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Strength reduction factor for multistory building-soil systems

Farhad Abedi Nik[*1] and Faramarz Khoshnoudian[2a]

[1]*Department of Civil Engineering, SADRA Institute of Higher Education, Tehran, Iran*
[2]*Department of Civil Engineering, Amirkabir University of Technology, Tehran, Iran*

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Abstract. This paper is devoted to investigate the effects of SSI on strength reduction factor of multistory buildings. A new formula is proposed to estimate strength reduction factors for MDOF structure-soil systems. It is concluded that SSI reduces the strength reduction factor of MDOF systems. The amount of this reduction is relevant to the fundamental period of structure, soil flexibility, aspect ratio and ductility of structure, and could be significantly different from corresponding fixed-base value. Using this formula, measuring the amount of this error could be done with acceptable accuracy. For some practical cases, the error attains up to 50%.

Keywords: dynamic analysis; soil-structure interaction; strength reduction factor; multi-story building

1. Introduction

In seismic analysis of buildings, it is customary to idealize the structural models as fixed at their base. Whereas, the response of the structure may be severely affected by kinematic and inertial soil-structure interaction (SSI) effects. Investigations of these effects have shown that the dynamic response of a structure supported on flexible soil may significantly differ from the response of the same structure when supported on a rigid base (Chopra and Gutierrez 1974, Bielak 1976 and Iguchi 1978). Therefore, fixed-base assumption may be the adequate representation of the structures founded on a firm base.

Several studies have been done on SSI mechanisms and its associated effects in the elastic range (Luco 1969, Jennings and Bielak 1973, Veletsos and Meek 1974 and Bielak 1975). These preliminary researches have exerted that the effects of inertial interaction could be expressed by an increase in the fundamental period and the associated modal damping of the fixed-base structure. In the inelastic range, the seismic behavior of the interacting system is even more complicated. Results of several studies showed that structural yielding increases the flexibility of the system and assists the beneficial role of SSI (Veletsos and Verbic 1974, Ciampoli and Pinto 1995, Rodriguez and Montes 2000 and Aviles and Perez-Rocha 2003). In contrast, other studies illustrated that SSI may have detrimental effects on the imposed seismic demand and neglecting foundation flexibility may lead to unsafe design of foundation and structure, especially for the structures built on soft soil conditions (Mylonakis and Gazetas 2000 and 2001, Mylonakis *et al.* 2006 and Moghaddasi *et*

[*]Corresponding author, Ph.D., E-mail: Abedinik@sadra.ac.ir
[a] Ph.D., E-mail: Khoshnud@aut.ac.ir

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al. 2010). Therefore, further studies are required to rigorously evaluate the SSI effects on seismic responses of structures.

The new building codes include the consideration of the effects of SSI. To account the SSI effects on design forces, the first mode period and associated damping of corresponding fixed-base structure are approximated by their effective values. Using effective period and damping, the design base shear may be reduced up to 30% (ASCE/SEI 7-10). FEMA 440 (2005) addresses kinematic interaction and recommends simplified procedure for computing foundation input motions. The approach of these codes essentially asserts that SSI effects have beneficial effects on the seismic design forces.

Seismic codes allow structures to behave inelastically during severe strong ground shaking. Under this philosophy, reduction in design forces produced by inelastic behavior is typically accounted for earthquake resistant design using strength reduction factor (SRF), which is usually presented by R_{μ_t}. This factor is defined as the ratio of the lateral yielding strength required to maintain the structure elastic to the lateral yielding strength required to limit the ductility demand, μ, equal to a maximum tolerable ductility ratio, μ_t.

$$R_{\mu_t} = \frac{V_y(\mu = 1)}{V_y(\mu = \mu_t)} \tag{1}$$

Over the past few decades, SRF has been the subject of many studies. The studies conducted by Veletsos and Newmark (1960) and Newmark and Hall (1973) may be known as the first investigations on this issue. They proposed simple formulas for SRF as a function of fundamental period and ductility demand of structure. Further researchers (Lai and Biggs 1980 and Riddel *et al.* 1989) proposed other formulas, and numerous investigations were conducted to understand the effect of stiffness degrading (Riddel and Newmark 1979, Nassar and Krawinkler 1991 and Vidic *et al.* 1992) and the influence of hysteretic models (Lee *et al.* 1999) on SRF. However, there are just a limited number of case study research works highlighting the effect of SSI on SRF. Avilés and Pérez-Rocha (2005) examined the variation of strength reduction factors, using nonlinear equivalent SDOF oscillator. It was found that the site effects observed for the rigid-base condition are increased or decreased by SSI, depending on the period ratio of the structure and site, and the effects of interaction on these factors were remarkable while the structure period was close to the site period. Therefore, the use of the strength reduction factors obtained from structure assuming rigid on its base may lead to strength demands considerably different from those obtained from the structure with flexible foundation. Ganjavi and Hao (2012) investigated the effects of SSI on SRF of systems through a parametric study of MDOF and its equivalent SDOF structures. The conclusion was that SSI effect reduces the SRF of both MDOF and more intensively SDOF systems.

Although considerable advancement on the SRF evaluation of structural systems have been made over the last few decades, such developments were usually restricted to fixed-base structures and a limited number of studies on SRF is available for interacting systems. Contrary to the perception of the SSI effects, no thorough quantitative relationship to assess the SRF of MDOF structure-soil systems has been presented yet. Considering a wide range of structural models and dimensionless parameters using the simplified SSI models with shallow foundation, we will present this quantitative relationship. A new formula, which is a function of fixed-base fundamental period, ductility ratio, aspect ratio of structure and dimensionless frequency, is proposed to represent the role of SSI on variation of SRF.

Table 1 Selected fundamental periods of the structures

Number of stories	Height of structure (m)	Fundamental periods (Sec.)
3	9.9	0.30, 0.40
5	16.5	0.50, 0.70
10	33	0.70, 0.90, 1.10
15	49.5	1.00, 1.25, 1.50
20	66	1.40, 1.65, 1.90
25	82.5	1.70, 2.00, 2.30

2. Soil-structure model

The MDOF structure is modeled as a shear building supported on a shallow foundation. Story heights are 3.3 meter, and total structural mass is distributed uniformly along the height of the structure. A bilinear elasto-plastic model with 5% strain hardening is applied to represent the hysteretic response of story lateral stiffness, and 5% Rayleigh damping is assigned to the first two effective modes of fixed-base structure.

As given in Table 1, to consider the influence of the fundamental period of vibration and the number of stories, several values of fundamental periods are investigated for each structure. These fundamental periods are selected to present approximately upper and lower bounds of those recommended by the ASCE/SEI 7-10.

Lateral yield strength and stiffness of stories are considered as proportional to story shear strength distributed over the height of the structure, in accordance with ASCE/SEI 7-10 lateral load patterns. The stiffness and yield strength corresponding to the first story of MDOF building, k_1 and V_{y1}, are obtained from an iterative procedure. k_1 is computed so that the fundamental period of fixed-base structure be equal to the specified periods. To determine V_{y1}, the response history of the structure with assumed yield strength is computed to determine the maximum ductility factor occurred over the height of the structure. If the obtained ductility is close to the target ductility within a 1% of tolerance error, the yield strength value is considered satisfactory; otherwise, it is modified to achieve with reasonable accuracy.

A Sub-structure method is used to model the soil–structure system, as shown in Fig.1. Using this method, the soil can be modeled separately and then combined to establish the soil–structure system. The soil beneath the foundation is considered as homogenous half-space and replaced by a simplified 3-DOF system based on the cone model concept. Cone model is proposed for evaluating the dynamic stiffness of soil (Meek and Wolf 1993 and Wolf 1994). Comparing to the more rigorous numerical methods, this model requires just simple numerical manipulation within reasonable accuracy in engineering practice (Wolf 2004). The coefficients used to define soil-foundation model are summarized in Table 2.

Two mechanisms of energy dissipation of soil involve, wave radiation and material damping. Lumped-parameter models of soil can just capture the radiation damping. Therefore, to incorporate the material damping of soil, nonlinear-hysteretic damping is idealized using frictional element. It is noted that the nonlinear-hysteretic damping independent of frequency is more appropriate and may be realized by introducing frictional elements, which permit causal analysis in the time domain (Meek and Wolf 1994). In this study, frictional elements are introduced for solving SSI governing equations.

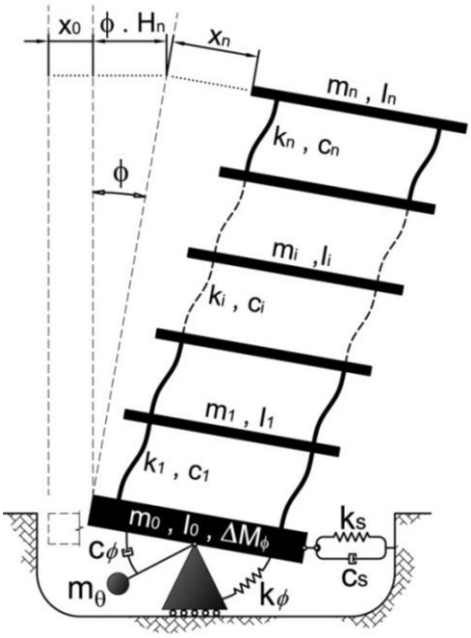

Fig. 1 MDOF Shear building model on flexible base and displacement components. Where for the structure at i^{th} story m_i is the mass, k_i is the stiffness, c_i is damping, I_i is the mass moment of inertia, r_i is the radius of the equivalent circular floor and H_i is the height of the story from the foundation surface. The foundation is replaced by a circular rigid disk of radius r_0, mass m_0, and mass moment of inertia I_0.

Table 2 Cone model for foundation on surface of homogeneous half-space (Wolf 2004)

Lumped Parameter Model			
Rocking motion			Horizontal motion
$k_\emptyset = \dfrac{8\rho\, V_s^2\, r^3}{3(2-\nu)}$			$k_s = \dfrac{8\rho\, V_s^2\, r}{2-\nu}$
$c_\emptyset = \dfrac{\pi}{4}\,\rho\, V_a r^4$			$c_s = \pi\rho V_s r^2$
$m_\theta = \dfrac{9\pi^2}{128}\,\rho r^5(1-\nu)\left(\dfrac{V_a}{V_s}\right)^2$			
$\Delta M_\emptyset = 0.3\pi\psi\left(\nu-\dfrac{1}{3}\right)\rho\, r^5$			
if	$\nu \le 1/3$	then	$\psi = 0, \quad V_a = V_p$
if	$1/3 < \nu \le 1/2$	then	$\psi = 1, \quad V_a = 2V_s$

It should be reminded that kinematic interaction results from the presence of relatively stiff foundation elements on or in soil that cause foundation motions to deviate from free-field motions, and affect the character of the foundation-level motion in a manner that is independent of the structure. The effects can be visualized as a filter applied to the high-frequency components of the ground motion. To consider kinematic effects in analysis of SSI systems, the simplified design

Table 3 Assumed values of Poison's ratio and mass density for the soil beneath the structure

Site class	Shear wave velocity *(m/s)*	Poisson's ratio	Mass density *(KN/m³)*
A. Hard rock	$V_s > 1500$	0.20	23.5
B. Rock	$1500 > V_s > 750$	0.25	
C. Very dense soil and soft rock	$750 > V_s > 360$	0.30	
D. Stiff soil	$360 > V_s > 180$	0.40	19.5
E. Soft clay soil	$180 > V_s$	0.45	

procedures have been presented in FEMA440. However, some limitations associated with application of this approach have been considered, by FEMA 440, such as neglecting kinematic effects for soft clay sites (Site Class E). Therefore, this investigation clarifies the effects of inertial interaction by assuming the building-foundation rests on the surface of the homogeneous half-space and the incoming waves to be vertically propagating coherent shear waves and neglecting the effects of kinematic interaction.

3. Key parameters

Dynamic structural responses of interacting systems under a given earthquake excitation depend on soil and structural characteristics. In other words, for a specific earthquake ground motion, the dynamic responses of the structure can be interpreted based on the properties of the structure relative to the soil beneath it. The effect of these factors can be described by the following dimensionless parameters:

1) Dimensionless frequency as an index for the structure-to-soil stiffness ratio defined as:

$$a_0 = \frac{\omega_{fix} H}{V_s} \tag{2}$$

Where V_s, H and ω_{fix} are the shear wave velocity, the total height of the structure and the circular natural frequency of the fixed-base structure. The practical values of a_0 is varied from infinitesimal values close to zero, for the fixed-base structures, to three for the cases with predominant SSI effect.

2) The aspect ratio of the building is defined as H/r, where r is the equivalent radius of floors and foundation. Here, this parameter can take different values from one to four to cover squat- to slender-structures.

3) Interstory displacement ductility demand of the structure is defined as:

$$\mu = \frac{\Delta_m}{\Delta_y} \tag{3}$$

Where Δ_m and Δ_y are the maximum interstory displacement and the yield interstory displacement, corresponding to the same story, resulted from a specific earthquake ground motion. It is noted that for the MDOF structure μ is referred to as the greatest value among all the story ductility ratios. Herein, this index varies between one and eight which are representative of elastic to hyper-ductile structures, respectively.

Table 4 Studied values of key parameters

Variable	Values
Dimensionless Frequency (a_0)	0, 1, 2, 3
Target Ductility (μ)	1, 2, 4, 6, 8
Aspect Ratio (H/r)	1, 2, 3, 4

4) Poison's ratio, ν, and mass density of soil, ρ, are set to constant values, as illustrated in Table 3, on basis of site class characteristics and shear wave velocity.
5) Material damping ratio of the soil, ξ_{soil} is assumed 5%. As mentioned earlier, to incorporate material damping of soil, non-linear-hysteretic damping is idealized using frictional elements.
6) The mass of foundation is assumed such that foundation uplift does not occur under design earthquake excitations.

The first two items are the key parameters, which define the main SSI effects and the third one controls the inelastic behavior of the structure. The assumed values of these parameters are presented in Table 4. The other parameters have less importance and set to some typical constant values, as aforementioned.

4. Time history and statistical data analysis

In this study, a dynamic SSI analysis program has been developed using MATLAB. The analyses of interacting systems are conducted in the time domain, by direct step-by-step numerical integration, using Newmark's method with modified Newton-Raphson technique.

Due to the variability in ground motion characteristics, which affects structural responses, an ensemble of 20 ground motions with different characteristics is selected from PEER strong motion database. All selected records satisfy the following criteria: (a) earthquake moment magnitude greater than or equal to 6 and less than or equal to 7, (b) recorded on "stiff soil" or "soft clay soil" (e.g., ASCE7-10 site class D or E, respectively), (c) source-to-site distance range from 15 to 60 km without pulse-type characteristics, and (d) recorded on free-field or at the basements of one-story lightweight buildings.

One of the most important challenges in dynamic analysis is the scaling of earthquake ground motions. The nonlinear structural response is often highly sensitive to the scaling of input ground motions. Various methods of scaling to specified severity are proposed in the literature. The capability of six conventional methods for scaling of earthquake records is evaluated (Abedi Nik and Khoshnoudian 2011 and 2012) and a two-parameter scaling method (Cordova *et al.* 2000) is selected due to its simplicity, efficiency and accuracy.

SSI systems corresponding to 16 MDOF structure (see Table 1) undergoing 5 levels of target ductility, 4 values of dimensionless frequency, and 4 values of aspect ratio of the structure (see Table 4) are subjected to the set of selected ground motion records.

The concept of trimmed mean is utilized to provide central values of response. Trimmed mean is a statistical measure of central tendency that is robust to outliers. If there are outliers in the data, the trimmed mean is a more representative estimation of the center of the data. The idea behind the trimmed mean is to ignore a small percentage (herein, assumed 10%) of the highest and lowest values of a sample, when determining the center of the sample.

5. Regression analysis

As mentioned previously, the objective of this study is the assessment of strength reduction factor for MDOF structures including SSI effects. Strength reduction factor prescribed in current seismic codes are based on fixed-base structure. Therefore, influence of subsoil flexibility on SRF should be investigated for accurate evaluation of this factor. For this purpose, strength reduction factor ratio, R_{a_0}, is defined as the SRF for SSI system normalized by corresponding fixed-base value, when subjected to the same ground motion. This is expressed as:

$$R_{a_0} = \frac{R_{\mu}^{SSI}}{R_{\mu}^{Fixed-Base}} \tag{4}$$

By extracting R_{a_0}, the effect of soil beneath the structure on SRF can be investigated in comparing to a fixed-base condition. According to this definition, $R_{a_0} \leq 1$ means that SRF obtained from interacting system is less than similar fixed-base structure. Therefore, the SSI has detrimental effect and using SRF computed from fixed-base structure can lead to underestimate design forces and higher structural ductility. In contrast, $R_{a_0} \geq 1$ indicates that the structure in interacting system requires larger value of SRF to achieve specified target ductility in comparison with fixed-base condition. Thus, in this case, SSI has beneficial effects and assigning SRF obtained from fixed-base structure to superstructure in interacting system leads to conservative demand estimation.

The development of a formula to determine R_{a_0} as a function of the key parameters, is done through the regression analysis. For this purpose, the regression analysis program has been developed using MATLAB. At first, averaged R_{a_0} results from 20 ground motions is governed by

$$R_{a_0} = f\left(a_0, \mu, \frac{H}{r}, T_{fix}\right) \tag{5}$$

A two-step regression analysis is carried out in 3-D domains. First, regressing R_{a_0}in $\mu - T_{fix}$ coordinate for discrete dimensionless frequency and aspect ratio, and then evaluating the effect of a_0 and H/r in the second step as well. The advantages of the various regression models were examined and the following equations are proposed, as the most appropriate alternatives, for the first step of regression analysis:

$$R_{a_0}(\%) = f_1(\mu, T_{fix}) = A_0 + R_1(T_{fix}) + R_2(\mu) + R_3(T_{fix}, \mu) \tag{6}$$

$$R_1(T_{fix}) = T_{Fix}(A_1 T_{Fix}^2 + A_2 T_{Fix} + A_3) \tag{7}$$

$$R_2(\mu) = \mu(A_4 \mu^2 + A_5 \mu + A_6) \tag{8}$$

$$R_3(T_{fix}, \mu) = \mu T_{Fix}(A_7 T_{Fix} + A_8 \mu + A_9) \tag{9}$$

Where A_0 to A_8 are independent coefficients computed from nonlinear regression analyses, for different levels of a_0 and H/r. In the next step, A_i coefficients can be determined using the following model:

$$A_i = f_2\left(a_0, \frac{H}{r}\right) = \beta_0 + \frac{H}{r}\left(\beta_1\left(\frac{H}{r}\right)^2 + \beta_2\frac{H}{r} + \beta_3\right) + a_0\frac{H}{r}\left(\beta_4\frac{H}{r} + \beta_5 a_0 + \beta_6\right) + a_0(\beta_7 a_0 + \beta_8) \tag{10}$$

Regression coefficients, β_i, and also the coefficients of determination, R^2, of proposed formula are represented in Table 5 and Fig.2, respectively.

The coefficient of determination is simply the squared value of the correlation coefficient. This parameter is useful because it gives the proportion of the variance (fluctuation) of one variable that is predictable from the other variable. It is a measure that allows us to determine how certain one can be in making predictions from a certain model/graph.

Vertical and horizontal axis of Fig. 2 present R_{a_0} obtained from nonlinear dynamic analysis vs.

Table 5 Regression coefficients

A_i	β_0	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8
A_0	93.8	1.181	-7.039	7.131	-0.9962	0.1755	6.514	-3.05	2.444
A_1	19.2	-0.5014	3.973	-9.557	-0.09462	-0.6105	2.645	3.676	-17.13
A_2	-64.52	2.251	-17.34	39.94	-0.01088	2.645	-8.834	-12.01	51.05
A_3	55.12	-3.259	23.67	-48.85	1.056	-2.752	2.71	9.352	-26.11
A_4	-0.00863	0.000327	-0.00328	0.01541	0.000246	0.001512	-0.00987	0.00248	-0.00968
A_5	0.1582	-0.00308	0.09258	-0.5103	-0.02538	-0.02282	0.281	-0.136	0.5853
A_6	0.2733	-0.1021	-0.4707	4.495	0.4274	-0.133	-1.85	1.911	-9.094
A_7	-0.1844	-0.02345	0.1505	-0.3916	-0.01496	-0.03277	0.2606	-0.08636	0.4164
A_8	0.03663	-0.00437	0.01228	-0.00806	0.008177	-0.00914	0.005587	0.01865	-0.07836
A_9	-0.4192	0.1579	-0.7333	1.265	-0.09219	0.1817	-0.5998	-0.05066	0.2577

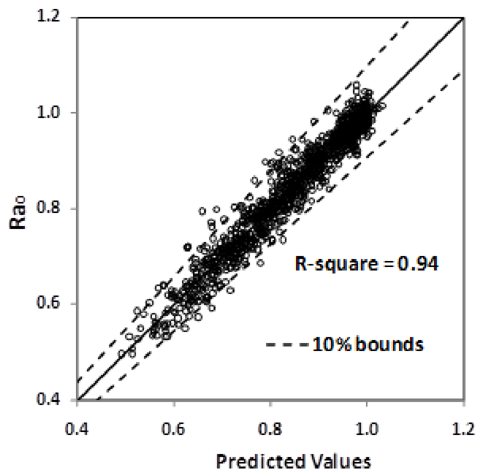

Fig. 2 Comparison of results obtained from nonlinear dynamic analysis vs. those obtained from proposed formula

those obtained from proposed formula, respectively. It is noted that the proposed formula has acceptable accuracy as indicated by its coefficient of determination, R^2. The coefficients of determination are greater than 0.94 for the all studied cases. It means that more than 94% of predicted results fall into acceptable range.

Figs. 3 to 6 illustrate the comparison of R_{a_0} obtained from dynamic nonlinear analysis and those obtained from proposed formula. As shown in these figures, the accuracy of suggested formula can be known as reliable.

It should be noted that the best regression model is not necessarily the one with the smallest standard error, but the simplicity (a small number of parameters) and accuracy are two principal factors required for practical application. Therefore, it is possible to simplify the proposed formula by eliminating the low-impact parameters. However, in this study, the authors have preferred to use the most accurate formula with minimum error to demonstrate the role of SSI on SFR values.

6. Results and discussion

In this section, the interpretation of the results and the effects of key parameters on SRF are discussed based on perspective views of R_{a_0} obtained from proposed formula, in Figs. 3-6.

It should be noted that some combinations of key parameters might be unrealistic. For instance, a tall-squat building with low ductility demand may not be found in engineering applications. However, these cases are studied to determine the tendency of response.

As shown in Figs. 3 and 4, the fundamental period of the structure and the flexibility of subsoil can have significant effects on SRF. It is observed that for the cases with SSI effect, R_{a_0} decrease from unity as dimensionless frequency enhance and as period of the structure decrease. Indeed, SSI effects on SRF become less significant as the fundamental period of structure increases. Meanwhile, the variation of R_{a_0}versus $a_0 - T$ also depends on the ductility and aspect ratio of the structure. R_{a_0} become less sensitive to the variation of the fundamental period in slender structures with low ductility. Therefore, the most influenced systems by SSI effects are squat-ductile structure having short period of vibration supported on soft soil medium.

The effect of structural aspect ratio on R_{a_0} is illustrated in Fig. 5. As t it is shown in this figure, for interacting systems with predominant SSI effect, $a_0 = 3$, the effect of aspect ratio is crucial for short periods, especially in ductile cases. It is obvious that a decrease in the amount of the aspect ratio reduces R_{a_0}, and the most significant effect of H/r on R_{a_0} is related to ductile structures with period of vibration less than 1 second.

Fig. 6 presents the sensitivity of R_{a_0} to ductility demand. For systems with predominant SSI effect, $a_0 = 3$, the ductility ratio is an important parameter which affects R_{a_0}. In studied cases, R_{a_0} reduces as ductility ratio increases. Meanwhile, the influence of ductility on R_{a_0}depends on the aspect ratio of the structure as well. In this regard, ductility variation has a more remarkable effect on the responses of the squat structures.

As results indicate, the SSI has a predominant influence on R_{a_0}, especially in short period structures. For instance, including SSI effect causes up to 50% reduction in SRF value depends on ductility demand, in comparison with fixed-base structure. Therefore, application of fixed base SRF for interacting structure could lead to a considerable error and it confirms the necessity of the present investigation.

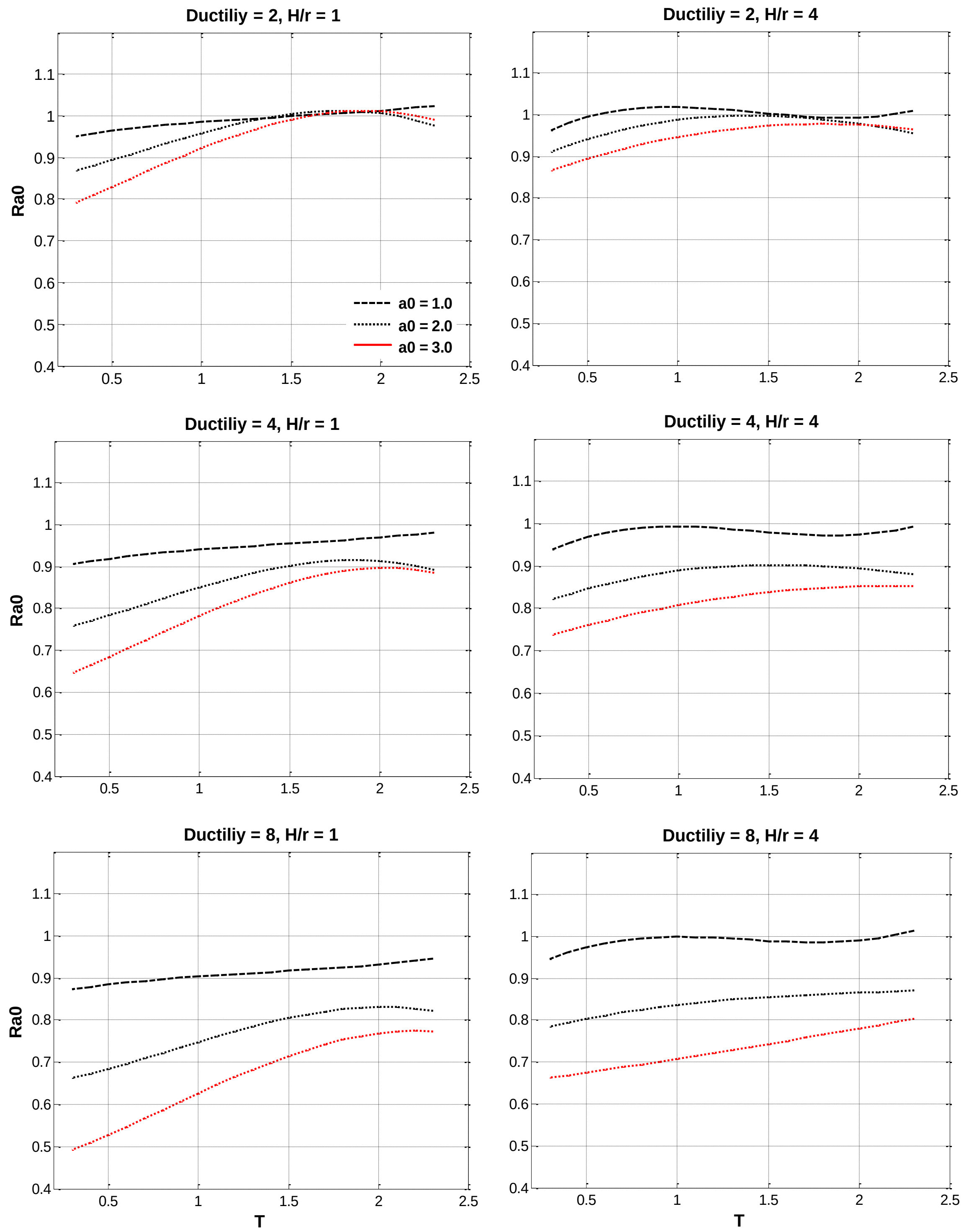

Fig. 3 Effect of dimensionless frequency on R_{a_0}

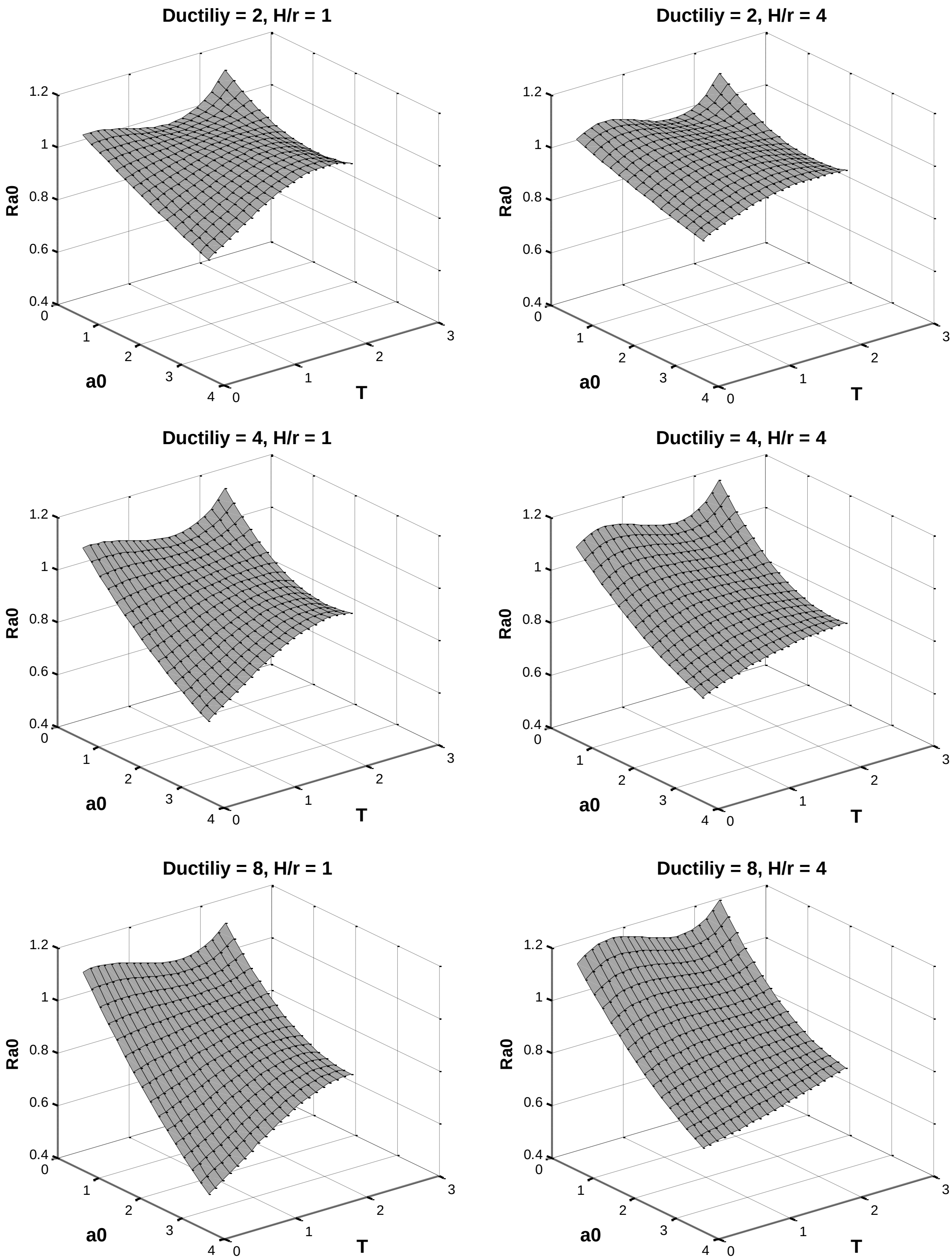

Fig. 4 Three dimensional perspective views of R_{a_0} surfaces in $a_0 - T$ coordinates

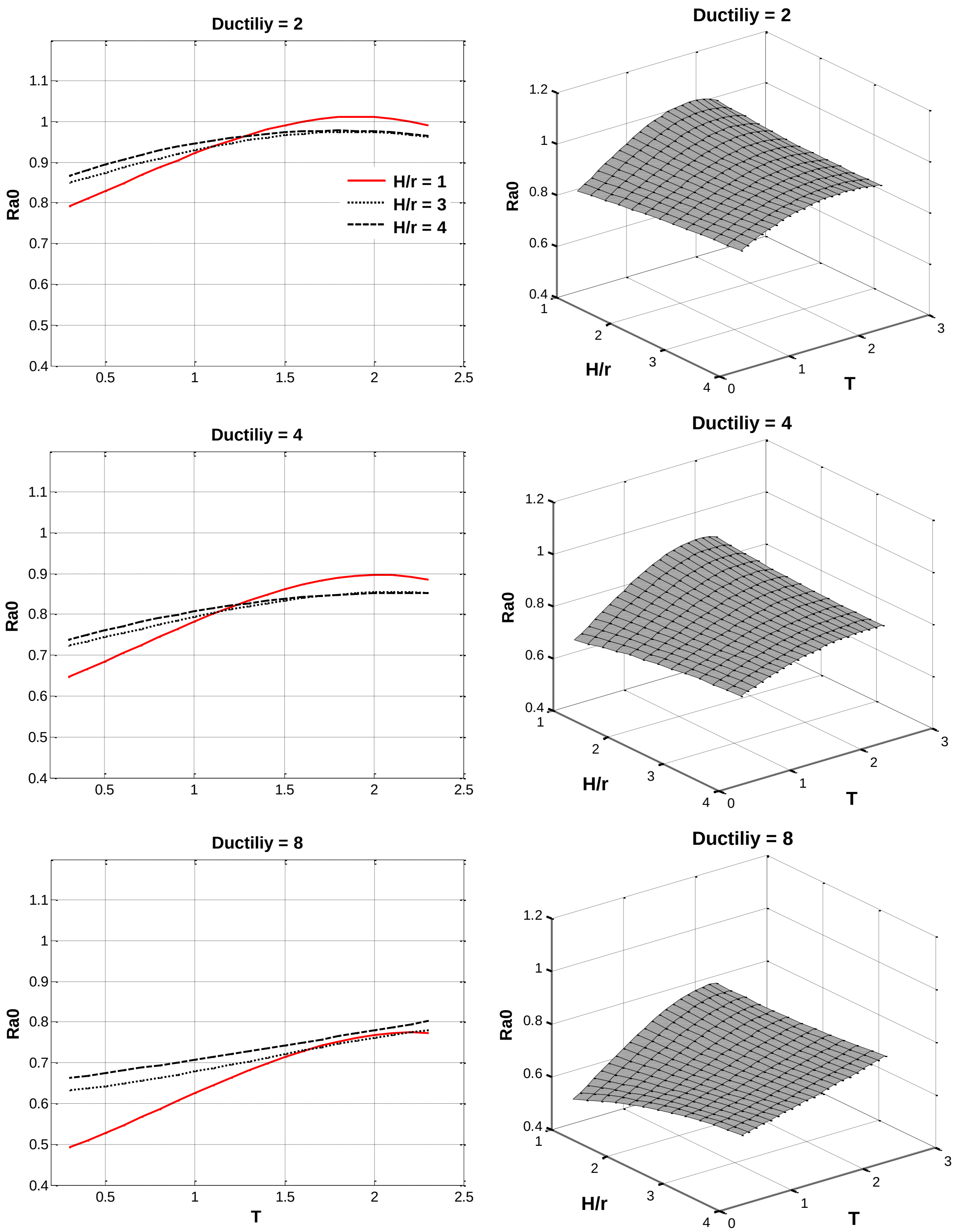

Fig. 5 Effect of the aspect ratio on R_{a_0} assuming $a_0 = 3$

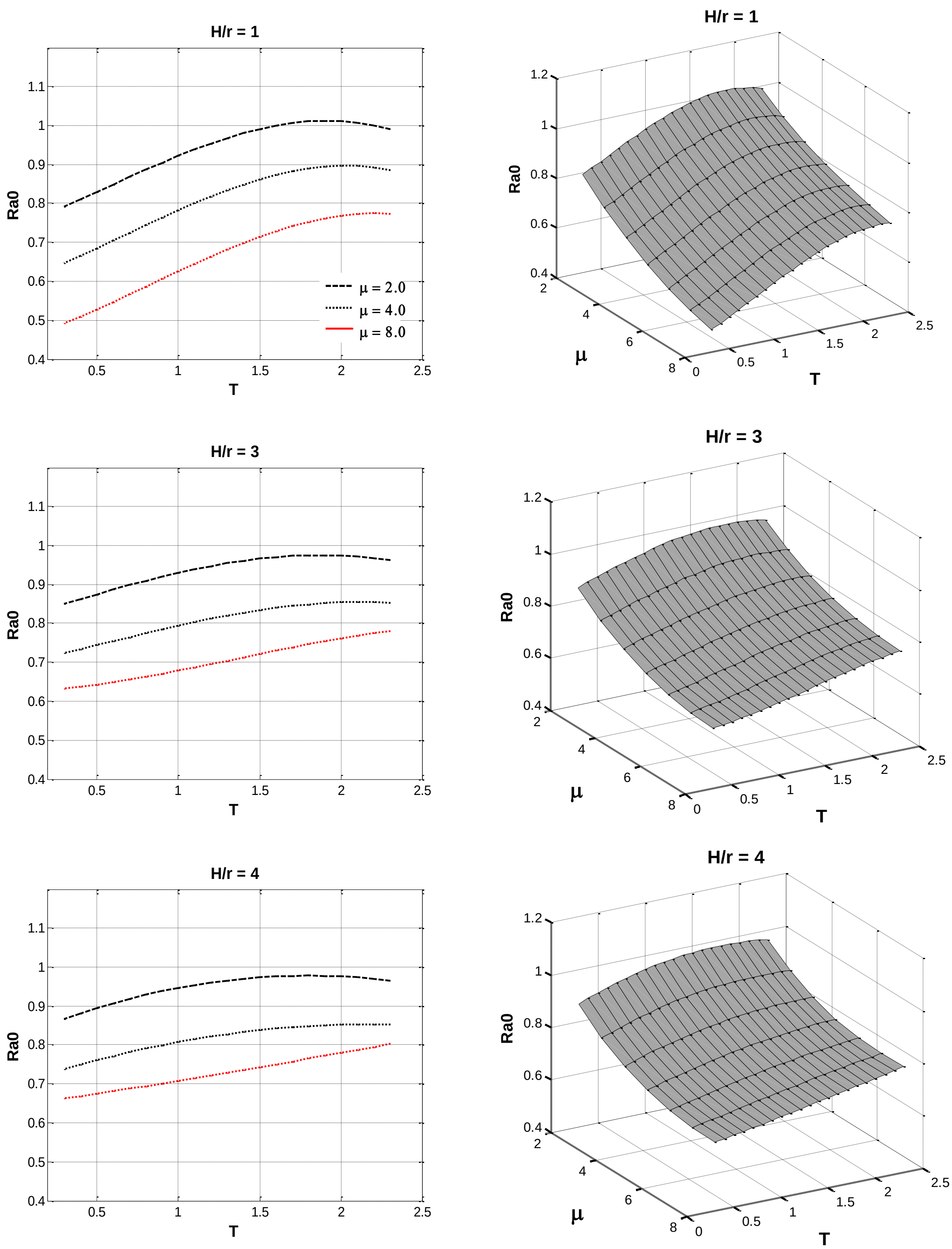

Fig. 6 Effect of target ductility on R_{a_0} assuming $a_0 = 3$

5. Conclusions

Present investigation attempts to examine the effects of soil-structure interaction on strength reduction factor of multistory buildings. In this regard, the effects of key parameters including fundamental period of the structure, ductility demand, number of stories, soil flexibility and aspect ratio of structure on SRF were intensively investigated.

Comprehensive nonlinear dynamic SSI analyses were accomplished to obtain sufficient data for regression analysis. A two-step regression analysis was performed to suggest reliable and accurate formula to predict the effects of base flexibility and other effective parameters on SRF of multistory buildings. The accuracy of the proposed formula in predicting strength reduction factor was demonstrated comparing the results obtained from nonlinear dynamic analysis with those obtained from proposed formula for enormous cases. In addition, based on proposed formula, perspective views of R_{a_0} were plotted in function of key parameters.

The results illustrate that the use of strength reduction factor derived from fixed-base assumption can lead to unsafe evaluation of the structures located on soft soil. The most influenced systems by SSI effects are squat-ductile structures having short period of vibration, which is supported on soft soil. For some usual cases, this underestimation reaches to about 50% that is why engineers should pay attention to this problem. Based on the results, ignoring SSI effects could lead to an unacceptable error in estimation of strength reduction factor and design engineers should keep this issue in their minds.

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