Thessaloniki-GREECE 2007

4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1695

INSIGHT INTO SOIL-PILE-STRUCTURE INTERACTION INCLUDING INERTIAL AND KINEMATIC EFFECTS

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ABSTRACT

The important role of soil-pile-structure interaction on the seismic response of pile-supported structures has been widely established by several theoretical and experimental studies. However, due to the complex nature of the physical phenomenon, the identification of the key parameters that affect the interaction mechanism remains a crucial task. Along these lines, the frequency content of the seismic motion constitutes an important parameter that affects the intensity of soil-pile-structure interaction phenomena and consequently the seismic response of pile-supported structures. In this paper, soil-pile-structure interaction is numerically examined in the frequency domain in order to obtain an insight on the effect of the natural frequencies of the system on pile and structural dynamic response. Kinematic soil-pile interaction is initially investigated under harmonic excitation applied at the base of the soil profile, emphasizing on the effect of the soil fundamental frequencies on the pile bending moments. Within the framework of the validation of the adopted soil-pile model, additional analyses were performed implementing pilehead loading in order to obtain pile impedance functions and compare them to existing analytical formulas. In a second stage of analysis the coupled soil-pile-structure system is examined, adopting single pile-supported structures with different dynamic characteristics. Soil-pile-structure interaction effects are discussed in terms of the fundamental frequency of the superstructure, the bending moments generated along the pile shaft and the pile head motion. The analysis results indicate that for certain soil-pile cases, the kinematic peak pile bending moments may occur at frequencies higher than the fundamental frequency of the soil deposit. On the other hand, the investigation of the coupled soil-pile-superstructure system revealed that structural oscillations transmit large bending moments on the pilehead when the modified frequency of the structure due to SSI effects is close to the fundamental frequency of the input motion. Furthermore, the combined effect of inertial and kinematic interaction may under certain conditions result in a significant amplification of the pilehead horizontal motion at the fundamental frequency of the pile-structure system.

Keywords: Kinematic interaction, inertial interaction, coupled soil-pile-structure system

INTRODUCTION

During the last two decades significant progress has taken place in the field of soil-pile-structure interaction. Well-documented centrifuge and shaking table tests (Wilson, 1998, Meymand, 1998) as well as post-earthquake investigations on pile failures (Mizuno, 1987, Tokimatsu et al. 1998, Berill and Yasuda, 2002) have elucidated some of the dominant parameters that affect pile and structural response during seismic shaking. Moreover, several numerical and analytical methods have been proposed for the analysis of soil-pile-structure systems, implementing simplified interaction models such as the Beam on Dynamic Winkler Foundation approach as well as more rigorous BEM or FEM

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formulations. The majority of these methods utilize the principle of superposition, decomposing therefore the total interaction mechanism into kinematic and inertial effects (Kagawa and Kraft, 1982, Nogami, 1983, Gazetas, 1984, Fan et al. 1991, Gazetas et al, 1992, Kaynia and Novak, 1992, Makris and Gazetas, 1992, Gazetas & Mylonakis, 1998). Although the implementation of the superposition approach is by definition restricted to linear response, it may be a reasonable approximation even when moderate non-linear soil behavior is anticipated (Mylonakis et al., 1997). An alternative approximation to this multi-step method is the direct analysis of the coupled soil-pile-structure system (Lok et al. 1998, Guin and Banerjee, 1998), which allows one to capture simultaneously the interaction effects between all the components of the system and additionally permits a more precise evaluation of the non-linear soil behavior.

The aforementioned theoretical and experimental studies have established the significant influence of the frequency content of the input motion on the seismic response of pile-supported structures. Both kinematic and inertial interaction effects present a strong frequency dependency, which accordingly affects the structural dynamic characteristics as well as the incident wave field imposed on the structure. Therefore, the identification of the role of the natural frequencies of the system on the soil-pile-structure interaction is required towards the prediction of the seismic response of pile-supported structures, especially in correlation with the frequency content of the input motion. Along these lines, resonance phenomena that may be generated during seismic shaking could modify substantially the interaction mechanism, imposing large seismic loads on the pile-structure system.

In this paper, soil-pile-structure interaction is numerically examined in the frequency domain, emphasizing on the effect of the soil and the structure fundamental frequencies on the dynamic response of the system. The adopted analysis procedure comprises two stages. In the first stage, pile dynamic response due to kinematic soil-pile interaction is investigated, utilizing a single pile embedded in a homogeneous soil stratum of finite depth. Emphasis is given on the effect of the soil fundamental frequencies on the distribution of the steady state bending moments along the pile shaft, while kinematic interaction factors are also computed for both fixed and free pilehead conditions. Within the framework of the validation of the adopted soil-pile model, the soil-pile system was reanalyzed implementing harmonic loading applied on the pilehead, in order to obtain pile impedance functions and compare them to existing analytical expressions. In the second stage of analysis, the dynamic response of the coupled soil-pile-structure system is examined, with emphasis on the role of the dynamic characteristics of the superstructure. Results are discussed in terms of the fundamental frequency of the superstructure, the bending moments generated along the pile shaft and the pile head motion.

KINEMATIC RESPONSE ANALYSIS OF THE SOIL-PILE SYSTEM

Based on the superposition approach, the analysis of the complete soil-pile-structure system under seismic excitation is performed with the following three consecutive steps (Makris et al. 1994, Gazetas & Mylonakis, 1998): (a) Estimation of the response at the pilehead (the so-called "foundation input motion") in the absence of the superstructure's mass which includes translational and rotational components (b) Calculation of the dynamic impedances (springs and dashpots) associated with each vibration mode of the foundation (swaying, rocking and cross swaying rocking oscillation) and (c) Computation of the superstructure's seismic response supported on the springs and dashpots of step b and subjected to the foundation input motion obtained from step a. Kinematic soil-pile interaction that is examined in step (a) holds therefore a significant role in the determination of the seismic response of pile supported structures since it can modify substantially the pilehead motion with respect to the free field response. Furthermore, soil deformations during seismic wave propagation may impose significant kinematic induced bending moments on the pile foundations (Tazoh et al. 1987).

In order to examine kinematic interaction effects, an end bearing pile of circular cross section embedded in a 30m thick homogeneous soil layer over rigid bedrock was employed herein. The shear wave velocity of the soil was considered constant with depth and equal to Vs=200m/sec that corresponds to soil type C according to EC8 (CEN 2002). The Poisson ratio and the hysteretic damping ratio of the soil were taken equal to v=0.33 and βs=0.05 respectively. The relative soil-pile stiffness was considered equal to

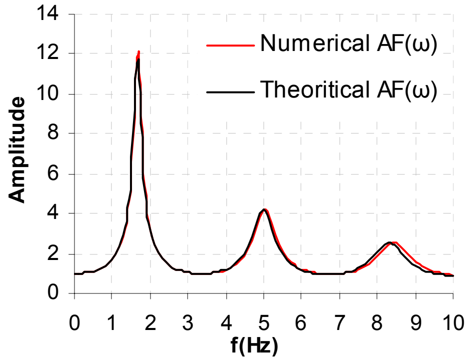


Figure 1. Amplification function of the examined soil deposit

E_p/E_s=1000 while the pile slenderness, i.e the ratio of the pile length L to the pile diameter D, was selected equal to L/D=20. The dynamic response of the soil-pile system was investigated in the frequency domain. The analyses were performed with the general purposed FE code ANSYS (Ansys, 2000), implementing a 3D finite element model of the soil-pile system. The soil stratum was meshed with 8-node solid elements while the pile was modelled with linear elastic beam elements attached to the FE mesh, thus ignoring in a first stage any potential soil-pile gapping mechanism. Introducing elementary boundaries at the lateral sides of the model revealed minimal interference to the free field soil response during the numerical analysis while the FE mesh size was adequately defined based on the anticipated wavelength of the shear waves propagating in the soil.

Soil response analysis

In order to prove that wave propagation effects are adequately captured by the employed FE model, soil response analyses were initially performed under harmonic displacement applied at the base of the soil profile. Based on the one-dimensional wave propagation theory (Roesset, 1977), for a monochromatic SV wave motion $u_g(t)=u_g e^{i\omega t}$ introduced at the bedrock level and a homogeneous soil stratum, the steady state displacement at the ground surface equals to $u_{ff}(t)=u_{ff}e^{i\omega t}$. The amplification function, AF, defined as the ratio of the amplitude of the motion at the free surface u_{ff} to the amplitude at the bedrock level u_g can be computed from the equation:

$$AF_{soil}(\omega) = \frac{u_{ff}}{u_g} = \frac{2}{\exp(i \cdot \omega \cdot \frac{V_s^*}{H}) + \exp(-i \cdot \omega \cdot \frac{V_s^*}{H})} \tag{1}$$

where H is the thickness of the soil layer and V_s^* is the complex shear wave velocity of the form $V_s^* = V_s \cdot \sqrt{1 + 2 \cdot i \cdot \beta_s}$. The amplification function obtained from the harmonic response analysis of the soil profile was compared to the theoretical solution given by Equation 1. Fig. 1 shows the aforementioned comparison where a very good agreement is observed, thus verifying that soil response is sufficiently reproduced by the FE model. The specific frequencies where the soil response is amplified correspond to the fundamental frequencies of the soil deposit, which in the particular case are equal to 1.6Hz, 5Hz and 8.33Hz respectively.

Kinematic interaction factors

Due to kinematic soil-pile interaction the horizontal displacement at the pile head u_p is generally different from the free field motion u_{ff}, while in the case of free head conditions the pile head is subjected to an additional rotational motion φ_p. The kinematic interaction effects, in terms of the pilehead response, are usually described by the kinematic interaction factors (Gazetas, 1984):

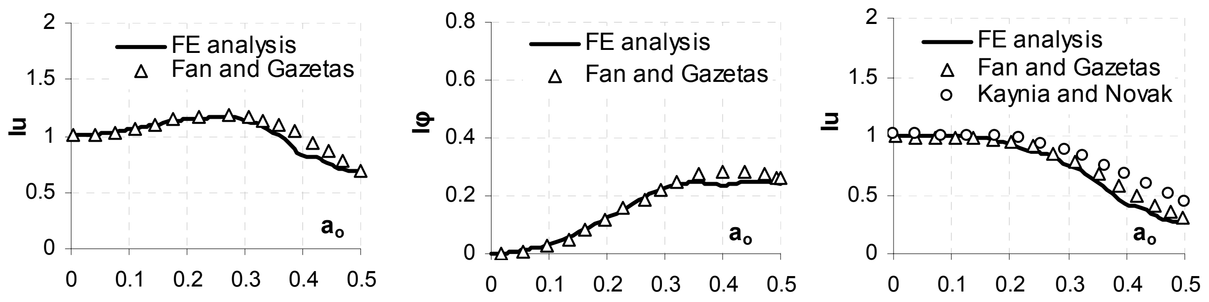
$$I_u = \frac{u_p}{u_{ff}} \qquad I_\varphi = \frac{\varphi_p \cdot r}{u_{ff}} \tag{2}$$

where r=D/2 is the pile radius. The pilehead to free field response ratios defined in Equation 2 were numerically obtained for both free and fixed pile head conditions and were then compared to kinematic interaction factors proposed by Fan and Gazetas, 1991 and Kaynia and Novak, 1992 for a similar soil-pile system. The comparative results shown in Fig.2 confirm further the accuracy of the obtained analyses, highlighting certain kinematic interaction effects with respect to the excitation frequency as well as to the pilehead conditions. It is observed that in the case of the fixed head pile, the kinematic soil-pile interaction has a dominant effect mainly in the high frequency range, where the inability of the relatively stiff pile of the present study to follow the free field deformation caused a significant reduction of the pilehead displacement with respect to the soil motion. On the other hand, when the rotational degree of freedom is released at the pilehead adopting free pilehead conditions, the I_u values exceed unity in the low to intermediate frequency range that implies a pilehead motion greater than the free field response. In the high frequency range though, the observed reduction of the pilehead motion with respect to the free field displacement is less severe than in the fixed head case. Furthermore, the rotation of the pilehead is increasing with frequency. Similar findings regarding the effect of the pilehead conditions on the kinematic interaction factors are also reported in the study of Gazetas et al., (1992).

Kinematic Pile Bending moments

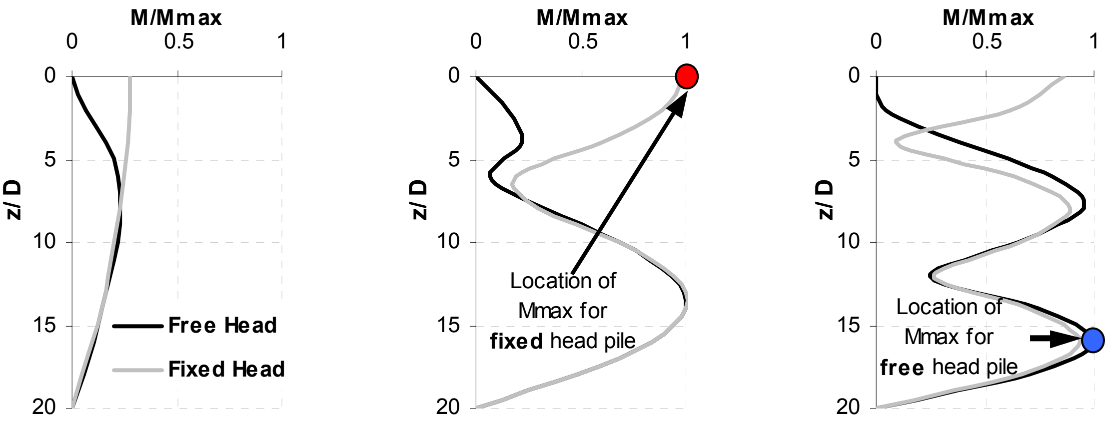
Although kinematic induced pile bending moments are usually significant in the presence of sharp stiffness discontinuities in the soil profile (Mylonakis, 2001), large soil curvatures may occur also in the case of a homogeneous soil stratum due to the "wavy" shape that characterizes the higher response modes of the soil (Kavvadas and Gazetas, 1993). The latter is further investigated herein, emphasizing on the role of the fundamental frequencies of the soil deposit on the pile response. The distribution of the steady state bending moment amplitude along the pile length was therefore computed at each one of the three fundamental frequencies of the considered homogeneous soil layer. The results obtained for free as well as for fixed pilehead conditions are shown in Fig. 3. It is noted that the distributions of the bending moments presented in Fig.3 are normalized to the maximum bending moment developed along the pile length. More specifically the bending moment profiles obtained for the free head pile are normalized to the maximum moment that occurred at the 3rd natural frequency of the soil deposit (the exact location is indicated in Fig.3 with a blue circle) while the bending moments computed for the fixed head case are normalized to the maximum moment obtained at the 2nd natural frequency of the soil (red circle in Fig.3). Reviewing the results, it is observed that bending moments of free and fixed head pile converge at a common depth and become practically identical beyond a certain distance from the ground surface. This depth should be correlated to the "active pile length" beyond which a head-loaded pile behaves like an infinitely long beam. Indeed, utilizing the analytical relationship (Poulos and Davies, 1980, Randolph, 1981):

$$La \approx 1.5 \cdot \left(\frac{Ep}{Es}\right)^{1/4} \cdot D \tag{3}$$



(a) (b) (c)

Figure 2. Kinematic interaction factors for: a -b) Free head pile c) Fixed head pile (Homogeneous soil stratum, Ep/Es=1000, L/D=20, βs=0.05, ν=0.33)



(a) (b) (c)

Figure 3. Effect of pile head conditions on kinematic bending moments amplitude obtained at the a) First b) Second and c) Third natural frequency of the soil deposit

results in an active pile length equal to 8.6D, which is very close to the depth below which the distribution of the pile bending moments is not affected by the different pilehead conditions. Moreover, the bending moment developed on the free head pile at the first natural frequency of the soil deposit increases with depth, reaching its maximum approximately at the mid-length of the pile, while the bending moment of a fixed head pile is a monotonically decreasing function of depth.

Similar findings are reported in the study of Nikolaou et al., 2001 where a Beam on Dynamic Winkler Foundation modeling approach was implemented. It is interesting to note though that based on the 3D FE analyses obtained herein, higher deformation modes generated larger pile bending moments for both free and fixed head pile. This is in contrast to the conclusions drawn by Nikolaou et al., 2001 and Gazetas et al. 1992, where the significant overall drift of the first mode was associated to larger bending moments. Although the pile curvature is affected by the overall drift between the top and the bottom of the pile, which is indeed larger in the first natural frequency of the soil, the curvature imposed on the pile due to the "wavy" shape of the higher modes seems to be the dominant response mechanism in this case. Consequently, the variation of the kinematic bending moment with frequency doesn't follow the pattern of the free field soil response shown in Fig.1 where greater amplification is observed at the first fundamental frequency of the soil deposit. This observation is in agreement with some earlier statements (Dobry & O'Rourke, 1983, Kavvadas and Gazetas, 1993) that higher modes can produce larger kinematic bending. However, the above results simply indicate a possible cause when large kinematic induced bending moments are observed and cannot therefore be easily generalized. Certainly a thorough investigation is required, including various soil-pile configurations, in order to establish further the effect of the soil fundamental frequencies on the pile response.

EVALUATION OF PILE HEAD IMPEDANCE FUNCTIONS

The evaluation of the pile head impedance functions constitutes one of the essential analysis steps for the inertial part of the decomposition approach that was described above. The soil-pile system was therefore reanalyzed under pilehead harmonic loading, in order to compare the numerically obtained dynamic stiffness of the pile with analytical expressions that have been proposed for the case of a free head pile embedded in a homogeneous soil. A convenient expression of the dynamic impedance functions associated with each vibration motion of the foundation is given by the equation (Gazetas, 1987):

$$K(\omega) = \bar{K}(\omega) + i \cdot \omega \cdot C(\omega) \quad (4)$$

where the real part of the complex valued impedance, $\bar{K}(\omega)$, represents the stiffness and the inertia of the supporting soil while the component $\omega \cdot C(\omega)$ (imaginary part) reflects the radiation and the material damping of the system. Neglecting the vertical component of motion, the dynamic stiffness of a free head pile can be expressed in a matrix form as:

$$K(\omega) = \begin{bmatrix} K_{XX}(\omega) & K_{XR}(\omega) \\ K_{RX}(\omega) & K_{RR}(\omega) \end{bmatrix} = \begin{bmatrix} \bar{K}_{XX}(\omega) + i \cdot \omega \cdot C_{XX} & \bar{K}_{XR}(\omega) + i \cdot \omega \cdot C_{XR} \\ \bar{K}_{RX}(\omega) + i \cdot \omega \cdot C_{RX} & \bar{K}_{RR}(\omega) + i \cdot \omega \cdot C_{RR} \end{bmatrix} \quad (5)$$

where the indices XX, XR and RR correspond to the swaying, the cross swaying rocking and the rocking component of the foundation motion respectively. The pilehead dynamic stiffness matrix given in Equation 5, was obtain herein by the inversion of the corresponding flexibility matrix that was in turn constructed from the numerically derived pilehead displacements and rotations due to a steady state horizontal force or moment imposed on the pilehead. Fig. 4 shows the pilehead impedance functions for the free head pile, which are in a satisfactory agreement with the analytical expressions proposed by Gazetas et al., 1992. Indeed the damping coefficient is reduced with increasing frequency in each vibration mode of the foundation while the real part of the dynamic soil stiffness, $\bar{K}(\omega)$, is practically insensitive to the frequency content of the excitation force.

However, a slight difference is observed regarding the amplitude of the real part of the impedance functions, where the FE analyses result in lower stiffness values with respect to the analytical expressions, especially for the swaying and the coupled swaying-rocking motion. This difference that occurs also for the static case (f=0) and is subsequently reproduced with increasing frequency, should be attributed to the different modeling approximations introduced in each approach. The latter is further established in Table 1 where the pile horizontal static stiffness obtained from the FE analysis is compared to the well-known relationship (Poulos and Davis, 1980):

$$K_S = \left(4 \cdot E_p \cdot I_p\right)^{1/4} \cdot k^{3/4} \quad (6)$$

implementing different expressions that have been proposed for the determination of the modulus of the soil subgrade reaction:

$$k \approx \delta \cdot E_S \quad (7)$$

where the coefficient δ depends mainly on the soil profile, the type of the head loading and the relative

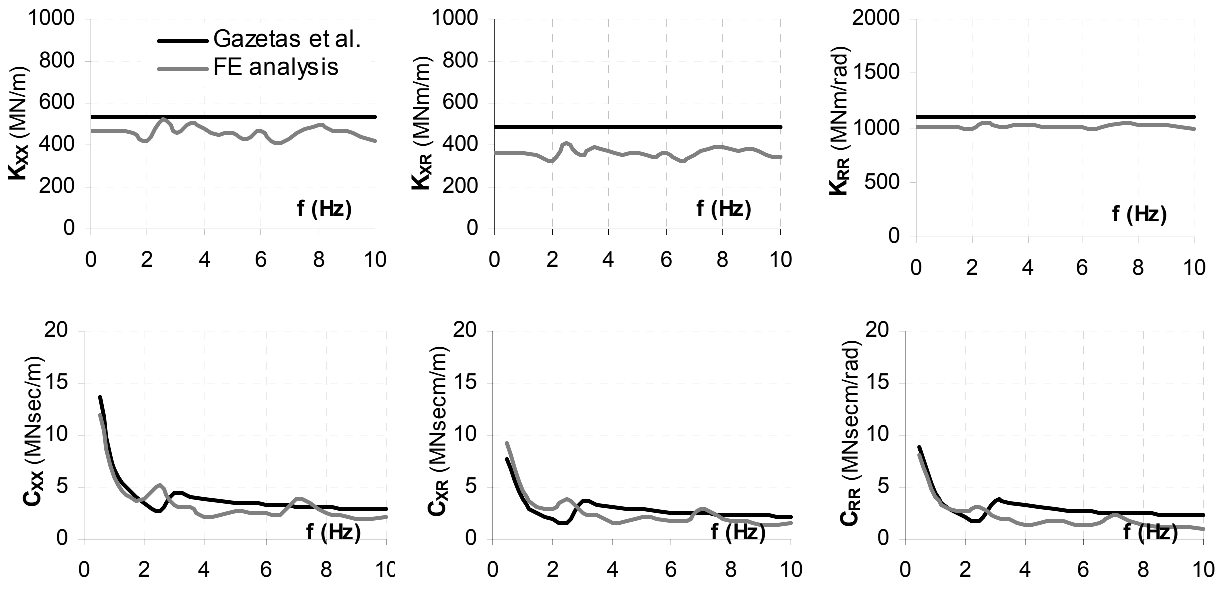


Figure 4. Numerical results compared to analytical expressions regarding the pilehead impedance functions of a free head pile

Table 1. Pile head static stiffness

Reference	Proposed expression for **δ**	**k** (KN/m2)	**Ks** (KN/m)
Dobry et al, 1982	$\delta = 1.67 \cdot \left(\frac{Ep}{Es}\right)^{-0.053} = 1.29$	247000	521400
Makris and Gazetas, 1992	1.2	229830	494000
Kavvadas and Gazetas (1993)	$\delta \approx \frac{3}{1 - v_s^2} \cdot \left(\frac{E_s}{E_p}\right)^{1/8} \cdot \left(\frac{L}{D}\right)^{1/8} = 2$	350000	670000
Vesic, 1961	$\delta = \frac{0,65}{1 - v_s} \cdot \left[\frac{E_s D^4}{E_p I_p}\right]^{1/12} = 0.83$	318400	630000
Davies and Budhu, 1986	$f_{uH} = \frac{1.3 \cdot K^{-0.18}}{Es \cdot D_{eq}}$		358000
*Gazetas et al., 1992	$K_{HH} = D \cdot E_s \cdot \left(\frac{E_p}{E_s}\right)^{0.21}$		532740
FE results (present study)			471000

*Compared to the FE analysis results shown in Fig.4

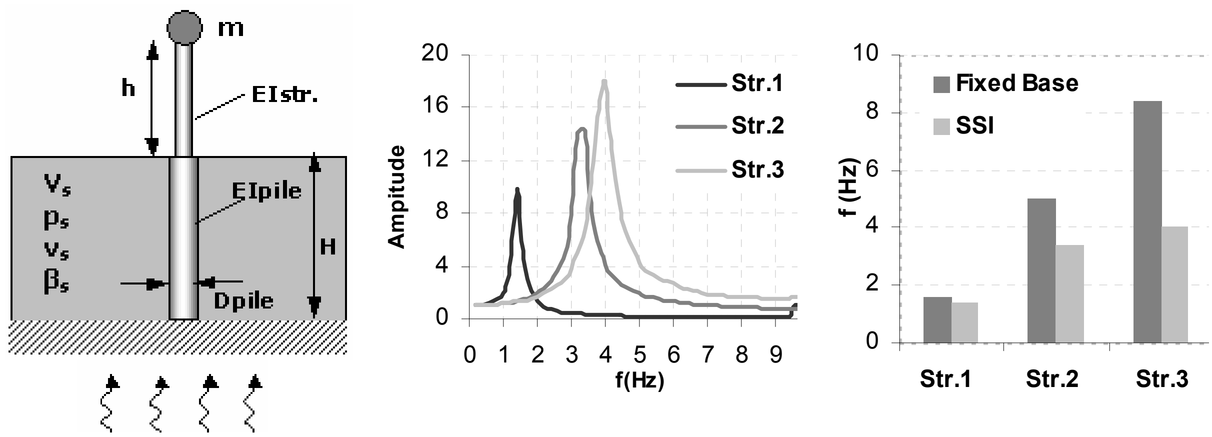
soil-pile stiffness. It is interesting to note the computed range for the pile static stiffness value, Ks, as a result of the different approach utilized by the various researchers to obtain δ. Given the aforementioned variation in predicting the pile stiffness based on the analytical expressions utilized, the FE analyses results are considered satisfactory, thus verifying the ability of the FE model to adequately reproduce soil-pile interaction under pilehead loading.

In a following stage, the calculated frequency dependent springs and dashpots are introduced at the base of the structure, in order to incorporate soil compliance and consequently evaluate the seismic response of the superstructure due to inertial interaction effects. This final step of the decomposition approach is not further examined herein.

ANALYSIS OF THE COUPLED SOIL-PILE-STRUCTURE SYSTEM

Although the decoupling of the total soil-pile-structure system provides a clear identification of the separate role of inertial and kinematic interaction on the final seismic response of the superstructure, the implementation of the coupled system provides on the other hand a direct and probably more realistic estimation of the pile and structural response, since inertial and kinematic effects are simultaneously accounted for. The dynamic response of the coupled soil-pile-structure system was therefore investigated in a second stage of analysis, implementing a single pile supported structure founded on a homogeneous soil layer (Fig. 5a). For this reason a mass was attached to an extension of the pile shaft, thus modelling the superstructure as a single degree of freedom oscillator. The coupled system was also analysed in the frequency domain under harmonic displacement applied at the bedrock level. Emphasis was given on the effect of the dynamic characteristics of the superstructure. Three sdof structures having different fundamental frequencies were therefore analysed. The fixed base frequency, f_{str}, of each structure was selected equal to the first, second and third natural frequency of the foundation soil respectively.

Table 2 in the following page summarizes the specific parameters utilized in the analysis of the coupled system. It is mentioned that the different fundamental frequency of the superstructure was obtained by modifying the stiffness of the SDOF structure. Since the mass as well as the height of the superstructure have been verified to play an important role in the interaction mechanism (Kirtas et al. 2007), they were kept constant throughout the parametric investigation in order to reduce the factors that contribute to the



(a) **(b)** **(c)**

Figure 5. a) The coupled soil-pile-structure system studied b) Structural top to base displacement ratio c) Effect of SSI on the fundamental period of the structure

modification of the fundamental frequency of the structure due to soil structure interaction. The following paragraphs present typical results obtained from the numerical analyses of the coupled system, emphasizing on the role of soil-pile-structure interaction on the pile and structural dynamic response.

Effect of soil-pile-structure interaction on the structural fundamental frequency

The increase of the fundamental period of structures constitutes one of the main effects of soil-structure interaction that has been widely verified (Wolf, 1985, Gazetas, 1987). In order to quantify this effect for the particular soil-pile-structure systems examined herein, the structural top to base displacement ratio was computed in each case (Fig.5b). The effect of soil-structure interaction on the fundamental frequency of the structure is depicted in Fig.5c, where the effective (SSI) fundamental frequency of the superstructure is compared to the fixed base frequency for each examined case. It is observed that stiffer structures (e.g Str.3) are subjected to stronger SSI effects, resulting therefore in a significant decrease in the fundamental frequency of the structure.

Effect of soil-pile-structure interaction on the pile bending moments

Soil-pile-structure interaction effects were subsequently investigated in terms of the pile bending moments developed on the pile foundation. The comparative distributions of the steady state bending moment amplitudes along the pile length presented in Fig.6a, 6b and 6c correspond to the first, second and third fundamental frequency of the soil deposit respectively after being normalized to the maximum bending moment that occurred at each frequency. More specifically, the bending moment distributions depicted in Fig.6a are normalized to the maximum bending moment observed at the first natural frequency, while the bending moment distributions depicted in Fig.6b and 6c are normalized to the maximum bending moment developed at the second and third natural frequency of the soil deposit respectively. The pile bending moments obtained at the same frequencies considering only kinematic

Table 2. Investigated cases of soil-pile-structure interaction

Soil – pile properties					Structural properties					
H(m)	**Vs**	**D_p**	**L/D**	**E_p/E_s**	**Structure**	**m**(t)	**h**(m)	**$D_{str.}$**	**$EI_{str.}/EI_p$**	**f_{str}** (Hz)
30	200	1.5	20	1000	**Str.1**	100	10	0.75	0.065	**1.6**
30	200	1.5	20	1000	**Str.2**	100	10	1.35	0.66	**5**
30	200	1.5	20	1000	**Str.3**	100	10	1.75	1.85	**8.4**

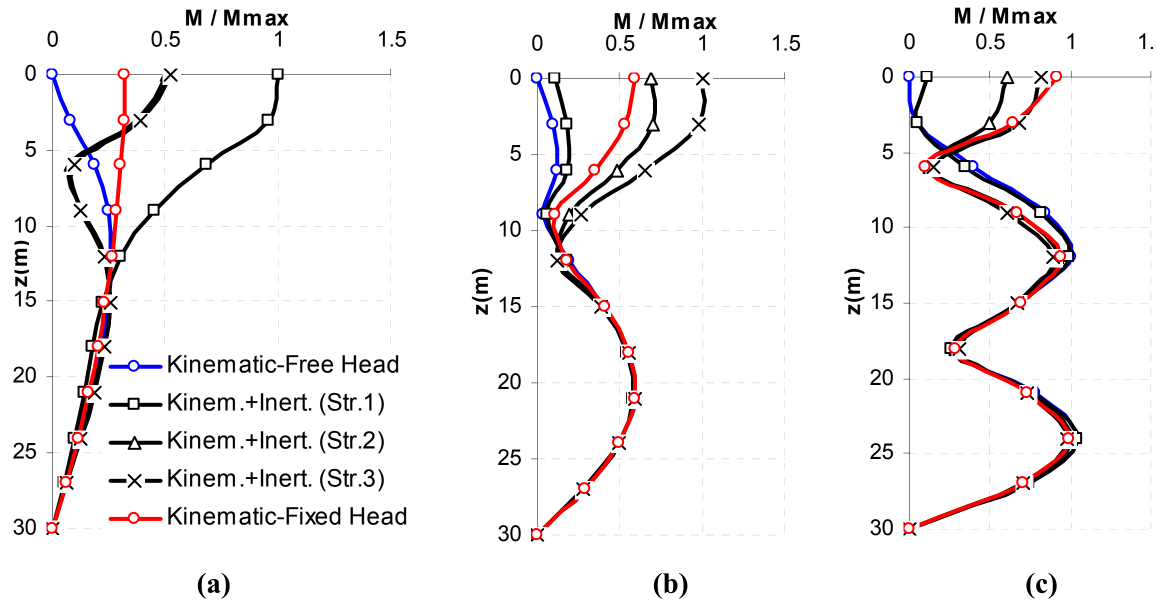
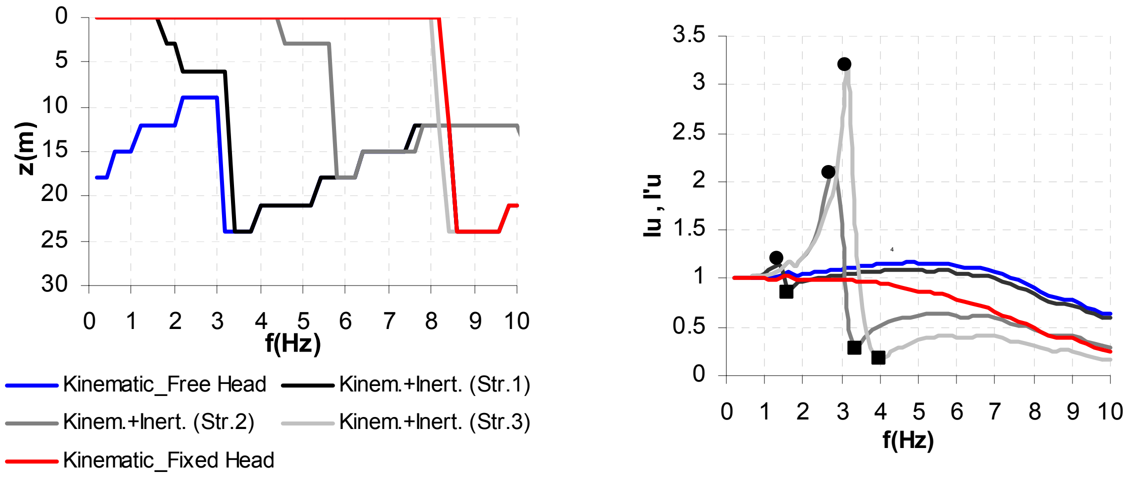


Figure 6. Distribution of bending moment amplitude at the (a) first (b) second and (c) third natural frequency of the soil deposit.

interaction are also depicted in Fig.6. It is observed that the bending moments generated due to the combined effect of inertial and kinematic interaction converge at a certain depth beyond which they become practically identical to the bending moments developed due to solely kinematic interaction. Therefore, structural oscillations affect pile response near the pile head where the inertial interaction is expected to become significant especially when the structure is in or near resonance. The latter is more pronounced in the case of the flexible superstructure Str.1. Soil structure interaction had a minor effect on the fundamental frequency of the particular structure and consequently the SSI frequency remained close to the fixed base case, which in turn was considered equal to the first natural frequency of the soil deposit. Thus, the large bending moment observed at the pilehead of the Str.1 pile foundation (Fig.6a) is actually the result of a double resonance phenomenon where both the soil and the structure are in resonance. A similar pile response is observed in the case of the stiffer structure Str.3, where in this case the effective (SSI) frequency of the structure is close to the second natural frequency of the soil deposit. Therefore, the distribution of the bending moments that corresponds to the pile foundation of Str.3 (Fig.6b), where the largest bending moment is also observed at the pilehead (a clearly inertial effect), results from the interplay between the soil in resonance and the structure near resonance. On the other hand, the pile bending moment profiles of Fig.6c obtained at the third natural frequency of the soil depict the predominant role of kinematic effects on the pile bending moments when the structure responds at a frequency different from that of the imposed motion while the soil is in resonance.

Conclusively, it can be stated that inertial interaction prevails when the excitation frequency is close to the effective (SSI) frequency of the superstructure imposing large bending moments at or near the pilehead. This should be correlated with the single pile foundation employed herein, where the large inertial force that is developed on the superstructure due to resonance effects is directly transmitted as a shear force and bending moment onto the pilehead (Mylonakis et al., 1997). On the other hand, when the fundamental frequency of the input motion excites higher soil modes and the structure is not in resonance, strong kinematic effects are activated that may also generate significant pile distress at greater depths. The latter is further illustrated in Fig.7a where the frequency variation of the depth that the maximum steady state pile bending moment occurs is depicted. It is interesting to note that the frequency range where the maximum bending moment occurs at the pilehead is increasing with the fundamental frequency of the superstructure. However, beyond a certain frequency the location of the maximum pile bending moment is shifted away from the pilehead, indicating additional cross sections along the pile length that may be subjected to large bending moments especially under high frequency excitations. Similar observations regarding the interplay between the kinematic and inertial interaction



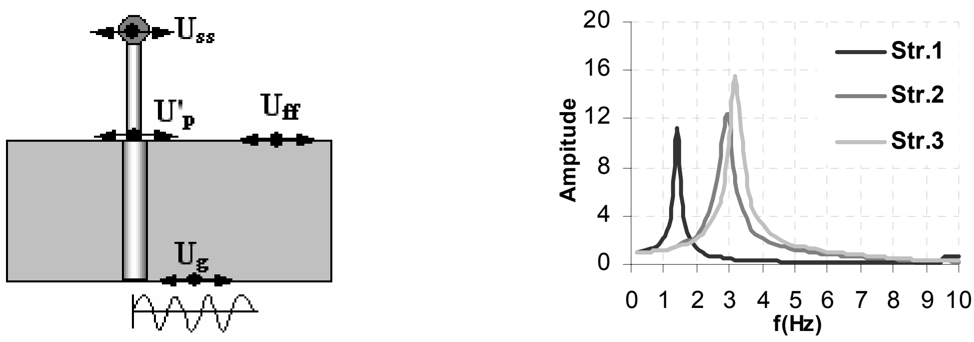
(a) (b)

Figure 7. a) Depth at which maximum bending moment occurs along the pile as a function of the excitation frequency b) Pile head to free field displacement ratio

in the development of pile forces under seismic loading have also been reported by Kaynia and Mahzooni, 1996, where the dynamic response of a SDOF oscillator founded on a typical 5x5 pile group was examined implementing a three-dimensional Green's function-based formulation.

Effect of soil-pile-structure interaction on the pile head motion

The response of the coupled soil-pile-structure system was further investigated in terms of the pilehead motion U'p (Fig.8a). For this reason the pile head to free field displacement ratio (I'_u=U'_p/U_{ff}) was computed for each one of the examined cases. The obtained results are shown in Fig.7b where the kinematic interaction factors for free and fixed pile head conditions are also plotted. It should be mentioned though that the pile head to free field motion ratio that is derived from the analysis of the coupled system is not directly correlated with the kinematic interaction factors, which are conventionally obtained considering a massless superstructure. However, the investigation of the pilehead motion under the combined effect of inertial and kinematic interaction indicated the natural frequencies of the system that actually affected the superstructure's base motion. Indeed the frequency variation of I'_u seems to be dominated by two discrete frequencies; a lower frequency (marked in Fig.7b with circles) where the pilehead motion is amplified and a higher one (marked in Fig.7b with rectangles) where the pilehead motion is suddenly deamplified with respect to the free field response. The particular variation pattern is in agreement with the analyses of real earthquake events that have been recorded on a pile-supported structure (Ohta et al., 1980). Trying to identify the specific frequencies it was observed that the frequency, where the deamplification of the pilehead motion occurs, coincides with the modified



(a) (b)

Figure 8. a) Illustration of the response parameters utilised in the investigation of the pilehead motion b) Structural top to free field displacement ratio

fundamental frequency of the superstructure due to soil-structure interaction effects (Fig.5b). On the other hand, the particular frequencies where the pilehead motion is amplified with respect to the free field motion were found to correspond to the fundamental frequency of the pile-structure system, that was in turn obtained from the structural top to free field displacement ratio (U_{ss}/U_{ff}) (Fig.8b). This ratio results actually from the structural top to soil base motion ratio (U_{ss}/U_g) after being divided by the soil amplification ratio (U_{ff}/U_g), thus removing the effect of the soil response. Furthermore, it is observed that the effect of the coupled interaction mechanism on the pilehead horizontal motion becomes more pronounced as the frequency of the superstructure increases, resulting in a stronger amplification at the fundamental frequency of the pile-structure system.

CONCLUSIONS

Certain aspects of the soil-pile-structure interaction mechanism were discussed in this paper in terms of the kinematic soil-pile interaction effects, the pile head impedance functions and the dynamic response of the coupled system. The harmonic response analyses that were performed on a validated finite element model aimed at obtaining an insight on the effect of the natural frequencies of the system on pile and structural dynamic response. Based on the results of the numerical analyses obtained herein it was observed that significant kinematic induced bending moments are developed on the pile at greater depths, when higher modes of the surrounding soil are excited. Thus, the maximum pile bending moment due to kinematic interaction may for certain soil-pile cases occur at frequencies higher than the fundamental frequency of the soil deposit. The examination of the entire soil-pile-superstructure system showed on the other hand that structural vibrations have a paramount effect on the pile bending moments when the frequency of the seismic motion is close to the effective (SSI) fundamental frequency of the structure, resulting in large bending distress at the pilehead. Finally, the combined effect of inertial and kinematic interaction resulted in a significant amplification of the pilehead motion with respect to the free field response, which was observed at the fundamental frequency of the pile-structure system.

ACKNOWLEDGEMENTS

The first author would also like to acknowledge the contribution of IKY foundation.

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