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THE EFFECT OF FOUNDATION EMBEDMENT ON INELASTIC BEHAVIOR OF STRUCTURES

M. Mahsuli[1] and M. A. Ghannad[2]

ABSTRACT

In this research, a parametric study is carried out on the effect of soil-structure interaction on the ductility demand of buildings with embedded foundation. Both kinematic and inertial Interaction effects are considered. By using the sub-structure method, the structure is represented by a simplified single degree of freedom system with idealized bilinear behavior and the soil sub-structure is considered as a homogeneous half-space and is modeled by a discrete model based on the concept of Cone Models. Finally, the whole soil-structure system is analyzed subjected to selected accelerograms directly in time domain using step by step integration method. By comparing the ductility demand of the fixed-base structure with those of the structure located on flexible soil, the effect of soil-structure interaction is investigated.

Introduction

It is well known that as a result of Soil-Structure Interaction (SSI), the response of a structure supported on soil is different from that of an identical structure in the fixed-base state. The principal effect of the interaction is to increase the natural period of the structure and usually, to increase its effective damping ratio. Therefore, depending on the response spectra ordinates at the resonant period, one may expect either increasing or decreasing of the structural response caused by a specific base excitation. The general SSI effect on structural response has been the subject of numerous researches over the last three decades (Chopra 1974, Novak 1974, Veletsos 1977 among the others). Besides, its effect has found its way into seismic codes as simplified guidelines (ATC 1978, NEHRP 2003). The SSI effect on the response of nonlinear structures, however, has attracted much less attention (Bielak 1976, Muller 1982, Rodriguez 2000). On the other hand, the current seismic design philosophy is based on nonlinear behavior of buildings during moderate and strong earthquakes. Most of the studies conducted on this issue are performed for a presumed set of system parameters. The work done by Aviles (2003) is an instance in which these parameters were fixed at conventional values in order to approximate typical buildings and site conditions in Mexico City. Ghannad (2006, 2007) studied the subject parametrically for structures with surface foundations. The approach is extended for embedded foundations here considering both kinematic and inertial interaction effects.

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[1] Graduate Student, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran
[2] Associate Professor, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran

Soil-Structure Model

A simplified model as shown in Fig. 1 is considered to represent the real problem. This model is based on the following assumptions:

1. The structure is replaced by an elasto-plastic Single Degree of Freedom (SDOF) system with effective mass m, effective height h, and mass moment of inertia I.
2. The foundation is replaced by a circular rigid disk with mass m_f, mass moment of inertia I_f, and embedment depth e.
3. The soil beneath the structure is considered as a homogeneous half-space and is modeled as a discrete model based on the concept of Cone Models (Wolf 1994). Cone Models, based on one dimensional wave propagation theory, can be used with sufficient accuracy in engineering practice (Meek 1993). Two degrees of freedom (DOF) are introduced in this model for the foundation namely sway, u_f, and rocking, φ. Consequently, by considering an internal DOF for the soil model, φ_1, a 4 DOF model is formed as shown in Fig. 1.

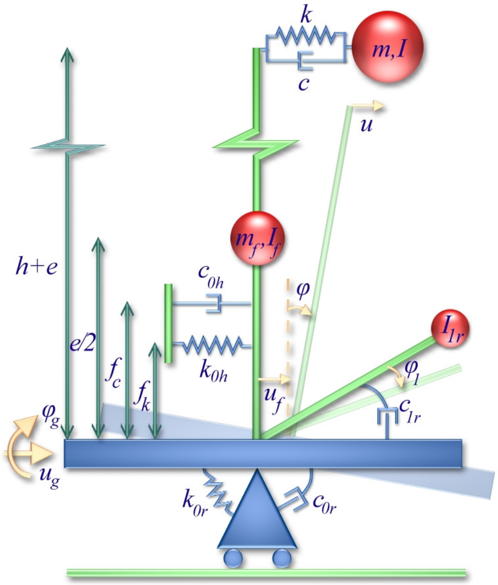

Figure 1. Soil-structure model.

The internal DOF allows the frequency dependency of soil stiffness also to be taken into account. All the coefficients in the model are frequency independent. The stiffness and damping coefficients for the sway DOF and rocking DOF as well as damping and mass coefficients for the internal DOF are evaluated using the following formulae respectively:

$$k_{0h} = \frac{8\rho {V_S}^2 r}{2-\upsilon}\left(1+{}^{e}\!/_{r}\right), \quad c_{0h} = \frac{r}{V_S}\gamma_{0h}k_{0h} \tag{1a}$$

$$k_r = \frac{8\rho {V_S}^2 r^3}{3(1-\upsilon)}\left(1+2.3\,{}^{e}\!/_{r}+0.58\left({}^{e}\!/_{r}\right)^3\right), \quad c_{0r} = \frac{r}{V_S}\gamma_{0r}k_r \tag{1b}$$

$$c_{1r} = \frac{r}{V_S}\gamma_{1r}k_r\,, \quad I_{1r} = \left(\frac{r}{V_S}\right)^2\mu_{1r}k_r \tag{1c}$$

where ρ, v, V_s, r, and e are the specific mass, Poisson's ratio, the shear wave velocity of soil, the radius of the equivalent circular foundation, and embedment depth respectively. Also, γ_{0h}, γ_{0r}, γ_{1r}, and μ_{1r} are non-dimensional coefficients of the discrete model in terms of e/r and are calculated using the following formulae:

$$\gamma_{0h} = 0.68 + 0.57\sqrt{e/r}\,,\ \gamma_{0r} = 0.15631(e/r) - 0.08906(e/r)^2 - 0.00874(e/r)^3 \tag{2}$$
$$\gamma_{1r} = 0.40 + 0.03(e/r)^2\,,\ \mu_{1r} = 0.33 + 0.1(e/r)^2$$

Sway springs and dashpots are connected to the superstructure model with the following eccentricities in order to account for the stiffness coupling terms:

$$f_k = 0.25e\,,\ f_c = 0.32e + 0.03e(e/r)^2 \tag{3}$$

The method proposed by Wolf (1994) is used to consider the soil material damping. The whole soil-structure model is then subjected to selected accelerograms after evaluating Foundation Input Motion.

Kinematic Interaction

Embedment of the foundation affects the SSI phenomenon in two ways: first, it changes the dynamic stiffness coefficients for sway and rocking DOFs which leads to the change of Inertial Interaction (II); second, it brings about a new part of interaction named Kinematic Interaction (KI) by transforming Free-Field Motion (FFM) into Foundation Input Motion (FIM). The method used here in order to evaluate KI effect is proposed by Meek and Wolf (1994). As the result of KI, two different FIM components are produced: Horizontal FIM and Rocking FIM. Horizontal FIM generally decreases in comparison to FFM especially for more embedment depths; however, rocking FIM amplitude usually increases as the depth of embedment increases. After evaluating FIM, the whole soil-structure system is analyzed subjected to the two mentioned horizontal and rocking input motions (respectively u_g and φ_g in Fig. 1).

Key Parameters

Basically, the response of the soil-structure system depends on the size of the structure, its dynamic characteristics, and the soil profile as well as the applied excitation. It is shown that the effect of these factors can be best described by the following non-dimensional parameters (Veletsos 1977, Ghannad et al. 1998):

1. A non-dimensional frequency as an index for the structure to soil stiffness ratio defined as

$$a_0 = \omega h / V_s \tag{5}$$

where ω is the circular frequency of the fixed base structure. It can be shown that the practical range of a_0 for ordinary building type structures is from Zero, for the fixed-base structure to about 3, for cases with predominant SSI effect (Ghannad 2006).
2. Aspect ratio of the building defined as h/r.
3. Embedment ratio defined as e/r.
4. Ductility demand of the structure defined as

$$\mu = u_m / u_y \tag{6}$$

where u_m and u_y are the maximum displacements caused by specific base excitation and the yield displacement of the structural stiffness respectively.

5. Structure to soil mass ratio index defined as

$$\overline{m} = m / \rho r^2 h \tag{7}$$

6. The ratio of the mass of the foundation to that of the structure defined as m_f/m.
7. Poisson's ratio of the soil indicated by ν.
8. Material damping ratios of the soil and the structure indicated by ξ_0 and ξ_s respectively.

The first three items are the key parameters that define the principal SSI effect (Ghannad et al. 1998) including both Kinematic Interaction and Inertial Interaction. The fourth one controls the level of nonlinearity in the structure. The other parameters, however, are of less importance and may be set to some typical values for ordinary buildings (Ghannad et al. 1998). Here, the following values are assigned to these parameters:

$$\overline{m} = 0.5\,,\ m_f / m = 0.1\,,\ \nu = 0.25\,,\ \xi_0 = 0.05\,,\ \xi_S = 0.05 \tag{8}$$

Analyses Procedure

In this analysis, a fixed-base structure and a soil-structure system are considered. The period of the structure in both systems is considered to be the same. Likewise, the damping ratio of both structures is assumed to be $\xi_s=0.05$. In fact, the fixed-base structure represents the ideal model which is usually used in the analysis and design of structures as well as in performance evaluation of existing or designed structures. However, the soil-structure system is a more realistic model for studying the performance of structures designed, based on the conventional design procedures in seismic codes, that is to say without considering the SSI effect in design. The superstructure is exactly the same in both systems; however, the response of the structure would be different for two systems by virtue of the SSI effect. In fact, the difference between the responses of the two systems reflects the problem that does exist in the conventional design methodology, that is to say the difference between our expectation of structural behavior as a fixed-base model and the way that structures behave in reality when located on flexible soil. Ductility demands of the soil-structure system can be more or less than those of the fixed-base system. Such a comparison between the ductility demands of the two systems can be accomplished using the following procedure:

1. Select a ground motion.
2. Consider a soil-structure system with a specific set of non-dimensional frequency, a_0, aspect ratio, h/r, and embedment ratio, e/r.
3. Select a target ductility demand for the fixed-base structure.
4. Select the natural period of the fixed-base structure.
5. Analyze the fixed-base structure under the selected ground motion and calculate the resulted yield strength, F_y, until the ductility demand of the fixed-base model is within 1% tolerance equal to the target value.
6. Evaluate FIM from the selected ground motion.
7. Assign the resulted yield strength in step 5 (F_y) to the superstructure of the soil-structure system.
8. Analyze the soil-structure system with yield strength F_y subjected to FIM evaluated in step 6 and compute the resulted ductility demand in the structure.
9. Repeat steps 4~8 for different periods.
10. Repeat steps 3~9 for different target ductility demands.
11. Repeat steps 2~10 for different sets of a_0, h/r, and e/r.
12. Repeat steps 1~11 for different ground motions.

The above mentioned procedure is implemented once with inclusion of the KI effect and once without it in order to investigate the KI effect.

Numerical Results

Analyses was carried out for a target ductility demand of $\mu=6$ for fixed-base structure, two different ground motions (NS component of El-Centro, Imperial Valley, 1940 and EW component of SCT, Mexico, 1985), three values of a_0 (1, 2, 3), three values of h/r (1, 3, 5), four values of e/r (0, 0.5, 1, 2), and 100 different periods ranging from 0.05 to 3 seconds. Only a selective portion of graphs will be presented here.

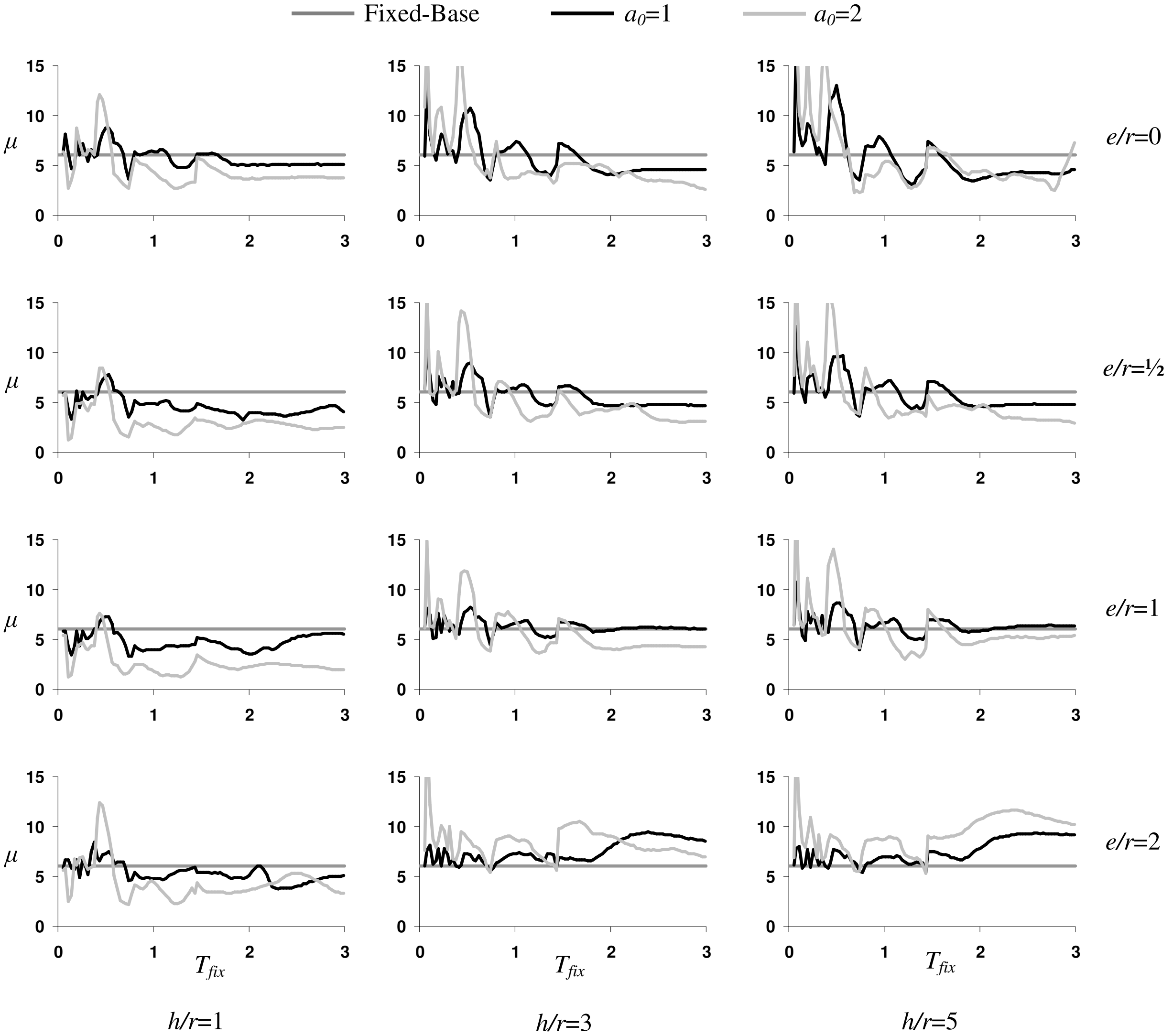

Figure 2. Comparison of the ductility demand of the soil-structure system with a presumed ductility demand of 6 for the fixed-base structure subjected to El-Centro ground motion.

Fig. 2 depicts the ductility demand of the soil-structure system with a presumed ductility demand of 6 for the fixed-base structure subjected to El-Centro ground motion. Results are provided for a_0=1, 2, e/r=0, 0.5, 1, and h/r=1, 3, 5. The abscissa in all figures is the fixed-base structure period. This figure shows a large difference between the ductility demand of the two systems for slender structures with h/r=3, 5 having short periods. Structures with small embedment ratio, e/r=0.5, show lower ductility demand than structures with surface foundation in small aspect ratios (h/r=1), yet by increasing aspect ratio to h/r=3 and 5 the difference becomes less. With increasing embedment ratio to e/r=1, 2, a trend of increasing in structural ductility demand can be seen. This is more obvious in slender structures with h/r=3, 5. In an extreme situation, slender structures (h/r=3, 5) with deeply embedded foundation (e/r=2) show higher levels of ductility demand than structures with surface foundation after a threshold period. These structures also show higher levels of ductility demand than fixed-base structures after that period. This period is greater in the case of structures subjected to SCT ground motion which is an earthquake with a greater predominant period (Fig. 3).

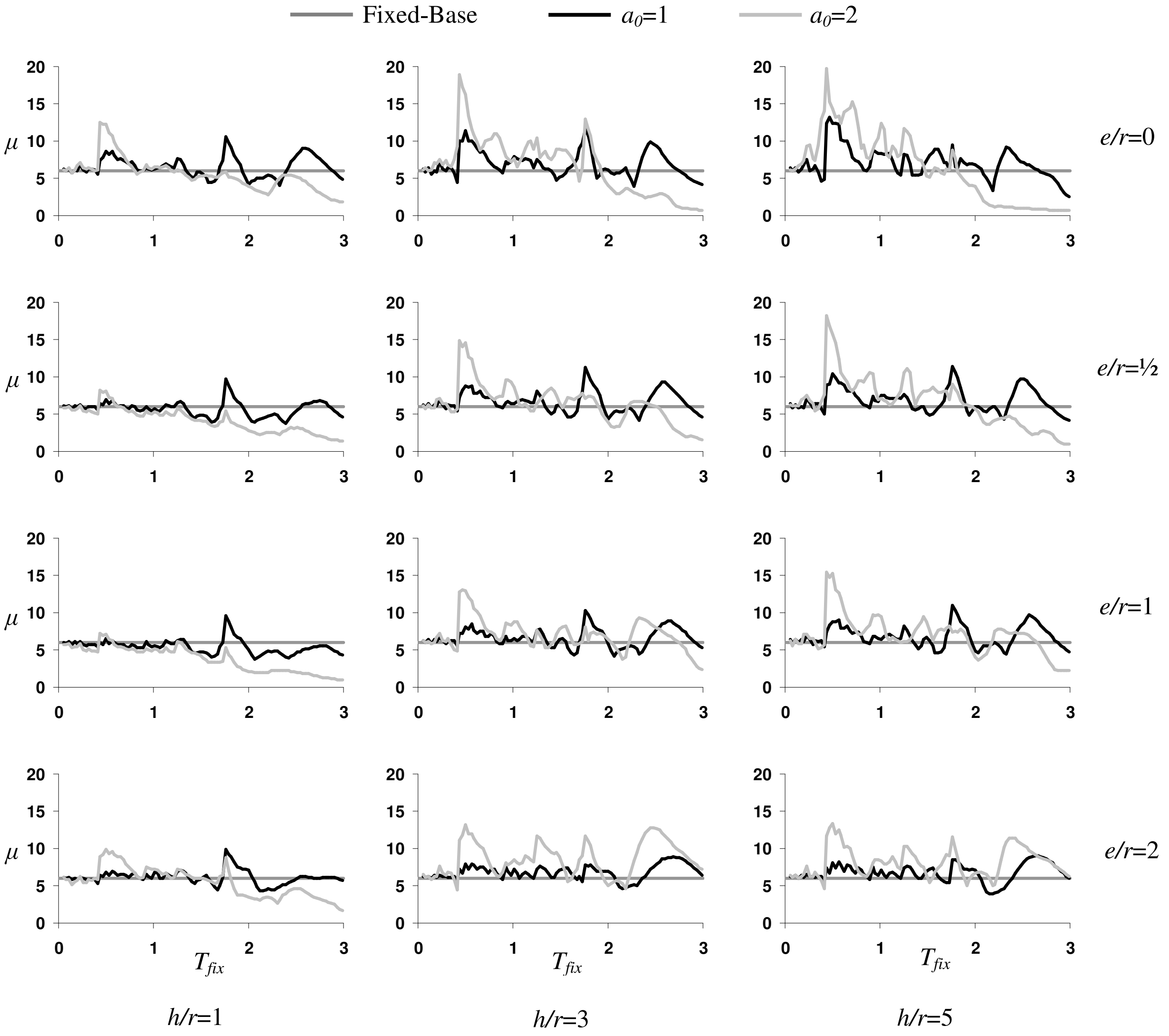

Figure 3. Comparison of the ductility demand of the soil-structure system with a presumed ductility demand of 6 for the fixed-base structure subjected to SCT ground motion.

The ductility demand of the soil-structure system with different embedment ratios is shown in Fig. 4 in a different fashion in order to emphasize the difference between various embedment ratios. The latter trend can be better seen in this figure. In $h/r=1$, ductility demand ordinates for $e/r=0.5$ and 1 are less than that of $e/r=0$, but for $e/r=2$, this trend is reversed and the ductility demand for $e/r=2$ is more than that of $e/r=0$ (surface foundation). But there is a small difference between the four curves in this aspect ratio ($h/r=1$). However, the difference becomes considerable in slender structures with $h/r=3$, 5. In these aspect ratios, ductility demand of the structure increases with increasing embedment ratio especially after the above mentioned threshold period. This trend can be explained by Kinematic Interaction effect. Fig. 5 illustrates

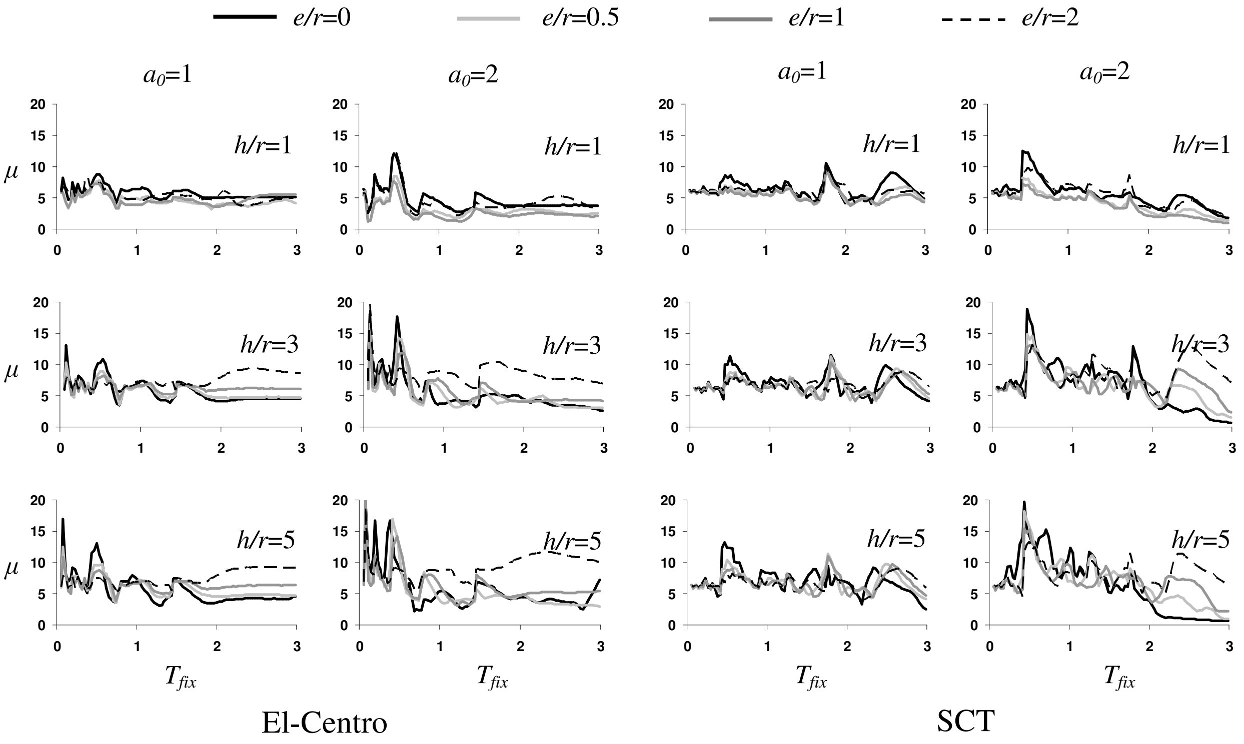

Figure 4. Comparison of the ductility demand of structures with different embedment ratios (e/r=0, 0.5, 1, 2) for the soil-structure system subjected to El-Centro and SCT ground motions

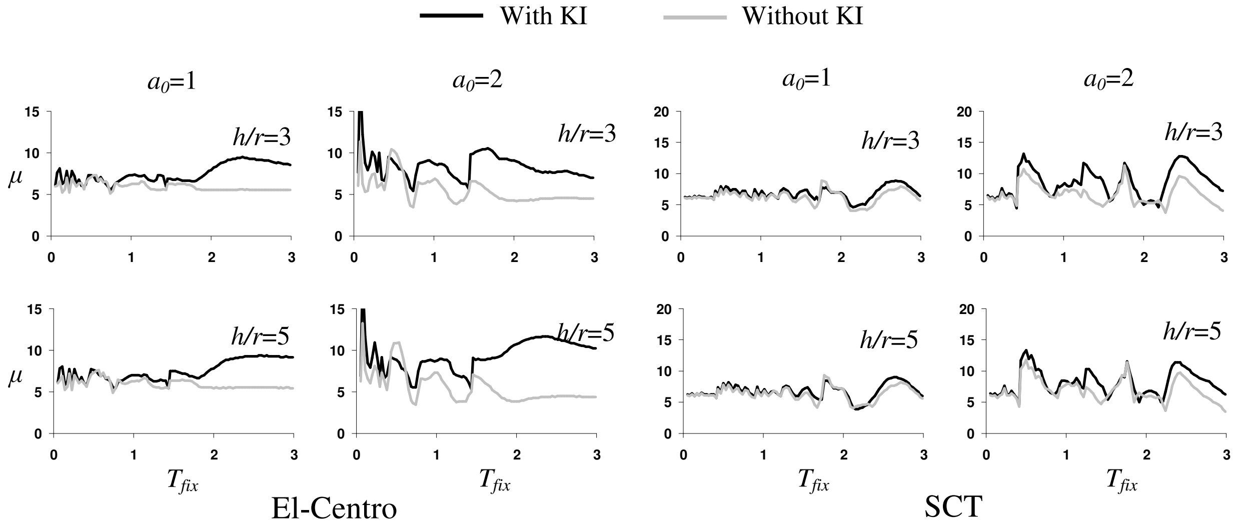

Figure 5. Comparison of the ductility demand of the soil-structure system with and without inclusion of Kinematic Interaction effect for e/r=2 subjected to El-Centro and SCT ground motions.

the ductility demand of the soil-structure system with and without inclusion of KI effect for structures with high embedment ratio (e/r=2). As can be seen, KI effect in this situation not only does not reduce the ordinates of ductility demand, but also it causes significant increase in ductility demand especially in long period structures. In fact, after a threshold period, neglecting embedment effect in analysis leads to less conservative results. In this range of periods, the more the embedment ratio, the greater the ductility demand ordinates. As mentioned before, an increase in embedment results in a raise in rocking motion; therefore, in large aspect ratios, the product of structure height and FIM rocking acceleration will be added to the FIM horizontal acceleration and dominates the horizontal acceleration of free-field which means that the excitation is intensified. As a result, the ductility demand of the structure will increase.

These results are more obvious in larger non-dimensional frequencies (a_0) in both squat and slender structures. The results for squat structures ($h/r=1$) are illustrated in Fig. 6. As is shown, the effect of KI in squat buildings ($h/r=1$) with small embedment ratio ($e/r=0.5$) is principally to decrease ductility demand. This is caused by a decrease in Horizontal FIM acceleration and insufficient increase in Rocking FIM acceleration which is multiplied with either a small height of the squat structure and produces a weak input motion compared to free-field motion.

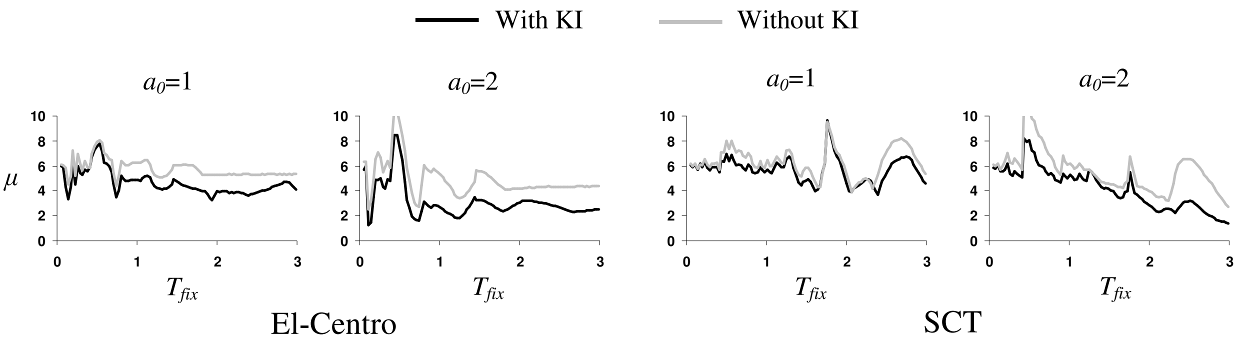

Figure 6. Comparison of the ductility demand of the soil-structure system with and without inclusion of Kinematic Interaction effect for $e/r=0.5$ and $h/r=1$ subjected to El-Centro and SCT ground motions.

Conclusions

It is concluded that SSI causes slender structures with short periods have higher levels of ductility demand than the fixed base structure. Hence, neglecting SSI effects in analysis of such structures is not in the safe side. Moreover, it is concluded that in slender structures with large aspect ratios and large embedment ratios, after a threshold period, embedment effect results in higher levels of ductility demand in the structure. This is caused by Kinematic Interaction which intensifies the excitation in large embedment ratios and large aspect ratios. In other words, neglecting Kinematic Interaction caused by embedment of the foundation is not conservative for such cases.

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