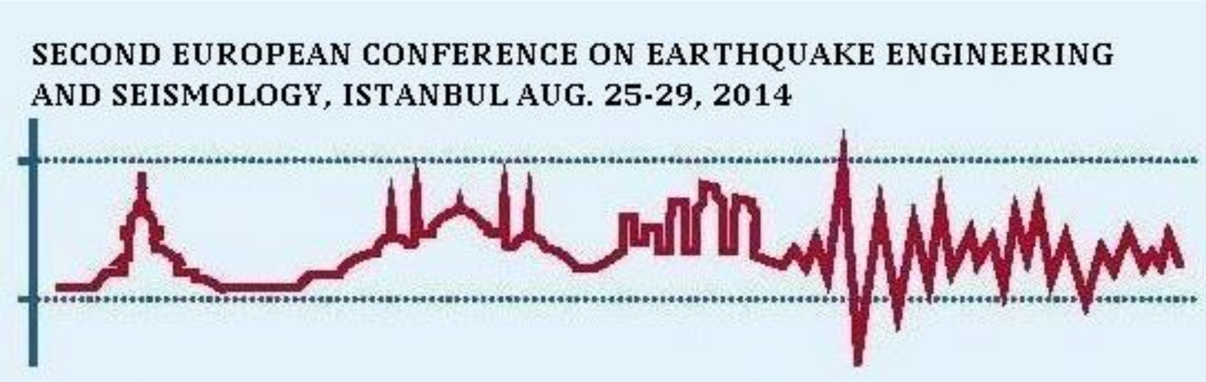

SEISMIC STRENGTH REDUCTION FACTOR FOR SINGLE AND MULTI-STOREY SHEAR BUILDINGS CONSIDERING SOIL-STRUCTURE INTERACTION

Yang LU[1], Iman HAJIRASOULIHA[2*]and Alec M. MARSHALL[3]

ABSTRACT

A parametric analysis has been performed to study the strength-ductility relationship of buildings with different fundamental periods considering Soil-Structure Interaction (SSI). Multi-storey shear buildings are combined with the cone model that represents a homogeneous soil half-space to provide a simplified SSI model. These buildings are designed with the IBC 2012 lateral force distribution and are then subjected to a group of 6 simulated spectrum compatible earthquakes. The effects of structure to soil stiffness ratio a_0, slenderness of the structure s and number of storeys N on the strength reduction factor R_μ and the modification factor R_M have been investigated. It is concluded that using R_μ calculated based on fixed-based systems in SSI design would underestimate the required strength for a given target ductility demand and, therefore, is not suitable for practical design purposes. It is also shown that the combined effect of a_0 and s invariantly results in an elongated period, while it can either increase or decrease the overall damping of SSI systems when compared to their fixed-base counterparts. The results indicate that the modification factor R_M for inelastic SSI systems is mainly affected by the structure to soil stiffness ratio, fundamental period and slenderness ratio of the building, but it is not sensitive to the variation of ductility demand and number of storeys.

INTRODUCTION

Modern seismic provisions allow structures to dissipate seismic energy by undergoing inelastic deformation in severe earthquake events. The expected level of inelasticity is usually achieved by reducing the elastic design response spectra. For example, the design lateral strength can be much lower than that required to maintain a structure in elastic state during strong ground motions. This reduction in strength is quantified by a reduction factor given by Equation 1(Miranda, 1997)

$$R = R_\mu \cdot R_M \cdot R_s \qquad (1)$$

where R_μ is associated with the reduction in strength for a single-degree-of-freedom (SDOF) structure due to its inelastic hysteretic behaviour; R_M is a modification factor that takes into account the multi-degree-of-freedom (MDOF) effects; and R_S accounts for the overstrength of structural components and other safety factors.

[1] PhD candidate, The University of Nottingham, Nottingham, evxyl7@nottingham.ac.uk
[2] Lecturer, The University of Sheffield, Sheffield, i.hajirasouliha@Sheffield.ac.uk
[3] Lecturer, The University of Nottingham, Nottingham, alec.marshall@nottingham.ac.uk

In the past four decades, extensive studies have been dedicated to R_μ (e.g. Riddell, *et al*., 1989; Fischinger *et al*., 1994) and R_M (Santa-Ana and Miranda, 2000; Moghaddam and Mohammadi, 2001) that are used in conventional design for fixed-base structures. In these studies, R_μ and R_M were obtained over a wind range of structural period T for different values of the ductility ratio μ. A comprehensive review of previous studies on the $R_\mu - \mu - T$ relationship was made by Miranda and Bertero (1994). On the other hand, the effects of soil flexibility have been seen to increase the natural period of the Soil-Structure Interaction (SSI) system. Moreover, the soil that is introduced to a SSI system dissipates some of the seismic energy absorbed by the structure through internal friction (hysteretic damping) and radiation damping. The period lengthening and damping effects have been regarded as beneficial and are coded into some of the design provisions (NERHP, 1997; ATC 3-06; FEMA 450). As a consequence, the above-mentioned reduction factors should be modified accordingly.

While a number of analyses have been performed to study the strength reduction factors of SDOF SSI systems (Avilés and Pérez-Rocha, 2005; Ghannad and Jahankhah, 2007; Jarernprasert, 2012), less attention has been paid to the inelastic force demands of multi degree-of-freedom (MDOF) SSI systems. In this study, the strength reduction factor R_μ and the modification factor R_M for SSI systems are calculated and compared to those obtained from their fixed-base counterparts. Analysis is performed on a simplified SSI model subjected to a group of 6 simulated earthquakes compatible with IBC-2012 design spectra for Site E (soft soil profile). Effects of soil flexibility, fundamental period and slenderness ratio of the structure, target ductility demand and number of storeys are investigated.

MODELLING AND ASSUMPTIONS

The multi-storey buildings in this study are modelled as shear buildings, consistent with previous seismic analyses of building structures (e.g. Hajirasouliha and Pilakoutas, 2012). The reliability and accuracy of these models can be found in Lai et al. (1992). In shear-building models, the mass of each floor is assumed to be lumped at the centre of the beam and is connected by an elastic-perfectly-plastic spring that models the shear deformation. Each building is considered to have a storey height of $h = 3m$ and a total mass m_{tot} which is uniformly distributed along the height. The strength and stiffness distribution is assumed to be proportional to the storey shear force distribution in accordance with the IBC 2012 lateral force pattern.

The homogeneous soil half-space is modelled by a discrete-element model based on the concept of the cone model (Ehlers, 1942). This model has been found to be adequate for practical applications (Meek and Wolf, 1992). A Sway-Rocking SSI model consisting of a translational and a rotational cone that supports a shear building is shown in Figure 1a. Both cones are constructed as an interconnection of a small number of masses, springs, and dampers whose properties are given by Wolf, (1994).

$$k_h = \frac{8\rho V_s^2 r}{2-\upsilon}, c_h = \rho V_s \pi r^2 \tag{2}$$

$$k_\theta = \frac{8\rho V_s^2 r^3}{3(1-\upsilon)}, c_\theta = \frac{\rho V_p \pi r^4}{4} \tag{3}$$

$$M_\varphi = \frac{9}{128}(1-\upsilon)\pi^2 \rho r^5 \left(\frac{V_p}{V_s}\right)^2 \tag{4}$$

where k_h, k_θ and c_h, c_θ are the coefficients of springs (denoted by k) and radiation damping dashpots (denoted by c) for the horizontal (denoted with subscript h) and rocking (denoted with subscript θ) motions, respectively, as illustrated in Figure 1a. The properties of the homogeneous soil half-pace include its mass density ρ, Poisson's ratio ν, shear wave velocity V_s and dilatational wave velocity V_p. The equivalent radius of the shallow foundation is assumed to be r. To account for the frequency dependence of the rocking components of the cone model in the time domain analysis, an additional rotational degree of freedom φ, with its own mass moment of inertia M_φ, is introduced as shown in Figure 1a.

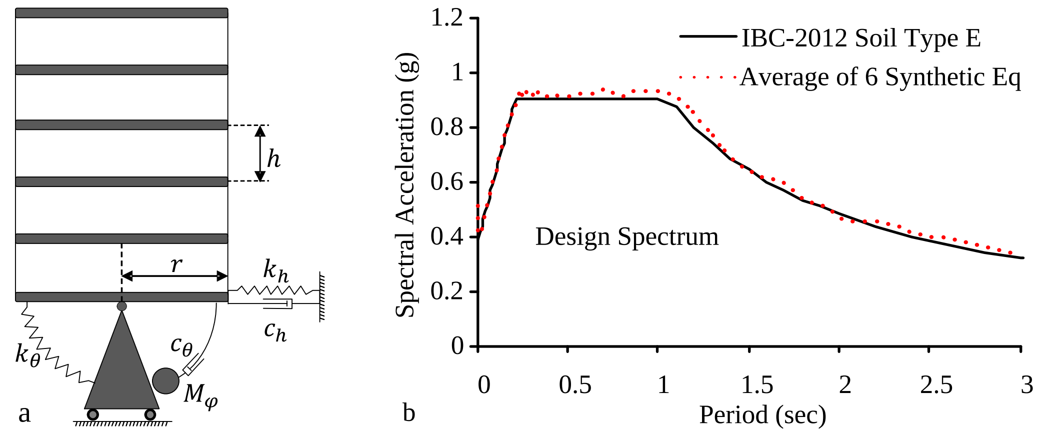

Figure 1. (a) Simplified Soil-Structure Interaction model; (b) Comparison of the IBC-2012 response spectrum for soil type E with the average spectrum of the synthetic earthquakes

Six spectrum-compatible synthetic earthquakes are generated to represent the elastic design response spectra of IBC-2012 corresponding to soil types E (Figure 1b), which is described as a very soft soil profile with $V_s \leq 180m/s$. This design response spectrum is assumed to be an envelope of the possible ground motions that could occur at the site.

MODELLING PARAMETERS

The main properties of a SSI system can be well described by the following non-dimensional parameters:

1. The structure-to-soil stiffness ratio a_0, which is defined as

$$a_0 = \frac{w_n \bar{H}}{V_s} \tag{5}$$

where $w_n = 2\pi/T_n$ is the circular frequency of the fixed-base structure corresponding to its first mode of vibration, with T_n being the fundamental period, and the effective height of the structure $\bar{H}$ is approximated as 0.7 times the total height (H_{tot}). a_0 indicates the degree of influence of SSI and generally varies from zero, for fixed-base structures, to about two, where the soil becomes very flexible compared to the structure.

2. The slenderness ratio of the structure s, which is given by

$$s = \frac{\bar{H}}{r} \tag{6}$$

3. The structure-to-soil mass ratio $\bar{m}$ that is

$$\overline{m} = \frac{m_{tot}}{\rho H_{tot} r^2} \quad (7)$$

Where m_{tot} is the totoal mass of the structure. Additional parameters used in this study include the structural ductility ratio μ_{max}, which is the maximum inter-storey ductility at the critical storey; the foundation-to-structure mass ratio m_f/m_{tot}, where m_f is the mass of the foundation that determines the mass moment of inertia of the foundation J_f $(0.25 m_f r^2)$; the damping ratio of the structure ζ_s; number of storeys N; and Poisson's ratio of the soil υ. The values of the parameters used in this study are presented in Table 1.

Table 1. Modelling parameters used in this study

Parameters	a_0	s	$\overline{m}$	μ_{max}	m_f/m_{tot}
	0,1,2,3	1,2,3,4,6,8	0.5	1,2,4,6	0.1
	N	ζ_s	υ	ρ (kg/m^3)	h (m)
	1,3,5,10,15	0.05	0.33	1800	3

RESULTS AND DISCUSSIONS

Strength Reduction Factor

For a SDOF system, R_μ is a factor which reduces the elastic base shear to that required to avoid the maximum ductility larger than the design target ductility μ_t.

$$R_\mu = \frac{V_{SDOF(\mu=1)}}{V_{SDOF(\mu=\mu_t)}} \quad (8)$$

where $V_{SDOF(\mu=1)}$ and $V_{SDOF(\mu=\mu_t)}$ are the base shear demands of SDOF structures to remain elastic ($\mu = 1$) and to limit their maximum ductility ratios to the target value (μ_t), respectively. In the present study, R_μ factors are calculated from constant ductility spectra obtained for given a_0 and s values. The mean R_μ factors, shown in Figure 2, are calculated by averaging the reduction factors obtained from the six spectrum compatible earthquakes.

As mentioned earlier, a_0 is a factor that controls the severity of the SSI phenomena, and s is the slenderness of the building. It is observed from Figure 2 that in general, regardless of a_0 and s, R_μ for nearly rigid structures (i.e. $T_n \to 0$) tends to one and increases with increasing the flexibility of the buildings. For fixed-base structures ($a_0 = 0$) having a long natural period (i.e. very flexible structure), R_μ approaches the target ductility ratio. These observations are consistent with the evidence presented by Miranda and Bertero (1994). Figure 2 also shows that increasing a_0 (including SSI) reduces R_μ of flexibly-supported structures when compared to their fixed-base counterparts. The reduction is more obvious when the a_0 value is smaller than 2, and is up to 75% for a structure with predominant SSI effects ($a_0 = 3$) as seen in Figure 2 (f). Unlike the rigidly-supported structures whose R_μ factors are not affected by the slenderness ratio in SSI systems, R_μ for slender structures is smaller than squatty structures. However, the strength reduction factor R_μ is mainly influenced by the relative stiffness a_0, and to a lesser degree, by the slenderness of the structures. This indicates that using fixed-base R_μ to design a slender building considering SSI can be unconservative.

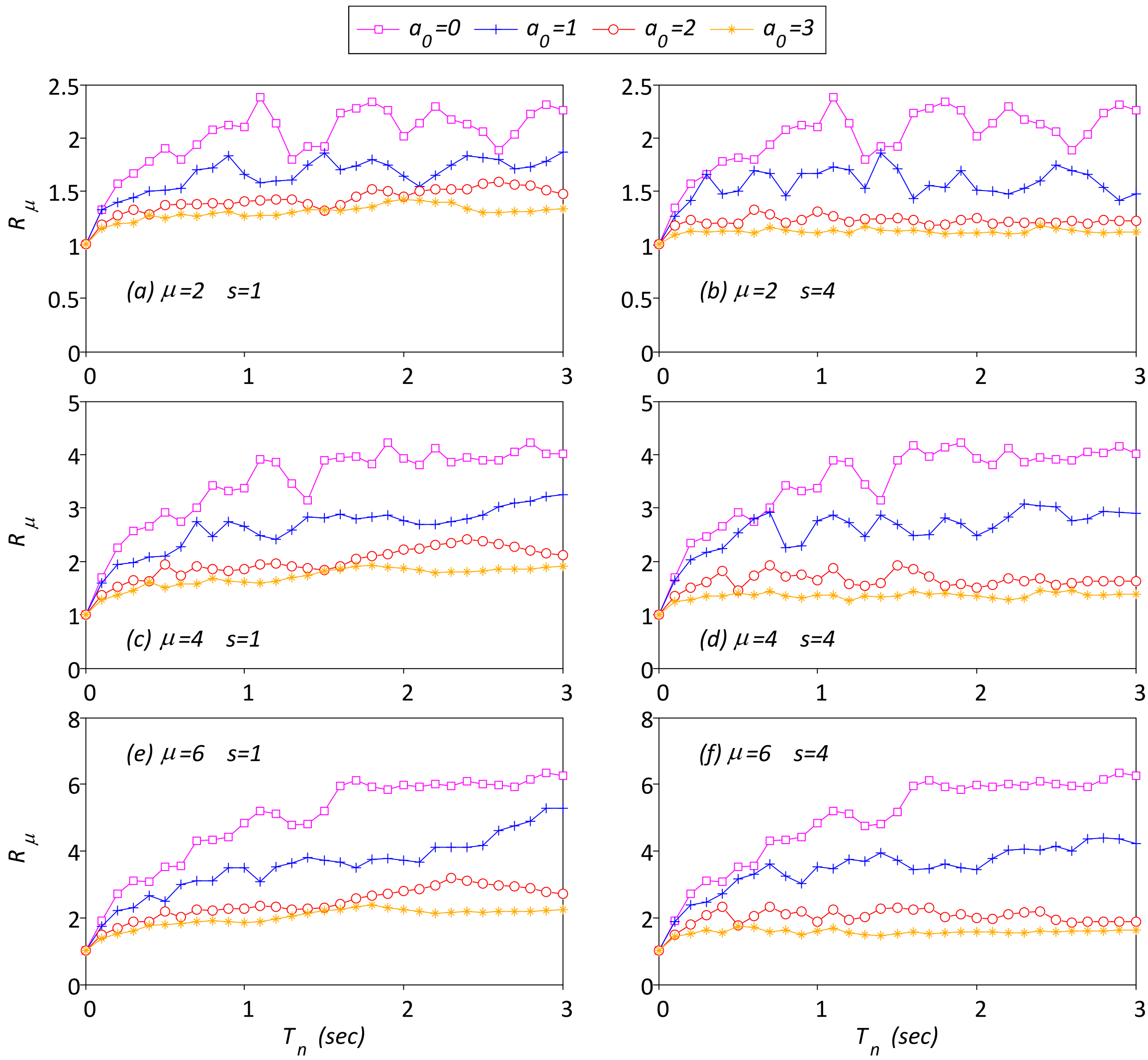

Figure 2. Strength reduction factor R_μ for SDOF SSI systems, average of six spectrum compatible earthquakes

It should be noticed that the R_μ factor is not only a function of the dynamic properties of the SSI system, but also related to site condition and the ground input motion. However, the mean R_μ factor for a SSI system subjected to a given set of earthquake ground motions (ignoring any strength hardening or softening) can be expressed as a function of the effective system period T, damping ratio ζ and the target ductility demand μ_t. The period and damping ratio of SSI systems can be calculated from their fixed-base counterparts T_n and ζ_s using the modified expressions based on the work of Veletsos and Meek (1974)

$$T = T_n \sqrt{1 + \left(\frac{2-\upsilon}{5.6}\right)\overline{m} a_0^2 s^{-1} + 1.093(1-\upsilon)\overline{m} a_0^2 s} \tag{9}$$

$$\zeta = \left(\frac{T}{T_n}\right)^3 \left\{\zeta_s + \frac{3}{256}(2-\upsilon)\overline{m} a_0^3 \pi \left[\frac{2-\upsilon}{s^2} + \frac{9(1-\upsilon)^2}{2-\upsilon}\right]\right\} \tag{10}$$

The effectiveness of these relationships is demonsterated in Figure 3, where the predicted curves from Equations (9) and (10) match very well with the data obtained from an Eigen analysis.

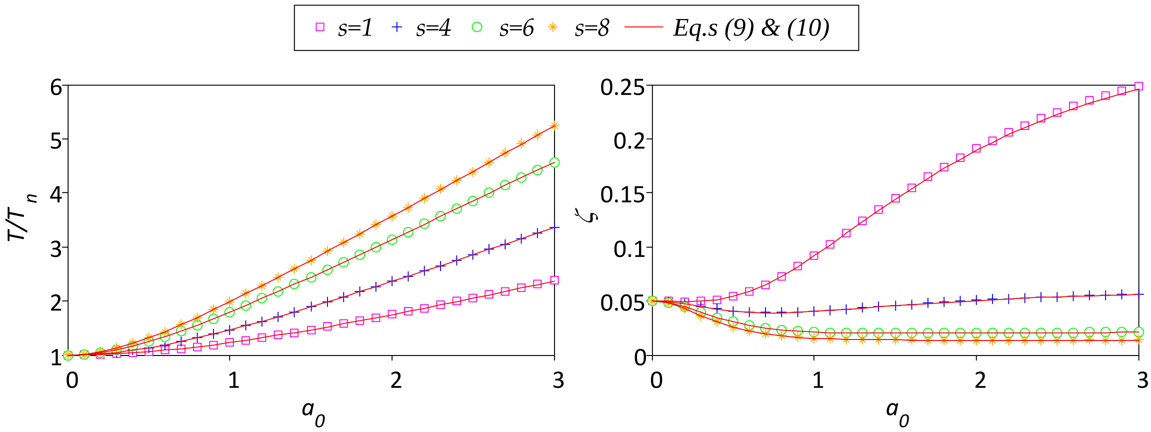

Figure 3. Comparison of the obtained and predicted effective periods and damping ratios of SSI systems

One of the controversial issues concerning the strength reduction factor is that R_μ obtained from a number of earthquakes may not be applicable to all cases given the variability of the ground motions and site conditions. It is worth mentioning that Ordaz and Pérez-Rocha (1998) proposed the following reduction rule, where R_μ is dependent on the elastic displacement spectra.

$$R_\mu = R_\mu\left(D(T_n, \zeta_s), D_{\max}, \mu_t\right) = 1 + \left(\frac{D(T_n, \zeta_s)}{D_{\max}}\right)^{\beta(\mu)}(\mu - 1) \quad (11)$$

where $D(T_n, \zeta_s)$ is the elastic spectral displacement; D_{max} is the peak ground displacement and β is a curve fitting variable as a function of the ductility. The effects of damping, site conditions and ground motions are implicitly incorporated in the shape of the displacement spectra, which can account for the case-to-case variability. This rule was further extended to SSI systems by Avilés and Pérez-Rocha (2005).

Modification Factor

For multi-storey buildings, it is proposed that the R_μ factor in Equation (8) be multiplied by a modification factor to account for the possible concentration of the ductility in certain floors. This modification factor, denoted by R_M is proposed as:

$$R_M = \frac{V_{SDOF(\mu=\mu_t)}}{F_{MDOF(\mu_{\max}=\mu_t)}} \quad (12)$$

where $F_{MDOF(\mu_{max}=\mu_t)}$ is the base shear strength that is required to limit the maximum inter-storey ductility of a MDOF system to the target ductility μ_t. The maximum ductility μ_{max} is defined as:

$$\mu_{\max} = MAX\left(\frac{\Delta u_{1\max}}{\Delta u_{1y}}, \frac{\Delta u_{2\max}}{\Delta u_{2y}}, \ldots, \frac{\Delta u_{i\max}}{\Delta u_{iy}}, \ldots, \frac{\Delta u_{N\max}}{\Delta u_{Ny}}\right) \quad (13)$$

where Δu_{imax} and Δu_{iy} are the maximum and yield lateral deformation exhibited by the i^{th} floor during an earthquake, respectively. By substituting Equations (8) and (12) into Equation (1) and ignoring the overstrength of structural components (i.e. $R_S = 1$), the base shear strength demand of a MDOF system (F_{MDOF}) to achieve the target ductility μ_t can be calculated by:

$$F_{MDOF(\mu_{\max}=\mu_t)} = \frac{V_{SDOF(\mu=1)}}{R_\mu R_M} \tag{14}$$

The modification factor R_M was studied by Santa-Ana and Miranda (2000) where eight multi-storey steel moment-resisting frame buildings were subjected to 28 earthquake ground motions recorded on different sites. They found that to achieve a target ductility demand, elastic MDOF systems experienced less base shear when compared with their corresponding SDOF systems whereas inelastic MDOF structures attracted higher base shear than that of the equivalent SDOF structures. They also observed that the modification factor R_M was mainly affected by the number of storeys, and to a small extent by the site conditions and fundamental period of the structure.

In this study, R_M is obtained for SSI systems by using Equation (12), where the base shear strength of MDOF systems and their corresponding SDOF systems (having the same total mass) are calculated for the same T_n, a_0, s and μ_t under a given excitation. The average results from the six spectrum compatible earthquakes are plotted against the number of storeys as presented in Figure 4. The data in Figure 4 (a) shows that $1/R_M$ (i.e. F_{MDOF}/V_{SDOF}) for $a_0 = 0$ (fixed-base) falls below $1/R_M = 1$, which agrees with the previously mentioned observation that elastic MDOF systems require lower base shear capacity than SDOF systems. Similar results are observed for structures under moderate SSI effects (i.e. $a_0 = 1$). On the contrary, for severe SSI effects (e.g. $a_0 = 2$ and 3), higher base shear strengths are required by MDOF systems than that of SDOF systems to remain elastic. Similar to R_μ, the modification R_M can also be expressed as a function of the system period $T(T_n, a_0, s)$, damping ratio $\zeta(\zeta_s, a_0, s)$ and the target ductility demand μ_t. Besides, R_M may be affected by the number of storeys N.

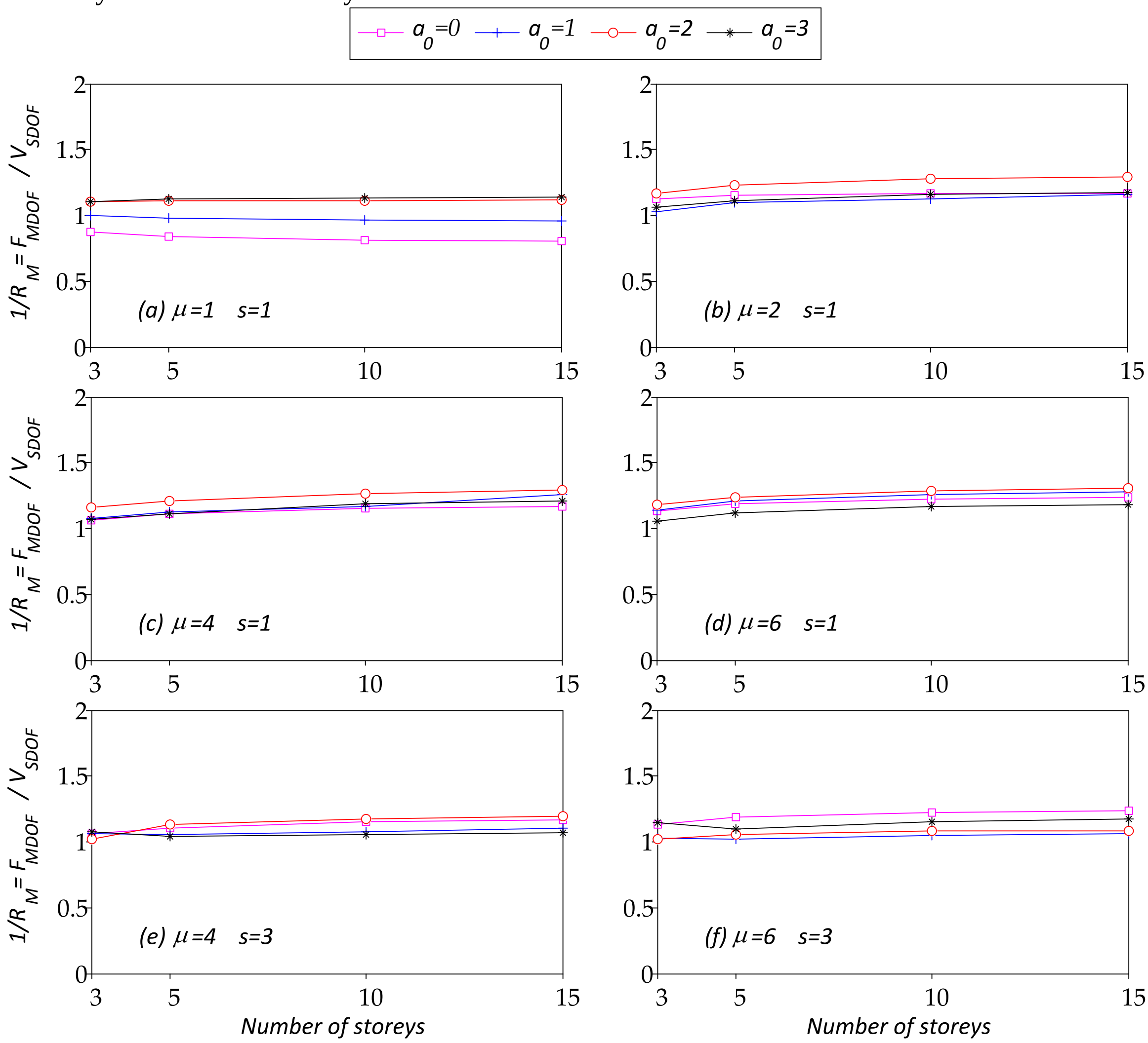

Figure 4. Modification factor R_M for MDOF SSI systems ($T_n = 1s$)

The natural period and overall damping of SSI systems depend on the combined effects of a_0 and s. It is shown in Figure 3 that the period of a SSI system increases with an increase in a_0 and s. By increasing a_0, the damping ratio increases for squatty structures, while it decreases for slender structures. For example, the damping ratio of a SSI system with $a_0 = 3$ and $s = 1$ is five times larger than that of the fixed-base structure. On the other hand, if the slenderness ratio s had been increased to four, the overall damping ratio would reduce by up to thirty percent. This can be explained by the fact that increasing a_0 increases the flexibility and damping of the system, while increasing s decreases the radiation damping by reducing the contact area between the foundation and soil. This will hinder the geometric attenuation of wave energy arising from the inertial interaction.

Considering the results in Figure 4 (b) – (f), the modification factor R_M for inelastic systems is mainly affected by a_0 and s, but it is not sensitive to the variation of target ductility demand and number of storeys. Generally, $1/R_M$ decreases with increasing s.The results show that R_M does not change monotonically with increasing a_0, and in general, $a_0 = 0$ and 2 lead to a higher strength demand for MDOF systems.

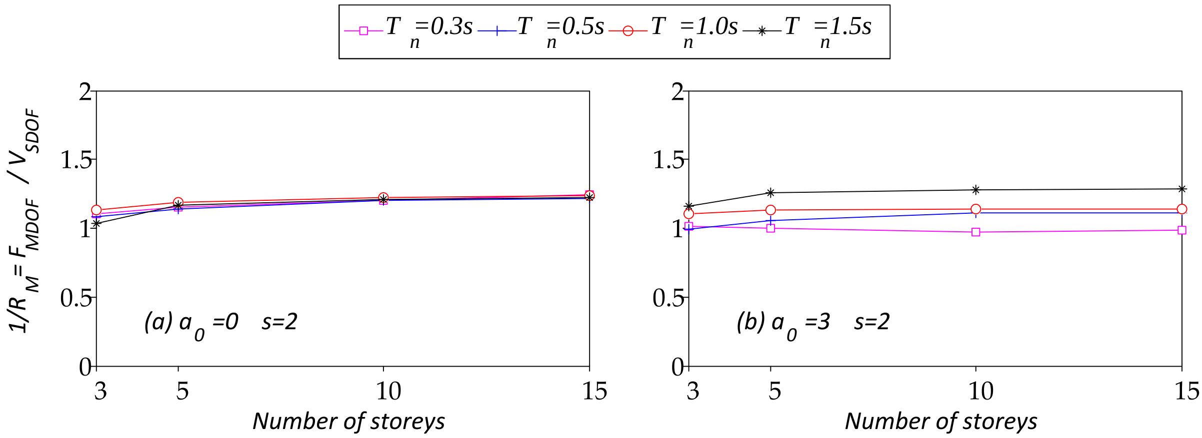

Figure 5. Effect of period on modification factor $R_M$for MDOF SSI systems ($\mu_t = 6$)

The effect of fundamental period of structures on the modification factor R_M is illustrated in Figure 5. The results indicate that R_M is considerably more sensitive to the variations of T_n for SSI systems compared to fixed-base systems. Generally, $1/R_M$ increases with increasing T_n for SSI systems, while it is almost unaffected by T_n for fixe-based systems. The results presented in Figures 4 and 5 indicate that, for the structures with similar fundamental period and slenderness ratio, the modification factor R_M is not sensitive to the number of storeys.

CONCLUSIONS

This study aimed to investigate the effects of effects of Soil-Structure Interaction (SSI) on the strength-ductility relationship of SDOF and MDOF systems. Based on the results from this study, the following conclusions can be drawn:

- Soil structure interaction in general reduces the strength reduction factor R_μ. This reduction can be up to 75% and decreases with increasing flexibility of the soil relative to the structure as well as the slenderness of the structure. Therefore, R_μ values which are calculated based on fixed-based systems in SSI design underestimate the required strength for a given target ductility demand and, therefore, are not suitable for practical design purposes.

- The combined effect of a_0 and s, though resulting in an elongated period, can either increase or decrease the overall damping of SSI systems when compared to their fixed-base counterparts. Generally, damping for flexibly-supported slender buildings is smaller than that of rigidly-supported structures, while SSI systems with squatty buildings have larger damping ratios than those of fixed-base buildings.

- Elastic MDOF systems with moderate SSI effects require lower base shear capacity than SDOF systems. However, for severe SSI effects, higher base shear strengths are required by MDOF systems than that of SDOF systems to remain elastic.

- The modification factor R_M for inelastic SSI systems is mainly affected by the structure to soil stiffness ratio, fundamental period and slenderness of the building, while it is not sensitive to the variation of ductility demand and number of storeys.

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