Effect of Structural Property Distribution on Strength Demand and Ductility Reduction Factor of MDOF Systems Considering Soil-Structure Interaction

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Abstract

It is known that structural stiffness and strength distributions have an important role in seismic response of buildings. The effect of using different code-specified lateral load patterns on seismic performance of fixed-base buildings have been investigated by researchers during the past two decades. However, no investigation has been carried out for the case of soil-structure systems yet. In the present study, through intensive parametric analyses of 21600 linear and nonlinear MDOF systems and considering five different shear strength and stiffness distribution patterns including 3 code-specified patterns as well as uniform and concentric patterns subjected to a group of earthquakes recorded on alluvium and soft soils, the effect of structural property distribution on strength demand and ductility reduction factor of MDOF fixed-base and soil-structure systems are parametrically investigated. Results of this study show that depending on the level of inelasticity, soil flexibility and number of degrees-of-freedoms, structural property distribution can significantly affect the strength demand and ductility reduction factor of MDOF systems. It is also found that at high level of inelasticity, ductility reduction factor of low-rise MDOF soil-structure systems could be significantly less than that of the fixed-base ones and the reduction is less pronounced as the number of stories increases.

Keywords: Soil-Structure systems, MDOF systems, structural property distributions, inelastic behaviour, Strength demand, Ductility reduction factor

1. Introduction

It is believed that structural configuration in terms of stiffness and strength distributions have a key role in seismic response of structures. The effect of using the code-specified lateral load patterns on seismic performance of fixed-base building structures have been investigated during the past two decades (Anderson et al., 1991; Gilmore and Bertero, 1993; Chopra, 1995). Chopra (1995) evaluated the ductility demands of several shear-building models with elastoplastic behavior subjected to the 1940 El Centro Earthquake. The relative story yield strength of these models complied with the lateral load pattern of the earthquake forces specified in the 1994 Uniform Building Code (UBC 94). Leelataviwat et al. (1999) evaluated the seismic demands of mid-rise moment-resisting frames designed in accordance to UBC 94. Mohammadi *et al.* (2004) investigated the effect of lateral load patterns specified by the United States seismic codes on drift and ductility demands of fixed-base shear building structures under 20 earthquake ground motions, and found that story stiffness and structural distribution would have significant effect on the structural damage distribution over the height of the structures. In many previous parametric studies such as those conducted by Veletsos and Vann (1971), Sirvastav and Nau (1987) and Mobasseri et al. (1992), it was assumed that story stiffness or strength were distributed uniformly along the height of the multi-degrees-of-freedom (MDOF) systems. Thus, in this idealization, the shear resistance is constant throughout the height while the required seismic shear resistance according to the current building codes decreases from bottom to top. Although in practical seismic design of low-rise building frames, i.e., buildings with less than 5 stories, story stiffness or strength may often be uniform, the assumption of uniformity may be questionable for mid- and high-rise buildings. Consequently, since the results of many previous studies are based on this assumption, the adequacy of this idealization should be fully investigated for elastic and inelastic behavior of fixed-base and flexible-base building structures.

On the other hand, seismic design of buildings is generally based on the assumption that the foundation flexibility has no significant effect on foundation–structure interacting forces. However, recent studies indicate that SSI is one of the important factors that may significantly affect the seismic responses of structures located on soft soils by altering the overall stiffness and energy dissipation mechanism of the systems. In fact, a soil-structure system behaves as a new system having longer period and generally higher damping due to energy dissipation by hysteretic behavior and wave radiation in the soil. The general effects of SSI on elastic response of SDOF and MDOF systems with an emphasis on the former were the subject of many studies in the 1970s (Jennings and Bielak, 1973; Chopra and Gutierrez, 1974; Veletsos and Meek, 1974; Veletsos and Nair, 1975; Veletsos, 1977). These works led to tentative provisions in ATC3-06 (ATC, 1978), which is actually the foundation of new provisions on earthquake-resistant design of soil-structure systems (BSSC, 2000; FEMA-440, 2005). Code-compliant seismic designs for SSI systems are, conventionally, based on the approximation in which the predominant period and associated damping of the corresponding fixed-base system are modified (Jennings and Bielak, 1973; Veletsos and Meek, 1974). In fact, the current seismic provisions consider SSI, generally, as a beneficial effect on seismic response of structures since SSI usually causes a reduction of total shear strength of building structures (BSSC, 2000; ASCE, 2005). However, the inelastic behavior of the superstructure, inevitable during severe earthquakes, coupled with SSI effect has not been well investigated. Moreover, the current seismic design philosophy is based on inelastic behavior of structures when subjected to moderate and severe earthquakes. Hence, there is a necessity to investigate the effect of SSI on inelastic response of building structures. One of the pioneering works on inelastic soil-structure systems were made by Veletsos and Verbic (1974) and Bielak (1978). Muller and Keintzel (1982) subsequently investigated the ductility demands of single-degree-of-freedom (SDOF) soil-structure systems. They showed that the ductility demand of structures, when considering soil beneath them, could be different from that of the equivalent SDOF systems without considering SSI.

Recently many efforts have been made to investigate the effect of SSI on strength and ductility demand of SDOF systems. The effects of SSI in inelastic SDOF systems, including both kinematic and inertial interaction, were evaluated by Aviles and Perez-Rocha (2003). In further works, considering nonlinear replacement SDOF oscillator, they also studied the effect of SSI on strength-reduction and displacement-modification factors of structures (Aviles and Perez-Rocha, 2005). Ghannad and Jahankhah (2007) parametrically investigated the effect of SSI on strength reduction factor (R_μ) of SDOF systems and concluded that SSI reduces the R_μ values, especially for the case of building located on soft soils. In more recent years, more studies have been made by researchers to investigate the SSI effect on inelastic behavior of SDOF systems (Mahsuli and Ghannad, 2009; Moghaddasi *et al*., 2011; Aviles and Perez-Rocha, 2011, Khodabakhshi et al., 2011). However, almost all researches made on nonlinear soil-structure systems focused on SDOF systems while the SSI effect on inelastic response of MDOF systems due its more complexity has not been investigated in detail. A few studies of SSI effects on MDOF systems are those conducted by Chouw and Hao (2005 and 2008), Barcena and Steva (2007) , Halabian and Kabiri (2010 and 2011) and Ganjavi and Hao (2011a, 2011b). However, the lack of clarity in SSI effects on seismic demands of MDOF systems deserved more special attention. In fact, SDOF systems having only one DOF may not be able to correctly reflect the realistic behavior of common building structures interacting with soil beneath them when subjected to strong ground motions. Ganjavi and Hao (2011a) through an intensive parametric study investigated the effect of SSI on the strength and ductility demands of MDOF as well as its equivalent SDOF buildings considering both elastic and inelastic behaviors and concluded that the common SDOF systems may not accurately estimate the strength and ductility demands of MDOF soil-structure systems, especially for the cases of mid- and high-rise buildings. This can be due to the lack of ability of a SDOF system to incorporate the effects of number of stories and higher modes as well as, more importantly the effect of height-wise distribution of lateral strength and stiffness on inelastic response of real soil-structure systems.

In the present study, considering 5 different shear strength and stiffness distributions, which will be explained in the next section, the effect of SSI on strength demand and ductility (strength) reduction factor (R_μ) of shear-building structures are parametrically investigated. This is carried out for a wide range of structural and non-dimensional parameters to investigate the role of structural property distribution on strength demand and

R_μ of MDOF soil-structure systems subjected to a group of earthquake ground motions recorded on alluvium and soft soils.

2. Superstructure modeling and assumptions

2.1. MDOF superstructure models

Different structural models may be used to estimate the nonlinear seismic response of MDOF building structures. Among them, the well-known shear-beam model is indeed one of the most frequently used models that facilitate performing a comprehensive parametric study of the MDOF systems (Sirvastav and Nau, 1987; Mobasseri et al., 1992; Karami et al., 2004; Moghaddam and Hajirasouliha, 2006; Hajirasouliha and Moghaddam, 2009). This model which has the capability of incorporating the effects of higher modes, the number of stories and lateral strength and stiffness distribution is utilized in this study. In the MDOF shear-building models utilized in the present study, each floor is assumed as a lumped mass to be connected by elasto-plastic springs. Story heights are 3 m and the total structural mass is considered as uniformly distributed along the height of the structure. A bilinear elasto-plastic model with 2% strain hardening in the force-displacement relationship is used to represent the hysteretic response of story lateral stiffness. This model is selected to represent the behavior of non-deteriorating steel-framed structures. To investigate the effect of different story shear strength and stiffness distributions on strength demands and ductility reduction factor of MDOF soil-structure systems, in all MDOF models, lateral story stiffness is assumed as proportional to story shear strength distributed over the height of the structure in accordance to the different presumed lateral load patterns. Five percent Rayleigh damping is assigned to the first mode and the mode in which the cumulative mass participation is at least 95%.

2.2. Selected story strength and stiffness distribution patterns

The general formula of the lateral load pattern specified by the most current seismic codes such as EuroCode 8 (CEN, 2003), Mexico City Building Code (Mexico, 2003), Uniform Building Code (UBC, 1997), NEHRP 2003 (BSSC, 2003), ASCE/SEI 7-05 (ASCE, 2005), Australian seismic code (AS-1170.4, 2007) and International Building Code, IBC-2009 (ICC, 2009) is defined as:

$$F_x = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k} . V \tag{1}$$

where F_x and V are respectively the lateral load at level x and the total design lateral force; w_i and w_x are the portion of the total gravity load of the structure located at the level i or x; h_i and h_x are the height from the base to the level i or x; n is the number of stories; and k is an exponent that differs from one seismic code to another. In IBC-2009 (ICC, 2009) , k is related to fundamental period of the structure, which is equal to 1 and 2 for structures having a period of 0.5 sec or less, and for structures having a period of 2.5 sec or more, respectively. For structures having a period between 0.5 and 2.5 sec, k is computed by linear interpolation between 1 and 2. It should be mentioned that, the distribution of lateral force based on IBC 2009 is identical to that of the NEHRP 2003 (BSSC, 2003) and ASCE/SEI 7-05 (ASCE, 2005) provisions. Note that when k is equal to 1, the pattern corresponds to an inverted triangular lateral load distribution and the response of building, thus, is assumed to be controlled primarily by the first mode. While k equal 2 corresponds to a parabolic lateral load pattern with its vertex at the base in which the response is assumed to be influenced by higher mode effects. In UBC-97, k is a constant and equal to 1. However, for structures having fundamental period greater than 0.7 sec, the force at the top floor calculated from Equation (1) is increased by adding a concentrated force $F_t = 0.07TV$. In this case, the base shear V in Equation (1) is replaced by $(V - F_t)$. It should be noted that F_t needs not exceed $0.25V$ and may be considered as zero when the fundamental period of vibration is 0.7 sec or less. Finally for EuroCode-8, k is also a constant and equal to 1 for all period ranges. In fact, seismic lateral load in height of the structure according to EuroCode-8 is an inverted triangular pattern, which is identical to UBC-97, and IBC 2009 load patterns when fundamental period is less than or equal to 0.7 and 0.5, respectively. In the present study, besides the above three mentioned code-specified lateral strength and stiffness patterns, two more patterns including uniform and concentric patterns are also considered to investigate the effect of structural property distributions on strength demand and R_μ of MDOF soil-structure systems. Uniform and concentric patterns can be defined by considering exponent *k* equals and is close to zero and infinity, respectively. Note that in concentric pattern the total shear force is concentrated on the roof story. Figure 1 illustrates a comparison of all the above-mentioned lateral force and normalized shear strength patterns for a 10-story building with T = 1.5 sec. As mentioned earlier, lateral story stiffness is assumed as proportional to story shear strength distributed over the height of the structure.

3. Soil-structure model

Sub-structure method is used to model soil-structure system. Using the sub-structure method, the soil can be modeled separately and then combined to establish the soil-structure system. The soil-foundation element is modeled by an equivalent linear discrete model based on the cone model with earthquake frequency-independent coefficients and equivalent linear model (Wolf, 1994; Moghaddasi et al., 2011). Instead, since all analyses were carried out in time domain, it was dependent to the natural frequency of the system through an iteration method. Cone model based on the one-dimensional wave propagation theory represents circular rigid foundation with mass m_f and mass moment of inertia I_f resting on a homogeneous half-space. In lieu of the rigorous elastodynamic approach, the simplified cone model can be used with sufficient accuracy in engineering practice (Wolf, 1994).The typical 5-, 10- and 15-storty shear-building models of flexible-base systems used in this study are shown in Figure 2. The sway and rocking degrees of freedom are defined as representatives of translational and rotational motions of the shallow foundation, respectively, disregarding the slight effect of vertical and torsional motion. The stiffness and energy dissipation of the supporting soil are represented by springs and dashpot, respectively. In addition, while being hysteretic inherently, soil material damping is assumed as commonly used viscous damping so that more intricacies in time-domain analysis are avoided. All coefficients of springs and dashpots for sway and rocking used to define the soil-foundation model in Figure 2 are summarized as follows:

$$k_h = \frac{8\rho v_s^2 r}{2-\upsilon}, \qquad c_h = \rho v_s A_f \ , \tag{2}$$

$$k_\varphi = \frac{8\rho v_s^2 r^3}{3(1-\upsilon)}, \qquad c_\varphi = \rho v_p I_f \tag{3}$$

where k_h, c_h, k_φ and c_φ are sway stiffness, sway viscous damping, rocking stiffness, and rocking viscous damping, respectively. Equivalent radius and area of cylindrical foundation are denoted by r and A_f . Besides, ρ, υ, v_p and v_s are respectively the specific mass density, Poisson's ratio, dilatational and shear wave velocity of soil. To consider the soil material damping, ζ_0, in the soil-foundation element, each spring and dashpot is respectively augmented with an additional parallel connected dashpot and mass. Also, to modify the effect of soil incompressibility, an additional mass moment of inertia ΔM_φ equal to $0.3\pi(\upsilon - 1/3)\rho r^5$ can be added to the foundation for υ greater than 1/3 (Wolf, 1994). It is clear that the shear modulus of the soil will change with soil strain such that it decreases as soil strain increases. Thus, a reduced shear wave velocity which is compatible with the corresponding strain level in soil should be considered to incorporate soil nonlinearity. Incorporating soil nonlinearity to the soil-foundation element, however, may be approximated through conventional equivalent linear approach in which a degraded shear wave velocity, compatible with the estimated strain level in soil, is utilized for the soil medium (Moghaddasi *et al*., 2011). This is currently used in the modern seismic provision such as NEHRP 2000 (BSSC, 2000) and FEMA-440 (2005) where the strain level in soil is implicitly related to the peak ground acceleration (PGA). In the present study, by considering a range of reasonable values for dimensionless frequency, this point has been approximately incorporated.

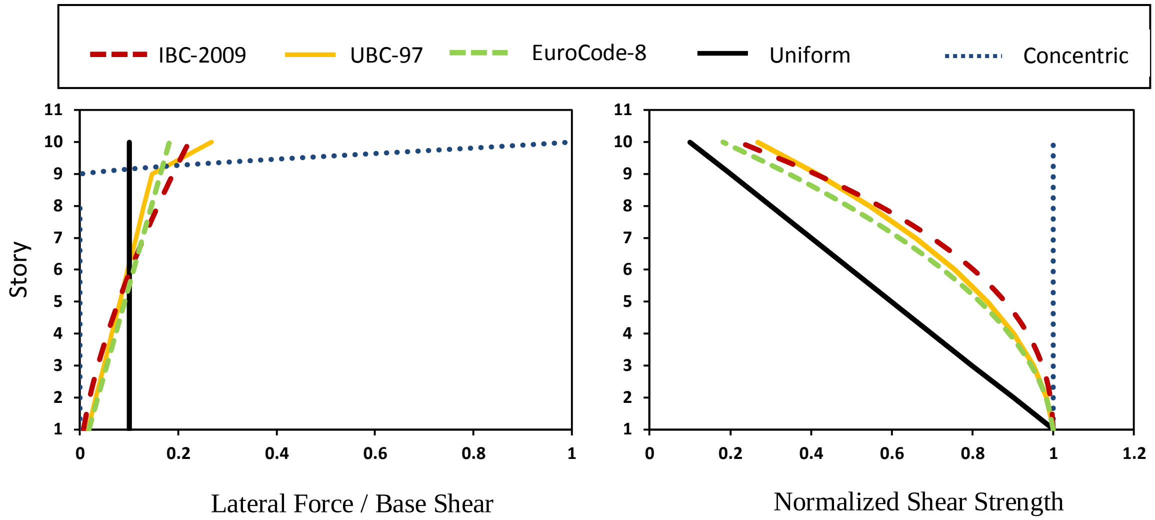

Figure 1: Different Lateral force and normalized shear strength patterns for a 10-story building with T_{fix} = 1.5 sec

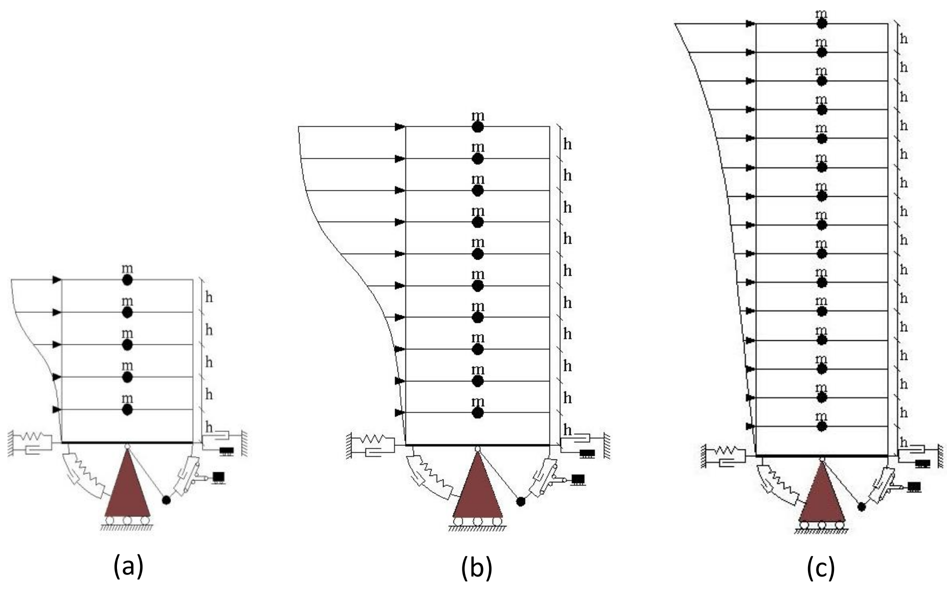

Figure 2: Typical MDOF soil-structure buildings used in this study: (a) 5-story building (b) 10-story building (c) 15 story building

4. Key parameters in soil-structure model

For a specific earthquake ground motion, the dynamic response of the structure can be interpreted based on the property of the superstructure relative to the soil beneath it. It has been shown that the effect of these factors can be best described by the following dimensionless parameters (Veletsos, 1977; Ghannad and Jahankhah, 2007):

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

$$a_0 = \frac{\omega_{fix}\bar{H}}{v_s} \tag{4}$$

where ω_{fix} is the natural frequency of the fixed-base structure. It can be shown that the practical range of a_0 for conventional building structures is from zero for the fixed-base structure to about 3 for the case with severe SSI effect (Ghannad and Jahankhah, 2007). Besides, $\bar{H}$ which is the effective height of structure corresponding to the fundamental mode properties of the MDOF building can be obtained from the following equation:

$$\bar{H} = \frac{\sum_{j=1}^{n}\left[m_j\varphi_{j1}\left(\sum_{i=1}^{j}h_i\right)\right]}{\sum_{j=1}^{n}m_j\varphi_{j1}} \tag{5}$$

where m_j is the mass of the *j*th story; h_i is the height from the base level to level *j;* and φ_{j1} is the amplitude at *j*th story of the first mode.

2. Aspect ratio of the building defined as $\bar{H}/r$, where *r* is the equivalent foundation radius.
3. Interstory displacement ductility demand of the structure defined as:

$$\mu = \frac{\delta_{\text{m}}}{\delta_y} \tag{6}$$

where δ_{m} and δ_{y} are the maximum interstory displacement demand resulted from a specific earthquake ground motion excitation and the yield interstory displacement corresponds to the structural stiffness of the same story, respectively. Note that for the MDOF building μ is referred to as the greatest value among all the story ductility ratios.

4. Structure-to-soil mass ratio defined as:

$$\bar{m} = \frac{m_{tot}}{\rho r^2 H} \tag{7}$$

where H and m_{tot} are the total height and mass of the structure, respectively.

5. Foundation-to-structure mass ratio defined as: m_f / m_{tot} , where m_f is the foundation mass.
6. Poisson's ratio of the soil denoted by υ .
7. Material damping ratios of the soil ζ_0 and the structure ζ_S .

The first two factors are usually considered as the key parameters which govern the main SSI effect. The third one controls the inelastic behavior of the structure. The other parameters, having less importance, may be set to some typical values for conventional buildings (Veletsos and Meek, 1974; Wolf, 1994; Mahsuli and Ghannad, 2009). In the present study, the foundation mass ratio is assumed to be 0.1 of the total mass of the MDOF buildings. The Poisson's ratio is considered to be 0.4 for the alluvium soil and 0.45 for the soft soil. Also, a damping ratio of 5% is assigned to the soil material.

5. Selected earthquake ground motions

In this investigation, an ensemble of 20 earthquake ground motions with different characteristics recorded on alluvium and soft soil deposits (soil type *C*, with shear wave velocity between 180 and 360 *m/s*, and *D*, with shear wave velocity lower than 180 *m/s*, based on the USGS site classification) are compiled and utilized in the nonlinear dynamic time history analyses. All selected ground motions are obtained from earthquakes with magnitude greater than 6 having closest distance to fault rupture more than 15 km without pulse type characteristics. The main characteristics of the selected ground motions are given in Table I. The ground motions were recorded on site with shear wave velocity between 90 and 350 m/sec.

6. Analysis procedure

The adopted soil-structure models introduced in the previous sections are used directly in the time domain nonlinear dynamic analysis. Step-by-step solution scheme in which dynamic imposed loads are incrementally applied to the model of the structure is utilized for all MDOF models. Variable load increments by considering events within steps are defined in order to control the equilibrium errors in each analysis step. An event is considered as any kind of state change that causes a change in the structural stiffness. To conduct parametric studies for both MDOF and SDOF systems with consideration of SSI effects subjected to a given earthquake ground motion, a computer program, "*OPTSSI"*, has been written specifically for this study. The software has the capabilities of computing many parameters such as elastic and inelastic strength demand, maximum drift, residual drift, strength reduction factors, MDOF modifying factor as well as optimization based on uniform damage distribution over the height of the structure. Many verification processes have been conducted, and the results have been compared with those generated by OPENSEES (2011). The accuracy of this program will be demonstrated in the next section.

A series of 5-, 10- and 15-story shear buildings are considered to investigate the effect of structural property distribution on strength demand and ductility reduction factor of MDOF soil-structure systems subjected to a group of earthquake ground motions recorded on alluvium and soft soils. In this regard, for a given earthquake ground motion, a large family of 21600 different MDOF soil-structure models including various predefined key parameters are considered. This includes MDOF models of three different number of stories (*N*= 5, 10, and 15) with 30 fundamental periods of fixed-base structures, ranging from 0.1 to 3 sec with intervals of 0.1, three values of aspect ratio ($\bar{H}/r$ =1, 3, 5), three values of dimensionless frequency (a_0 =1, 2, 3) as well as the corresponding fixed-base model, four values of target interstory displacement ductility ratio (μ_t = 1, 2, 4, 6) where μ_t =1 corresponds to the elastic state, and 5 different lateral strength and stiffness distribution patterns. It should be noted that the range of the fundamental period and aspect ratio, considered in the present study, are wider than those of the most practical structures. They are considered here, however, to cover all possible combinations of building structures of different number of stories. For each earthquake ground motion, strength demand and therefore ductility reduction factor for different patterns are computed by a proposed iterative procedure in order to reach the target ductility (μ_t) in the structure, as a part of the soil–structure system, within a 0.5% error. The procedures described above are summarized below:

1. Define the MDOF model depending on the prototype structure height and number of stories.
2. Assign an arbitrary value for total stiffness and strength and then distribute them along the height of the structure based on the presumed strength and stiffness pattern described in Section 2.2.
3. Select an earthquake ground motion listed in Table I.
4. Consider a presumed set of aspect ratio, $\bar{H}/r$, and dimensionless frequency, a_0, as the predefined key parameters for SSI effects.
5. Select the fundamental period of fixed-base structure and scale the total stiffness without altering the stiffness distribution pattern such that the structure has a specified target fundamental period.
6. Refine $\bar{H}/r$ based on the fundamental modal property of fixed-base MDOF structure as indicated in Eq. 5.
7. Select a target interstory-displacement ductility demand ratio for the MDOF soil-structure system.
8. Perform nonlinear dynamic analysis for the MDOF structure subjected to the selected ground motion and compute the total shear strength demand, as a part of the soil–structure system, within a 0.5% error

To calculate strength demands of MDOF systems, an iterative procedure were proposed by the authors (Ganjavi and Hao, 2011a) as follows:

$$(V_y)_{i+1} = (V_y)_i \, \mathrm{Re}l_\mu \tag{8}$$

where $(V_y)_i$ is the total base shear strength of MDOF system at *i*th iteration and $\mathrm{Re}l_\mu$ is defined as:

$$\mathrm{Re}l_\mu = \left(\frac{\mu_{\max}}{\mu_t}\right)^\beta \tag{9}$$

in which β is the iteration power larger than zero. Results of this study indicate that β for $\mu_t \leq 1$(elastic state) can be taken as a constant value for all MDOF and SDOF shear-building structures when subjected to any earthquake excitation. For $\mu_t > 1$ (Inelastic state), however, the β value is generally more dependent on the fundamental period and less on the level of inelasticity and earthquake excitation characteristics. It is found that for elastic shear-building models a very fast convergence, i.e. less than 5 iterations, can be obtained for β equal to 0.8. For Inelastic state ($\mu_t > 1$) β value, depending on the fundamental period, can be approximately defined as:

$$\begin{aligned} \beta &= 0.1 \qquad \mathrm{T_{fix}} \leq 0.5 \\ \beta &= 0.2 \qquad 0.5 < \mathrm{T_{fix}} < 1.5 \\ \beta &= 0.3 \qquad \mathrm{T_{fix}} > 1.5 \end{aligned} \tag{10}$$

9. Repeat steps 7–8 for different target ductility demand ratios.
10. Repeat steps 5–9 for different presumed target periods.
11. Repeat steps 4–10 for different sets of $\bar{H}/r$ and a_0.
12. Repeat steps 3–11 for different earthquake ground motions.
13. Repeat steps 1–12 for different number of stories.

7. Effect of structural property distribution on strength demand of MDOF systems

To study the effect of structural property distribution on strength demand of MDOF fixed-base and flexible-base buildings, systems of 5- and 15-story are considered. They are representatives of the common buildings of relatively low- and high-rise models. Results illustrated in Figures 3 and 4 are the mean response values from 20 earthquake ground motions for systems with $\bar{H}/r$ = 3, corresponding to three ductility ratios (μ_t = 1,2, 6) representing respectively elastic, low and high inelastic behaviours, and soil-structure system with dimensionless frequency 3, as well as the fixed-base structures. As stated before, a_0 is an index for the structure-to-soil stiffness ratio controlling the severity of SSI effects, and also the value of 3 for this parameter is representative of the system in which SSI effect is predominant for common building structures. The vertical axis in all figures is the averaged strength demands normalized by the total structural mass times PGA for each earthquake ground motion, and the horizontal axis is the fixed-base fundamental period of the structure. Based on the results presented in Figures 3 and 4, it can be observed that:

1. In elastic and low level inelastic response of both fixed-base and flexible-base low-rise buildings (i.e., 5-story building in Figure 3), with exception of short periods, there is a significant difference among the strength demand values of the structures designed in accordance to the different lateral strength and stiffness distribution patterns, especially for the case of uniform pattern which yields completely different strength demand. However, the results corresponding to IBC-2009 and UBC-97 are to some extent coincident.

2. In high level inelastic response of both fixed-base and flexible-base low-rise buildings, except for uniform pattern, the strength demand values corresponding to all patterns considered in this study are somewhat coincident and thus independent of the lateral story strength and stiffness pattern.
3. In the 15-story building (Figure 4) which represents high-rise buildings in this study, except for short periods, the difference among the results corresponding to the different patterns are more pronounced than those of the 5-story building for both fixed-base and flexible-base buildings. It can also be seen that even in the high level of inelasticity region, the differences among the results of UBC-97, EuroCode-8, IBC-2009 and the concentric patterns are very prominent for structures having long periods.
4. Different from those of low-rise buildings, except in the regions with short periods, there is a significant difference between the strength demand spectra of IBC-2009 and UBC-97 for both fixed-base and flexible-base 15-story buildings, especially in the longer period region. As an instance, for the case of severe SSI effect (i.e., a_0 =3) with fundamental period of 1.5 sec, the strength demand values of IBC-2009 pattern are respectively 33%, 24% and 46% greater than those of UBC-97 pattern for target ductility demands of 1, 2 and 6, respectively. This is because of the difference between the two code-specified load patterns which in turn reflect the effect of higher modes on high-rise buildings.
5. Generally, with exception of short period structures, EuroCode-8 pattern regardless of the level of inelastic response has the greatest strength demand values among the three code-specified strength and stiffness patterns for both fixed-base and flexible-base models. The concentric pattern, except in the short period region, has generally the least strength demand values among all the patterns considered in this study.

Figure 5 shows the effect of number of stories on the strength demand spectra of structures designed in accordance to the different strength and stiffness distribution patterns. Results provided are mean values of all earthquake ground motions listed in Table 1 for systems of 5-, 10- and 15-strory buildings with $\bar{H}/r$ =3, two ductility ratios (μ_t = 2, 6) as well as two values of dimensionless frequencies (a_0 =1, 3) and the fixed-base models. The vertical axis in all figures is the averaged ratio of strength demand in uniform pattern to that of the IBC-2009 pattern and the horizontal axis is the fundamental period of the corresponding fixed-base structure. As seen, in both the fixed-base and flexible-base models, with exception of very short periods, the ratios generally increase with the number of stories. The ratios are generally greater than 2 and even in some cases will reach to the value of 4. It is also obvious that these ratios for 10- and 15-story buildings are significantly larger than that of the 5-story building. This means that using the results of the uniform story strength and stiffness distribution pattern as has been commonly assumed in many previous research works would result in a significant overestimation of the strength demands, generally from 2 to 4 times, for MDOF systems designed in accordance to the code-compliant design patterns.

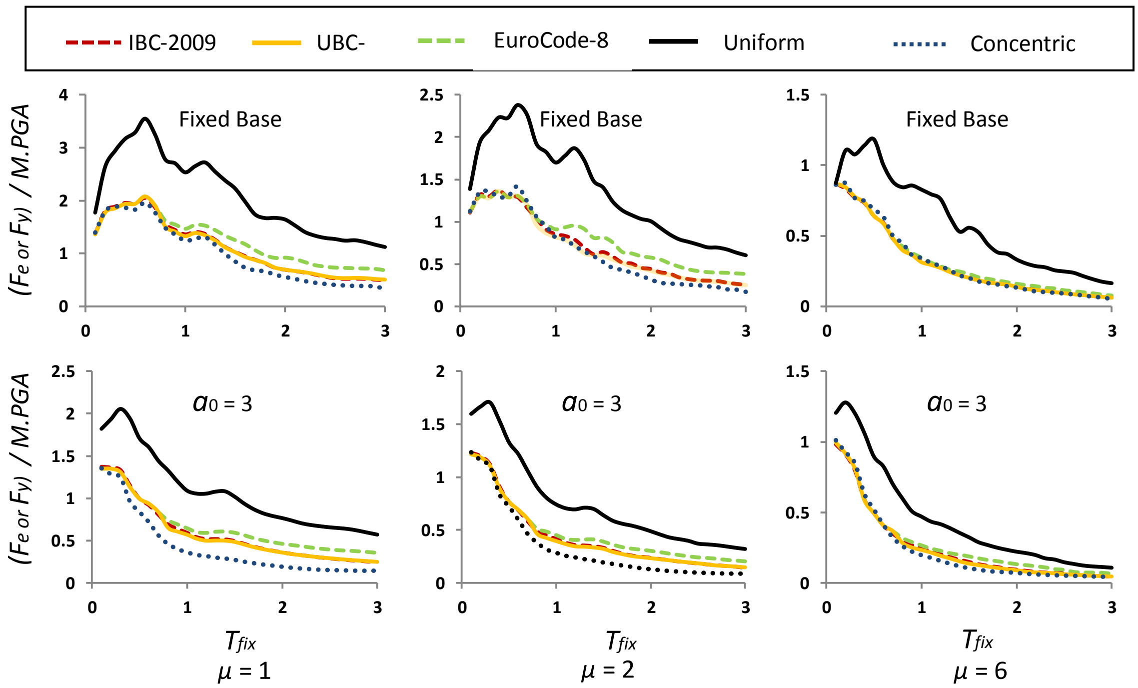

Figure 3: Effect of structural property distribution on strength demand for MDOF systems with N= 5 and $\bar{H}/r$ = 3

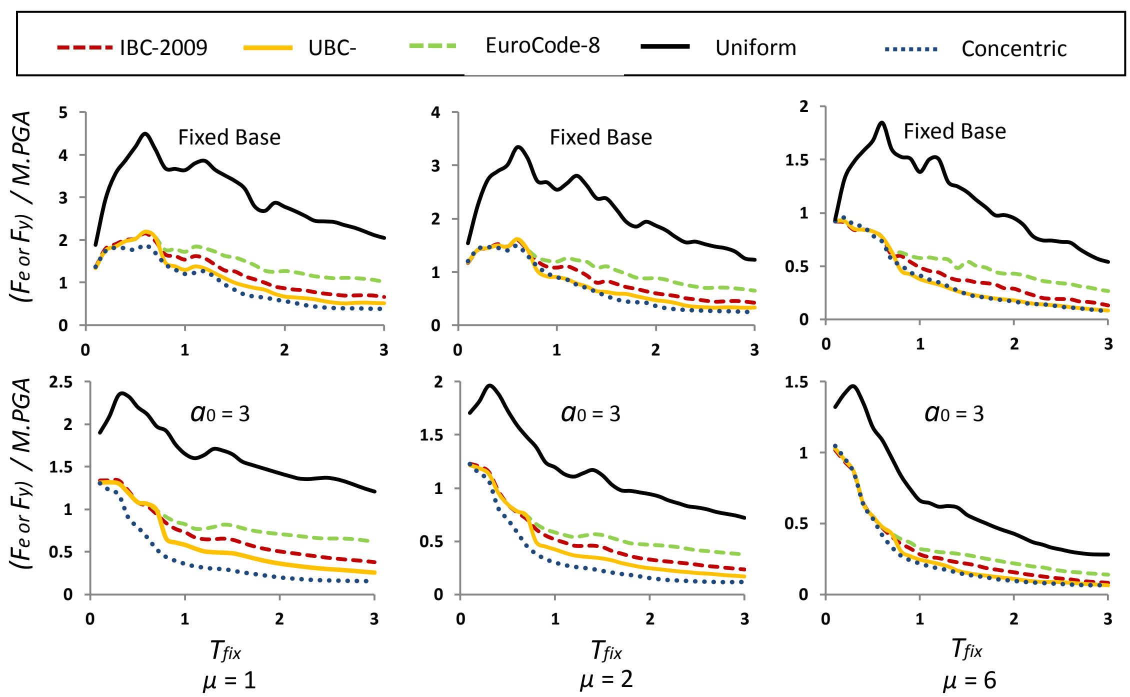

Figure 4: Effect of structural property distribution on strength demand for MDOF systems with N= 15 and $\bar{H}/r$ = 3

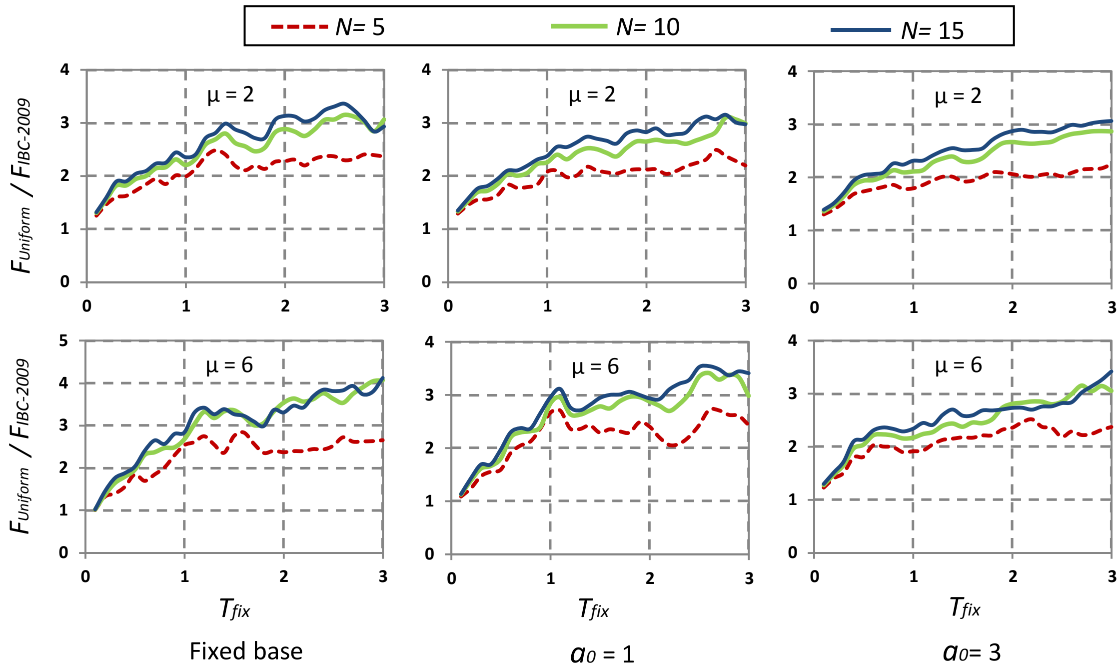

Figure 5: Averaged ratio of strength demand in uniform pattern to that of the IBC-2009 pattern for systems with $\bar{H}/r = 3$

8. A Comparison between strength demands of fixed-base and flexible-base shear-buildings

In this section, to study the effect of SSI on strength demands of MDOF systems designed in accordance to different strength and stiffness patterns the 10-story building is considered. The averaged ratios of the strength demands of soil-structure systems to those of the fixed-base systems for three different story strength and stiffness patterns, i.e., IBC-2009, EuroCode-8 and the uniform pattern, subjected to 20 ground motions are computed and the results are illustrated in Figure 6. Results are provided for systems with three values of aspect ratios ($\bar{H}/r$ =1, 3, 5) which respectively represent squat, medium and slender buildings, and with three values of ductility ratios (μ_t = 1, 2, 6) for the case of severe SSI effect (i.e., a_0 = 3). It can be observed that in elastic range of vibration, except for slender structures with very short periods in which strength demand values of soil-structure systems are nearly equal to those of the fixed-base ones, the strength demands of soil-structure systems are remarkably lower than those of the fixed-base models. This is compatible with the current seismic codes which are mainly based on the elastic behavior of structures. However, for inelastic response by increasing the level of inelastic behavior the strength demands of medium and slender soil-structure systems (i.e. $\bar{H}/r$ = 3, 5) with short periods of vibration are generally greater than those of the fixed-base systems. This trend becomes more pronounced for the case of slender buildings with high level of inelastic behavior, which is more obvious in structures designed in accordance to the uniform pattern. This finding is consistent with the results of SDOF systems investigated by Ghannad and Jahankhah (2007).It is also seen that the effect of aspect ratio on the strength demands of soil-structure systems with respect to the fixed-based models is reversed in long periods range; however, it is still less than unity. Figure 7 is also plotted to better show the effect of the three aforementioned strength patterns on the averaged ratios of strength demands of soil-structures systems to those of the fixed-base systems for slender buildings. The results are provided in the same format as Figure 6. It can be found that in the cases of elastic and low level inelastic response (μ_t = 1, 2) there is no significant difference between the results of three patterns while the difference is significant for the case with high level inelastic behavior (i.e., μ_t = 6).

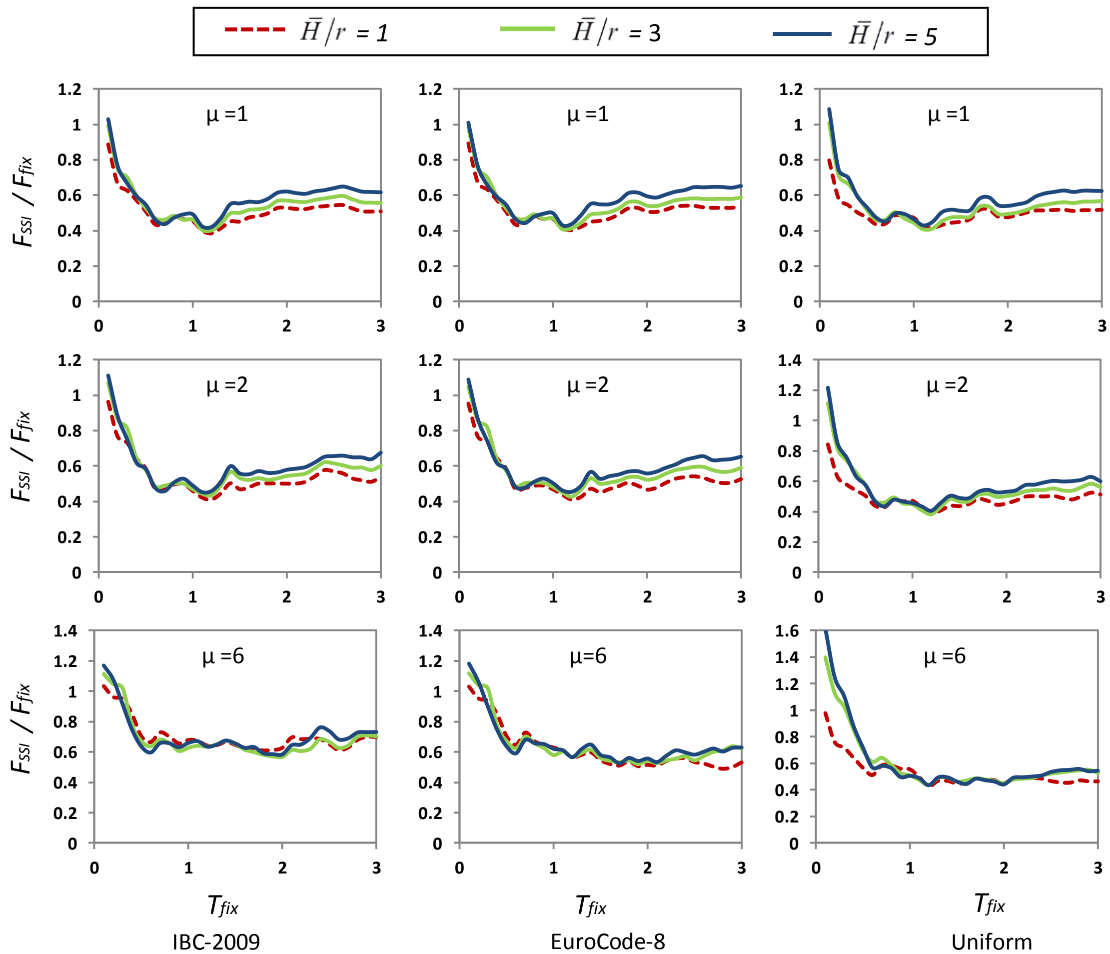

Figure 6: Averaged ratios of strength demands of soil-structures systems with respect to the fixed-base systems with different story strength and stiffness patterns (N= 10)

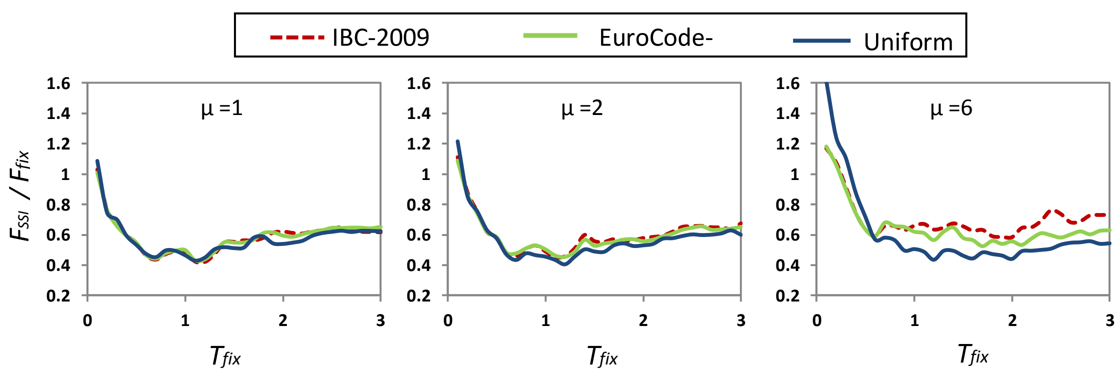

Figure 7: Effect of structural property distribution on averaged ratios of strength demands of soil-structure systems to the fixed-base systems for systems with N = 10 and $\bar{H}/r$ =5

9. Validation of the numerical results

In this section, to validate the accuracy of the numerical results of this study the 15-story building with $\bar{H}/r$ = 3, three ductility ratios (μ_t = 1, 2, 6) representing respectively elastic, low and high inelastic response corresponding to severe SSI effect (a_0 = 3) have been considered and analyzed using OPENSEES (2011). All the soil-structure systems considered here are designed in accordance to the IBC-2009 lateral load pattern. Figure 8 shows a comparison of the averaged strength demands of all earthquake ground motions. As seen, there are excellent agreement between the results obtained with the computer program developed for this study and OPENSEES for both elastic and inelastic ranges of response, demonstrating the accuracy of the developed computer program.

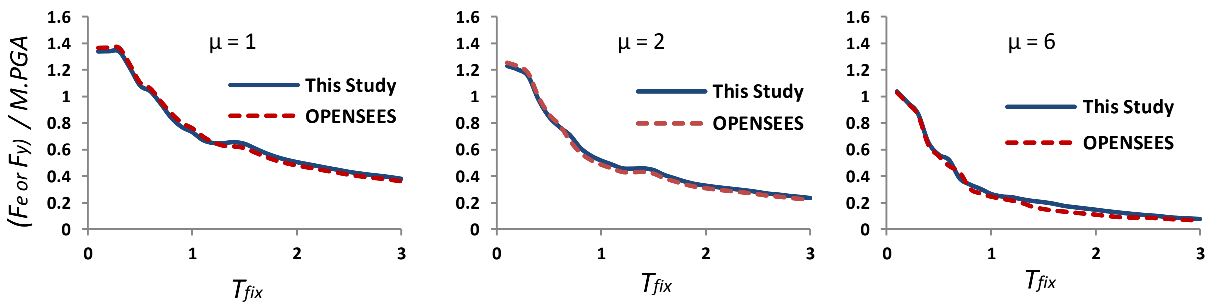

Figure 8: Comparisons of the averaged strength demands resulted from this study and OPENSEES for the 15-story building with a_0 = 3 (20 earthquakes)

10. Ductility reduction factor of MDOF soil-structure systems

In this part, effect of lateral strength and stiffness distributions on ductility (strength) reduction factor (R_μ) of MDOF systems are investigated. For an MDOF system R_μ is defined as:

$$R_\mu = \frac{F_{eMDOF}(\mu = \mu_i)}{F_{yMDOF}(\mu = \mu_i)} \tag{11}$$

where F_{eSDOF} and F_{yMDOF} are respectively elastic and inelastic strength demands of the MDOF system subjected to a given ground motion for presumed target ductility demand.

10.1. Effect of structural property distribution

To parametrically investigate the effect of presumed structural property distributions on ductility reduction factors (R_μ) of fixed-base and flexible-base buildings the 10-story building with $\bar{H}/r$ = 3, three ductility ratios (μ_t = 2, 4, 6), as well as soil-structure system with two dimensionless frequencies (a_0 = 1, 3), and the fixed-base structures is considered. The results illustrated in Figure 9 are the average values of responses to all the selected ground motions listed in Table 1. The vertical axis in all figures is the averaged ductility reduction factor and the horizontal axis is the fundamental vibration period of the respective fixed-base structure. Based on the results presented in Figure 9, it is seen that in both the fixed-base and flexible-base structures, by increasing the level of inelastic behavior, the difference between the results of different patterns increases. However, for the case of severe SSI effect (i.e., a_0 = 1, 3), except for the concentric pattern, there is no significant difference between the results of other patterns considered in this study for structures with short and medium periods. As an instance, for the case of severe SSI effect and with high level of inelastic behavior (μ_t = 6), the averaged values of R_μ for the structures designed in accordance to different story strength and stiffness patterns including concentric, UBC-97, EuroCode-8, IBC-2009 and uniform patterns are respectively 2.51, 3.94, 4.3, 4.6 and 4.9. As seen, for this case the most dispersion is associated to the concentric pattern. This trend has also been observed for models of 5- and 15- story buildings. Overall, it can be concluded that in low level of inelastic behavior, effect of story strength and stiffness distribution patterns on the values of R_μ is not significant and hence practically negligible for both the fixed-base and flexible-base models. Moreover, in all patterns considered here, generally, increasing the fundamental period of vibration is always accompanied by an increase in averaged value of R_μ. This trend is further intensified by increasing the inelastic range of vibration. Figure 10 shows the variation of the ratio of R_μ of different patterns with respect to that of the IBC-2009 pattern for the same 10-story building with two levels of ductility ratios (μ_t = 2, 6). Besides confirmation of the above observations, it may be concluded that generally for both the fixed-base and flexible-base models with low level of inelastic behavior there is no significant difference between the values of ductility reduction factor of the structures designed in accordance to the aforementioned code-compliant patterns. For the cases of fixed-base and less SSI-effect models (a_0 = 1), by increasing the level of inelastic behaviour this difference could become significant for some periods. This phenomenon, however, is negligible as SSI effect becomes more important.

10.2. Effect of soil flexibility

To study the effect of soil flexibility on force reduction factor of MDOF systems two models with 5 and 15 stories designed in accordance to IBC-2009 load pattern are considered. Results illustrated in Figure 11 are the mean values of responses from 20 earthquake ground motions for systems with $\bar{H}/r$ = 3, three ductility ratios (μ_t = 2, 4, 6), soil-structure systems with two dimensionless frequencies (a_0 = 1, 3), and the corresponding fixed-base structures. For the case of 5-strory building, it is seen that by increasing the inelastic behavior SSI effect on force reduction factor becomes more important such that increasing SSI effect is always accompanied by decreasing in value of R_μ. This finding is compatible with the results of the study carried out for SDOF systems by Ghannad and Jahankhah (2007). However, the results of 15-story building show that SSI effect decreases such that in low level inelastic response there is no prominent difference between the results of the fixed-base and soil-structure systems. By increasing the level of inelastic behavior, although the difference again increases, it is still to a large extent less than that of the 5-story building. Hence, it may be concluded that the results of SDOF soil-structure systems for force reduction factor may not be directly applicable to MDOF soil-structure systems, and some modifications such as those carried out for fixed-base systems should be taken into account for soil-structure systems as well. It should be mentioned that in some periods the mean R_μ in fixed-base and less SSI effect cases are equal or even less than those models with the severe SSI effect for the 15-story building. To have a better understanding of SSI effect on R_μ of MDOF systems another procedure is utilized here. First the elastic total shear strength for each soil-structure MDOF system is computed when subjected to a designated earthquake ground motion. Subsequently, using the same ductility reduction factor of MDOF fixed-base structure, the inelastic strength demand of the soil-structure system with presumed target ductility ratio is reduced and computed. Finally, each MDOF soil-structure system is again analyzed subjected to the same earthquake ground motion and the new ductility demand is calculated. The effect of SSI on force reduction factors of MDOF systems can then be examined by comparing the difference between the new resulted ductility demand and that of the target one. To investigate this phenomenon Figure 12 is illustrated. Results are plotted for 5-, 10- and 15-story buildings with severe SSI effect, $\bar{H}/r$ =3 and with high level of inelastic behaviour. As seen, using R_μ of Fixed-base MDOF systems for soil-structure systems will result in large values of ductility demand which in some cases are 3 times that of presumed target one. This phenomenon is less prominent as the number of stories increases but still significant at some periods.

10.3. Effect of aspect ratio

In order to examine the effect of aspect ratio on force reduction factor of MDOF-soil structure systems a 10-story building with three values of aspect ratio ($\bar{H}/r$ = 1, 3, 5) and with three ductility ratios (μ_t = 2, 4, 6) as well as two dimensionless frequencies (a_0 = 1, 3) is considered and analyzed subjected to the selected ground motions listed in Table 1. Figure 13 shows the average results for IBC-2009 load pattern. It is clear that for the case of less SSI effect, the values of averaged R_μ are insensitive to the variation of aspect ratio while for the case with severe SSI effect and high inelastic behavior, except in the short period range, the value of mean R_μ increases with the aspect ratio.

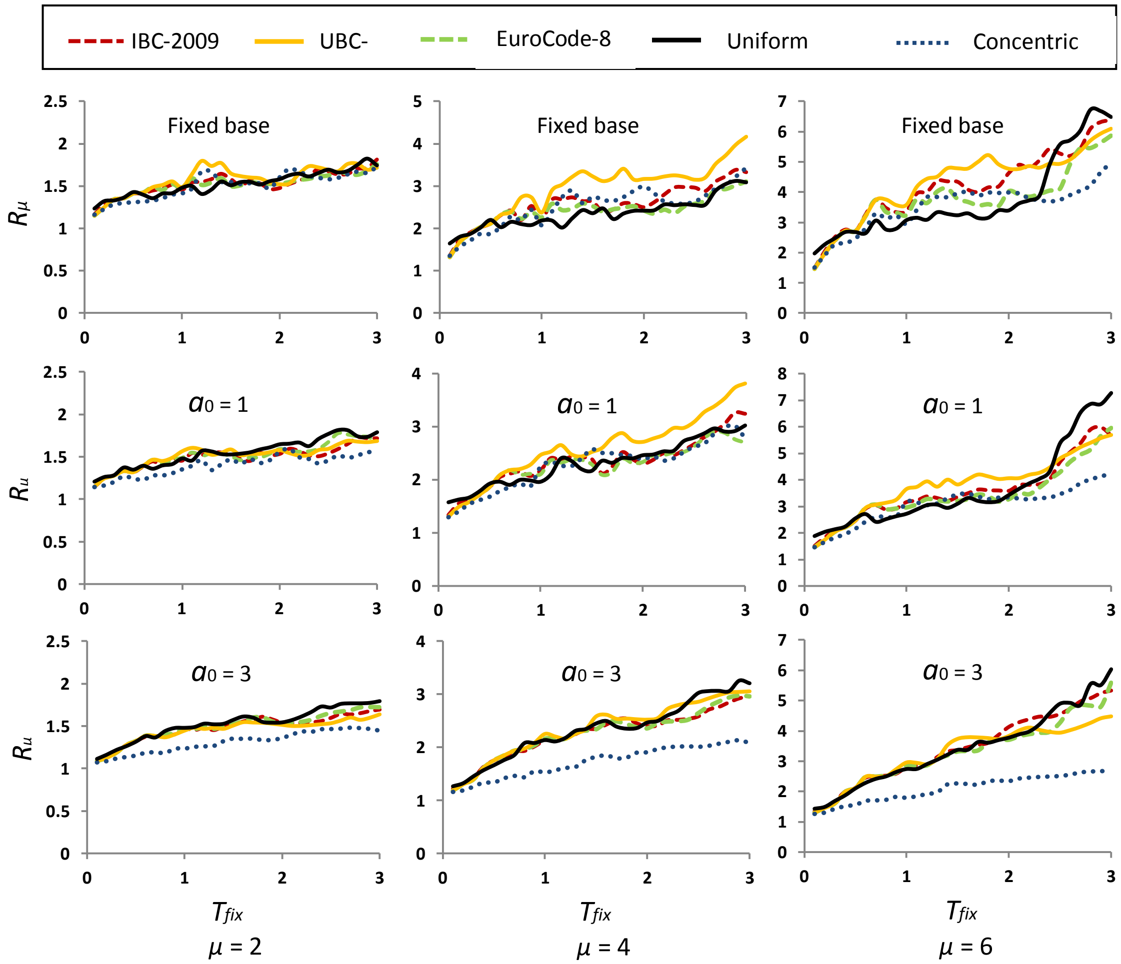

Figure 9: Effect of structural property distribution on averaged force reduction factor of fixed-base and soil-structure systems (N = 10 and $\bar{H}/r$ = 3)

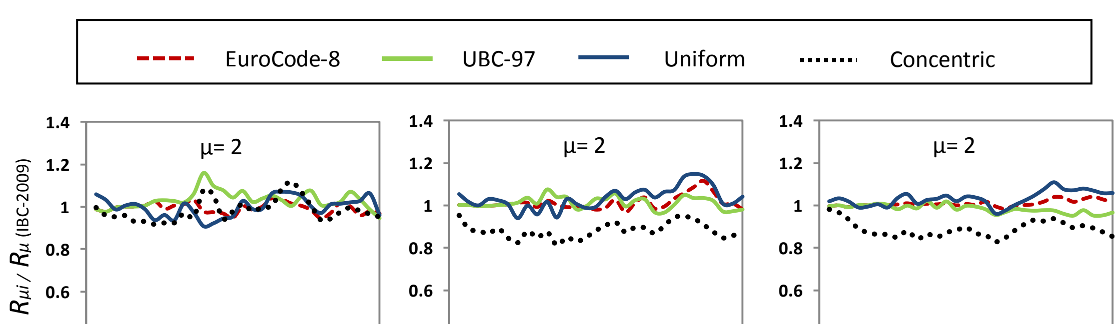

Figure 10: Comparison of the averaged ratios of force reduction factor of different load patterns to those of the IBC-2009 pattern for systems with N = 10 and $\bar{H}/r$ = 3

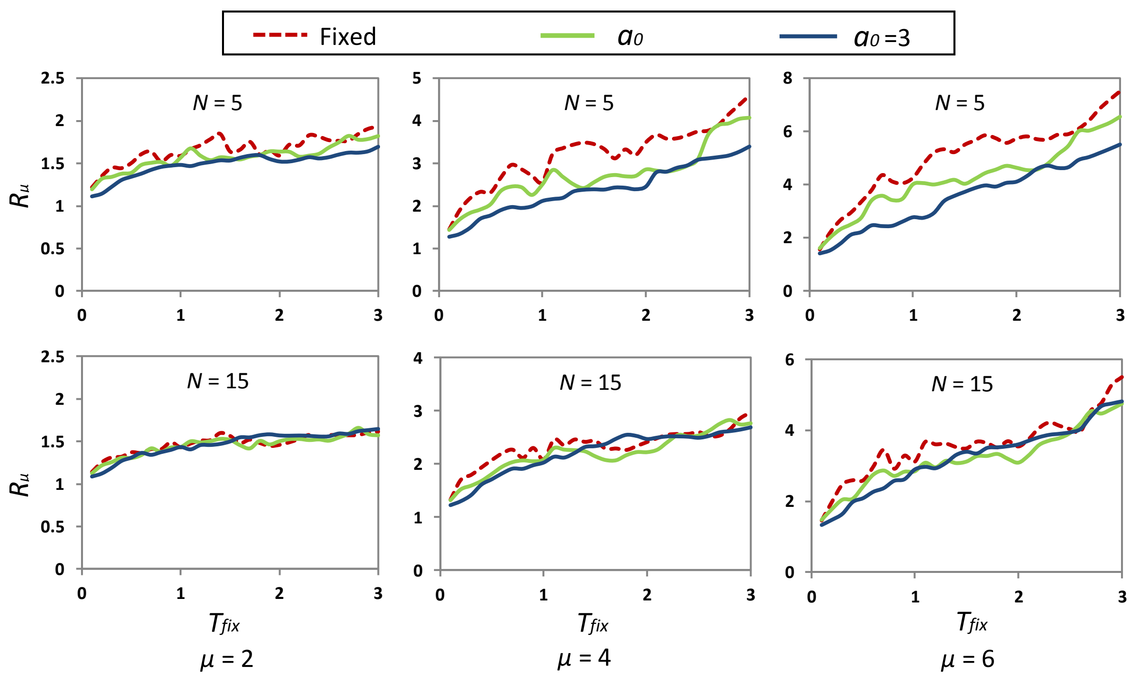

Figure 11: Effect of soil flexibility on averaged ductility reduction factor of MDOF systems ($\bar{H}/r$ = 3)

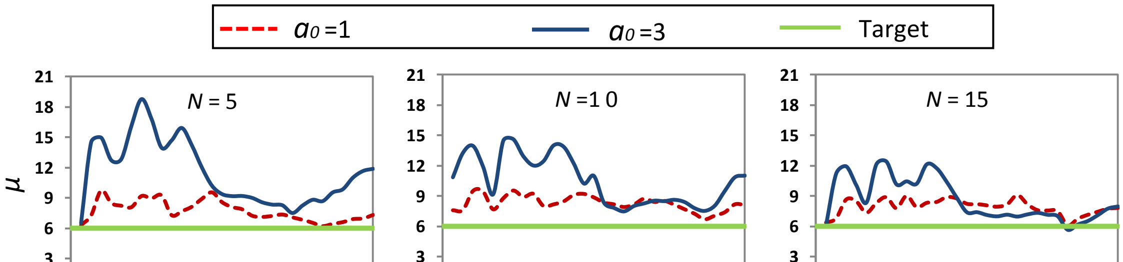

Figure 12: Averaged ductility demand spectra of MDOF soil-structure systems designed based on fixed-base force reduction factor ($\bar{H}/r$ = 3 and μ = 6)

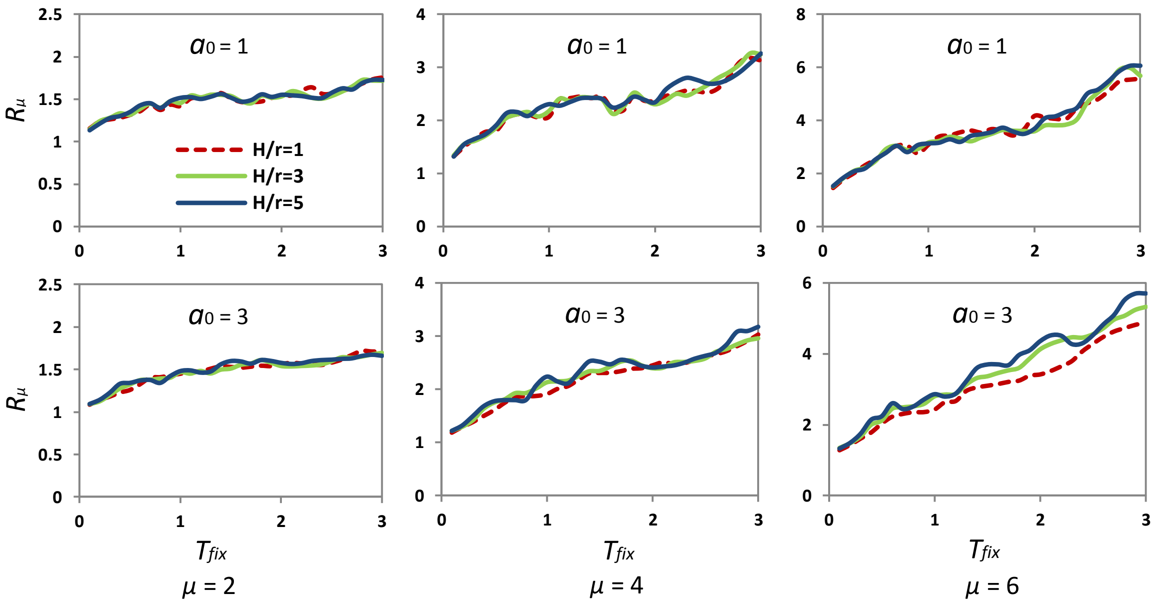

Figure 13: Effect of aspect ratio on averaged force reduction factor of MDOF soil-structure systems (N = 10)

10. Summary and Conclusion

An intensive parametric study has been performed to investigate the effect of different story strength and stiffness distribution patterns including three code-specified and two arbitrary patterns on strength demand and ductility reduction factor of MDOF fixed-base and soil-structure systems. In this regard, effect of many parameters including fundamental period, level of inelastic behavior, level of soil flexibility, and structure aspect ratio on strength demand and ductility reduction factor of MDOF systems subject to a large number of earthquake ground motions have been intensively investigated. The results of this study can be summarized to the following broad conclusions:

1. In elastic and low level inelastic response, both fixed-base and flexible-base low-rise buildings, with exception of those having short periods, show significant differences among the strength demand values of the structures designed in accordance to the different lateral strength and stiffness distribution patterns, especially for that obtained with the uniform pattern. However, the results of IBC-2009 and UBC-97 are to some extent coincident. In high level inelastic response, except for

uniform pattern, the results of all patterns are somewhat coincident and thus independent of the lateral story strength and stiffness pattern. However, by increasing the number of stories, differences among strength demand values of all patterns increase.

2. For both fixed-base and flexible-base models, with exception of those with very short periods, the averaged strength demand values of uniform pattern are significantly greater than those of the other patterns considered in this study. This phenomenon is even more pronounced by increasing the number of stories. The ratios of strength demand in uniform pattern to that of the IBC-2009 pattern are generally greater than 2 and in some cases will reach to the value of 4. Therefore, It can be concluded that using the results of the uniform story strength and stiffness distribution pattern which has been the assumption of many previous research works would result in a significant overestimation of the strength demands, generally from 2 to 4 times, for MDOF systems designed in accordance to the code-compliant design patterns.
3. In elastic range of vibration, except for slender structures with very short periods in which strength demand values of soil-structure systems are nearly equal to those of the fixed-base ones, the strength demands of soil-structure systems are remarkably lower than those of the fixed-base models. This is compatible with the current seismic-code regulation on SSI effects based on the elastic analysis. However, for inelastic state by increasing the level of inelastic response the strength demands of average and slender soil-structure systems with short periods of vibration are usually greater than those of the fixed-base systems. This trend is more significant for the case of slender buildings with high level of inelastic behavior, which is more obvious for the case of uniform pattern which have the strength demand values about 60% greater than those of the fixed-base models.
4. Overall, in low level of inelastic behavior, effect of story strength and stiffness distribution patterns on the values of R_μ is not significant and hence practically negligible for both fixed-base and flexible-base models. By increasing the level of inelastic behavior the difference between the results of different patterns increases. However, for the case of severe SSI, except for the concentric pattern which is the most different pattern from other patterns, the difference is insignificant for structures with short and intermediate periods.
5. A comparison between the mean results of force reduction factor of MDOF fixed-base and soil-structure systems shows that for the case of 5-strory building, SSI effect on R_μ becomes more significant with increasing inelastic response, and thus increasing SSI effect is always accompanied by decreasing the value of R_μ. This finding is compatible with the results of the study carried out for SDOF systems by Ghannad and Jahankhah (2007). However, by increasing the number of stories SSI effect decreases such that in low level of inelastic response there is no significant difference between the results of fixed-base and soil-structure systems. By increasing the level of inelastic response, although the difference again increases, it is still to a large extent less than that of the 5-story building. Hence, it may be concluded that the results of SDOF soil-structure systems for ductility reduction factor may not be directly applicable to MDOF soil-structure systems, and some modifications such as those carried out for fixed-base systems should be taken into account for soil-structures systems. It is also shown that using R_μ of MDOF Fixed-base systems for soil-structure systems when SSI effect is predominant will result in large values of ductility demand which in some cases are 3 times that of the presumed target one. This phenomenon is less prominent as the number of stories increases but still significant in some periods.
6. For the cases of insignificant SSI effect, the values of mean R_μ are nearly insensitive to the variation of aspect ratio. However, for the case of severe SSI with high inelastic response, except for those with short periods, the value of mean R_μ increases with the aspect ratio.

Table I. Selected ground motions recorded at alluvium and soft sites based on USGS site classification

Event	Year	Station	Distance (km)	Soil type (USGS)	*M*	*Component*	PGA (g)

Imperial Valley	1979	Cucapah	23.6	C	6.9	85	0.309
Imperial Valley	1979	El Centro Array #12	18.2	C	6.9	140	0.143
Loma Prieta	1989	Agnews State Hospital	28.2	C	7.1	0	0.172
Loma Prieta	1989	Gilroy Array #4	16.1	C	7.1	0	0.417
Loma Prieta	1989	Sunnyvale - Colton Ave	28.8	C	7.1	270	0.207
Northridge	1994	LA - Centinela St	30.9	C	6.7	155, 245	0.465, 0.322
Northridge	1994	Canoga Park - Topanga Can	15.8	C	6.7	196	0.42
Kobe	1995	Kakogawa	26.4	D	6.9	0, 90	0.251, 0.345
Kobe	1995	Shin-Osaka	15.5	D	6.9	0, 90	0.243, 0.212
Loma Prieta	1989	APEEL 2 - Redwood City	47.9	D	7.1	43	0.274
Loma Prieta	1989	Foster City - 355 Menhaden	51.2	D	7.1	360	0.116
Superstitn Hills(B)	1987	5062 Salton Sea Wildlife Refuge	27.1	D	6.6	315	0.167
Morgan Hill	1984	Gilroy Array #2	15.1	C	6.2	90	0.212
Northridge	1994	LA - N Faring Rd	23.9	C	6.7	0, 90	0.273, 0.242
Northridge	1994	LA - Fletcher Dr	29.5	C	6.7	144, 234	0.162, 0.24

Acknowledgments

The first author gratefully acknowledges the IPRS scholarship provided by The University of Western Australia and Australian Government towards a successful completion of the present work.

References

Anderson JC, Miranda E and Bertero VV (1991), Kajima Research Team. "Evaluation of the seismic performance of a thirty-story RC building," *UCB/EERC-91/16, Earthquake Engineering Research Center*, University of California, Berkeley.

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

AS-1170.4. (2007), *Structural design actions*: Earthquake actions in Australia.

Aviles J and Perez-Rocha L (2003), "Soil–structure interaction in yielding systems," *Earthquake Engineering and Structural Dynamics*, **32**(11): 1749–1771.

ASCE/SEI 7-05 (2005), *Minimum Design Loads for Buildings and Other Structures*. American Society of Civil Engineers: Reston, VA.

Aviles J and Perez-Rocha JL (2005), "Influence of foundation flexibility on R_{μ} and C_{μ} factors," *Journal of Structural Engineering* (ASCE) **131**(2): 221–230.

Aviles J and Perez-Rocha JL (2011), "Use of global ductility for design of structure–foundation systems," *Soil Dynamics and Earthquake Engineering* **31**(7): 1018–1026.

Barcena A and Esteva L (2007), "Influence of dynamic soil–structure interaction on the nonlinear response and seismic reliability of multistory systems," *Earthquake Engineering and Structural Dynamics* **36**(3): 327-346.

Bielak J (1978), "Dynamic response of non-linear building–foundation systems," *Earthquake Engineering and Structural Dynamics*, **6**(1): 17–30.

Building Seismic Safety Council (BSSC), (2000) *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures,* Federal Emergency Management Agency, Washington, DC

Building Seismic Safety Council (BSSC) (2003), National Earthquake Hazard Reduction Program (NEHRP) Recommended Provisions for Seismic Regulations for 348 New Buildings and Other Structures—Part 2: Commentary (FEMA 450-2). *Federal Emergency Management Agency*, Washington, D. C.

CEN (2003), EuroCode 8: Final draft of EuroCode 8: Design of structure for earthquake resistance – Part 1: General rules for buildings. Bruxelles: European Committee for Standardization.

Chopra AK and Gutierrez JA (1974), "Earthquake response analysis of multistory buildings including foundation interaction," *Earthquake Engineering and Structural Dynamics* **3**(1): 65–77.

Chopra AK (1995), *Dynamics of Structures- Theory and Applications to Earthquake Engineering*, 1st edition, Prentice Hall, Englewood Cliffs, New Jersey.

Chouw N and Hao H (2005), " Study of SSI and non-uniform ground motion effect on pounding between bridge girders," *Soil Dynamics and Earthquake Engineering* **25**:717–728.

Chouw N and Hao H (2008), "Significance of SSI and non-uniform near-fault ground motions in bridge response I: effect on response with conventional expansion joint," *Engineering Structures* **30**(1):141–153.

FEMA 440 (2005), "Improvement of nonlinear static seismic analysis procedures," *Report No. FEMA 440, Federal Emergency Management Agency*, prepared by Applied Technology Council.

Ganjavi B. and Hao H (2011a), "Elastic and Inelastic Response of Single- and Multi-Degree-of-Freedom Systems Considering Soil Structure Interaction Effects," *Australian Earthquake Engineering Society Conference*, Barossa Valley, South Australia.

Ganjavi B and Hao H (2011b), "Evaluation of the Adequacy of Code Equivalent Lateral Load Pattern and Ductility Demand Distribution for Soil-Structure Systems," *Australian Earthquake Engineering Society Conference*, Barossa Valley, South Australia.

Ghannad MA And Jahankhah H (2007), "Site dependent strength reduction factors for soil–structure systems," *Soil Dynamics and Earthquake Engineering* **27**(2): 99–110.

Gilmore TA and Bertero VV (1993), "Seismic performance of a 30-story building located on soft soil and designed according to UBC 1991". *UCB/EERC-93/04*. Earthquake Engineering Research Center, University of California, Berkeley.

Hajirasouliha I and Moghaddam, H (2009), "New lateral force distribution for seismic design of structures," *Journal of Structural Engineering (ASCE)* **135**(8): 906–915.

Halabian AM, Erfani M. 2010. The effect of foundation flexibility and structural strength on response reduction factor of RC frame structures. *The Structural Design of Tall and Special Buildings* doi: 10.1002/tal.654

Halabian A and Kabiri S (2011), "Effect of foundation flexibility on ductility reduction factors for R/C stack-like structures," *Earthquake Engineering and Engineering Vibration* **10**(2): 277-290.

International Code Council (ICC) (2009), *International Building Code*, ICC, Birmingham, AL.

Jennings PC and Bielak J (1973), "Dynamics of buildings–soil interaction," *Bulletin of Seismological Society of America* **63**(1): 9–48.

Mohammadi R, K., El-Naggar M.H and Moghaddam H (2004) "Optimum strength distribution for seismic resistant shear buildings," *International Journal of Solids and Structures* **41**: 6597–6612.

Khodabakhshi P, Jahankha H and Ghannad MA (2011), "A discrete model for response estimation of soil-structure systems with embedded foundations," *Earthquake Engineering and Engineering Vibration* **10**(2): 263-276.

Leelataviwat S, Goel SC and Stojadinovic´ B (1999), "Toward performance-based seismic design of structures," *Earthquake Spectra* **15:** 435–461.

Mahsuli M and Ghannad MA (2009) "The effect of foundation embedment on inelastic response of structures" *Earthquake Engineering and Structural Dynamics* **38**(4): 423–437.

Mexico City Building Code (2003).

Mobasseri M, Roesset JM and Klingner RE (1992) "The relation between local and overall ductility demands in multi-degree-of-freedom frmaed type structures," *The 10th World Conference on Earthquake Engineering,* Madrid, Spain, Vol. 1 pp. 849-858.

Moghaddam H and Hajirasouliha I (2006), "Toward more rational criteria for determination of design earthquake forces," *International Journal of Solids and Structures* **43**(9): 2631–2645.

Moghaddasi M, Cubrinovski M, Chase JG, Pampanin S, and Carr A (2011) “Probabilistic evaluation of soil–foundation–structure interaction effects on seismic structural response,” *Earthquake Engineering and Structural Dynamics* **40**(2): 135–154.

Muller FP and Keintzel E (1982), “Ductility requirements for flexibly supported anti-seismic structures,” *Proceedings of the Seventh European Conference on Earthquake Engineering*, Athens, Greece, Vol. 3, 20–25 September, 27–34

OPENSEES, (2011)., *OpenSees Command Language Manual.* Open System for Earthquake Engineering Simulation. Mazzoni, S., McKenna, F., Scott. M. H., Fenves, G. L. Available at http://opensees.berkeley.edu/.

Srivastav S and Nau JM (1988), “Seismic analysis of elastoplastic MDOF structures,” *ASCE Journal of Structural Engineering*, **1114**(6): 1339-1353.

UBC (1994), Uniform Building Code, *International Conference of Building Officials*, Whittier, California.

UBC (1997), Uniform Building Code, *International Conference of Building Officials*, Whittier, California.

Veletsos AS and Vann P (1971) “Response of ground-excited elastoplastic systems,” *Journal of the Structural Division*, (ASCE) **97**(4): 1257-1281.

Veletsos AS and Meek JW (1974), “Dynamic behavior of building–foundation system,” *Earthquake Engineering and Structural Dynamics* **3**(2): 121–138.

Veletsos AS and Verbic B (1974), “Dynamic of elastic and yielding structure-foundation systems,” *Proceedings of the 5th world conference on Earthquake Engineering* Rome.

Veletsos AS and Nair VVD (1975) ”Seismic interaction of structures on hysteretic foundations,” *Journal of the Structural Division (ASCE)* **101**(1): 109–129.

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

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