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STRENGTH REDUCTION FACTORS CONSIDERING SOIL-STRUCTURE INTERACTION

Mohammad Ali GHANNAD[1], Hossein JAHANKHAH[2]

SUMMARY

This study is an investigation on Strength Reduction Factor Spectra (SRFS) including the effect of Soil-Structure Interaction (SSI). A wide range of non-dimensional parameters, which define the whole problem, are considered. The structure is replaced by an elasto-plastic Single Degree of Freedom (SDOF) model, whereas the underlying soil is modeled as a 3DOF system, by discrete models based on Cone Models concept. The whole 4DOF model is then analyzed under 24 strong motions recorded on alluvium deposits. It's concluded that SSI reduces the SRFS values. Consequently, using the fixed-base SRFS for soil-structure systems lead to non-conservative design forces.

INTRODUCTION

The current seismic design philosophy is based on non-linear behavior of buildings during moderate and strong earthquakes. As a result, the design base shear provided by seismic codes is usually much lower than the lateral strength required to maintain the structure in the elastic range. The ratio of the structural strength demand, to stay elastic, to the provided lateral strength is known as Strength Reduction Factor (SRF) in the literature. Considering an idealized elasto-plastic SDOF system, as shown in Figure 1, this factor is defined as follows.

$$R_\mu = f_e / f_y \tag{1}$$

During the last four decades, SRF has been the topic of numerous investigations. The pioneering work done by Newmark and Hall [1] may be considered as the first well-known study on the subject. They proposed formulas for approximating strength reduction factors as a function of target ductility and period of structure. Nassar and Krawinkler [2] studied the effect of stiffness degrading on SRF by using a bilinear model. Also, the effect of hysteretic models on SRF was studied by Lee *et al* [3]. Elghadamsi and Mohraz [4] were the first ones who studied the effect of soil condition on SRFS. Later, more detailed investigations were conducted by different researchers, e.g. Krawinkler and Rahnama [5] and Miranda [6] among the others, which pointed to the significant effect of soil conditions on SRFS, especially in the case of soft soils. However, the effect of soil-structure interaction on SRF values has not been considered yet. On the other hand, recent studies on inelastic behavior of soil-structure systems point to the

[1] Assistant professor, Sharif University of Technology, Tehran, Iran. Email: ghannad@sharif.edu
[2] Graduate student, Sharif University of Technology, Tehran, Iran. Email: jahan807@yahoo.com

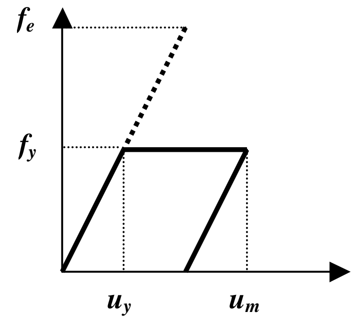


Figure 1: Idealized elasto-plastic behavior

considerable effect of SSI on ductility demand of structures [7-9]. It means that SRF is also affected by SSI and any rational investigation on SFRS should consider the SSI effect too.

MODELING

A simplified model as shown in Figure 2 is considered to represent the real problem. This model is based on the following assumptions:

1- The structure is replaced by an elasto-plastic 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, and mass moment of inertia, I_f.
3- The soil beneath the foundation is replaced by a system with three DOF including those for sway and rocking modes as well as an internal DOF for considering the frequency dependency of soil stiffness. This 3DOF model is based on Cone Models concept, which is based on one dimensional wave propagation theory. It is shown that Cone Models are accurate enough for engineering applications [10].

The mass, stiffness and damping coefficients of the soil model, shown in Figure 2, are as follows:

$$k_\varphi = \frac{8\rho V_p^{\,2} r^3}{(2-\upsilon)} \quad , \quad c_\varphi = \rho V_P I_f \qquad M_\varphi = \frac{9\rho\pi r^5 (1-\upsilon)^2}{64(1-2\upsilon)} \tag{2a}$$

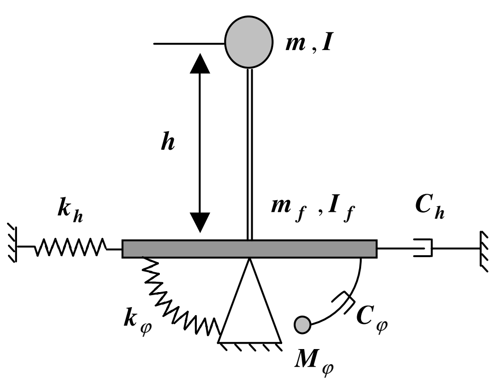


Figure 2: Soil-structure model

$$k_h = \frac{8\rho V_S^{2} r}{2-\upsilon} \quad , \quad c_h = \rho V_S A_f \tag{2b}$$

where V_S, V_P, υ, ρ are the shear wave velocity, the dilatational wave velocity, the Poisson's ratio and the soil density, respectively. Also, A_f and r are the foundation area and the equivalent radius of foundation.

PROBLEM PARAMETERS

The whole mathematical model can be defined by the following main parameters, which are all non-dimensional.

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

$$a_0 = \omega h / V_S \tag{3}$$

where ω is circular frequency of the fixed base structure.

2- Aspect ratio of the building that is defined as (h/r)

3- Ductility demand of structure defined as

$$\mu = u_m / u_y \tag{4}$$

where u_m and u_y are the maximum displacement due to specific base excitation and the yield displacement, respectively.

4- Structure-to-soil mass ratio index that is defined as

$$\overline{m} = m / \rho r^2 h \tag{5}$$

5- The ratio of the mass of the foundation to that of the Structure (m_f/m)

6- Poisson's ratio of the soil (υ)

7- Material damping ratios of the soil and the structure (ξ_0, ξ_S)

The first two items are the key parameters that define the principal SSI effect [11]. The third one controls the level of nonlinearity in the structure. The other parameters, however, are those with less importance and may be set to some typical values for ordinary buildings. Here the following values are assigned to these parameters:

$$\overline{m} = 0.5 \quad , m_f / m = 0.1 \quad , \upsilon = 0.4 \quad , \xi_0 = \xi_S = 0.05 \tag{6}$$

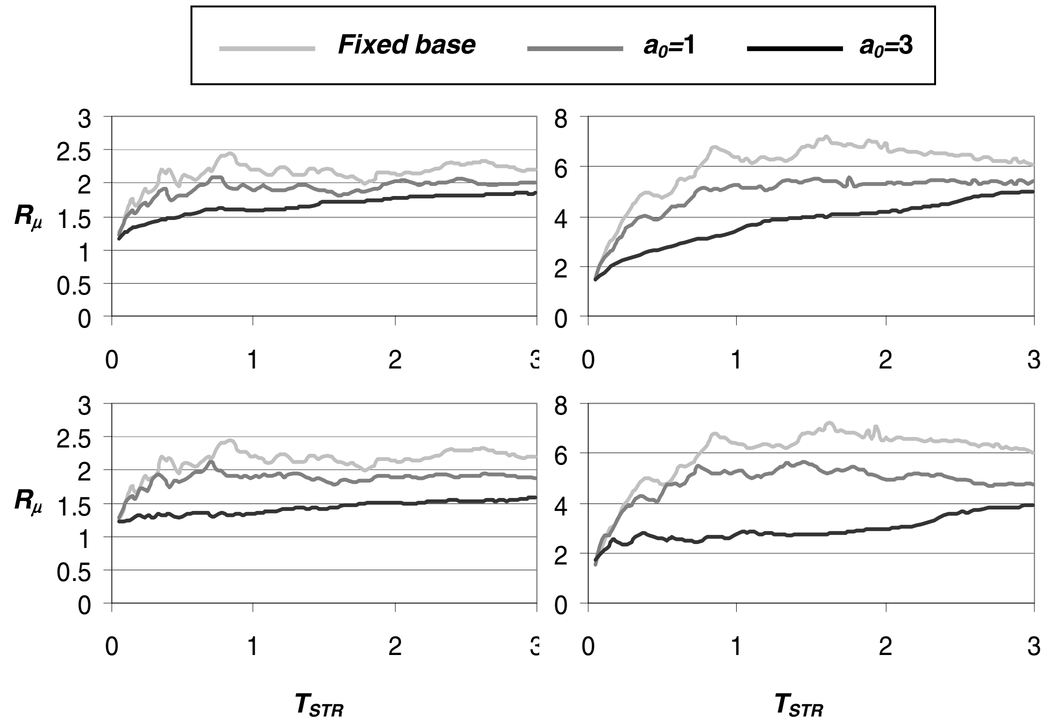
NUMERICAL RESULTS

The soil-structure model has been analyzed subjected to 24 ground motions recorded on alluvium deposits and the results are presented in this section. Details of the selected ground motions have been summarized in Table 1. The ground motions have been categorized based on their site geology. However, it should be mentioned that in practice, different methods are used by researchers for categorizing soils. Geology, shear wave velocity and frequency content of recorded ground motions are some of the most common basis to classify the soil, which don't necessarily lead to consistent classifications. Analyses are performed for three values of aspect ratio (h/r=1,3,5) , three values of non-dimensional frequency (a_0=0,1,3) and three values of ductility demands (μ=1,2,6). Values a_0=0 and μ=1 are related to the fixed-base and elastic states, respectively. Although for alluvium sites, $\mathbf{a_0}$ is approximately limited to the range of 1 to 2, here, because of the uncertainty on $\mathbf{a_0}$ values for this type of soil, the results are presented for a_0=1, 3 in comparison to the fixed base case (a_0=0). The results for

SRFS are shown in Figure 3 where the abscissa is the period of structure in the fixed-base state, T_{STR}. It is clearly seen in this figure that SSI reduces SRF values and the reduction becomes more significant as a_0

Table 1: Selected Ground Motions

Earthquake Date	*Station*	*Geology*	*Magnitude*	*Epicentral Distance(km)*	*Component*	*PGA(g)*
Imperial Valley, May 18, 1940	*El Centro-Irrigation Distinct*	*Alluvium*	*6.3(M_L)*	*8*	*S90W, S00E*	*0.21, 0.31*
Kern County, July 21, 1952	*Taft _ Lincoln School Tunnel*	*Alluvium*	*7.7(M_S)*	*56*	*308 , 218*	*0.15, 0.18*
San Fernando, February 9, 1971	*Figueroa _ 445 Figueroa St.*	*Alluvium*	*6.5(M_L)*	*41*	*N52E, S38W*	*0.14, 0.12*
San Fernando, February 9, 1971	*Ave. of the stars _ 1901 Ave. of the Stars*	*Silt and Sand Layers*	*6.5(M_L)*	*38*	*N46W, S44W*	*0.14, 0.15*
Imperial Valley, October 15, 1979	*Meloland_ Interstate 8 Overpass*	*Alluvium*	*6.6(M_L)*	*21*	*360 , 270*	*0.31, 0.30*
Imperial Valley, October 15, 1979	*Bond Corner _ Heighways 98 and 115*	*Alluvium*	*6.6(M_L)*	*3*	*140 , 230*	*0.51, 0.78*
Whitter_ Narrows, October 1, 1987	*Alhambra _ Freemont School*	*Alluvium*	*6.1(M_L)*	*7*	*270 , 180*	*0.41, 0.30*
Whitter_ Narrows, October 1, 1987	*Altadena _ Eaton Canyon Park*	*Alluvium*	*6.1(M_L)*	*13*	*90 , 360*	*0.15, 0.30*
Whitter_ Narrows, October 1, 1987	*Burbank_ California Fedral Saving Building*	*Alluvium*	*6.1(M_L)*	*26*	*250 , 340*	*0.23, 0.19*
Whitter_ Narrows, October 1, 1987	*Los Angeles _ Baldwin Hills*	*Alluvium over Shale*	*6.1(M_L)*	*27*	*90 , 360*	*0.06, 0.13*
Loma Prieta, October 17, 1989	*Capitola_ Fire Station*	*Alluvium*	*7.1(M_S)*	*9*	*90 , 360*	*0.44,0 .53*
Loma Prieta, October 17, 1989	*Holister _ South and Pine*	*Alluvium*	*7.1(M_S)*	*48*	*90 , 180*	*0.25, 0.21*



(a) $\mu = 2$ (b) $\mu = 6$

Figure 3: Strength reduction factor spectra

increases. However, it should be noted that although SSI affects the inelastic strength demands, this reduction in SRF values is mainly due to SSI effect on elastic response of structures. This means, referring to the SRF definition in Equation (1), the effect of SSI on SRF is basically due to the change in f_e rather than f_y. This is shown in Figure 4 where the variation of elastic and inelastic strength demands are drawn for different cases. The results have been normalized to the weight of structure, *W*. It is clear from this figure that the SSI effect on strength demands becomes less important as the structure undergoes more inelastic deformations.

According to foregoing discussion, estimating the SSI effect on inelastic strength demand of structures just from the effect on their elastic response, i.e. using the same SRF for the fixed-base structure and soil-structure system, leads to underestimation of design forces. This idea is indeed the basis of some current code provisions like NEHRP2000 [12]. Consequently, the structure may experience higher ductility when the SSI effect is considered in design in this way. For confirming this conclusion, the ductility demand of soil-structure systems designed based on this idea are depicted in Figure 5. The results are shown for structures with different aspect ratios (h/r=1,3) undergoing two different levels of inelastic deformation in the fixed-base state (μ_{fixed} =2,6), located on different soils (a_0=1,3). As seen, the ductility demand in the structure, as a part of the soil-structure system, is always larger than the target ductility for the fixed-base structure (μ_{fixed}) and may exceed 5 times in some cases.

CONCLUSION

The effect of Soil-Structure Interaction (SSI) on Strength Reduction Factors (SRF) was investigated. It was concluded that SSI may strongly affect SRF values, especially for the case of structures located on relatively soft soils, i.e., larger values of non-dimensional frequency a_0. Consequently, employing the same SRF as computed for the fixed-base state, for the soil-structure system, leads to much higher ductility in the structure.

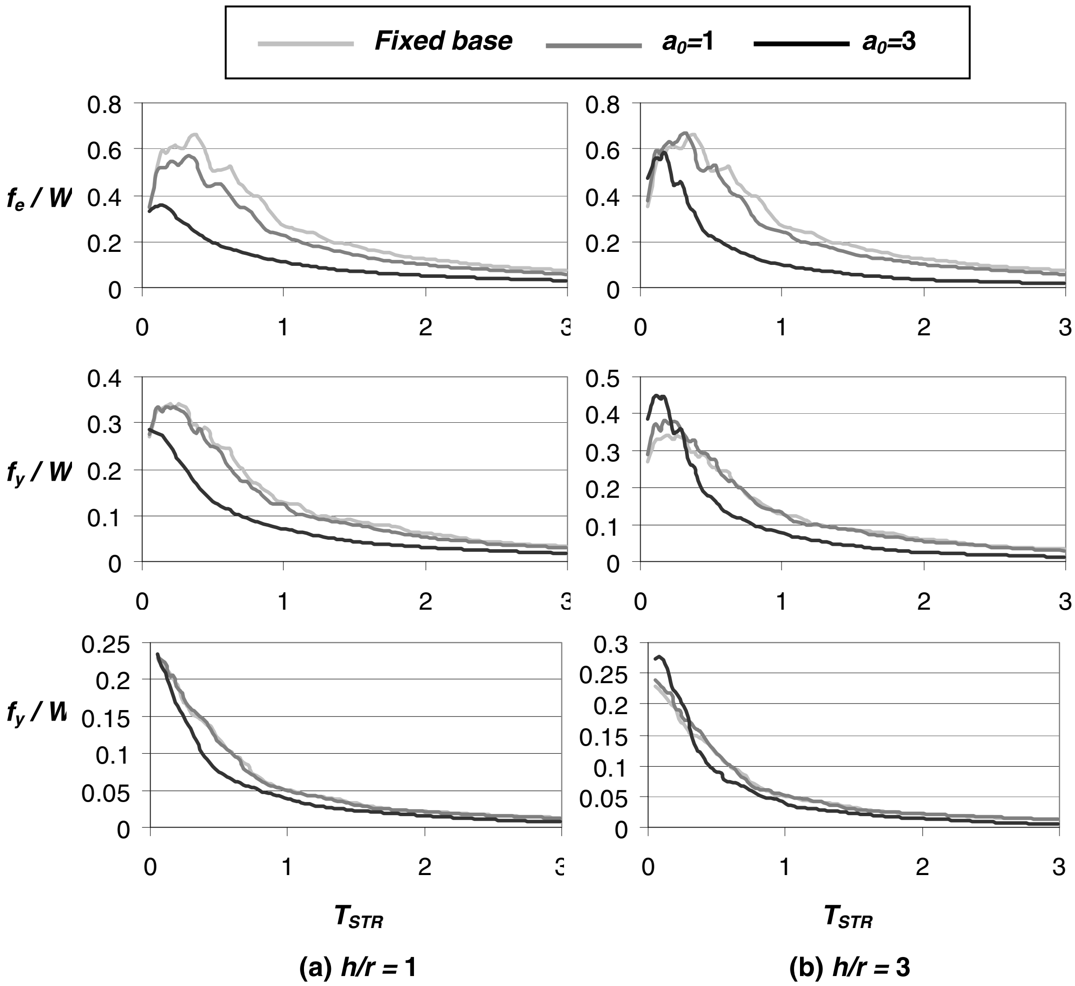


Figure 4: Normalized elastic and inelastic strength demand spectra

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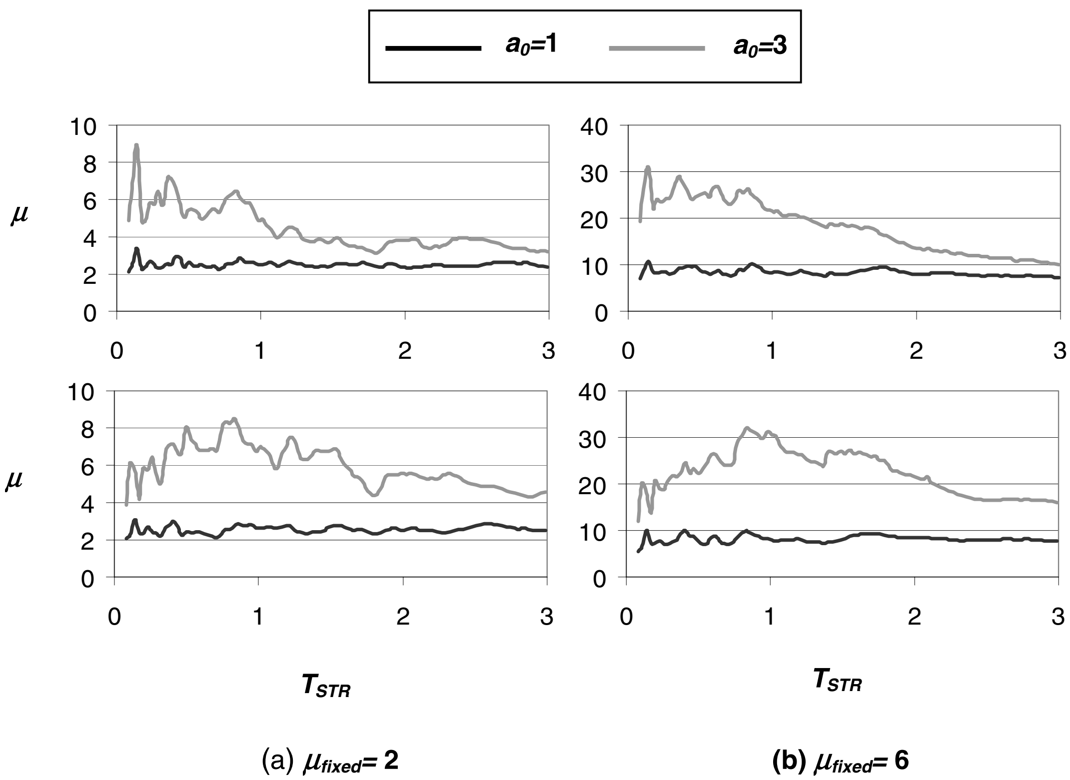

Figure 5: Ductility demand spectra for soil-structure system, using the fixed-base SRFS