



Evaluation of the Adequacy of Code Equivalent Lateral Load Pattern and Ductility Demand Distribution for Soil-Structure Systems

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Abstract

Soil-structure interaction (SSI) of structures located on alluvium and soft soils during an earthquake shaking is inevitable. The current code-compliant equivalent lateral load patterns are based on the elastic behavior of fixed-base structure without considering soil-structure interaction (SSI) effects. As a result, the implementation of such a load pattern in seismic design of soil-structure systems may not be appropriate when compared to the fixed-base ones. This paper performs intensive parametric analyses of 5760 shear buildings with SSI subjected to a group of 30 earthquakes recorded on alluvium and soft soils to investigate the effect of SSI on distributions of ductility demands along the building height. In addition, the adequacy of IBC-2009 code-complaint lateral loading patterns which is similar to that of Australian seismic code is parametrically investigated for soil-structure systems. Results indicate that using the code-specified load pattern leads to nearly uniform ductility demands distribution for structures within the elastic range of behaviour. For structures with longer periods, however, it loses its efficiency as the number of stories and soil flexibility increase. In inelastic range, the seismic performance (i.e., uniformity of ductility demand distribution) of the structures is significantly reduced even in short period, and this reduction is more intensified by increasing the inelastic response level and SSI effects.

Keywords: Soil-Structure Interaction; shear building; Ductility demand distribution; Inelastic behavior; Seismic code

1. Introduction

The equivalent lateral load patterns along the height of structures from various seismic code 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) depends only on the fundamental period of the structures and their mass. These load distribution patterns are based primarily on elastic dynamic analysis of fixed-base structures without considering soil-structure interaction (SSI). For example, in the United States, the current seismic design procedures are mainly based on the NEHRP Provisions published in 2003 (BSSC, 2003). The seismic design criteria in ASCE/SEI 7-05 (ASCE, 2005), which is exclusively based on the NEHRP 2003, is adopted in IBC 2009 (ICC, 2009). The seismic lateral load patterns in all aforementioned provisions are based on the assumption that the soil beneath the structure is rigid, and hence no separate load pattern accounting for SSI effects is considered. 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 designed according to 1994 Uniform Building Code (UBC 94) loading pattern with elastoplastic behavior subjected to the 1940 El Centro Earthquake. It was concluded that utilizing this load pattern does not lead to equal ductility demand in all stories, and that generally the maximum ductility demands occurs in the first story. Leelataviwat et al. (1999) evaluated the seismic demands of mid-rise moment-resisting frames designed in accordance to UBC 94. They proposed improved load patterns using the concept of energy balance applied to moment-resisting frames with a pre-selected yield mechanism. In a more comprehensive research, Karami Mohammadi *et al.* (2004) investigated the effect of lateral load patterns specified by United States seismic codes on drift and ductility demands of fixed-base shear building structures under 21 earthquake ground motions, and found that using the code-specified design load patterns does not lead to a uniform distribution and minimum ductility demands. In another study, Moghaddam and Hajirasouliha (2006), based on the nonlinear dynamic analyses on fixed-base shear building models subjected to 20 earthquake ground motions recorded on alluvium soil, proposed a new lateral load pattern as a function of the fundamental period of the structure and target ductility. Ganjavi et al. (2008) investigated the effect of equivalent static and spectral dynamic lateral load patterns specified by the governing seismic codes on height-wise distribution of drift, hysteretic energy and damage subjected to severe earthquakes in fixed-base reinforced concrete buildings. They concluded that in strong ground motions, none of the lateral loading patterns will lead to uniform distribution of drift, hysteretic energy and damage, and an intense concentration of the values of these parameters can be observed in one or two stories especially in equivalent static method. More recently, several studies have been conducted by researchers to evaluate and improve the code-specified design lateral load patterns based on the inelastic behavior of the structures (Park and Medina, (2007); Hajirasouliha et al., 2009; Goel et al., 2010). However, all researches have been concentrated on the different types of structures with rigid foundation, i.e., without considering SSI effects. In recent years, many studies have been made by researchers to investigate the SSI effects on inelastic behavior of structures (Aviles and Perez-Rocha, 2005; Ghannad and Jahankhah, 2007; Moghaddasi *et al.*, 2011). However, most of them 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 Dutta et al. (2004), Barcena and Steva (2007), Chouw and Hao (2005) and Tang and Zhang (2011). However, the lack of clarity in SSI effects on seismic demands of MDOF systems deserves special attention. Here, in this paper an intensive study has been performed to investigate the effect of inertial SSI on height-wise distribution of ductility demand in shear-building structures with different structural properties, with emphasis on code-specified-seismic design load pattern, using simplified soil-structure model for surface foundation in which the kinematic interaction is zero. This is carried out for a wide range of structural models and non-dimensional parameters to investigate the role of SSI on seismic demands distribution along the height of the MDOF building structures.

2. Soil-structure model

Due to its simplicity and capability to consider higher modal effects, the well-known shear-beam model is indeed one of the most frequently used models that facilitate performing a comprehensive parametric study (Karami et al., 2004; Moghaddam and Hajirasouliha, 2006). 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 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. However, the effect of different post yield behavior is also investigated. This model is selected to represent the behavior of non-deteriorating steel-framed structures of different heights. In all MDOF models, lateral story stiffness is assumed as proportional to story shear strength distributed over the height of the structure, which is obtained in accordance to the different lateral load patterns (Karami et al., 2004). Five percent Rayleigh

damping was assigned to the first mode and the mode in which the cumulative mass participation was at least 95%. 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 frequency-independent coefficients and equivalent linear model (Wolf, 1994; Moghaddasi et al., 2011). A typical 10-story shear-building model of flexible-base system used in this study is shown in Fig. 1. The sway and rocking degrees of freedom are defined as representatives of translational and rotational motions of the 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. 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. 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.

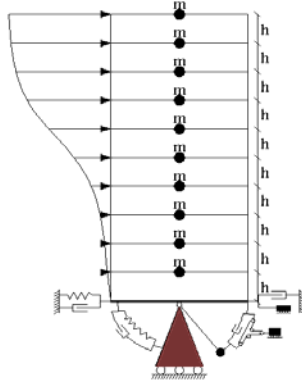


Fig. 1. Typical 10-story shear building model located on flexible soil

3. Key parameters in soil-structure model

It is well known that the response of the soil-structure system essentially depends on the size of structure, dynamic characteristics of the soil and structure, the soil profile as well as the applied excitation. In other words, for a specific earthquake ground motion, the dynamic response of the structure can be interpreted based on the properties 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 (Ghannad and Jahankhah, 2007):

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

$$a_0 = \frac{\omega_{fix} \bar{H}}{v_s} \quad (3)$$

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:

$$\bar{H} = \frac{\sum_{j=1}^n \left[m_j \varphi_{j1} \left(\sum_{i=1}^j h_i \right) \right]}{\sum_{j=1}^n m_j \varphi_{j1}} \quad (4)$$

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:

$$\mu = \frac{\delta_m}{\delta_y} \quad (5)$$

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:

$$\bar{m} = \frac{m_{tot}}{\rho r^2 H} \quad (6)$$

where H is total height of the structure.

5. Foundation-to-structure mass ratio m_f / m_{tot} .
6. Poisson's ratio of the soil denoted by ν .
7. Material damping ratios of the soil ζ_0 and that of the structure ζ_s .

The first two factors, participating within higher powers in the equation of motion, are usually considered as the key parameters which define 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 (Wolf, 1994; Ghannad and Jahankhah, 2007). 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.

4. Procedure for analysis

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. A series of 5-, 10-, 15- and 20-story shear buildings are considered to investigate the effect of SSI on height-wise distribution of ductility demand in shear-building structures with different structural properties. In this regard, for a given earthquake ground motion, a family of 5760 different MDOF soil-structure models including various predefined key parameters are considered. This includes MDOF models of four different number of stories ($N= 5, 10, 15$ and 20) 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 fixed-base model, four values of

target interstory displacement ductility ratio ($\mu_i = 1, 2, 4, 6$) where $\mu_i = 1$ corresponds to the elastic state. 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 conditions and to compare the results obtained from MDOF systems of different number of stories with each other. For each earthquake ground motion, ductility demand distribution pattern along the height of the structure are computed in order to reach the μ_i in the structure, as a part of the soil-structure system, within a 0.5% error.

5. Evaluation of ductility demand distribution in MDOF soil-structure systems

5.1. Effect of number of stories

To study the effect of number of stories on height-wise distribution of ductility demand in fixed-base and flexible-base shear buildings, systems of 5-, 10, 15 and 20-stories are considered, which represents the common low- to high-rise building structures. Fig. 2 shows the mean values of responses from 30 earthquake ground motions for systems with $\bar{H}/r = 3$, $T_{fix} = 1$ sec, and with three ductility ratios ($\mu_i = 2, 6$) representing respectively the low and high inelastic behaviours, and two dimensionless frequencies ($a_0 = 1, 3$) in comparison with the fixed-base structures. The abscissa in all figures is the averaged ductility demands and the vertical axis is relative height of the structure. The results generally exhibit a same trend for all MDOF buildings with different number of stories such that the maximum ductility demand usually happens in the top story (roof). It can be seen that, however, as the number of stories increases, height-wise distribution of the ductility demand becomes more non-uniform, which can show the significance of higher-mode effects on height-wise distribution of seismic demands. This trend is intensified for the case of higher inelastic behavior for both fixed-base and flexible-base systems. Therefore, it may be concluded that IBC-2009 code specified load pattern which is based on elastic fixed-base structures may not effectively incorporate higher-mode effect. It is also worth mentioning that even for low level of inelastic behaviour the ductility demands distributions become more non-uniform when SSI effect becomes predominant ($a_0 = 3$), which will be discussed in details in the next sections.

5.2. Effect of aspect ratio and dimensionless frequency

Fig. 3 is illustrated to show the effect of aspect ratio and dimensionless on averaged ductility demand distribution along the height of the soil-structure systems. As stated before, aspect ratio and dimensionless frequency are two of key parameters that can affect the response of the soil-structure systems subjected to earthquake excitation. The results are plotted for a 10-story shear building with fundamental period of 1sec, and for three target ductility demands ($\mu_i = 1, 2, 6$), three values of aspect ratio ($\bar{H}/r = 1, 3, 5$), representing squat, average and slender building and for three values of dimensionless frequency ($a_0 = 1, 2, 3$) as well as the corresponding fixed-base model. It can be observed that SSI effect will become more significant as the aspect ratio increases, i.e., for the case of slender building. The trend is less intensified as the level of inelasticity increases but still significant leading to more non-uniform distribution of ductility demand along the height of the structure with respect to the corresponding fixed-base model.

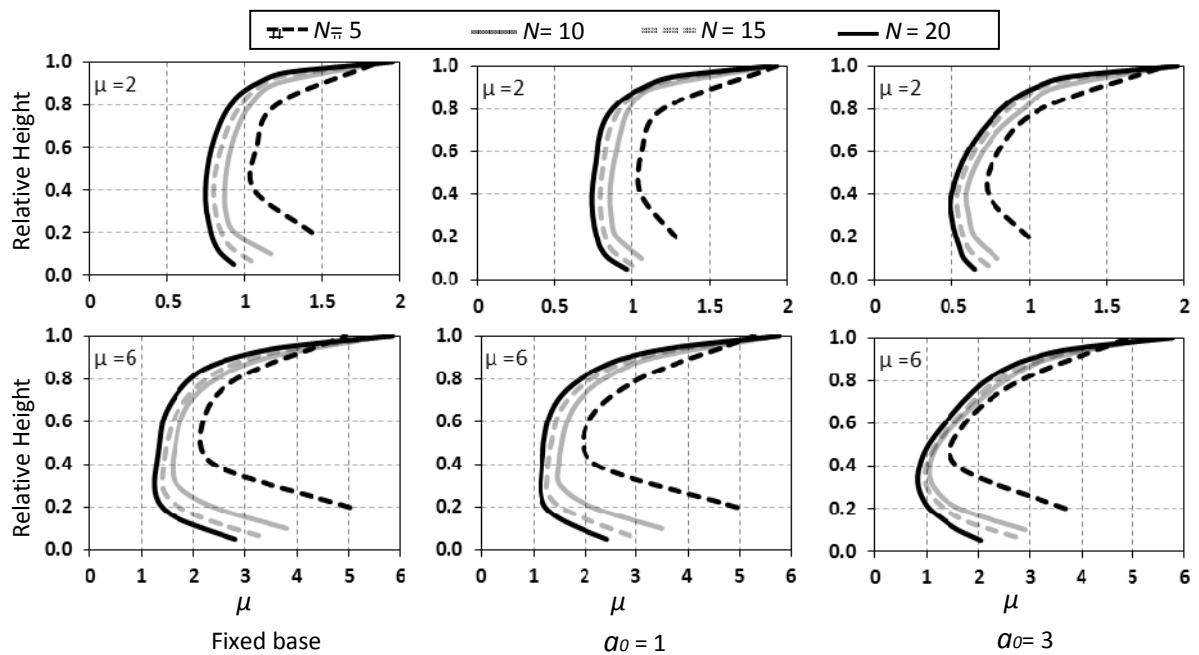


Fig. 2. Effect of number of stories on averaged ductility demand distribution for systems with $T_{fix} = 1$ and $\bar{H}/r = 3$

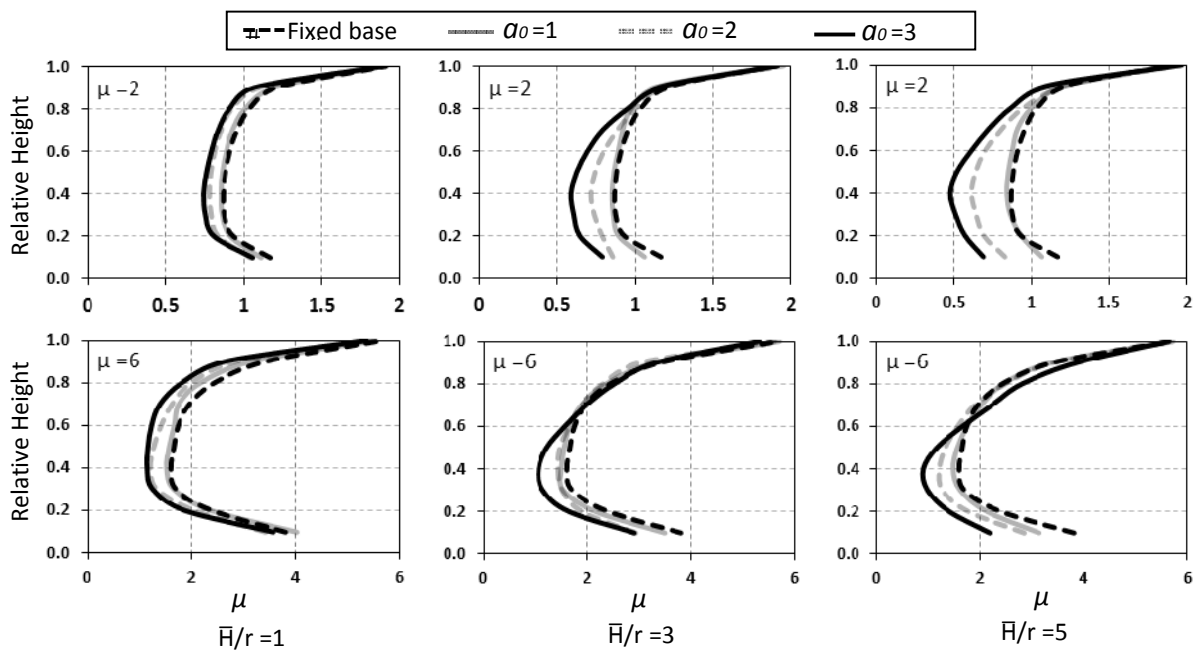


Fig. 3. Effect of aspect ratio and dimensionless frequency on averaged ductility demand distribution for systems with $N = 10$ and $T_{fix} = 1$

6. Adequacy of IBC-2009 code-specified loading pattern

It is believed that the the coefficient of variation (COV) of ductility demand distribution could be used as a means of assessing the adequacy of design load patterns to optimum use of material (Karami et al., 2004). Hence, the more uniform the ductility demand distribution, the better is the seismic performance. The COV is a statistical measure of the dispersion of data points, here ductility demand ratio along the

building height. It is defined as the ratio of the ductility demand standard deviation to the mean ductility demand among all stories. To investigate the efficiency of IBC-2009 loading patterns in seismic performance of the soil-structure systems in comparison to the fixed-base one, 5-, 10-, 15 and 20-story shear-building models with 30 fundamental periods, 4 ductility demands ($\mu_i = 1, 2, 4, 6$), 3 dimensionless frequencies ($a_0 = 1, 2, 3$) and 3 aspect ratios ($\bar{H}/r = 1, 3, 5$) are subjected to 30 selected ground motions. In each case, shear strength and stiffness are distributed along the stories according to IBC-2009 code-specified load pattern. The total structural stiffness then is scaled to adjust the presumed fixed-base fundamental period. With an iterative procedure, without altering the stiffness and strength distribution pattern, the total shear strength of the structure is scaled until the target ductility ratio is resulted with less than 0.5% error. Consequently, COV of the story ductility demands can be calculated for each case.

6.1. Effect of number of stories and target ductility demand

Effect of number of stories on COV of story ductility demands in flexible-base structures designed according to the IBC-2009 load pattern is presented in Fig. 4. Results are provided as mean values of 30 earthquake ground motions for systems with $\bar{H}/r = 3$, and with three ductility ratios ($\mu_i = 1, 2, 6$) as well as for dimensionless frequency of 2. The vertical axis in all figures is the averaged COV of story ductility demands and the horizontal axis is the fixed-base fundamental period of the structure. It can be seen that regardless of the number of stories, using IBC-2009 load pattern leads to nearly uniform ductility demands distribution for the structure with short periods within the elastic range of behaviour. For the longer periods i.e., $T_{fix} > 0.4$ sec, however, the efficiency of the IBC-2009 load pattern is reduced as the number of stories and fundamental period increase, which could be interpreted as the effect of higher modes that has not been considered sufficiently in the IBC-2009 load pattern. For inelastic range the story is completely different such that the variation of the ductility demand of the structures is a lot more non-uniform even in short period, which is more intensified by increasing the inelastic level of vibration. It is interesting that in low level of inelastic behavior (i.e., $\mu_i = 2$) seismic performance of the structure increases (i.e. decreasing COV) with number of stories for the structures with short period. To better investigate the effect of target ductility demands on the averaged COV of story ductility demands Fig. 5 is provided. The results are for a 15-story shear building with $\bar{H}/r = 3$, and with four ductility ratios ($\mu_i = 1, 2, 4, 6$) as well as for two dimensionless frequencies ($a_0 = 1, 2$) in comparison with the fixed-base structures. It is observed that for both fixed-base and flexible-based models increasing the target ductility is always accompanied by increasing in COV of story ductility demands, which is compatible with the results of the study carried out for fixed-base shear-building systems by Moghaddam and Hajirasouliha (2006). For the fixed-base structures within large inelastic range of vibration the COV of story ductility demands for the structures having short periods is significantly greater than that of the long periods while by increasing the soil flexibility (i.e. increasing the SSI effect) this phenomenon will be reversed. The reason is that the fundamental period of soil-structure systems always increases with soil flexibility, which caused that the new soil-structure system has always a fundamental period of vibration greater than that of the fixed-base model. It is also seen that for both fixed-base and flexible- base models with long period of vibration, COV of story ductility demands is more dependent on the level of inelasticity (i.e. target ductility demand value) than the fundamental period of the building. As stated before, however, nearly all code-specified seismic load patterns are not considered the target ductility demand of the structure.

6.2. Effect of dimensionless frequency and aspect ratio

Fig. 6 shows the effect of dimensionless frequency (i.e. soil flexibility) by illustrating the average of COV obtained in 30 earthquake ground motions versus fixed-base fundamental period for a 15-story shear-building with $\bar{H}/r = 3$ and various target ductility demands. It is observed that, with exception of very short periods, the COV of story ductility demands increases with soil flexibility leading to reduction of

the seismic performance of the soil-structure systems with respect to the fixed-base ones. This trend is less intensified as the level of inelastic behaviour increases but still significant. The effect of aspect ratio also presented in Fig. 7 with the same format as Fig.6 for the case of sever SSI effect (i.e. $a_0 = 3$). As seen, the results can be classified into two parts; first, the set of curves associated with elastic and low level of inelastic ranges (i.e., $\mu_t = 1$ and 2, respectively) in which, except for very short periods, the COV of ductility demands increases with aspect ratio; second, the curves corresponded to the high level of inelastic behaviour ($\mu_t = 6$) in which the COV decreases with aspect ratio in short range of periods; afterwards, this trend is reversed similar to the first part but with less intensity.

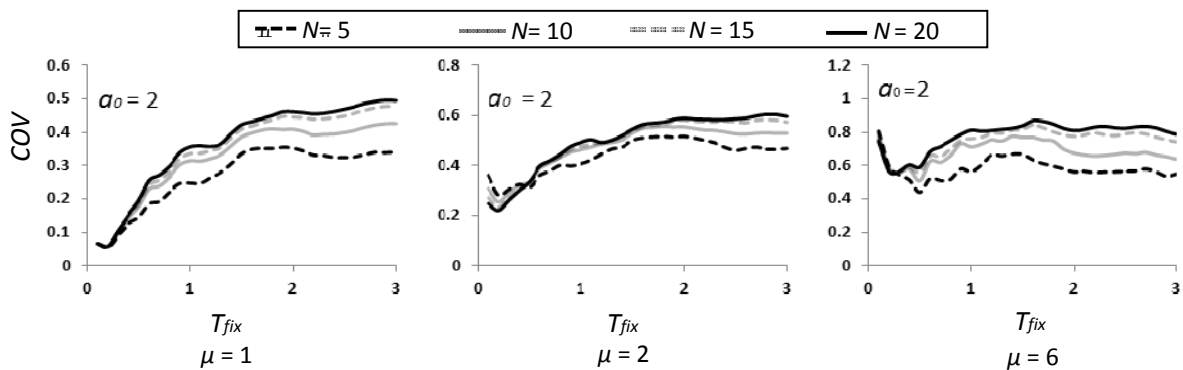


Fig. 4. Effect of number of stories on averaged COV of story ductility demands for systems with $\bar{H}/r = 3$

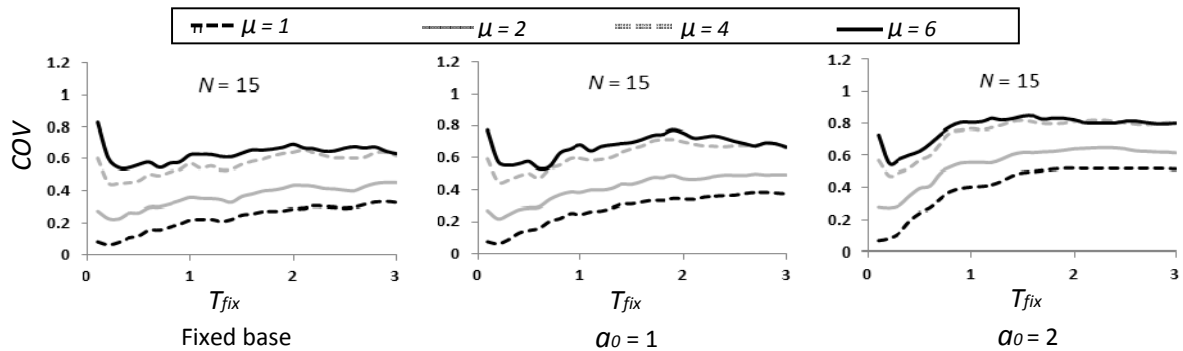


Fig. 5. Effect of maximum ductility on averaged COV of story ductility demands for systems with $\bar{H}/r = 3$

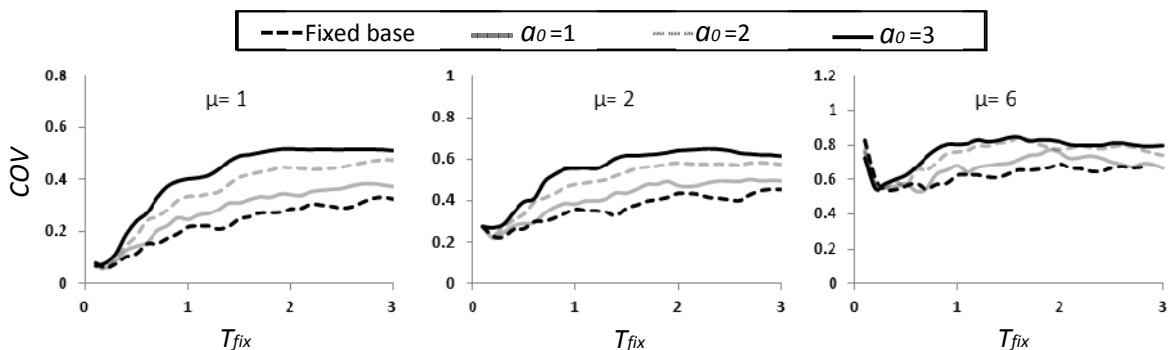


Fig. 6. Effect of soil flexibility on averaged COV of story ductility demands for systems with $N=15$ and $\bar{H}/r = 3$

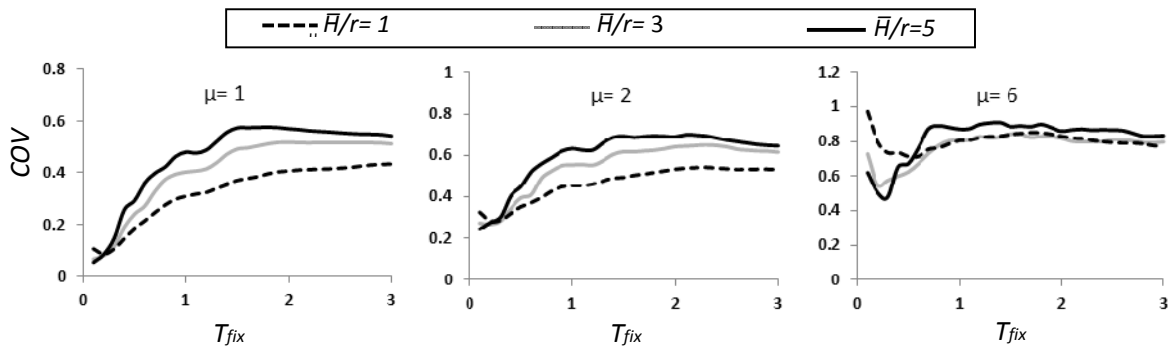


Fig. 7. Effect of aspect ratio on averaged COV of story ductility demands for systems with $N=15$ and $a_0=3$

7. Conclusion

A parametric study has been carried out to investigate the effect of SSI on ductility demands distribution and seismic performance of shear-building structures designed in accordance to code-specified design lateral load pattern using simplified soil-structure model. Results of this study can be summarized as follows:

1. For both fixed-base and flexible-base structures, regardless of the number of stories, using IBC-2009 load pattern leads to nearly uniform ductility demands distribution for the structure with short periods within the elastic range of behaviour. For the longer periods i.e., $T_{fix} > 0.4$ sec, however, the efficiency of the IBC-2009 load pattern is reduced as the number of stories and fundamental period increase, which could be interpreted as the effect of higher modes that has not been considered sufficiently in the IBC-2009 load pattern. In inelastic range, the performance of the structures is significantly reduced even in short period, which is more intensified by increasing the inelastic level of vibration and soil flexibility.
2. For the fixed-base structures within large inelastic range of vibration the performance of the structures having short period is significantly less than that of the long periods while by increasing the soil flexibility (i.e. increasing the SSI effect) and consequently increasing the fundamental period of soil-structure systems this phenomenon will be reversed. It is also concluded that for both fixed-base and flexible-base models with long period of vibration, the performance of the structure is more dependent on the level of inelasticity (i.e. target ductility demand value) than the fundamental period of the building while nearly in all code-specified seismic load patterns this point are not considered.
3. Generally, SSI effect will become more significant as the aspect ratio increases i.e., for the case of slender building. The trend is less intensified as the level of inelasticity increases but still significant leading to more non-uniform distribution of ductility demand along the height of the structure with respect to the corresponding fixed-base model.

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