An Impact of Pile Foundation Configurations on the Interaction of Seismic Soil, Pile, and Structure

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Abstract

In the dynamic analysis and seismic design of large or stiff structures and pile foundations, soil-pile-structure interaction (SPSI) plays a significant role. Configurations of pile foundations impact the seismic response of soil-pile-structure systems because soil stiffness degrades in the presence of earthquake excitations. In order to quantify the seismic response of a soil-pile foundation system, this paper develops an effective computational method. The effects of pile foundation configurations on the seismic soil-pile-structure interaction are taken into consideration in this thorough study. In order to provide a way for evaluating the seismic performance of the soil-pile system with different pile foundation configurations included, both linear and nonlinear analyses are done in the time domain using a three-dimensional finite element model of a soil-pile foundation system. Radiation damping is simulated using a boundary condition for infinite elements. We take into account both harmonic and particular seismic excitations. This study demonstrates that the effects of pile spacing ratios on pile head responses are not statistically significant and that soil parameters have a major impact on the seismic interaction of the soil-pile system. It is advised to do a thorough investigation of how the number of piles affects the soil-pile system's seismic performance.

Key words: *Pile Foundation, Seismic Soil-Pile-Structure, ABAQUS, Nonlinear dynamic, kinematic*

1. Introduction

In order to sustain buildings and other structures on soft soil, pile foundations are frequently used. earthquake vibrations are a common dynamic stress on a soil-pile-structure system, and seismic assessment and design of both new and existing structures depend heavily on the performance of the structure-foundation system. According to certain researchers, pile damage from earthquake excitations is prevalent. [1] looked into pile damage caused by earthquakes in [2] described pile damage caused by the 1995 Kobe earthquake. In earthquakes, such as Soil-Pile-Structure Interaction (SPSI), pile damage is also seen. SPSI is crucial for the soil-pile-structure system's seismic responses. By increasing the damping of a pile-supported structure due to energy dissipation in the soil, SPSI often lengthens the period of the structure and tends to lessen its peak seismic response, as shown by [3]. As a result, by taking SPSI into account in traditional seismic design practise, structural seismic "demand" is frequently reduced. But by taking SPSI into account, spectral values can also be extended by a longer duration. The performance of the structure-foundation systems during the earthquake in Mexico City gave adequate justification to think that SPSI effects should be researched more thoroughly and precisely. In order to have a more dependable seismic design for pile foundations and superstructures, the mechanism of pile damages needs to be better investigated [4].

Kinematic interaction and inertial interaction make up the effects of SPSI on the seismic performance of soil-pile-structure systems. The effects of the pile foundation on free-field ground motion—i.e., motion at the foundation level without the foundation present—are explained by kinematic interaction. The transmission of inertial loads from the superstructure to the pile base is represented by inertial interaction. In seismic soil-pile-structure interaction study, radiation damping is crucial because of the properties of soil's unbounded domain [5]. To depict the energy lost as waves propagate through the soil field, suitable boundary conditions are needed.

2. Materials and Methods

One of the most challenging geotechnical engineering issues is seismic SPSI, and there are still many fundamental questions to be answered. Since the early 1980s, significant effort has been devoted to analysing and simulating the dynamic behaviour of piles and pile groups subjected to seismic excitations. The development of analytical techniques for the lateral reaction of pile foundations under dynamic loads has advanced significantly. Three types of techniques can be used to analyse seismic soil-pile-structure interaction: the elastic continuum method, the nonlinear Winkler foundation method, and the finite element method [6].

In 1966, Tajimi applied the elastic continuum approach for the first time to study a dynamic soil-pile interaction problem, based on Mindlin's solution for point loads to a semi-infinite domain. This methodology was gradually updated by a number of studies to take into account the inertial effects of superstructures, the deterioration of soil resistance, layered soil, material damping, etc. Swane and Poulos' 1984 subgrade response approach took into account bilinear elastic-plastic springs and soil-pile gapping. The fully nonlinear p-y springs and dashpots used in the nonlinear Winkler foundation method are assumed to be linear elastic beamcolumns that represent the pile. [7] First, undertake dynamic study of offshore structures using an uncoupled methodology. Many researchers have since used a similar strategy to investigate the dynamic responses of soil-pile-superstructure systems.

The elastic continuum method was first applied by Tajimi in 1966 to study a dynamic soil-pile interaction problem based on Mindlin's solution for point loads to a semi-infinite domain. This was edited by several researchers. The "free-field" acceleration time histories are first calculated using a site response analysis method. In order to analyse the dynamic responses of the pile-superstructure system, the corresponding displacement time histories are then applied to the nonlinear p-y springs. In the prediction of superstructure responses, the site response calculations are a bigger source of uncertainty than the dynamic p-y computations, according to [8].

Any soil-pile-structure arrangement can be easily analysed in 2-D or 3-D fully linked fashion using the Finite Element Method (FEM). Direct techniques and substructure methods are both a part of FEM. The structure, piling foundation, and the materially non-homogenous and irregularly shaped soil constitute the finite element region in the substructure technique. A strict interaction force-displacement connection is used to model the infinite soil as a regular layered homogeneous semi-infinite domain.

The dynamic analysis of soil-pile-structure systems is built by incorporating this interaction force-displacement connection of the unbounded domain into the equations of motion of the structure. The structure, piling foundation, and soil profile up to the artificial border are all included in the direct method's finite element region. Artificial boundary conditions serve as a representation of the soil's semi-infinite half-space, simulating wave propagation and energy dissipation to ensure that no wave reflection occurs from the waves that are travelling outward. The soil-pile-structure systems' nonlinear seismic reactions are not taken into account by the substructure method because it is often formulated in the frequency domain, and thus cannot be applied to a nonlinear SPSI study. Due to a significantly wider finite element region than in the substructure technique, the direct method involves a significant number of degrees of freedom and takes into account the nonlinearity of the near-site soil domain. Because of its direct time solution and high computational demands, this method is often used in nonlinear SPSI analysis.

3. Experimental model work

This study examines a system made up of soil and a pile foundation in order to better understand the kinematic interaction caused by various pile foundation configurations. Figure 1 depicts the analytical model of a soil-single pile. For the soil with an embedded 1m*1m pile, the soil-pile system with dimensions of 35m*28m*15m is modelled using eight-node hexahedral three-dimensional finite elements. To take into account the energy absorption from the unbounded soil domain, an infinite number of elements are used to represent the far-field soil.

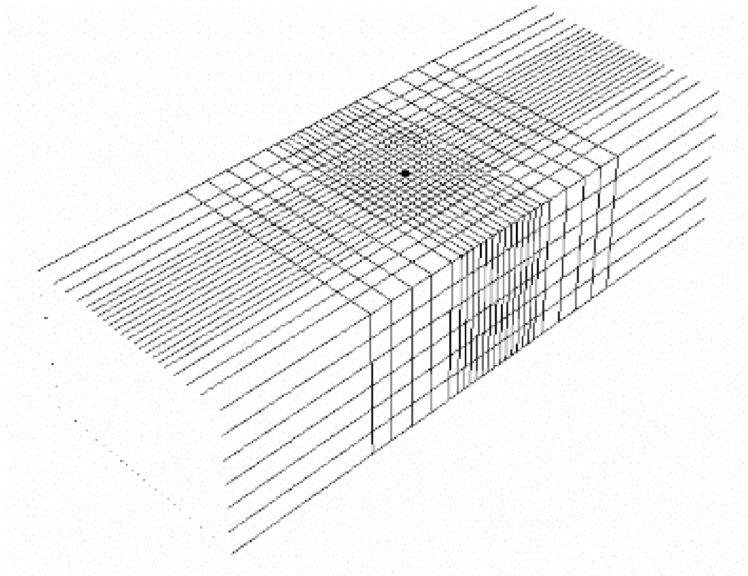
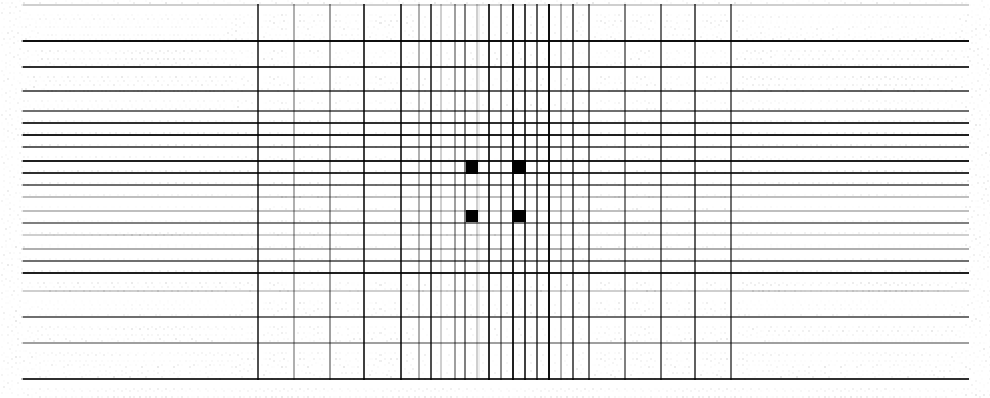


Figure 1. Finite Element Model of a Soil-Single Pile Foundation System

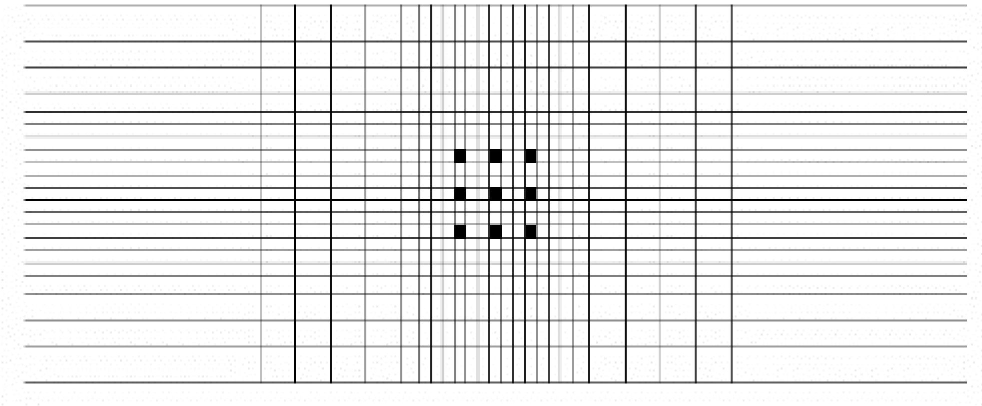
According to [9], the maximum mesh dimension in wave propagation issues relies on the shortest wavelength and should be less than (1/91/6). In order to maximise computational efficiency, the soil is discretized into distinct size meshes for near-site soil and far-site soil. For materials close to the pile, a soil mesh measuring 2m by 2m was used in this investigation. The size of the soil mesh grows as one gets farther away from the pile. On the border between finite elements and infinite elements, the maximum mesh dimension for finite elements is 5m in plan. The mesh size is 4 m in depth for all finite and infinite elements when taking into account the uniform distribution of wave propagation in the vertical direction. The proposed model consists of 2898 finite elements and 314 infinite elements.

The pile's length is equal to the soil media's depth. Modeling the concrete pile in three dimensions with eight nodes in a hexahedron and assuming linear behaviour with a Young's modulus of 3.5712 13 Pa and a Poisson's ratio of 0.24 Either harmonic or seismic stimulation in one direction fixes the soil's bottom and the single pile.

Similar to this, Figures 2(a) and 2(b) show the plans for soil-pile foundation systems for 2*2 and 3*3 pile groups, respectively. In this research, various pile spacing to diameter ratios (S/D) are taken into consideration in order to analyse the effects of pile foundation configurations on soil-pile kinematic interaction.



(a) 2*2 Pile Groups with S/D = 6



(b) 3*3 Pile Groups with S/D = 5

3.1 Radiation Damping

The energy lost by waves that are propagating outward from the finite element region of a soil-pile system is known as radiation damping. Appropriate boundary conditions must be used to simulate this energy dissipation since radiation damping is crucial to the investigation of seismic soil-pile-structure interactions. [10] presented a frequency independent viscous dashpot boundary to take radiation damping into account in an unbounded domain finite element analysis. [11] examined, using a frequency independent viscous dashpot boundary and an infinite element boundary, the dynamic response of a soil-pile foundation system. Dynamic responses utilising an infinite element boundary were discovered to be consistent with earlier findings from elastic analysis. In order to prevent reflecting dilatational and shear wave energy back into the finite element model, an infinite element boundary is taken into consideration in this work to represent the energy absorption by the far-field soil. It is presumpted that infinite elements will behave linearly [12].

4. Results and Discussions

This research examines both 2*2 pile groups and 3*3 pile groups with various soil parameters and pile spacing ratios incorporated to analyse the effects of pile group configurations on seismic soil-pile kinematic interaction. First, a study of the dynamic properties of both 2*2 and 3*3 pile foundation systems is conducted using natural frequency extraction. Then, in nonlinear assessments of soil-pile foundation systems under a harmonic excitation, the impacts of soil characteristics and pile spacing to diameter ratios (S/D) on kinematic interaction are investigated. In order to evaluate the impact of the number of piles on the seismic responses of soil-pile systems, the motion of the El Centro earthquake is used.

4.1 Dynamic Characteristics

In Tables 1 and 2, respectively, the fundamental frequencies of 2*2 and 3*3 pile foundation systems with different soil Young's moduli and pile spacing ratios are provided. In 2*2 pile foundation systems, the effects of pile spacing ratios are minimal, increasing from 1.168 Hz to 1.1785 Hz (0.9% increase) corresponding to S/D=2 and S/D=8, while the effects of soil Young's Modulus are significant, decreasing from 1.6311 Hz for Es=410 7 Pa to 0.8401 Hz for Es=110 7 Pa (28.1% increase) and increasing from 1.6311 Hz for Es=210 7 When taking into account the 1m*1m pile embedded in the 40m*30m*18m soil, the minor contribution of pile groups to the stiffness of the soil-pile systems can be used to explain this.

Table 1. Frequencies of 2*2 pile foundation system

S.no	Soil Young's Modulus Es (Pa)	Pile Spacing Ratio (S/D)	Natural Frequency (Hz)
1	1.00E+08	2	0.9541
2	3.00E+08	2	1.245
3	5.00E+08	4	1.279
4	2.00E+08	6	2.987
5	2.00E+08	6	1.578
6	2.00E+08	8	1.647

Table 2. Frequencies of 3*3 pile foundation systems

S.no	Soil Young's Modulus Es (Pa)	Pile Spacing Ratio (S/D)	Natural Frequency (Hz)
1	1.00E+08	2	0.874
2	2.00E+08	4	1.743
3	4.00E+08	4	1.325
4	2.00E+08	6	1.624
5	2.00E+08	6	1.247
6	2.00E+08	4	1.689

Effects of Soil Properties

It is assumed that soil qualities will have a significant impact on the interaction between seismic soil-pile-structure, as revealed by the natural frequency extraction analyses. Figure 3 shows the pile head acceleration and displacement for a 2*2 pile foundation system with a harmonic excitation of 1 m/s 2 amplitude and 1 Hz acting at the bottom of the soil and pile. It has been discovered that stiffer soil results in smaller pile head responses.

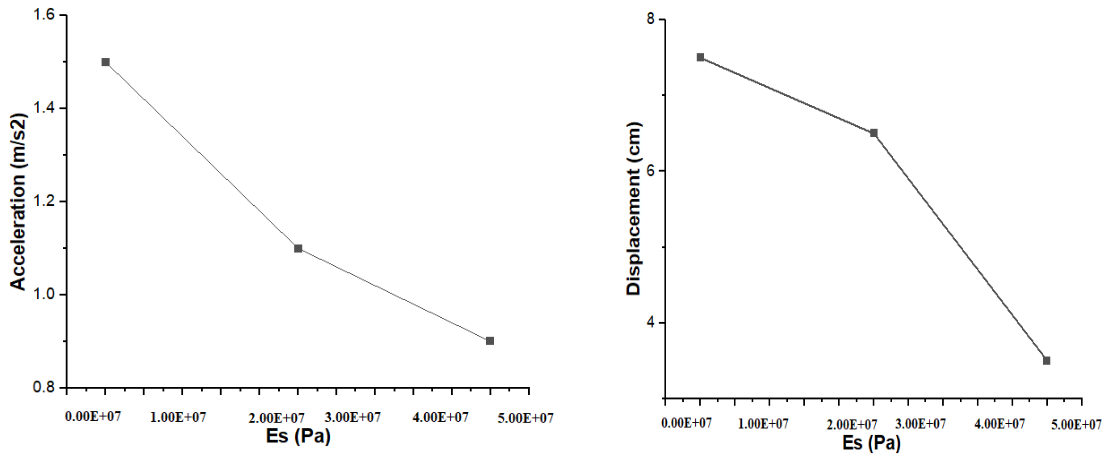


Figure 3. Effects of Es on Pile Head Response in 2*2 Pile Foundation Systems

Effects of soil characteristics on the pile head responses for a 3x3 pile foundation system with unit amplitude and 1 Hz harmonic excitation acting at the bottom of the soil and pile are shown in Figure 4. Figure 4 illustrates how strongly pile head acceleration and displacement are impacted by soil conditions. Due to the firmer soil, the pile head acceleration and displacement in the 3*3 pile foundation system increase, following the same pattern as the 2*2 pile foundation.

On the other hand, because of the interaction between the piles in the pile group foundation, the centre pile's pile head responses—including pile head acceleration and relative displacement to the base—are less than those of the corner pile. The pile group interaction depends on the soil qualities, as shown by a further comparison of the centre pile and corner pile's pile head responses. For soil with Es = 410 7 Pa, the responses of the centre and corner piles are identical, which is consistent with complete pile-soil-pile interaction caused by the stiff soil properties in the pile group systems.

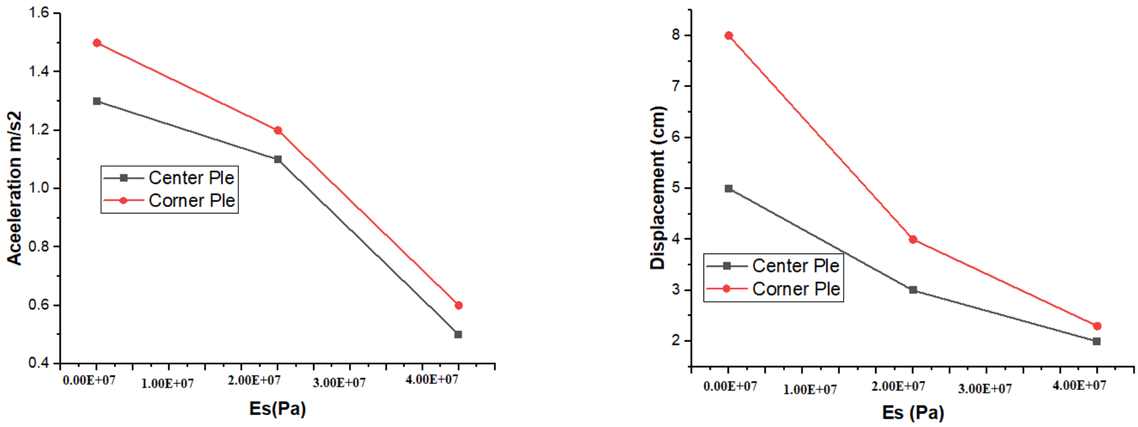


Figure 4. Effects of Es on Pile Head Response in 3*3 Pile Foundation Systems

Effects of Pile Spacing Ratios (S/D)

According to natural frequency extraction analyses, the effects of pile spacing ratios on the fundamental frequencies of the soil-pile system are negligible, so pile head responses and soil-pile kinematic interaction are hardly impacted by pile spacing ratios, as shown in Figures 5 and 6 for 2*2 and 3*3 pile groups, respectively. For both 2*2 and 3*3 soil-pile foundation systems, largely spaced pile groups have slightly larger pile head responses (acceleration and displacement) than closely spaced pile groups. This is due to the systems' higher stiffness and lower pile-soil-pile interaction in largely spaced pile foundation systems.

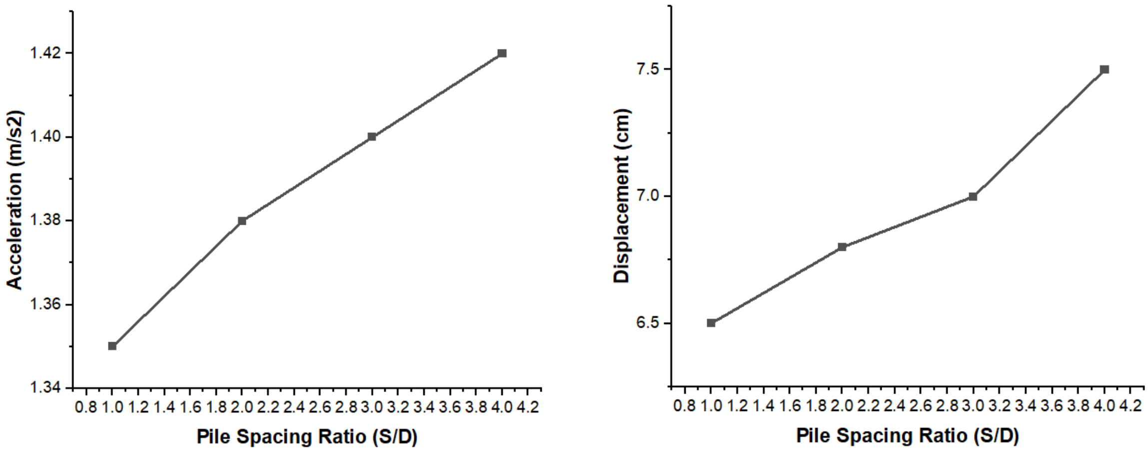


Figure 5. Effects of S/D on Pile Head Response in 2*2 Pile Foundation Systems

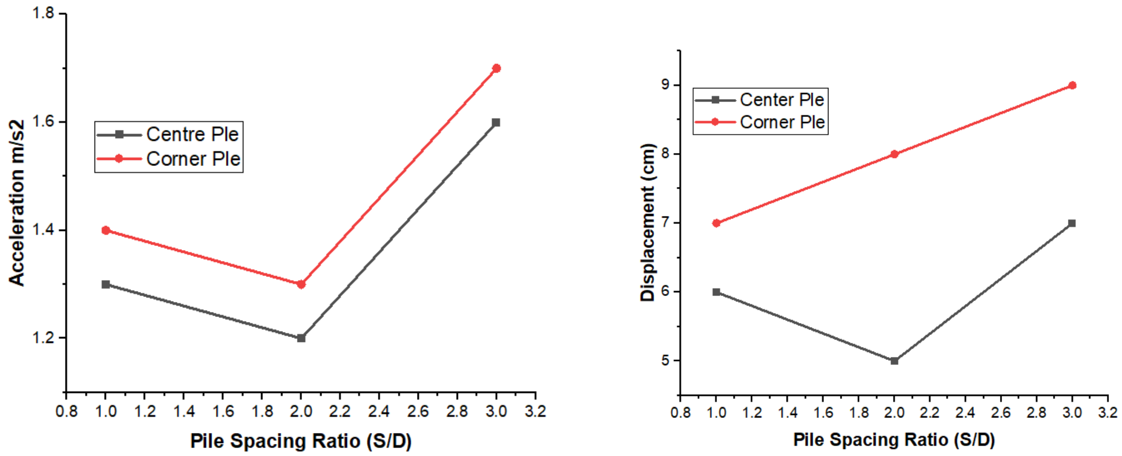


Figure 6. Effects of S/D on Pile Head Response in 3*3 Pile Foundation Systems

In closely spaced pile groups (S/D=3), as illustrated in Figure 6 for 3*3 pile foundation systems, the accelerations and displacements of the centre pile and corner pile are identical. This means that because of the relatively strong pile-soil-pile interaction for closely spaced pile group systems, all the piles in the pile foundation and the nearby soil react to the base excitation together.

Conclusions

Results for the interaction of soil-pile group foundation systems are based on three dimensional nonlinear dynamic analyses presented here. This research investigates a 2*2 pile foundation system and a 3*3 pile foundation system with various soil parameters and pile spacing ratios incorporated to study the effects of pile group configurations on seismic soil-pile kinematic interaction. For the investigated pile spacing ratios and El Centro excitation, the effects of the number of piles on pile head acceleration are inconsequential, however the effects of the number of heaps on pile head displacement are substantial. The impact of the number of piles on the seismic performance of soil-pile foundation systems are advised to be studied in more depth.

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