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EFFECT OF SINGLE PILE ON SITE RESPONSE

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Abstract. *Piles are generally the preferred foundation system when loads from the superstructure are larger than what shallow foundations can carry feasibly, or when the soils near the surface have poor/insufficient characteristics. Pile foundations display a complex behaviour during earthquakes due to effects of their interaction with the surrounding soil. These interaction effects are typically classified into two distinct—namely, inertial and kinematic—categories. During an earthquake, the soil medium vibrates the piles and the superstructure, and when inertial interaction is significant, the accelerated/mobilized masses of the piles and the superstructure shake the soil back. Kinematic interaction, on the other hand, is the collective term given to the effects of the rigidity of piles, which usually is significantly different than that of the soil; and this alters the incoming seismic waves. In a typical design of pile foundations, kinematic effects are usually ignored, and only the inertial effects are considered. It is also common for design engineers to assume foundations as fixed supports and completely omit the potential effects of soil-structure interaction. Nevertheless, kinematic interaction can significantly affect both the behaviour of the piles and the superstructure. Incident seismic waves generate strain in the ground and these strains act on the piles, generating moments and shear, even in the absence of a superstructure. The presence of piles impacts the site response by diffracting the seismic waves, and this may alter the peak ground acceleration (PGA), which is a common metric used in superstructure design. In this study, we investigate the effects of kinematic interaction on single piles through numerical simulations carried out with two-dimensional finite element models. These models are developed using OpenSees, wherein the soil is considered as an elastoplastic material. The primary objective is to quantify the effects kinematic interaction on the site response.*

1 INTRODUCTION

Pile foundations resist soil displacements and scatter seismic waves that emanate from base layers (bedrock) during earthquakes. Therefore, the soil motion recorded at an adequate distance away from the piles (a.k.a. the free-field motion) is different from that recorded at the pile-head [1]. The presence of the piles generally is ignored in the engineering practice, and the superstructure is assumed to rest on a rigid base that is prescribed to displace in unison with the free-field.

In this study, the effects of the pile foundation on the site response and kinematic interaction are investigated through simulations with the finite element method. Parametric studies are performed by applying harmonic input motions and real earthquake records to two-dimensional (plane strain) models to examine the behaviour of the soil-pile system. Parameters taken into account in these analyses are the stiffness ratio between pile and soil (E_p/E_s) and the pile length (L).

Soil layer properties have a substantial effect on the site response analysis since the soil domain directly affects the response characteristics with the layers either amplifying or de-amplifying the motions depending on the frequency content of the input excitation. Natural soils might be formed as clay, silt, sand, or as mixtures such as sandy clay; and the constitutive behaviour of these different soil types can be remarkably different from each other. In the present study, only homogeneous clay soil layers were considered, due to the more complex modelling considerations for sand for which liquefaction may occur during strong ground shaking. Nevertheless, kinematic interaction *can be* important for clayey soils—to which less attention was directed in general by the engineering community as compared to sand, because of the incorrect assumption that clayey soils do not pose problems as much as sandy soils.

2 PROBLEM DEFINITION AND SOLUTION METHOD

Three single floating (friction) piles with different lengths (of 10 m, 15 m, and 20 m) that are embedded in a homogeneous soil deposit with a layer thickness of H = 30 m, which rests on elastic bedrock were subjected to vertically propagating S-waves (Figure 1). All of the piles respond linear elastically, and have diameters of 1 m. On the other hand, the soil domain was considered to be either a linear-elastic, or an elastoplastic material. The effects of the pile-head boundary condition (free- or fixed-head) on the kinematic interaction were also investigated.

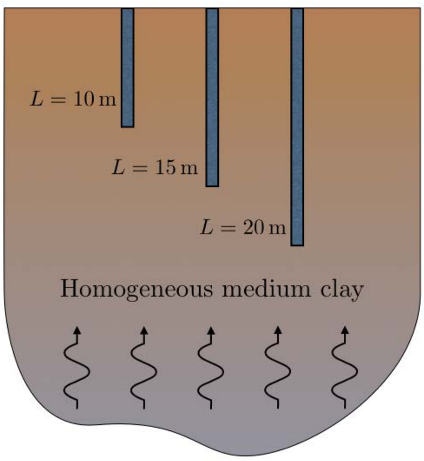

Figure 1: Single floating piles subjected to vertically propagating S-waves in homogeneous medium clay on elastic bedrock.

Analyses of the soil-pile foundation systems were performed using the OpenSees finite element platform [2]. The system was modelled in two-dimensions and a Lysmer-Kuhlemeyer [3] dashpot was used to represent the elastic half-space to account for the finite rigidity of underlying bedrock. To represent the truncated horizontal boundaries, free-field soil columns were placed on both sides of the model. The free-field columns have to be located sufficiently far away from the studied region so that it is not affected by the said truncation. An analysis of the size of the computational domain was carried out, and a horizontal distance of 30*D* from the pile was found sufficient. Also, the finite element mesh sizes are important to attain adequate accuracy in the analysis in seismic wave propagation problems, and the general recommendation is to remain below one-fifth to one-eighth of the shortest wavelength [4]. This condition was taken into account and the element sizes in the vertical direction were 0.25 m or less.

The homogeneous soil was considered as a clay material for which a pressure-independent elastoplastic model—that can simulate responses under monotonic as well as cyclic loading—was used. VonMises-type yield surfaces delineate the hardening zone as shown in Figure 2. The outmost surface determines the shear strength of the material. Masing-type hysteretic behaviour is reproduced by employing nonlinear kinematic hardening and associative flow rules as described in [5]. Clay and pile material properties are presented in Table 1. Interface elements between the soil and pile were not considered and not gap or frictional sliding was allowed between them.

Symbol	Description	Equation	Value
ρ_s	Soil mass density (Mg/m^3)		1.7
V_s	Shear wave velocity (m/s)		250
ν_s	Soil poisson ratio		0.35
G	Soil shear modulus (kPa)	$\rho \times V_s^2$	
E_s	Young modulus of soil (kPa)	$2G\ (1+\nu)$	
K	Bulk modulus of soil (kPa)	$E/[3\times(1-2\nu)]$	
c	Cohesion (kPa)		50
ϕ	Soil friction angle (^{o})		0
γ_{peak}	Peak shear strain		0.05
σ_{ref}	Reference pressure		80
d	Pressure dependency coefficient		0
ρ_p	Pile mass density (Mg/m^3)		2.5
ν_s	Pile poisson ratio		0.15
E_p	Young modulus of pile (kPa)	Variable depending on soil parametric studies	

Table 1: Soil and pile properties used in analysis.

Analyses were performed in two stages: First stage is the gravity loading in which prior site conditions are established. In the second stage, dynamic loading is applied as a force time-history to the base of the geometry using Joyner and Chen’s Method [6]. The force time-history was created by multiplying the velocity time-history of a given motion by the mass density and the shear wave velocity of the bedrock and the base area of the model.

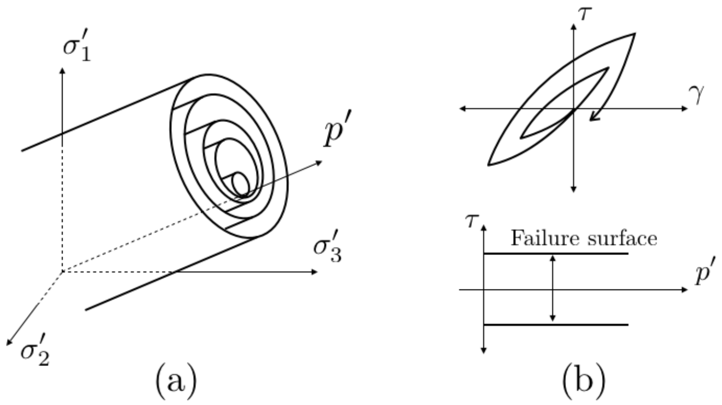

Figure 2: Pressure independent soil material constitutive model: (a) shape of yield surface in principal effective stress space, and (b) response of constitutive model (figure adapted from [5]).

3 SITE RESPONSE ANALYSIS

Three groups of analyses were carried out to investigate the effects of the presence of the piles on the site response and to quantify kinematic interactions. The first set of simulations were the site response analyses without the piles. These two-dimensional OpenSees models were verified through comparisons with a well-established software package (Shake2000). The second group analyses were site response analyses with the piles using harmonic motions as input. The third group analyses were identical with the second group, but were carried out with input motions that are actual earthquake time histories recorded during the 1999 Kocaeli Earthquake of Turkey.

3.1 Site Response Analysis without the Pile

One-dimensional equivalent site response analyses are performed using the Shake2000 [7] program to verify our two-dimensional model. The geometry of the model used in the site response analysis without the pile was the same with that used in the parametric studies including the pile. An actual earthquake time-history from the 1999 Kocaeli Earthquake recorded at the Mecidiyekoy Station was used in this analysis.

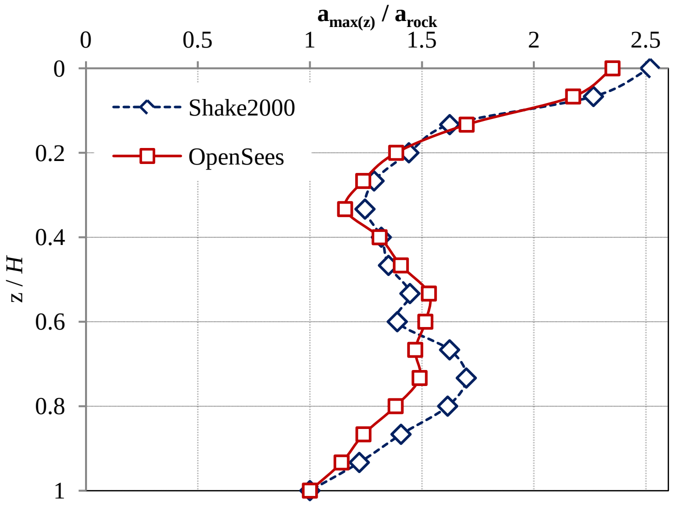

Figure 3: Comparison of the two-dimensional OpenSees model and Shake2000 results.

The results of the site response analyses are shown in Figure 3 where z denotes the depth, a_{max} (z) is the maximum acceleration at depth z, and a_{rock} represents acceleration of the bedrock input motion. The soil was modelled as linear-elastic material with elastic shear modulus that is computed as a function of the initial effective confinement, as Shake2000 considers the soil as an equivalent linear elastic material. The comparison indicates that OpenSees results agree with Shake2000 results reasonably well.

3.2 Harmonic Responses

In order to understand the effects of piles on the site response, parametric studies were performed using harmonic input motions with increasing dimensionless frequency "*a*" defined in Eq. (1). In these analyses, the influences of the slenderness ratio "L/D" and the stiffness ratio "E_p/E_s" on site response were examined; and the parameter variations are given in Table 2.

L (m)	E_p / E_s
10	100
15	500
20	1000
	2000

Table 2: Used parameters in site response analyses.

$$a = \omega \times D/V_s \tag{1}$$

The effects of the variation of the said parameters on the site response are quantified in the form of a "kinematic interaction factor" that is defined as the ratio of the measured acceleration at pile head (a_p) to the free-field acceleration (a_{ff}) as defined in Eq. (2). To explore the effects of material behavior and the magnitude of input motions, linear and nonlinear analyses were performed for the free-head case using a pile length of 20 m and pile-soil stiffness ratio of 1000. The results of these analyses results are shown in Figure 4 where it can be seen that linear models' results vary more mildly that the nonlinear models' results and at low frequencies (a = 0.05 to 0.2) the kinematic interaction for nonlinear models can be significantly higher. Furthermore, the kinematic interaction effects generally increase with magnitude.

$$I = a_p / a_{ff} \tag{2}$$

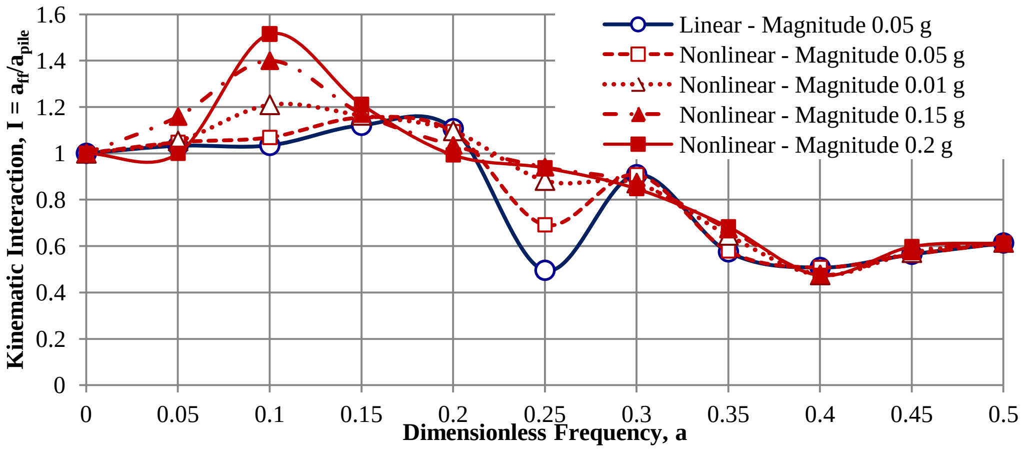

Figure 4: Comparison of nonlinear and linear analysis results for free head case.

The effects of the relative stiffness between the soil and the pile (E_p/E_s) on the kinematic interaction factor for the fixed-head case for a pile length of 15 m is shown in Figure 5. At the low frequency region (0.05 < a < 0.15), the kinematic interaction factor tends to increase if the stiffness ratio decreases, while it generally decreases with frequency. At the intermediate frequency region (0.15 < a < 0.35), this factor declines rapidly especially for high stiffness ratio values (E_p/E_s=1000 to 2000). Finally, the interaction factor behaves smoothly at high frequencies. Additionally, the kinematic interaction factors for high stiffness ratios generally decline with frequency from the start to the end.

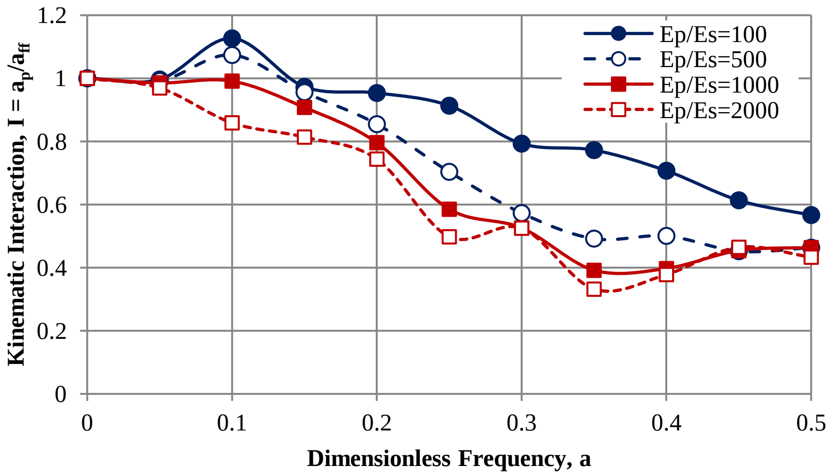

Figure 5: Effect of stiffness ratio on site response for fixed head condition.

The pile-length effect is shown in Figure 6 for the relative stiffness ratio (E_p/E_s) of 1000 and the free-head case. The variation of the kinematic interaction factor for short piles is not sharp; on the contrary its value changes sharply with increasing pile length.

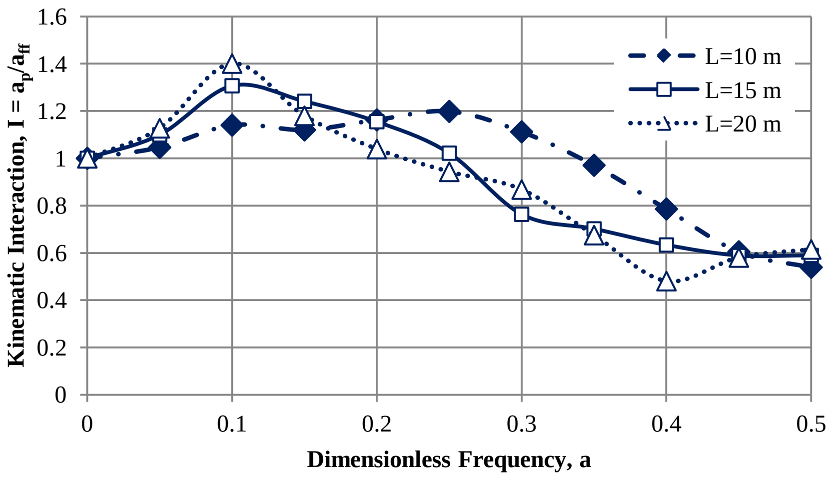

Figure 6: Effect of pile length on kinematic interaction for free-head condition.

The effect of the pile-head boundary condition is demonstrated in Figure 7, for the case of free- and fixed-head piles with lengths of 15 m and stiffness ratios of 1000. Kinematic interaction factor for the free-head pile is greater than that for the fixed-head pile when the pile-head boundary condition is taken into account. Furthermore, kinematic interaction factor doesn't rise with increasing frequency.

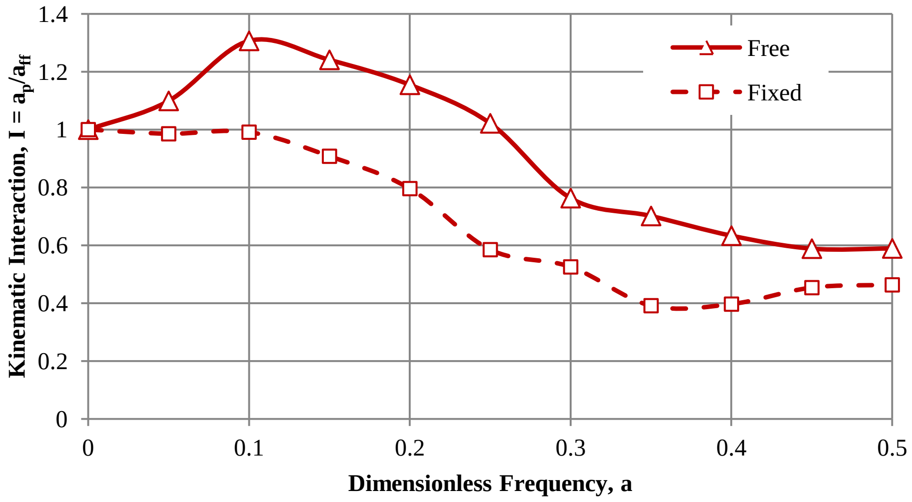

Figure 7: Pile head boundary condition effect on kinematic interaction.

3.3 Transient Responses

Site response analyses with the piles were performed by using three real earthquake acceleration time-histories selected from the 1999 Kocaeli Earthquake records. These time history records, the station names, and the Fourier spectra of the signals are shown in Figure 8. The records were selected according to seismic intensity. Peak ground acceleration of the records, parameter variations, and the analysis results are presented in Table 3.

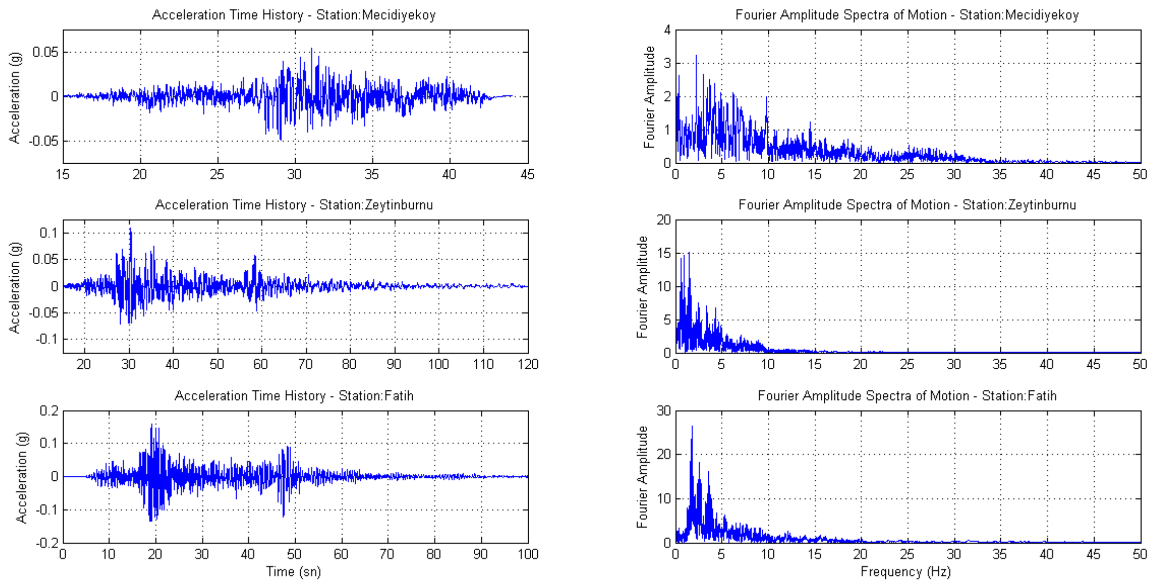

Figure 8: 1999 Kocaeli, Turkey Earthquake time histories and Fourier spectra.

The transient motion analyses were executed for the fixed-head condition except for the Fatih Station record to evaluate the pile-head boundary condition effect. The effect of the pile length is less than the other factors, as it may be deduced from the results. Some of the kinematic interaction factors are greater than unity, and the values depend mainly on the stiffnesses of the soil layer and the pile foundation, along with the input signal's frequency content.

Station Name	Considered Parameter	Peak Ground Acceleration PGA (g)	Stiffness Ratio Ep/Es	Pile Length L (m)	Free-Field "a_{ff}" Acceleration (g)	Pile-Head "a_p" Acceleration (g)	Kinematic Interaction $I = a_p / a_{ff}$
Zeytinburnu	Stiffness Ratio	0.108	100	15	0.1034	0.1172	1.133
Zeytinburnu	Stiffness Ratio	0.108	1000	15	0.1033	0.1036	1.003
Mecidiyekoy	Pile Length	0.054	1000	10	0.0641	0.0536	0.836
Mecidiyekoy	Pile Length	0.054	1000	20	0.0642	0.0519	0.808
Fatih	Earthquake Record	0.159	1000	15	0.1372	0.1582	1.153
Zeytinburnu	Earthquake Record	0.108	1000	15	0.1033	0.1036	1.003
Mecidiyekoy	Earthquake Record	0.054	1000	15	0.0641	0.0533	0.832
Fatih	Fixed-Head	0.159	1000	15	0.1372	0.1582	1.153
Fatih	Free-Head	0.159	1000	15	0.1378	0.1833	1.330

Table 3: Transient analysis parameters and results.

4 CONCLUSIONS

Soil-structure system analysis is usually performed using the free-field motions during the design process. However, the presence of piles affects the overall system behaviour, as the piles resist the seismic motions, thereby altering the soil's deformations. Consequently, the acceleration under the superstructure (e.g., at the pile cap) is usually significantly different from the free-field acceleration. The free-field motion should be modified when analysing the foundation-superstructure system, using a kinematic response factor derived from rigorous soil-structure interaction analyses.

Parametric site response analyses with solitary piles were carried out under harmonic as well as various recorded earthquake motions in order to examine the effects of the stiffness of the piles on the foundation input motions. The results were quantified using a *kinematic interaction factor*, which is a measure of the differences between the pile-cap and the free-field motions. The results can be summarized as follows:

- A general picture of the kinematic interaction depending on parameters such as the stiffness ratio between the pile and the soil, pile length, pile-head boundary condition, and dimensionless frequency was obtained (cf., Figures 4-7). Accordingly, at low frequencies, the kinematic interaction factor increases or remains constant. For intermediate frequencies it decreases up to a certain value, finally becoming smooth at high frequencies.
- Some inferences could be made using results from transient analyses. However, they are not valid for all situations; and generalizations do not appear possible because there are a great numbers of parameters affecting the overall system behaviour such as soil and pile properties, earthquake characteristics, and superstructure features.
- Design engineers generally assume that the presence of the piles contribute to seismic safety in a positive direction. However, results in this study demonstrate that kinematic

interaction factor sometimes could be greater than unity, which means that seismic demands on the superstructure might be larger than currently assumed in practice.

In summary, kinematic interaction can be a significant aspect of soil-structure interaction behavior and it should be considered in the design of important superstructures (e.g., tall buildings, harbor structures, or nuclear power plants) supported on pile foundations.

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