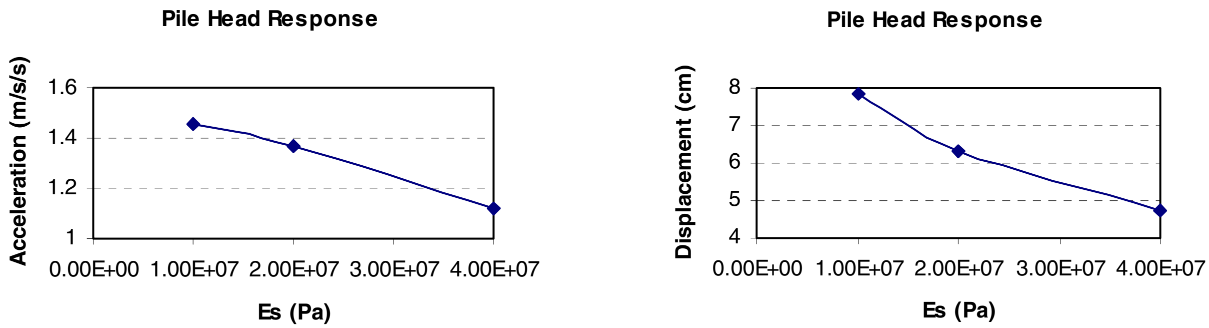


Figure 3. Effects of Es on Pile Head Response in 2*2 Pile Foundation Systems

For a 3*3 pile foundation system under a unit amplitude and 1 Hz harmonic excitation acting at the bottom of the soil and pile, effects of soil properties on the pile head responses are given in Figure 4. As shown in Figure 4, soil properties affect pile head acceleration and displacement significantly. The pile head acceleration and displacement in the 3*3 pile foundation system become larger due to stiffer soil, which is the same trend as in the 2*2 pile foundation.

On the other hand, pile head responses of the center pile in pile groups, including pile head acceleration and relative displacement to the base, are smaller than those of the corner pile due to the interaction among piles in the pile group foundation. Further comparison of pile head responses of the center pile and corner pile shows the pile group interaction depends on the soil properties. The responses of the center and corner pile are identical for soil with Es = 4×10^7 Pa, which can be explained by complete pile-soil-pile interaction due to stiff soil properties in the pile group systems.

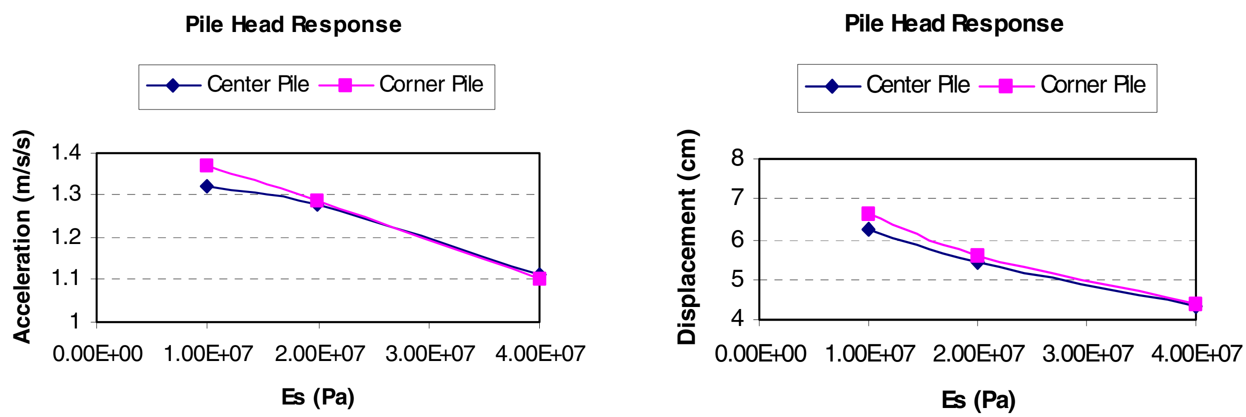


Figure 4. Effects of Es on Pile Head Response in 3*3 Pile Foundation Systems

Effects of Pile Spacing Ratios (S/D)

Effects of pile spacing ratios on fundamental frequencies of the soil-pile system are insignificant from the natural frequency extraction analyses, so pile head responses as well as soil-pile kinematic interaction are hardly affected by pile spacing ratios, as shown in Figures 5 and 6 for 2*2 and 3*3 pile groups, respectively. Compared with closely spaced pile groups, largely spaced pile groups have slightly larger pile head responses (acceleration and displacement) for both 2*2 and 3*3 soil-pile foundation systems, which is contributed to the higher stiffness of the systems and less pile-soil-pile interaction in the largely spaced pile foundation systems.

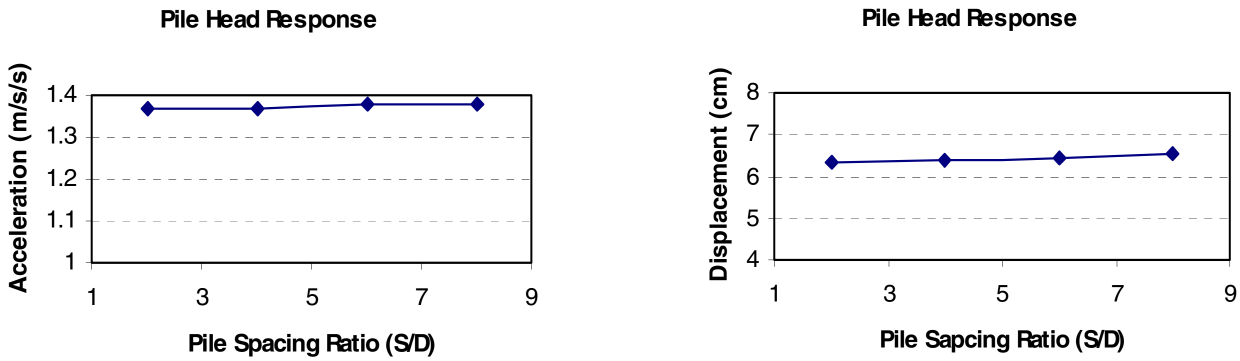


Figure 5. Effects of S/D on Pile Head Response in 2*2 Pile Foundation Systems

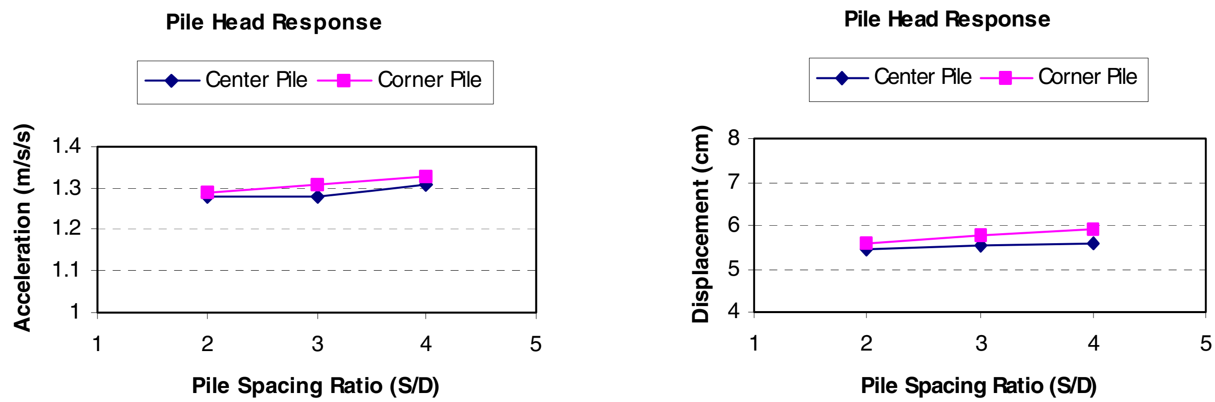


Figure 6. Effects of S/D on Pile Head Response in 3*3 Pile Foundation Systems

As shown in Figure 6 for 3*3 pile foundation systems, pile head accelerations and displacements of center pile and corner pile are identical in closely spaced pile groups (S/D=2). That means, all piles in the pile foundation and the nearby soil respond together to the base excitation because of relatively large pile-soil-pile interaction for closely spaced pile group systems.

Effects of Number of Piles

Effects of number of piles in pile foundations on seismic responses of a soil-pile system are studied in present research. The seismic performance of a 2*2 pile foundation with S/D=2 is compared with pile head responses of a 3*3 pile foundation with S/D=2 under El Centro earthquake excitation. As calculated in the frequency extraction analyses, the first frequency of the 2*2 pile group system is 1.168 Hz, which is smaller than 1.2074 Hz for the 3*3 pile group system. The seismic responses of the pile head for 2*2 and 3*3 pile foundations are shown in Figures 7 and 8, respectively.

The maximum pile head acceleration in the 2*2 pile foundation system is 0.481g, while the maximum pile head acceleration is 0.524g for the center pile and 0.443g for the corner pile in the 3*3 pile foundation system. The difference between pile head responses of the center pile and the corner pile is due to the assumption of free pile head rotation in this study. Since the pile head in the 2*2 pile foundation system is located between the center and corner pile in the 3*3 pile groups, the effects of number of piles on pile head acceleration are not significant for considered cases. The maximum pile head displacement is 7.15 cm in 2*2 pile foundation system and 6.17 cm for the center pile and 6.28 cm for the corner pile in the 3*3 pile foundation system, so the effects of number of piles on pile head displacement are significant for considered pile spacing ratio and El Centro excitation. To study the effects of number of piles on seismic performance of the soil-pile system in detail, a systematic research is needed to include various excitation frequencies and different pile group configurations.

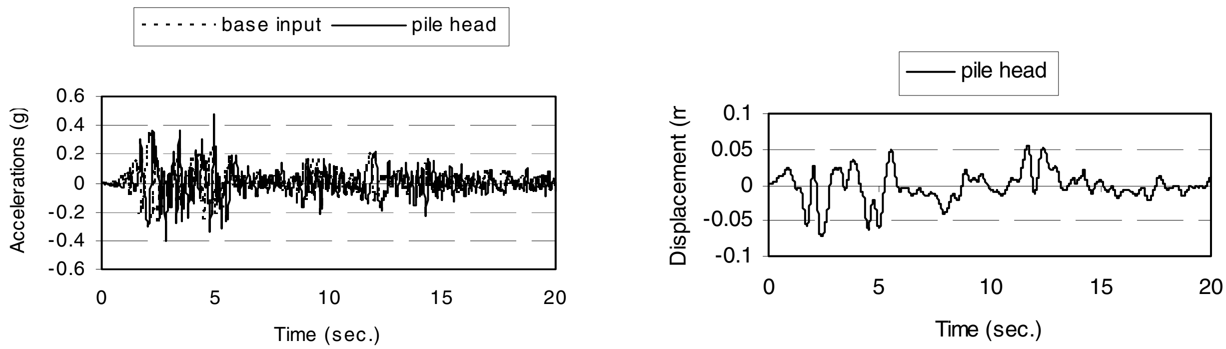


Figure 7. Pile Head Acceleration and Displacement of 2*2 Pile Groups

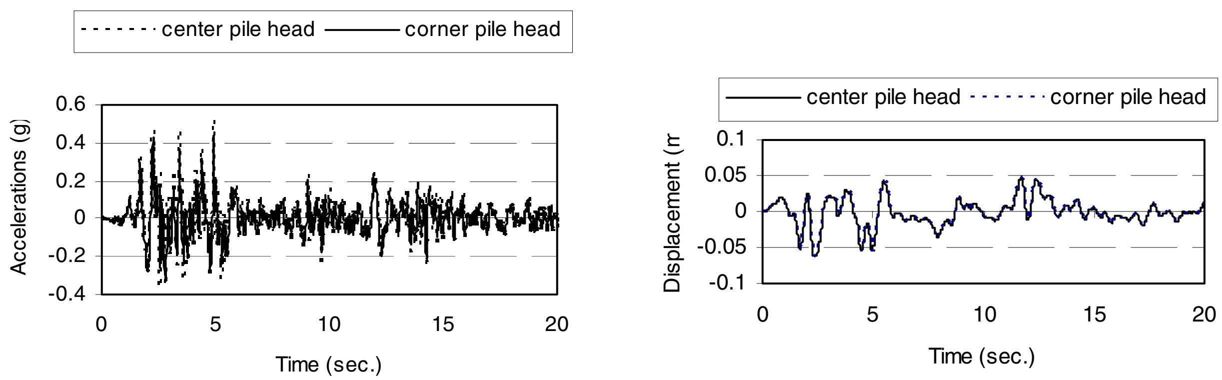


Figure 8. Pile Head Acceleration and Displacement of 3*3 Pile Groups

CONCLUSIONS

Results presented here are based on three dimensional nonlinear dynamic analyses for the interaction of soil-pile group foundation systems. This paper studies the effects of pile group configurations on seismic soil-pile kinematic interaction by investigating a 2*2 pile foundation system and a 3*3 pile foundation system with different soil properties and pile spacing ratios included.

Soil properties affect pile head acceleration, pile head displacement, and seismic interaction of the soil-pile system greatly. Although largely spaced pile groups have slightly larger pile head responses than closely spaced pile groups, the general effects of pile spacing ratios on seismic responses of the soil-pile systems are insignificant. The effects of number of piles on pile head acceleration are not significant, while the effects of number of piles on pile head displacement are considerable for considered pile spacing ratios and El Centro excitation. A more detailed research is suggested to study the effects of number of piles on seismic performance of soil-pile foundation systems.

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