EFFECT OF SOIL-STRUCTURE INTERACTION ON SEISMIC DEMANDS OF STRUCTURES IN DESIGN PROCEDURES

Leila KHANMOHAMMADI
PhD student, Babol University of Technology, Babol, Iran
L.khanmohammadi@yahoo.com

Javad VASEGHI AMIRI
Associate Professor, Babol University of Technology, Babol, Iran
vaseghi@nit.ac.ir

Mohammad Ali GHANNAD
Professor, Sharif University of Technology, Tehran, Iran

Keywords: Soil-Structure Interaction (SSI), Kinematic Interaction (KI), Inertial Interaction (II), Ductility Demand, Elastic and Inelastic Seismic Demands

ABSTRACT

In this research, both kinematic interaction (KI) and inertial interaction (II) effects of soil-structure interaction (SSI) on seismic demands of structures are investigated by applying ground motions recorded at soil site E that SSI effect is considerable. Carrying out a parametric study, the structure and underlying soil are modeled as a Single Degree Of Freedom (SDOF) structure with elasto-plastic behaviour and a simplified 3DOF system, based on the concept of Cone Model, respectively. The foundation is considered as a rigid cylinder embedded in the soil. Then the soil-structure systems are analyzed under 15 ground motion recorded at site class E and a comprehensive parametric study is performed for a wide range of non-dimensional parameters defining SSI problem. Consequently, comparing the results with and without inclusion of SSI effects reveals that both II and KI play an important role in analyses or design procedures and ignoring them may cause un-conservative results in cases of deep embedded foundation and slender structures.

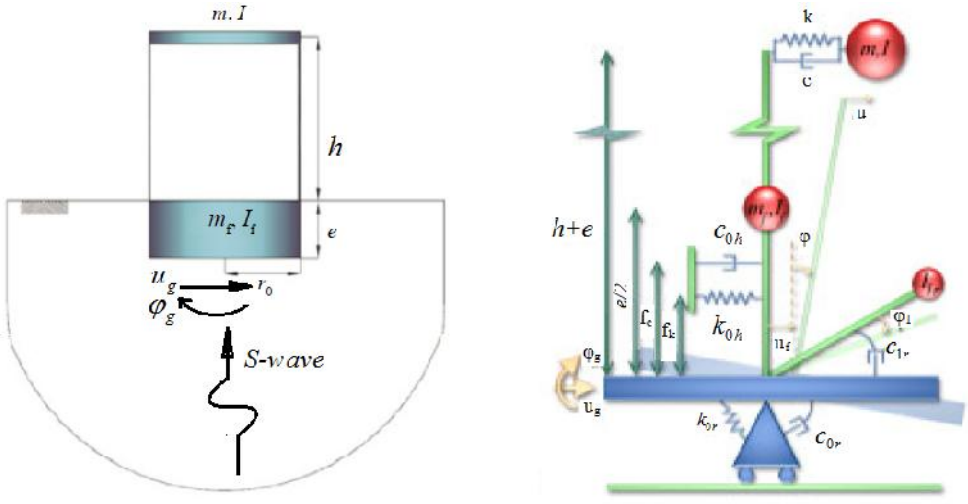
INTRODUCTION

The flexibility of structure’s underlying soil affects the response of the structure due to SSI. This phenomenon has two main effects. The difference between stiffness of the foundation and the surrounding soil induces the difference between the motion experienced by the essentially rigid foundation that is the foundation input motion (FIM) and the free-field motion (FFM). This effect is called the KI effect and happens even if the foundation has no mass. In other words, the FIM is the result of geometric averaging of the seismic input motion in the free field (Meek and Wolf, 1994). The flexibility of soil affects the response of the structure subjected to FIM. In fact, the soil-structure system behaves as a new system with different dynamic properties (longer natural period and usually higher damping). This effect is called II effect. Numerous researches have been done on the effects of SSI over the past few decades. Veletsos and Meek (1974) recognized that the effects of inertial interaction on elastic structures could be approximated by modifying the fundamental period and the damping ratio of the fixed base replacement oscillator. The variations of the equivalent natural period and damping ratio have been studied by Wolf (1985) and Aviles and Perez-Rocha (1999). But the inelastic behavior of structures has recently been given more attention by some researchers. Bielak (1978) first studied this matter by investigating the harmonic response of a bilinear structure supported on a visco-elastic half-space and found that the resonant structural deformation could be significantly larger than fixed-base structure.

Aviles and Perez-Rocha (2003) considered a SDOF elasto-plastic structure supported on a rigid foundation embedded in a visco-elastic stratum of constant thickness over a uniform visco-elastic half-space. They concluded that the effects of foundation flexibility and yielding of structure are beneficial for slender structures with a natural period somewhat larger than the site period, but detrimental if the structural period is shorter than the site period. Aviles and Perez-Rocha (2005) employed this replacement oscillator formulation in NEHRP provisions (2003). Behmanesh et al. (2010) also investigated FEMA-440 (2005) procedure for considering SSI effects in surface foundation. But most of these documents were prepared for surface foundations and the KI effect was ignored. In some researches effect of foundation embedment was introduced as simplified factors to modify the soil dynamic stiffness (Beredugo and Novak, 1972). Morray (1975) studied the KI problem of embedded circular foundations parametrically for a varied range of parameters typically found in nuclear reactor design. Luco et al. (1975) pointed to the influence of rocking input motion due to KI effect on the response of structures. The general effect of the foundation embedment on the structural response through simplified methods was also studied by Bielak (1975), Aviles and Perez-Rocha (1998) and Takewaki et al. (2003). In this research, soil-structure systems are analyzed parametrically for a set of non-dimensional parameters, which define the problem, using 15 ground motions recorded at soil site E. Then KI and II effects of SSI and site effect are investigated on seismic demands of structures.

SOIL-STRUCTURE MODEL

The soil-structure system considered in this study is shown in Figure 1. (a). The super-structure is modeled as an equivalent elasto-plastic SDOF system with height *h*, mass *m* and mass moment of inertia *I*, which may be considered to be the effective values for the first mode of vibration of a real MDOF system. The foundation is considered to be rigid with embedment depth e and mass and mass moment of inertia m_f and I_f, respectively. The soil beneath the structure is considered as a homogeneous half-space and replaced by a discrete model based on the concept of cone model for embedded foundation (Wolf, 1994). In this model, two DOFs are introduced for foundation that are sway (u_f) and rocking ($\ddot{}_f$). An additional internal DOF ($\ddot{}_1$) is introduced to consider frequency dependency of soil stiffness. Soil springs behave elastically. Effect of soil nonlinearity is introduced using a degraded shear wave velocity for the soil medium, consistent with the estimated strain level in soil (Kramer, 1996). In NEHRP (2003) and FEMA-440 (2005), this strain level is related to the peak ground acceleration (PGA). Consequently, a 4-DOF model is formed for the whole soil-structure system as shown in Figure 1(b). The parameters, introduced in Figure 1(b), are defined as follows:



(a) (b)

Figure 1. (a) The soil-structure system; (b) Mathematical model of soil-structure

$$k_{0h} = \frac{8°V_s^2 r}{2-³}(1+\frac{e}{r}) \quad , \quad c_{0h} = \frac{r}{V_s}¥_{0h}\,k_{0h} \tag{1}$$

$$k_r = \frac{8°V_s^2 r^3}{3(1-³)}(1+2.3\frac{e}{r}+0.58(\frac{e}{r})^3) \;\; , \;\; k_{0r} = k_r - k_{0h}\,f_k^2 \tag{2}$$

$$c_{0r} = \frac{r}{V_s}¥_{0r}\,k_r \quad , \quad c_{1r} = \frac{r}{V_s}¥_{1r}\,k_r \quad , \quad I_{1r} = (\frac{r}{V_s})^2 «_{1r}\,k_r \tag{3}$$

Where, $°$, $³$, V_s and r are the specific mass, Poisson’s ratio, shear wave velocity in soil and the radius of the cylindrical foundation, respectively. $¥_{0h}$, $¥_{0r}$, $¥_{1r}$ and $«_{1r}$ are non-dimensional coefficients of the discrete model in terms of *e/r*. Sway springs and dashpots are connected to the super-structure with f_k and f_c eccentricities, respectively to consider the coupling terms of the sway and rocking DOFs in the stiffness matrix. These coefficients are calculated by optimum fitting of the stiffness coefficients of discrete model with corresponding values in cone model. The soil-structure model is subjected to sway and rocking components of FIM.

PROBLEM PARAMETERS

The SSI effect can be best described by following non-dimensional parameters (Veletsos, 1997):

- A non-dimensional frequency as an index for the structure-to-soil stiffness ratio: $a_0 = \frac{µ_{fix}h}{V_s}$

Where $µ_{fix}$ is frequency of the fixed-base structure. a_0 can have values of up to 3 for conventional structures resting on very soft soil, while the value close to zero in the case of fixed-base structures.

- Aspect ratio of the building h/r, an index for its slenderness ratio.
- Embedment ratio of the foundation defined as *e/r*.
- Ductility demand of the structure defined as: $« = \frac{u_m}{u_y}$

Where, u_m and u_y are the maximum and yield displacement of the structure caused by a specific base excitation, respectively.

- Strength reduction factor (SRF) of the structure defined as: $R = \frac{F_0}{F_y}$

Where, F_0 and F_y are elastic and inelastic strength demands of the structure, respectively.

- Structure-to-soil mass ratio index defined as: $\overline{m} = \frac{m}{°r^2h}$

This parameter varies between 0.4 and 0.6 for ordinary structures and is set 0.5 in this study.

- Foundation-to-structure mass ratio $m_f\,/\,m$ that is assigned 0.1.
- Poisson’s ratio of soil $³$ that is considered 0.45 for soft soil in this study.
- Material damping ratios of the structure $¶_{str}$ that is set to 5% of the critical damping.

The first three factors participate within higher exponents in the equations of motion and have a vaster range of variations. So, they are selected as the key parameters of the system (Ghannad, 1998).

KINEMATIC INTERACTION EFFECT

As introduced in soil-structure model of Figure 1, two different FIM components are produced as a result of KI: Horizontal FIM (u_g) and rocking FIM ($¨_g$).

Horizontal FIM component generally decreases in comparison with FFM especially for more embedment depths. But rocking FIM has an increase as the depth of embedment increases. To evaluate FIM components, the Meek and Wolf (1994) method is used based on the concept of double-cone models. Double cones are used to represent a disk embedded in a full space. An embedded foundation is then replaced by a stack of N disks. To provide stress-free condition on the ground surface, the mirror images of the former disks are considered on the other side of the ground surface as demonstrated in Figure 2. These mirror image disks are excited by the same excitations as the original disks, therefore, stress-free conditions on the ground surface will be guaranteed. Using the green functions at the level of each disk and its mirror image, the N×N flexibility matrix of the free field is evaluated. The inverse of this flexibility matrix is the dynamic stiffness matrix of the free field ($\mathbf{S}_f$). Then by extracting the excavated part of the soil from the model and inserting the rigid foundation, the dynamic stiffness of the embedded foundation can be evaluated. Because the rigid foundation is inserted, the dimension of the stiffness matrix is reduced from N to 2 for introduced sway-rocking foundation model. This can be done using an N×2 kinematic conditions matrix (**A**) calculated based on the foundation geometry. Thus, the dynamic stiffness matrix of the rigid foundation ($\mathbf{S}_g$) is calculated using the mass matrix of the excavated part of the soil (M) as follows:

$$\mathbf{S}_g = \mathbf{A}^T \mathbf{S}_f \mathbf{A} + \mu^2 \mathbf{M} \tag{11}$$

Subsequently, the FIM is evaluated from $\mathbf{u}_f$ that is FFM evaluated at the level of the disks:

$$\mathbf{u}_g = \begin{bmatrix} u_g \\ .. \\ {}_g \end{bmatrix} = \mathbf{S}_g^{-1} \mathbf{A}^T \mathbf{S}_f \mathbf{u}_f \tag{12}$$

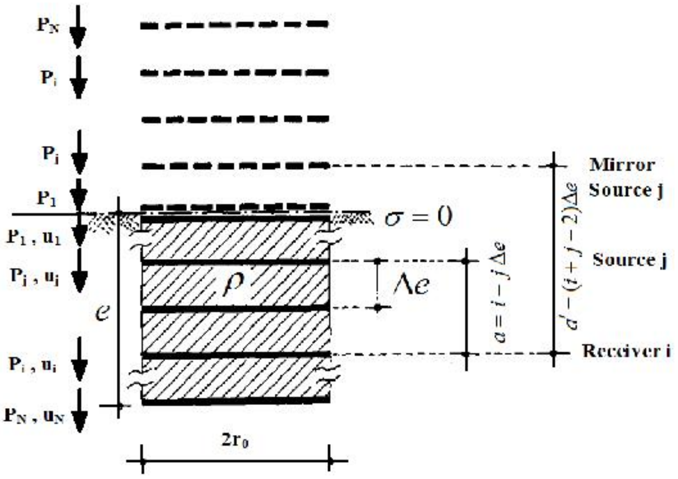


Figure 2. Model of embedded foundation with stack of N disks and their mirror image (Meek and Wolf, 1994)

METHOD OF ANALYSIS

To assess inelastic response of soil-structure systems, the introduced soil-structure model can be analyzed directly in a time domain by step-by-step integration, using β-Newmark method, subjected to a total of 15 strong motions recorded at soil type E (as classified in FEMA-440, 2005). It is known that for any specific base excitation, inelastic response of fixed-base structures is mainly a function of the natural period of the structure, T_{fix} and the level of inelastic deformation. The material damping and the type of hysteretic behavior of structure have been found to be less important. In soil-structure systems the three non-dimensional key parameters a_0, h/r and e/r also play an important role. Thus, a parametric study has been conducted using the five above-mentioned parameters (T_{fix}, μ or R, a_0, h/r and e/r). For each earthquake record, a set of 2,160 soil-structure systems consisting of 60 SDOF structures with fixed-base periods ranging from 0.05 to 3 s with three different values of aspect ratio (h/r =1, 3, 5), four values of embedment ratio (e/r=0, 0.5, 1,2) and three values of non-dimensional frequency (a_0=0, 1, 3) are investigated. Cases with a_0 = 0 are indeed related to fixed-base state.

The response of each system is investigated both with and without inclusion of KI effect. For any given case, the inelastic strength demand of structure (F_y) was calculated by iteration in order to reach the target ductility (μ=2, 4) in the structure, in addition to the elastic case (μ=1), within 1% of accuracy. In each case, the difference between the ductility demand of the fixed-base model and that of the structure as a part of the soil-structure system reflects the problem that does exists in conventional design methodology, i.e. 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. Using MATLAB software, a comprehensive code is conducted to support mentioned purposes.

EFFECT OF SSI ON SEISMIC DEMANDS OF STRUCTURES

Through a comprehensive statistical study, the effects of SSI on elastic and inelastic demands of structure are investigated as following sections. Results for site class E include both KI and II effects and are the average values for soil-structure systems subjected to 15 strong motions listed in Table 1.

Table 1. Selected ground motions recorded at site class E

Distance (km)	PGD (cm)	PGA (cm/s^2)	Dir.	Station No.	Station Name	Earthquake Name	Date	No.
58.65	4.192	231.5	0	58223	San Francisco, International Airport	Loma Prieta	10/17/89	E1
58.65	6.023	322.7	90	58223	San Francisco, International Airport	Loma Prieta	10/17/89	E2
72.20	3.526	191.3	180	58224	Oakland, Title & Trust Bldg. (2-story)	Loma Prieta	10/17/89	E3
72.20	7.238	239.4	270	58224	Oakland, Title & Trust Bldg. (2-story)	Loma Prieta	10/17/89	E4
94.6	4.876	134.7	270	1590	Larkspur Ferry Terminal	Loma Prieta	10/17/89	E5
94.6	3.267	94.6	360	1590	Larkspur Ferry Terminal	Loma Prieta	10/17/89	E6
76.9	8.398	254.7	260	1662	Emeryville, 6363 Christie Ave.	Loma Prieta	10/17/89	E7
76.9	3.790	210.3	350	1662	Emeryville, 6363 Christie Ave.	Loma Prieta	10/17/89	E8
43.8	6.285	277.6	90	58375	Foster City (APEEL 1;Redwood Shores)	Loma Prieta	10/17/89	E9
43.8	15.038	63.0	360	58375	Foster City (APEEL 1; Redwood Shores)	Loma Prieta	10/17/89	E10
43.23	12.610	270.0	43	1002	Redwood City (APEEL Array Stn. 2)	Loma Prieta	10/17/89	E11
43.23	6.839	222.0	133	1002	Redwood City (APEEL Array Stn. 2)	Loma Prieta	10/17/89	E12
77.42	4.411	112.0	0	58117	Treasure Island (Naval Base Fire Station)	Loma Prieta	10/17/89	E13
77.42	11.488	97.9	90	58117	Treasure Island (Naval Base Fire Station)	Loma Prieta	10/17/89	E14
12.85	20.98	216.8	230	5057	El Centro Array 3, Pine Union School	Imperial Valley	10/15/79	E15

- EFFECT OF SSI ON INELASTIC STRENGTH DEMAND SPECTRA

This effect is depicted in Figure 3 for structures with μ = 4 located on soil site E. The effect of SSI on inelastic strength demand of structures to reach a ductility level of (μ = 4) is shown in Figure 4. All the results have been normalized by the product of mass of structure and PGA.

The results indicate a general trend of lower strength demands for soil-structure systems in comparison to the fixed-base structures. The exceptions are short period buildings with aspect ratio h/r = 1. This trend is clearer for the case of a_0 = 3 where SSI effect is predominant. This trend is identical in different embedment ratio.

- EFFECT OF SSI ON STRENGTH REDUCTION FACTOR (SRF) SPECTRA

In this section, SRF of soil-structure systems are computed. The graphs of SRF for structures located on site class E, with μ=4 are presented in Figure 4 as a function of structural period (T_{fix}). All graphs indicate a common trend of apparent lower SRF for larger values of a_0.

Because SSI affects on elastic strength demands more than inelastic one, so SSI reduces SRF values considerably and the more SSI effect, the more reduction in SRF. The effect of SSI on SRF is higher for slender buildings (h/r = 3 and 5) and for larger target ductility (μ=4). In ATC3-06 provisions (1978), it is believed that the SRFs proposed for fixed-base models can be used to approximate the inelastic strength demands of soil-structure systems as well. However, given the results of Figure 4, it can be concluded that using this idea leads to underestimation inelastic strength demands of soil-structure systems. Consequently, the structure would experience higher ductility ratios than expected.

- EFFECT OF SSI ON DUCTILITY DEMAND OF STRUCTURES

In this part, ductility demand of the structure, as a part of the soil-structure system, is calculated for soil-structure systems with different values of a_0, *h/r* and *e/r*, providing the same yield strength for the structure as calculated in the fixed-base state. As seen in Figures 5, 6 and 7, for structures with surface foundation (*e/r*=0), there is a threshold period before that the flexible-base ductility is greater than that of the fixed-base one, afterwards, this trend is reversed. The more the aspect ratio, the greater is the difference between ductility demands of the flexible-base and the fixed-base models. As shown in the figure 7, though the embedment of structure reduces ductility demands of squat buildings (*h/r*=1), it results in higher demands for slender buildings (*h/r*=3 and 5).The effect is intensified by increasing the embedment ratio. Thus, the SSI increases the ductility demand of slender structures with deep embedment almost in the whole range of periods. All trends discussed above are intensified by increasing a_0. Hence, it can be concluded that foundation embedment is beneficial for squat structures while it may increase ductility demands for the case of slender structures. Even for slender structures, the increase in ductility demands is not significant for embedment ratios up to *e/r*=1. However, for deeply embedded structures, the ductility demand can be much higher than expected. As seen, the ductility demand for the case of *h/r*=3, increases with the embedment ratio and reaches a value of 9 in embedment ratio of 2, 50% more than the target ductility.

- EFFECT OF KI ON DUCTILITY DEMAND OF STRUCTURES

Figure 8 demonstrate the ductility demand curves evaluated both with and without inclusion of KI effect for structures located on soil site E, with fixed-base target ductility of 4. As seen, for squat structures (*h/r*=1), inclusion of KI effect generally reduces the flexible-base ductility. In fact, the ductility demand of soil-structure systems without KI effect is very close to fixed-base target ductility, for whole range of periods. This trend is observed more clearly in case of a_0= 3. For slender structures with *h/r*=3 and 5, however, the importance of KI depends on the embedment ratio. For shallow foundations (*e/r*=0.5), the effect of KI is negligible. But, by increasing the embedment ratio, KI affects the ductility demand more considerably leading to a significant effect for *e/r*=2. In other words, the FIM is considered as a more severe input motion than the original FFM in such cases.

CONCLUSIONS

The soil-structure systems are analyzed parametrically to assess both II and KI effects of SSI on structures with embedded foundation. Results expressed that SSI reduces the elastic and inelastic strength demand of structures. But when the structure has more inelastic deformations, this effect becomes less important. So, SSI reduces SRF, which in turn may result in larger design forces. This conclusion has an important effect on practical design of structures when SSI effect is predominant. For structures with surface foundation, SSI increases the ductility demand of structure, before a threshold period that is close to the predominant period of the site. It means that structures having periods less than this threshold period may experience larger deformation than predicted by using fixed-base models. In particular, the effect deserves special attention for the case of larger values of non-dimensional frequency a_0, where the predominant period of the record is long enough to cover the practical range of conventional buildings. It is also observed that increasing the aspect ratio of the structure increases the SSI effect before the threshold period. The embedment of structure generally reduces ductility demands of squat buildings, but results in higher demands for slender structures. The effect is intensified by increasing *e/r* and a_0. Comparing the results with and without KI effect reveals that the rocking input motion may play an important role in tall and slender structures.

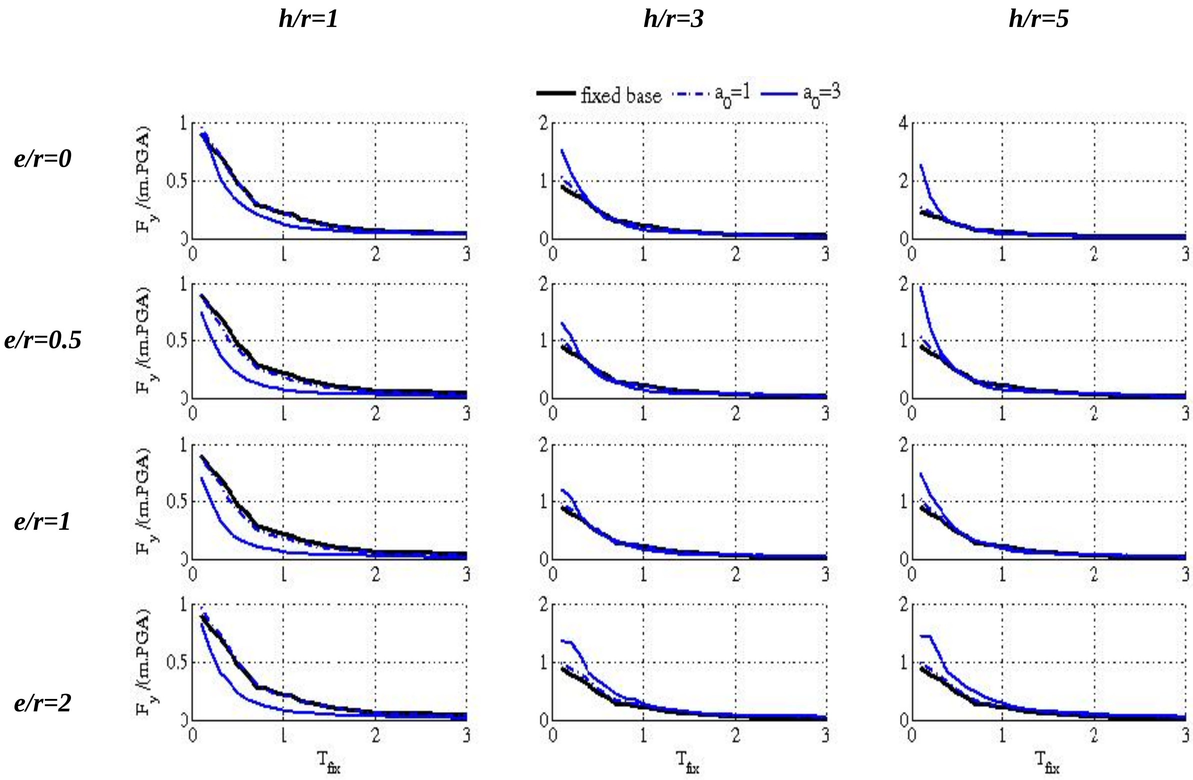


Figure 3. Normalized inelastic strength demand spectra (μ=4)

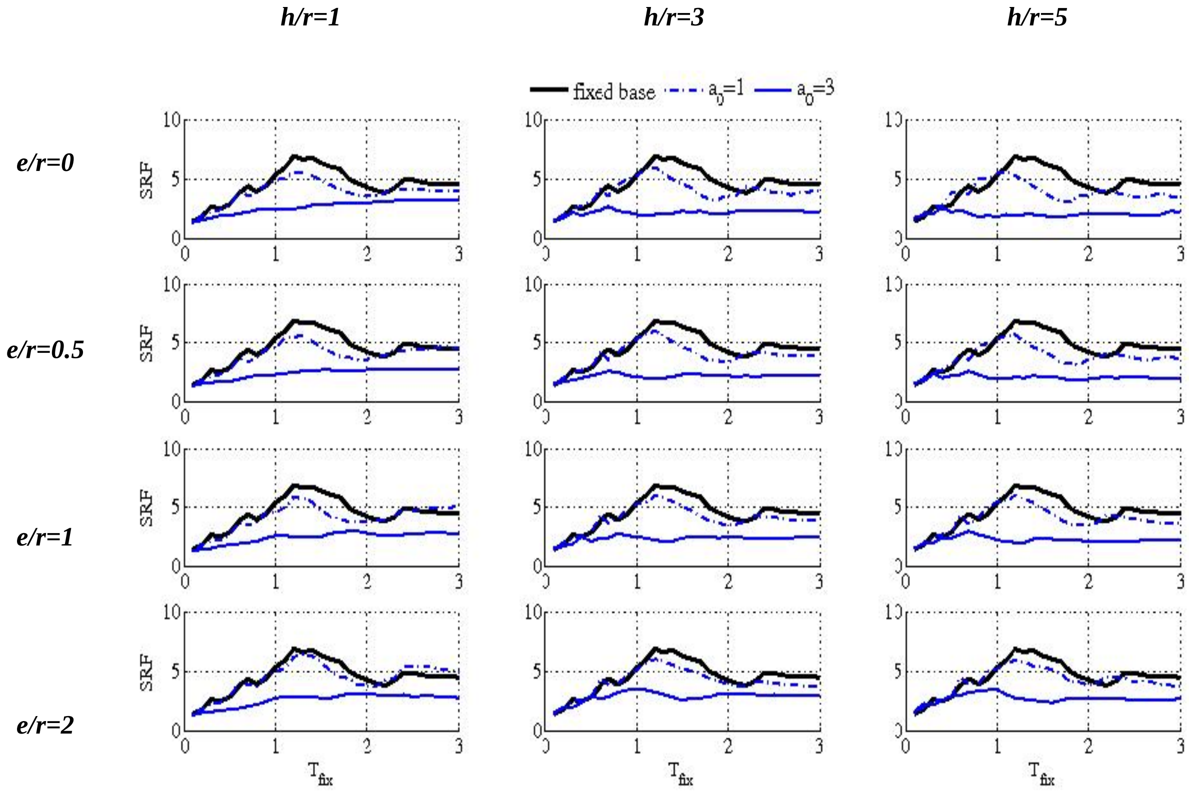


Figure 4. Strength reduction factor spectra (μ=4)

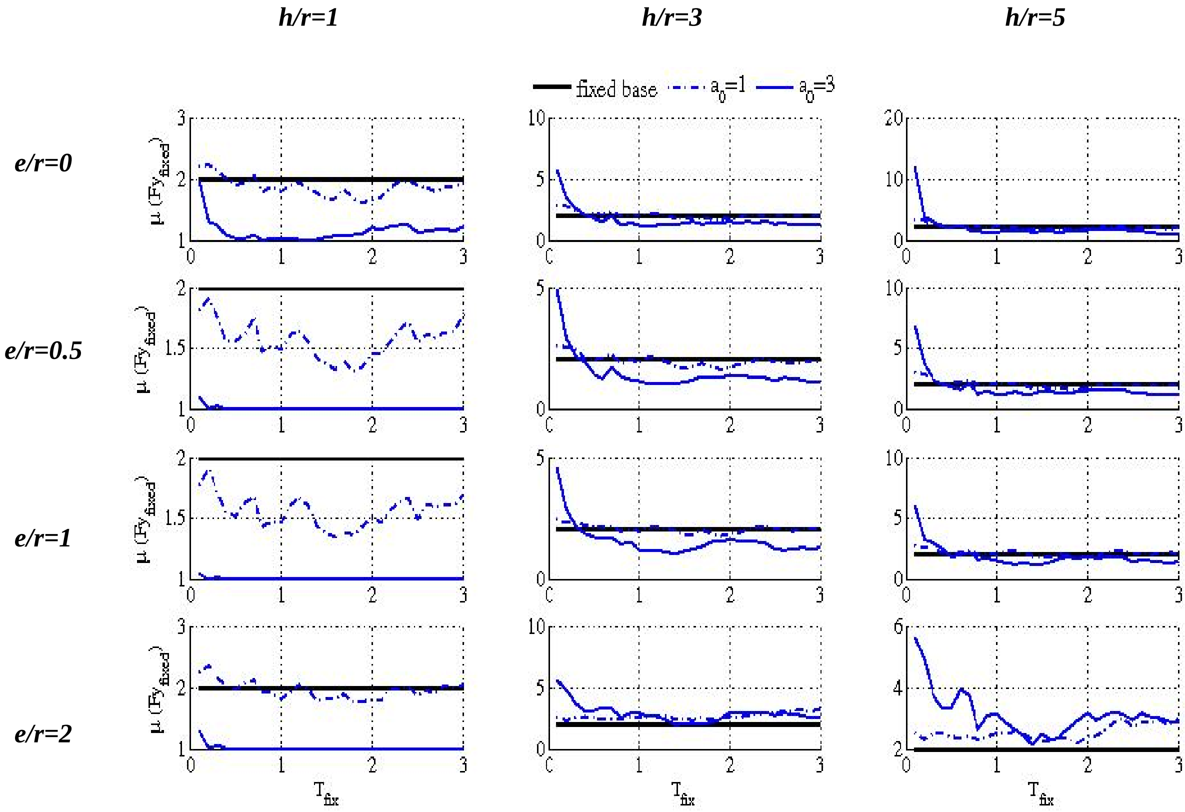


Figure 5. Averaged ductility demand of soil-structure systems located (μ_{fixed} =2)

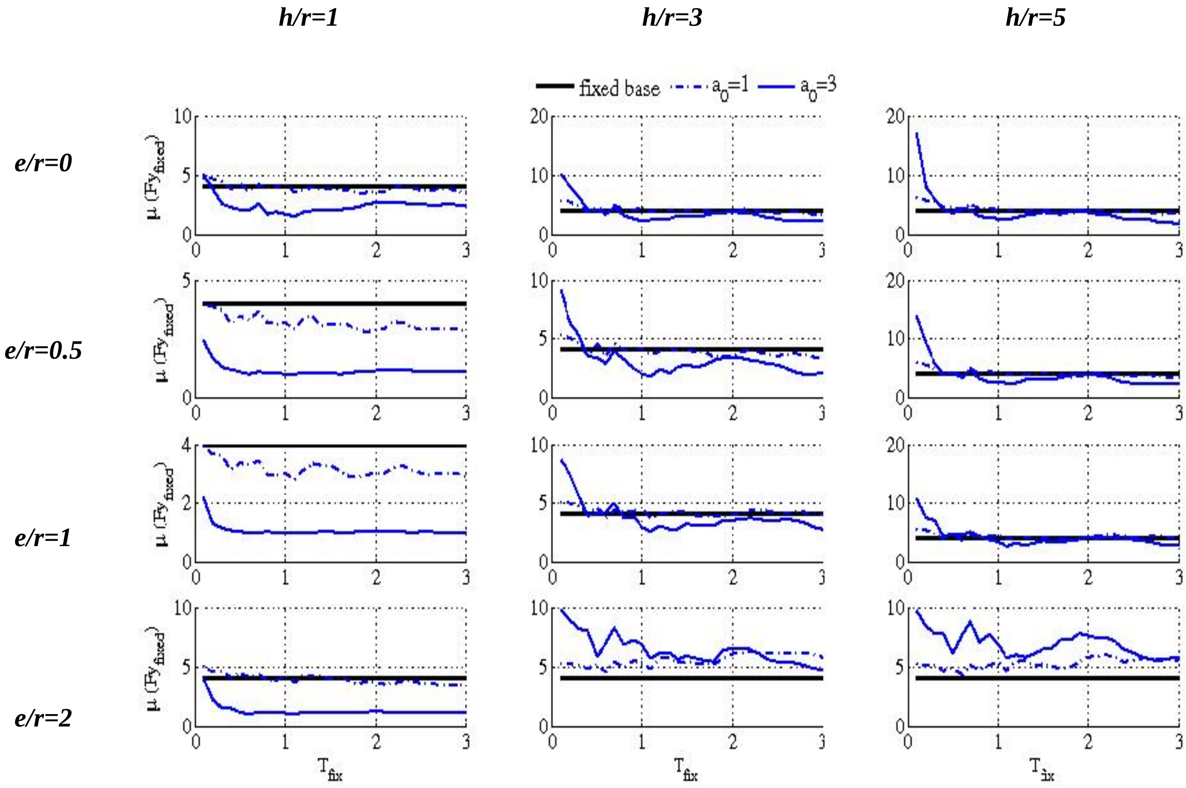


Figure 6. Averaged ductility demand of soil-structure systems located on (μ_{fixed} =4)

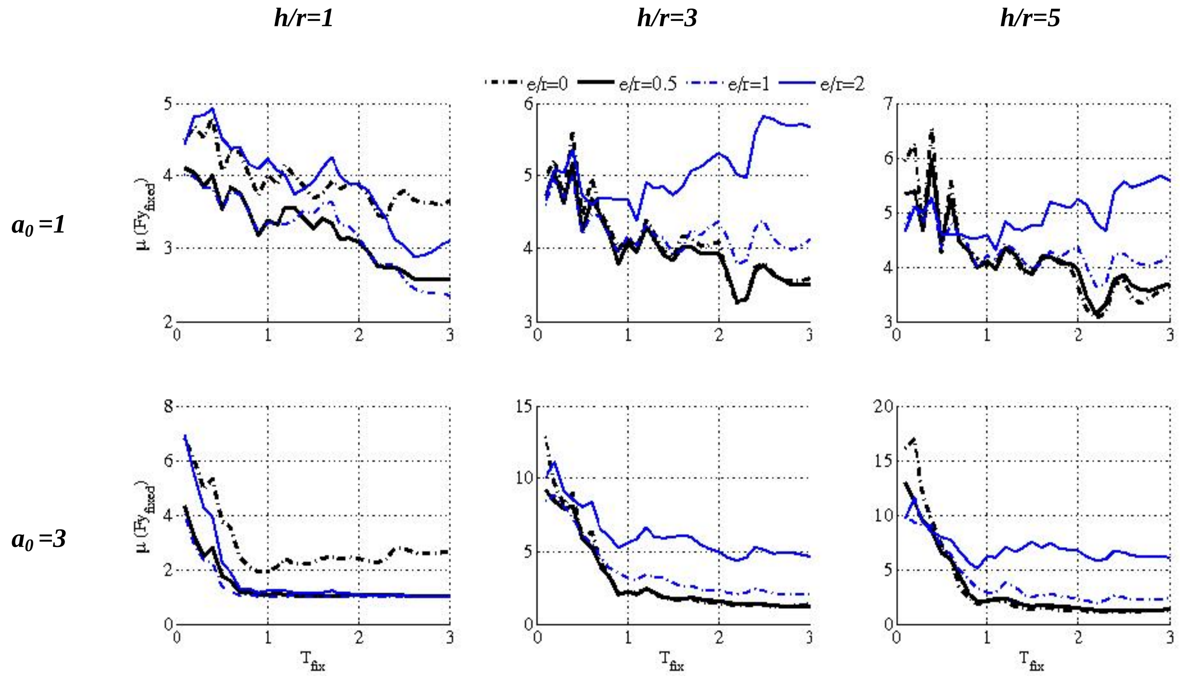


Figure 7. Effect of embedment ratio on ductility demand of soil-structure systems (μ_{fixed} =4)

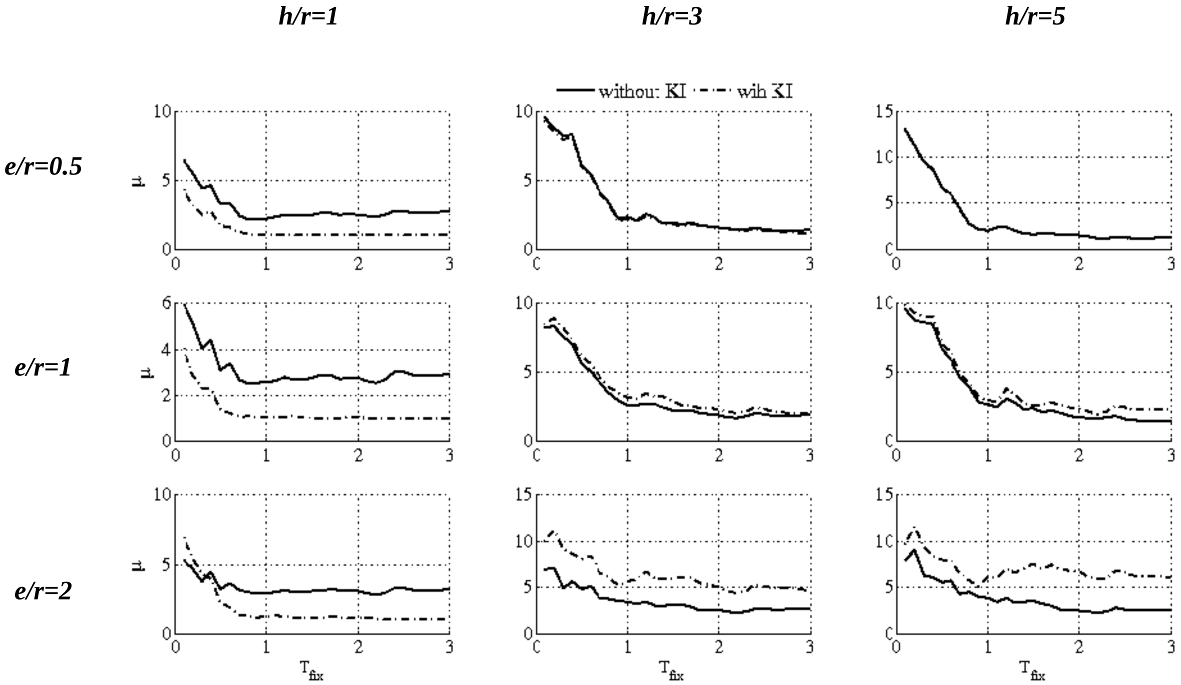


Figure 8. Averaged ductility demand of different soil-structure systems with and without KI (μ_{fixed} =4, a_0=3)

REFERENCES

ATC-3-06 (1978) Applied Technology Council, Tentative provisions for the development of seismic regulations for buildings, California

Aviles J and Perez-Rocha LE (1999) Diagrams of Effective Periods and Damping of Soil-structure Systems, *Journal of Geotechnical and Geo-environmental Engineering*, 125: 711–715

Aviles J and Perez-Rocha LE (2003) Soil-structure Interaction in Yielding Systems, *Earthquake Engineering and Structural Dynamic*, 32: 1749–1771

Aviles J and Perez-Rocha LE (2005) Design Concepts for Yielding Structures on Flexible Foundation, *Engineering Structure,* 27: 443–454

Aviles J and Perez-Rocha LE (1998) Effects of foundation embedment during building–soil interaction, *Earthquake Engineering and Structural Dynamics*, 27(12): 1523–1540

Beredugo YO and Novak M (1972) Coupled horizontal and rocking vibration of embedded footings, *Canadian Geotechnical Journal*, 9(4): 477–497

Bielak J (1978) Dynamic Response of Non-linear Building-foundation Systems, *Earthquake Engineering and Structural Dynamic*, 6: 17–30.

Bielak J (1975) Dynamic behavior of structures with embedded foundations, *Earthquake Engineering and Structural Dynamics*, 3(3): 259–274

BSSC (2003) NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures (FEMA-450), Washington

FEMA-440 (2005) Improvement of nonlinear static seismic procedures (ATC-55 Draft), Washington

Ghannad MA (1998) A study on the effect of soil-structure interaction on the dynamic properties of structures using simplified methods, Ph.D. Thesis, Japan: Nagoya University

Khoshnoudian F and Behmanesh I (2010) Evaluation of FEMA-440 for including soil-structure interaction, *Earthquake Engineering & Engineering Vibration*, 9: 397-408

Kramer SL (1996) Geotechnical Earthquake Engineering, Prentice-Hall: Englewood Cliffs, NJ

Luco JE, Wong HL and Trifunac MD (1975) A note on the dynamic response of rigid embedded foundations, *Earthquake Engineering and Structural Dynamics*, 4(2): 119–127

Meek JW and Wolf JP (1994) Cone models for embedded foundation, *Journal of Geotechnical Engineering Division (ASCE)*, 120(1): 60–80

Morray JP (1975) Kinematic interaction problem of embedded circular foundations, M.Sc. Thesis, Department of Civil Engineering, Massachusetts Institute of Technology

Takewaki I, Takeda N and Uetani K (2003) Fast practical evaluation of soil–structure interaction of embedded structures, *Soil Dynamics and Earthquake Engineering*, 23(3): 195–202

Veletsos AS and Meek JW (1974) Dynamic Behavior Building-Foundation Systems, *Earthquake Engineering and Structural Dynamic*, 34: 121–138

Veletsos AS (1977) Dynamic of structure-foundation systems, *Hal WJ, editor, Structural and Geotechnical Mechanics, Prentice- Hall: Englewood Cliffs, NJ.* A Volume Honoring N.M. Newmark: 333–361

Wolf JP (1985) Dynamic Soil-structure Interaction, Prentice Hall: New Jersey

Wolf JP (1994) Foundation Vibration Analysis using Simple Physical Models, Prentice-Hall: Englewood Cliffs, NJ