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INFLUENCE OF HIGHER MODES ON STRENGTH AND DUCTILTY DEMANDS OF SOIL-STRUCTURE SYSTEMS

BEHNOUD GANJAVI

Assistant Professor, Department of Civil Engineering, University of Mazandaran, Babolsar, Iran

HONG HAO

Professor, Department of Civil Engineering, Curtin University, WA, Perth, Australia

IMAN HAJIRASOULIHA

Lecturer, Department of Civil & Structural Engineering, University of Sheffield, Sheffield, UK

Abstract

Due to the inherent complexity, the common approach in analysing nonlinear response of structures with soil-structure interaction (SSI) in current seismic provisions is based on equivalent SDOF systems (E-SDOF). This paper aims to study the influence of higher modes on the seismic response of SSI systems by performing intensive parametric analyses on more than 6400 linear and non-linear MDOF and E-SDOF systems subjected to 21 earthquake records. An established soil-shallow foundation-structure model with equivalent linear soil behaviour and nonlinear superstructure has been utilized using the concept of cone models. The lateral strength and ductility demands of MDOF soil-structure systems with different number of stories, structure-to-soil stiffness ratio, aspect ratio and level of inelasticity are compared to those of E-SDOF systems. The results indicate that using the common E-SDOF soil-structure systems for estimating the strength and ductility demands of medium and slender MDOF structures can lead to very un-conservative results when SSI effect is significant. This implies the significance of higher mode effects for soil-structure systems in comparison with fixed-based structures, which is more pronounced for the cases of elastic and low level of inelasticity.

Keywords: Soil-structure interaction, equivalent SDOF, MDOF systems, seismic strength demand, ductility demand; higher modes effect

1. Introduction

Extensive damage to building structures during recent major earthquakes around the world (e.g. Kashmir, 2005; China, 2008; Indonesia, 2009; Haiti, 2010; Turkey, 2011) has emphasized the need for better understanding of the structural responses subjected to earthquake ground motions to reduce their vulnerability through better design and retrofitting. The seismic response of a building structure depends on many factors such as structural properties, ground motion characteristics, site conditions as well as soil-structure interaction (SSI). SSI is one of the important factors that can significantly affect the seismic performance of structures located on soft soils by changing 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 ratio due to energy dissipation attributed to hysteretic behaviour and wave radiation in the soil. The general effects of SSI on elastic response of SDOF and MDOF systems were the subject of many studies in the 1970s (e.g. Sarrazin et al. [1972], Jennings and Bielak [1973], Chopra and Gutierrez [1974], Veletsos and Meek [1974], Veletsos and Nair [1975], and Veletsos [1977]). These works led to providing tentative provisions in ATC3-06 [1978], which is the foundation of more recent provisions on earthquake-resistant design of soil-structure systems such as BSSC [2000] and 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 based on the soil and structures characteristics [Jennings and Bielak, 1973; Veletsos and Meek, 1974]. Some of the current seismic provisions consider SSI, generally, as a beneficial effect on seismic response of structures since SSI usually results in a reduction of total shear strength of building structures [BSSC, 2000; ASCE, 2005]. However, the inelastic behaviour of the superstructure, inevitable during severe earthquakes, has not been well investigated. One of the early works on inelastic soil-structure systems were conducted by Veletsos and Verbic [1974], Bielak [1978] and Muller and Keintzel [1982]. The results of their study showed that the ductility demand of non-linear SDOF structures can be different from that of the equivalent SDOF systems without considering SSI effects. Rodriguez and Montes (2000) investigated the seismic response of buildings located on flexible soil and concluded that the inelastic displacement demands of soil-structure systems can be approximated by using equivalent fixed-base systems having an elongated period. Aviles and Perez-Rocha [2003, 2005] first developed the concepts of equivalent elastic soil-structure system to predict the nonlinear behaviour of structures by using a nonlinear replacement SDOF oscillator defined by an effective ductility together with the effective period and damping of the system for the elastic condition. This was followed by more studies to investigate the SSI effects on inelastic behaviour of SDOF systems (e.g. Takewaki and Fujimoto [2004], Ghannad and Ahmadnia [2006], Kishida and Takewaki [2006], Ghannad and Jahankhah [2007], Mahsuli and Ghannad [2009], Aviles and Perez-Rocha [2007 and 2011], Aydemir [2013], and Khoshnoudian et. al. [2015]). They concluded that, in general, seismic design regulations using simplified SDOF systems (e.g. ATC3-06 [1978]) lead to higher ductility demands, especially for short period buildings located on soft soils.

While most studies on nonlinear soil-structure systems are focused on SDOF systems, equivalent SDOF systems may not be able to correctly reflect the realistic SSI behaviour of multi-storey structures when subjected to strong ground motions. This can be due to ignoring the effects of higher modes and also height-wise distribution of lateral strength and stiffness on inelastic response of MDOF soil-structure systems. A few studies on the effects of SSI on seismic behaviour of MDOF systems are those conducted by Dutta *et al*. [2004], Barcena and Esteva [2007], Galal and Naimi [2009], Tang and Zhang [2011], Ganjavi and Hao [2012 and 2013], and more recently Abedi-Nik and Khoshnoudian [2014]. However, the lack of clarity in SSI effects on seismic demands of MDOF systems requires more attention.

In this paper, an intensive parametric study is performed to investigate the seismic response of more than 6400 soil-structure systems with different number of storeys, structure-to-soil stiffness ratio, aspect ratio and level of inelasticity subjected to 21 real earthquake records. The results are then used to assess the adequacy of equivalent SDOF (E-SDOF) systems in estimating the strength and ductility demands of MDOF soil-structure systems under design earthquakes, with the emphasis on the effects of higher modes.

2. Soil-Shallow Foundation-Structure Models and Key Design Parameters

2.1. Specifications of superstructure models

Shear buildings are one of the most frequently used models that facilitate performing a comprehensive parametric study [Diaz *et al.*, 1994; Mohammadi *et al.*, 2004; Moghaddam and Hajirasouliha, 2008; Hajirasouliha and Moghaddam, 2009; Abedi-Nik and Khoshnoudian 2014]. In the MDOF shear-building models utilized in the present study, storey 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 simulate the hysteretic response of each storey. This model is selected to represent the behaviour of non-deteriorating steel-framed structures. In all MDOF models, lateral storey stiffness is assumed as proportional to storey shear strength distributed over the height of the structure in accordance with the ASCE/SEI 7-10 [2010] design load pattern [Hajirasouliha and Pilakoutas, 2012]. Five percent Rayleigh damping was assigned to the first mode and the mode in which the cumulative mass participation was at least 95%. In this study, for each MDOF building an equivalent SDOF system is also introduced. The mass of the E-SDOF system is the same as the total mass of the MDOF building. The period of vibration, damping ratio and effective height of the E-SDOF system are obtained based on the fundamental mode properties of the corresponding MDOF building.

2.2. Soil-foundation-structure model and key parameters in interacting systems

The widely-used sub-structure method is adopted to model soil-structure systems. Using this method, soil material is modelled separately and then combined with superstructure model to establish the whole soil-structure system. The soil-foundation element is modelled by an equivalent linear discrete model based on the concept of cone model with frequency-dependent coefficients (Wolf, 1994). The cone model represents a circular rigid foundation with mass m_f and area moment of inertia I_f resting on a homogeneous half-space. In lieu of the rigorous elasto-dynamical approach, it is shown that the simplified cone model can be used with sufficient accuracy in engineering practice [Wolf, 1994].

Figure 1 shows the typical MDOF and E-SDOF soil-structure systems in this study. The sway and rocking DOFs are defined as representatives of translational and rotational motions of the shallow foundation, respectively, disregarding the slight effect of vertical and torsional motions. The stiffness and energy dissipation of the supporting soil are represented by springs and dashpot, respectively. Since all analyses are carried out in the time domain, the soil spring and dashpot values at any time instant are assumed to be compatible with the current natural frequency of the system and are determined by using an iterative process [Ganjavi and Hao, 2013]. While being inherently hysteretic, soil material damping is treated as viscous damping so that more intricacies in time-domain analysis are avoided. The properties of the soil-shallow foundation elements in Figure 1 are summarized in Table 1.

Table 1: Properties of soil–foundation elements based on the cone model concept

<table>
<tr><th colspan="2">Motion</th><th>Stiffness</th><th>Viscous Damping</th><th>Added Mass</th></tr>
<tr><td colspan="2">Horizontal</td><td>$k_h = \frac{8\rho v_s^2 r}{2-\upsilon},$</td><td>$c_h = \rho v_s A_f$</td><td>------</td></tr>
<tr><td rowspan="5">Rocking</td><td>$\upsilon < 1/3$</td><td rowspan="2">$k_\varphi = \frac{8\rho v_s^2 r^3}{3(1-\upsilon)},$</td><td>$c_\varphi = \rho v_p I_f$</td><td>-------</td></tr>
<tr><td>$1/3 \le \upsilon \le 1/2$</td><td>$c_\varphi = \rho(2v_s)I_f$</td><td>$\Delta_{m\varphi} = 0.3\pi(\upsilon - 1/3)\rho r^5$</td></tr>
<tr><td colspan="4">Internal Mass Moment of inertia</td></tr>
<tr><td>$\upsilon < 1/3$</td><td colspan="3">$m_\varphi = \frac{9\pi}{32}\rho I_f r(1-\upsilon)(\frac{v_p}{v_s})$</td></tr>
<tr><td>$1/3 \le \upsilon \le 1/2$</td><td colspan="3">$m_\varphi = \frac{9\pi}{8}\rho I_f r(1-\upsilon)$</td></tr>
<tr><td colspan="2" rowspan="3">Material Damping</td><td colspan="3">Additional Parallel Connected Element (*i= 0 or* ϕ)</td></tr>
<tr><td colspan="2">Viscous Damping to Stiffness $\bar{k}_i$</td><td>Viscous Damping to Mass $\bar{C}_i$</td></tr>
<tr><td colspan="2">$\bar{C}_i = 2k_i(\frac{\zeta_0}{\omega_0})$</td><td>$\bar{m}_i = c_i(\frac{\zeta_0}{\omega_0})$</td></tr>
</table>

The parameters k_h , c_h , k_φ and c_φ in Table 1 represent 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. The relationship between v_p and v_s is defined as $v_p = v_s\sqrt{2(1-\upsilon)/(1-2\upsilon)}$ *if* $\upsilon < 1/3$, and $v_p = 2v_s$ *if* $1/3 \le \upsilon \le 1/2$. In this study, υ is considered to be 0.4 and 0.45 for alluvium soil and soft soil, respectively.

To consider the soil material damping, ζ_0, each spring and dashpot used in the soil-foundation model is respectively augmented with an additional parallel connected dashpot and mass [Ganjavi and Hao, 2013]. Also, to modify the effect of soil incompressibility, an additional mass moment of inertia ΔM_{φ} equal to $0.3\pi(\upsilon-1/3)\rho r^5$ is added to the foundation for υ greater than 1/3 [Wolf, 1994]. Incorporating soil nonlinearity to the soil-foundation element is 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 [FEMA-440, 2005]. It has been shown that the effect of these factors can be best described by using the following dimensionless parameters [Veletsos, 1977; Wolf and Deeks, 2004]:

(1) A dimensionless frequency as an index for the structure-to-soil stiffness ratio defined as: $a_0 = \omega_{fix}\bar{H}/v_s$, where ω_{fix} is the natural frequency of the fixed-base structure. 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 Ahmadnia, 2006]. $\bar{H}$ is the effective height of the structure corresponding to the fundamental mode properties and can be obtained from $\bar{H} = \sum_{j=1}^{n}\left[m_j\varphi_{j1}\left(\sum_{i=1}^{j}h_i\right)\right] \Big/ \sum_{j=1}^{n} m_j\varphi_{j1}$,where m_j is the mass of the j^{th} storey; h_i is the height from the base level to level *j;* and φ_{j1} is the amplitude at j^{th} storey of the first mode.

(2) Aspect ratio of the building defined as $\bar{H}/r$, where *r* is equivalent foundation radius.

(3) Inter-storey displacement ductility demand defined as $\mu=\delta_{\mathrm{m}}/\delta_y$, where δ_{m} and δ_{y} are the maximum inter-storey displacement and the yield inter-storey displacement, respectively. For MDOF buildings, μ is the greatest value among all storey ductility ratios.

(4) Structure-to-soil mass ratio defined as $\bar{m}=m_{tot}/\rho r^2 H$, where m_{tot} and H are the total weight and height of the structure, respectively.

(5) Foundation-to-structure mass ratio m_f/m_{tot} , where m_f is the mass of the rigid foundation. In the present study, the foundation mass ratio is assumed to be 0.1 of the total mass of the MDOF buildings.

3. Procedure for Parametric SSI Analysis

The adopted soil-foundation structure model explained in previous section is used to assess the effects of SSI on the seismic response of both MDOF and E-SDOF systems. To perform non-linear dynamic analysis on soil-structure systems, a comprehensive computer program that was developed and validated by Ganjavi and Hao [2012 and 2013] is utilised. A series of 5, 10, and 15-storey shear buildings are used to obtain the strength and ductility demands of both MDOF and E-SDOF systems. In this investigation, an ensemble of 21 earthquake ground motions recorded on alluvium and soft soil deposits (soil type C and D based on USGS site classification) are used 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 characteristics of the selected ground motions can be found in Ganjavi and Hao [2012].

For each given earthquake ground motion, a set of 6400 different soil-structure models were developed using a wide range of key parameters discussed in the previous section. This includes MDOF and E-SDOF models with 30 fixed-base fundamental periods, ranging from 0.1 to 3 sec with intervals of 0.1, three values of aspect ratio ($\bar{H}/r$ =1, 3, 5), four values of structure-to-soil stiffness ratio (a_0= 0, 1, 2, 3), and three values of target inter-storey drift ductility (μ_t = 1, 2, 6). 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 to cover all possible conditions.

4. Effect of SSI on Strength Demand of MDOF and E-SDOF Systems

4.1 Strength Demand of MDOF and E-SDOF Soil-Structure Systems

In this section, the effect of SSI on total strength demand of both MDOF and E-SDOF soil-structure systems is studied. Figure 2 compares the elastic strength demand spectra of E-SDOF systems with 5 and 15-storey buildings, which are respectively representative of relatively low- and high-rise buildings. The vertical axis is the total normalized shear strength that is defined as the total shear strength demands divided by the total structural mass and normalized to the peak ground acceleration (PGA). The presented results are the average of 21 selected earthquakes and are provided for systems with two aspect ratios $\bar{H}/r = 1$ and 5, as representative of squat and slender buildings, and two structure-to-soil stiffness ratios a_0 = 1 and 3, to represent low and high SSI effects, respectively.

The results in Figure 2 show a very similar trend for both MDOF and E-SDOF systems in elastic state, where the strength demands of soil-structure systems are generally lower than those of corresponding fixed-base structures. This conclusion is consistent with the results of the study carried out for SDOF systems by Ghannad and Jahankha [2007]. However, a significant difference can be found between the strength demands of MDOF structures and those of E-SDOF systems when SSI effect is predominant (i.e. $a_0 = 3$).

It is shown in Figure 2 that for fixed-base systems, the difference between the results of SDOF and MDOF systems are significantly lower than those of the SSI systems. By increasing the SSI effect (i.e. larger a_0 values), the elastic strength demand of MDOF systems can be significantly larger than that of E-SDOF systems especially for the longer periods. This phenomenon is intensified for slender structures with $\bar{H}/r = 5$, as well as by increasing the number of stories. As an instance, for a soil-structure system with $a_0 = 3$ and $T_{fix} = 2$, the strength demands of 5 and 15-storey buildings are, respectively, 1.78 and 2.57 times the corresponding E-SDOF systems for squat structure with $\bar{H}/r = 1$; 5.5 and 8.16 times for very slender systems with $\bar{H}/r = 5$; and 1.2 and 1.55 times for the fixed-base systems. Hence, it can be concluded that in elastic domain, using the base shear obtained from E-SDOF may lead to significant underestimation of strength demand the MDOF soil-structure systems, especially when SSI effect is predominant. This will be more discussed in next sections.

The same calculations were carried out for ESDOF and MDOF soil-structure systems with target ductility ratios μ_t = 2 and 6, which can be representatives of low and high inelastic behaviours. The mean values for all 21 selected earthquake ground motions are calculated for each fundamental fixed-base period (T_{fix}) as shown in Figures 3 and 4 for the cases of μ_t = 2 and 6, respectively. The results for near elastic systems in Figure 3, in general, follow the same trend as the elastic systems. The exception is for very short period structures with high aspect ratios (i.e. slender buildings), that soil-structure systems exhibit larger strength demands in comparison to the fixed-base systems. The difference between elastic and inelastic systems is intensified by increasing the target ductility ratio as shown in Figure 4 for $\mu_t = 6$. The results indicate that the strength demands of both MDOF and E-SDOF soil-structure systems, irrespective of the number of stories, are only greater than those of the corresponding fixed-base systems for the slender structures having very short periods. However, considering the fact that typical slender MDOF buildings usually do not have such short periods, it may be concluded that SSI effects can generally reduce the lateral structural strength demands of typical building structures. Similar conclusions are made by Ghannad and Jahankhah [2007] for SDOF soil-structure systems.

Comparison between Figures 1, 2 and 3 shows that, for the practical range of periods for multi-storey buildings (i.e. $T_{fix} > 0.1$ sec), the SSI effect decreases as target ductility demands increases, which is more prominent for E-SDOF and low-rise MDOF systems (i.e. N=1 and 5). The results for $\mu_t = 6$ in Figure 4 show a considerable reduction in the lateral strength demands of 15-storey soil-structure systems with $a_0 = 3$ compared to their corresponding fixed-base structures. This implies that although the SSI effects may become less prominent as the structure experiences higher inelastic deformations, they can be still significant for tall buildings on soft soil deposits (high structure-to-soil stiffness ratio).

The presented results indicate that by increasing the SSI effect, i.e. larger a_0, strength demands of MDOF systems can be considerably larger than those of E-SDOF systems for both elastic and inelastic structures, especially in the long period range. To get a better understanding of this observation, Figure 5 illustrates the difference between the strength demands of 5, 10 and 15-storey MDOF and associated E-SDOF models for both fixed-base and soil-structure systems. This figure can explain better the effect of number of storeys on the strength demands of both fixed-base and soil-structure systems when undergoing different levels of ductility. It is shown that in the elastic state (i.e. $\mu_t = 1$), except for very short periods, the strength demands increase by increasing the number of stories. This trend is intensified by increasing the value of a_0, such that for the severe SSI effects (i.e. a_0=3) the strength demands of E-SDOF systems can be up to 6 times less than those of the corresponding 15-storey buildings. In the inelastic domain, for a specific fixed-base period, strength demand increases as the number of storeys increases, but the rate of increment becomes smaller with the increase of the number of stories. By increasing the level of inelasticity, the difference between the strength demand values of MDOF systems and those of the corresponding E-SDOF systems reduces, especially for the systems with high structure-to-soil stiffness ratio (i.e. higher SSI effects).

4.2. Effect of Higher Modes in Strength Demands of Soil-Structure Systems

To better investigate the adequacy of using common E-SDOF systems in estimating the strength demands of MDOF systems for both fixed-base and soil-structure systems, Figure 6 presents the mean ratio of strength demands of 10-storey buildings to those of associated E-SDOF systems. The results are provided for fixed-base structures and soil-structure systems with three levels of ductility demands (μ =1, 2, 6), three aspect ratios ($\bar{H}/r$ = 1, 3, 5), and three structure-to-soil stiffness ratios (a_0 = 1, 2, 3). It is shown that for fixed-base structures in elastic range (i.e. μ =1), there is no significant difference between the strength demands of MDOF and corresponding E-SDOF systems. However, for soil-structure systems with elastic behaviour or low ductility demands (i.e. μ =1, 2), the ratio of strength demands of MDOF systems to their corresponding E-SDOF systems can be significant. This phenomenon is more pronounced for the structures with high aspect ratio (slender structures). As an instance, it is shown in Figure 6 that for a MDOF structure with fundamental period of 2.5 sec, the strength demand ratio is 1.6 for the fixed-base system, while it increases to 2.5, 5.6 and 9.3 for squat, medium and slender soil-structure systems, respectively. This implies that, opposed to fixed-base structures, using E-SDOF soil-structure systems for estimating the strength demands of MDOF structures when SSI effect is significant can lead to very un-conservative results.

The results presented in Figure 6 also indicate that, by increasing the level of inelasticity, the strength demand ratio of MDOF structures to their corresponding E-SDOF systems increases for fixed-base systems, while it decreases for soil-structure systems. Nevertheless, for medium and slender soil-structures systems, the strength demand ratios are still greater than those of the fixed-base systems. For instance, the strength demand of a MDOF system with T_{fix} = 2 is 2.1 and 2.4 times the strength demand of its corresponding E-SDOF system for target ductility demands of 1 and 2, respectively. This ratio can increase to 5.5 and 3.6 times for slender soil-structure systems with severe SSI effect (i.e. $\bar{H}/r$ = 5, and a_0 = 3).

It can be also seen from Figure 5 that for MDOF systems the strength demands usually increase with increasing the number of stories. This phenomenon may be justified by studying the distribution pattern of storey ductility demands along the height of MDOF structures. The ductility demand for MDOF systems is conventionally referred to as the greatest value among all storey ductility ratios; which implies that the ductility ratios in all other stories are lower than the target ductility. This may result in a greater strength demand when compared to the same MDOF building, in which all stories have identical ductility ratio equal to the target value. For example, Figure 7 compares the Coefficient of Variation (COV) of storey ductility ratios for 5, 10 and 15-storey MDOF systems with aspect ratio of 3, target ductility ratio of 6 and structure-to-soil stiffness ratios of 1 and 3. The results are the average values of 21 earthquake ground motions used in this study. As seen, except for structures with very short periods, COV of ductility ratios increases by increasing the number of storeys. For better comparison, Figure 8 shows the height-wise distribution of averaged ductility demands for the same MDOF soil-structure systems with T_{fix} = 1.5. It can be seen that, in general, by increasing the number of stories, more stories have the ductility demands lower than the target value, which supports the above discussion. It should be noted that the averaged maximum ductility ratios are not exactly equal to the target ductility, since the maximum ductility ratio depends on a given earthquake ground motion and, therefore, it may happen in different stories.

5. Effect of SSI on Ductility Demand of MDOF and E-SDOF Systems

To investigate the effect of SSI on maximum ductility demands of MDOF and E-SDOF structures with different values of a_0 and $\bar{H}/r$, the following procedure is adopted in this study. First, by using an iterative process the elastic and inelastic strength demands of MDOF and E-SDOF fixed-base systems (i.e. without considering SSI effects) are calculated to reach a predefined target ductility ratio, μ_t, when subjected to the design earthquake ground motion. Subsequently, the soil-shallow foundation elements (see Figure 1) are added to the designed structures and the ductility demands are calculate for the soil-structure systems. The effect of SSI can then be examined by comparing the results of the fixed-base models and the corresponding soil–structure systems.

As an example, Figure 9 compares the average ductility demand spectra of MDOF and E-SDOF soil-structure systems with structure-to-soil stiffness ratios a_0= 1, 2 and 3. The vertical axis in all plots is the ratio of ductility demand in flexible-base structure to that of the fixed-based structure. For the E-SDOF systems, irrespective of the structure-to-soil stiffness ratio or the level of inelasticity, there is a threshold period before which the ductility demand of the structure with SSI is always larger than that of the corresponding fixed-base system. However, SSI effects reduce the ductility demand of the soil-structure systems with fixed-based periods above the threshold value. It is shown that the difference between the ductility demands of the fixed-base and flexible-base systems increases by increasing structure-to-soil stiffness ratio (i.e. higher SSI effects).

It is shown in Figure 9 that the effect of SSI on the ductility demand of MDOF systems can be completely different from that of the E-SDOF systems, depending on the structure-to-soil stiffness ratio and the level of inelasticity. For MDOF systems with low SSI effects (a_0= 1), the ductility demand ratios for almost all fixed-based periods are greater than unity. This trend is intensified as the number of storeys increases and, hence, is more obvious for the case of 15-storey building. For more significant SSI effects (a_0= 2 and 3), it can be seen that there is a threshold period before which the ductility demand ratios are always less than one. However, unlike E-SDOF systems, there is not a clear trend beyond this limit and after reaching to a minimum level, ductility demand ratios again rises as period increases.

To study the effect of aspect ratio on the ductility demands of MDOF and E-SDOF soil-structure systems, Figures 10 and 11 present the results for three aspect ratios ($\bar{H}/r$ = 1, 3, 5) at two different ductility levels (μ_t = 2 and 6). For E-SDOF systems, it can be observed that by increasing the aspect ratio, the difference between ductility demands of fixed-base and flexible-base systems increases. This conclusion is consistent with the studies carried out on SDOF SSI systems by Ghannad and Ahmadnia [2006] and Mahsuli and Ghannad [2009]. For MDOF systems, the difference between ductility demands of the structures with or without considering SSI is less significant. It should be noted that, in contrary to the E-SDOF systems, the flexible-base to fixed-base ductility demand ratios for MDOF systems with low structure-to-soil stiffness ratio (a_0= 1) are in general greater than unity, which is especially evident for structures with higher number of storeys and aspect ratio. This implies that the E-SDOF soil-structure systems generally underestimate the effects of SSI on ductility demands of this type of structural systems.

6. Conclusions

An intensive parametric study was performed to investigate the effect of SSI on strength and ductility demands of MDOF structures with different number of stories, structure-to-soil stiffness ratio, aspect ratio and level of inelasticity compared to their equivalent SDOF systems (E-SDOF). Based on the results presented in this paper, the following conclusions can be drawn:

1. The elastic strength demands of E-SDOF and MDOF soil-structure systems are considerably lower than those of the fixed-base structures for both squat and slender structures. This is especially evident for the systems with high structure-to-soil stiffness ratios (i.e. soft soil profiles).
2. For the same ductility level, flexible-base E-SDOF and MDOF soil-structure systems require lower strength demands compared to their fixed-base counterparts. The only exception is for the slender soil-structure systems with very short periods. Considering the fact that typical slender MDOF buildings usually do not have such short periods, it can be concluded that SSI effects can generally reduce the lateral structural strength demands of typical building structures. By increasing the level of inelasticity, however, the difference between the flexible-base and fixed-base strength demands becomes less significant.
3. Opposed to the fixed-base condition, using E-SDOF soil-structure systems for estimating the strength demands of medium and slender MDOF systems can lead to very un-conservative results when SSI effect is significant (i.e. high structure-to-soil stiffness ratio). This phenomenon, which is more pronounced for elastic and low ductility levels, demonstrates the significance of higher mode effects for soil-structure systems in comparison with fixed-based structures. This is especially important, since current seismic regulations for considering SSI effects are mainly based on E-SDOF systems.
4. For both E-SDOF and MDOF systems, irrespective of the structure-to-soil stiffness ratio or the level of inelasticity, there is a threshold period before which the ductility demand of the SSI system is larger than that of the corresponding fixed-base structure. However, it is shown

that E-SDOF soil-structure systems generally underestimate the effects of SSI on ductility demands of high-rise and slender MDOF buildings with low structure-to-soil stiffness ratios.

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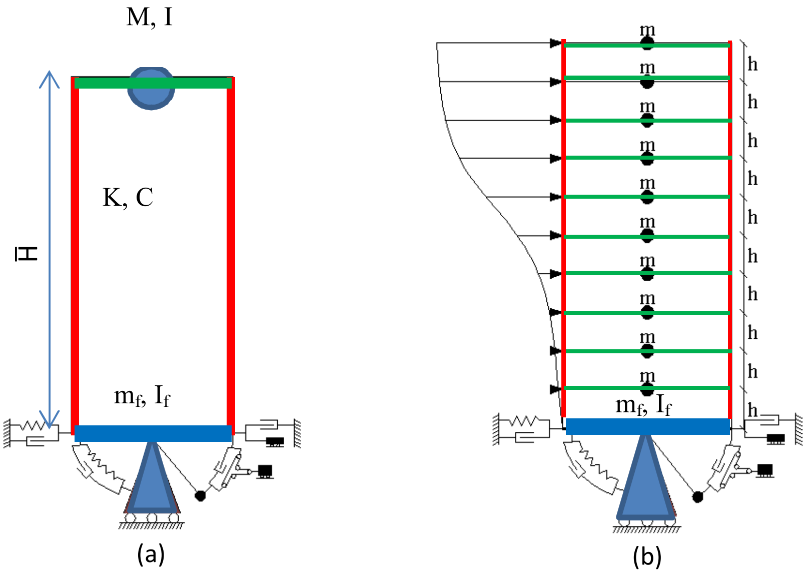


Figure 1: Soil-shallow foundation-structure models for sway and rocking motions (a) E-SDOF system (b) Typical MDOF system

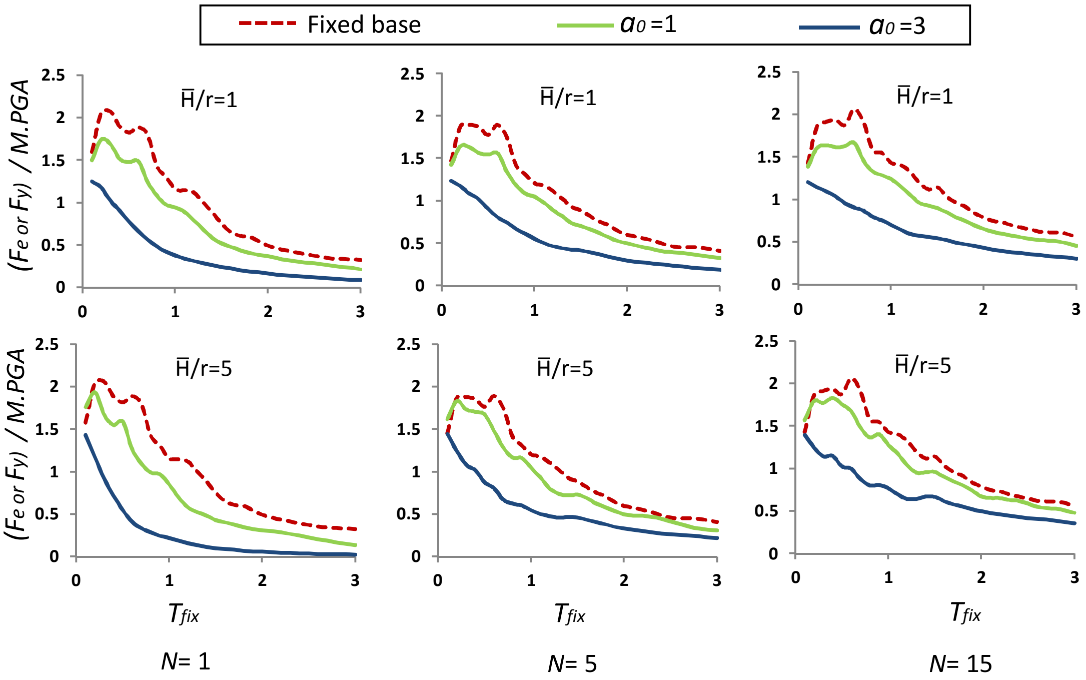


Figure 2: Comparison of the average elastic strength demand for ESDOF and 5 and 15-storey MDOF soil-structure systems, μ =1

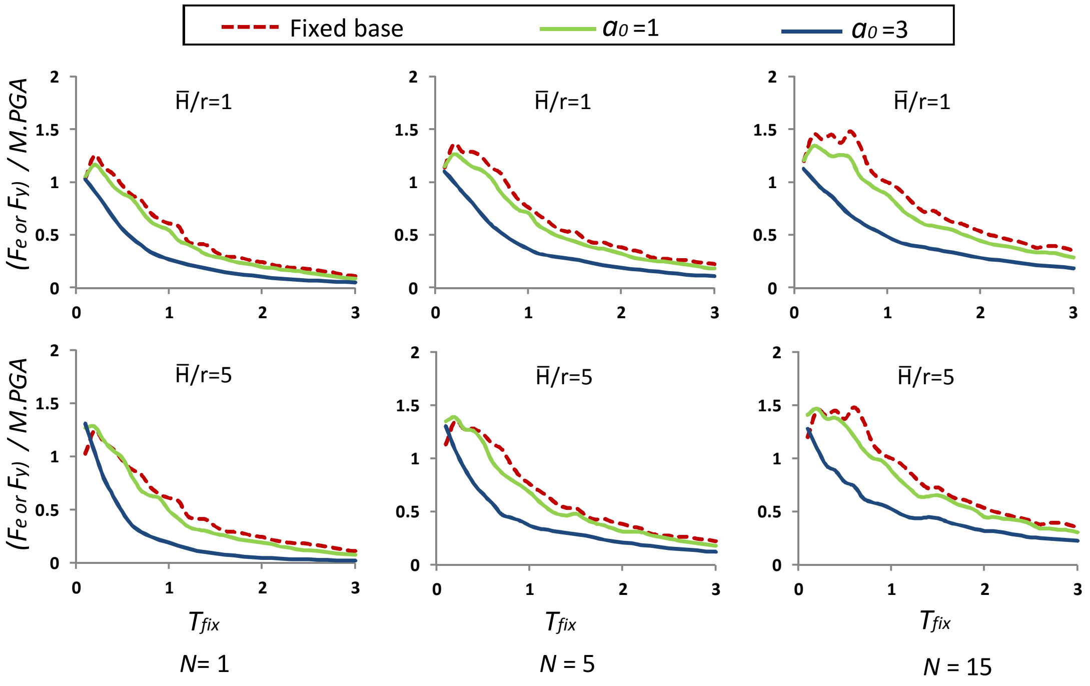


Figure 3: Comparison of the average inelastic strength demand for ESDOF and 5 and 15-storey MDOF soil-structure systems, μ =2

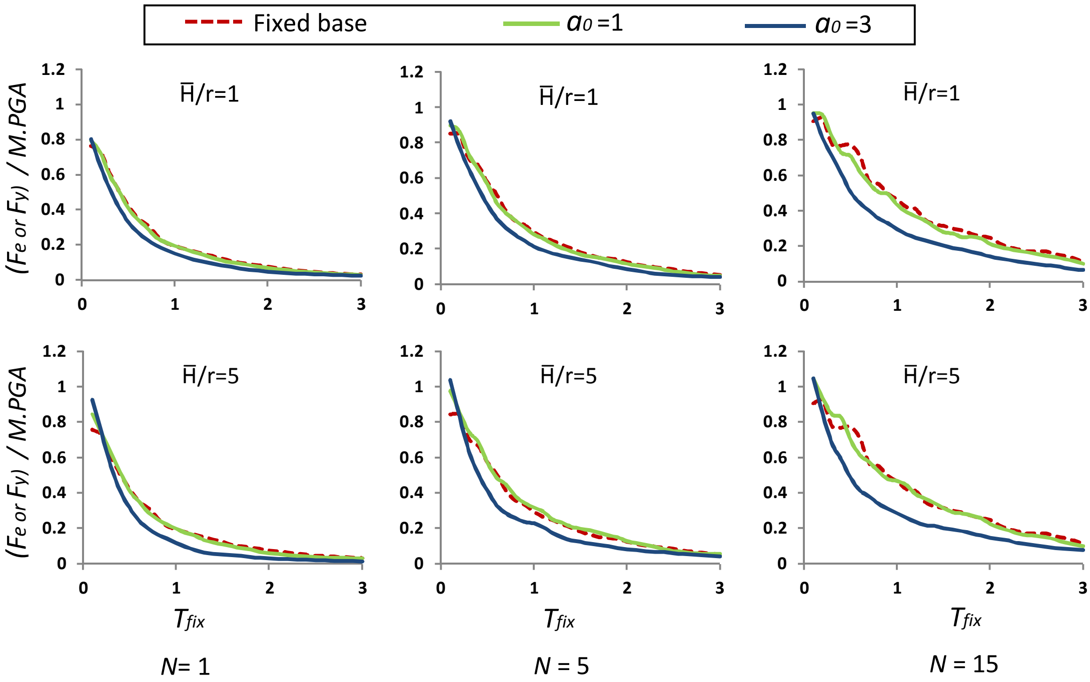
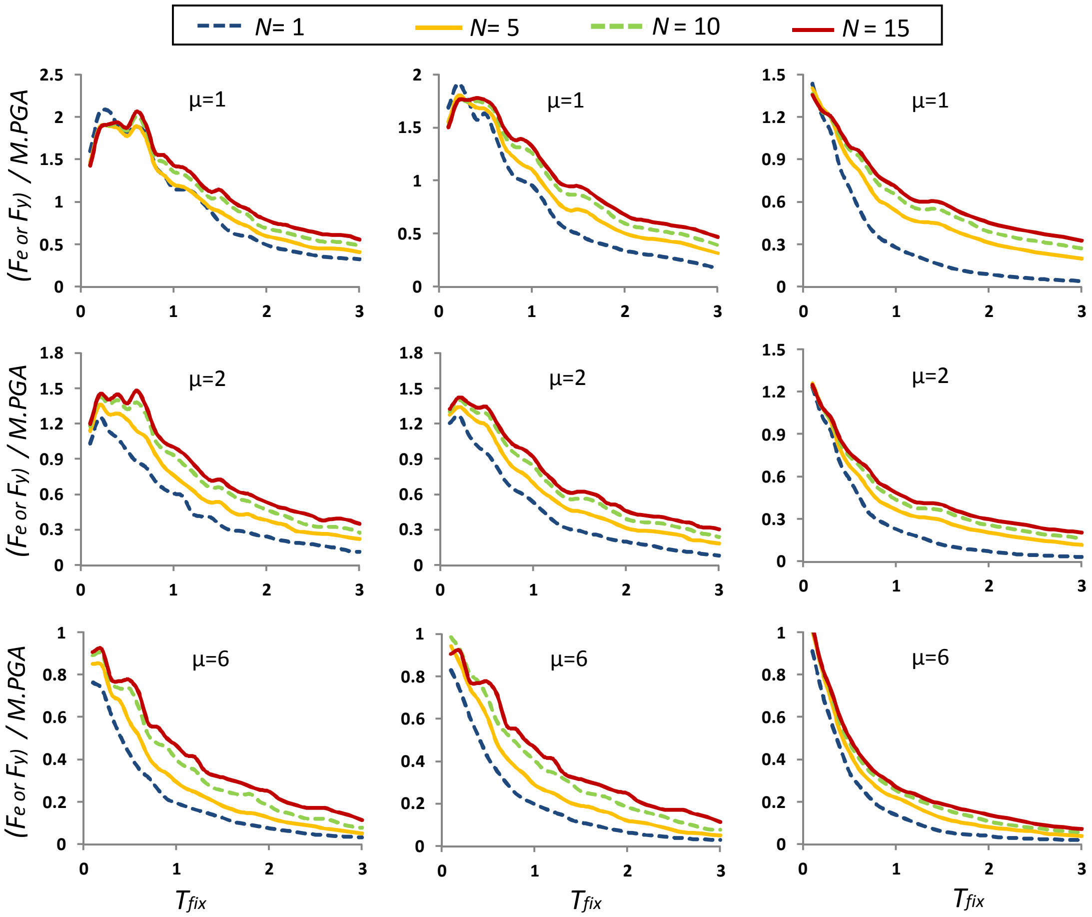


Figure 4: Comparison of the average inelastic strength demand for ESDOF and 5 and 15-storey MDOF soil-structure systems, μ =6

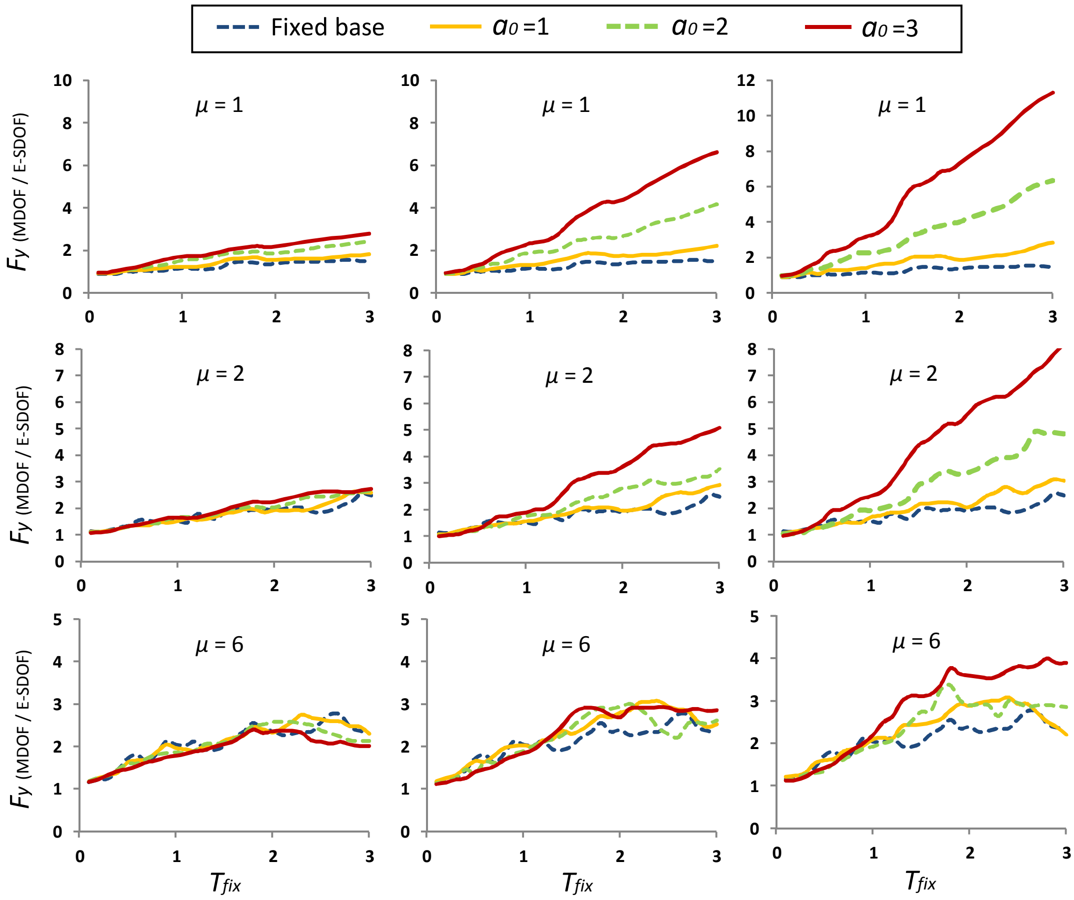


Fixed base

$a_0 = 1$

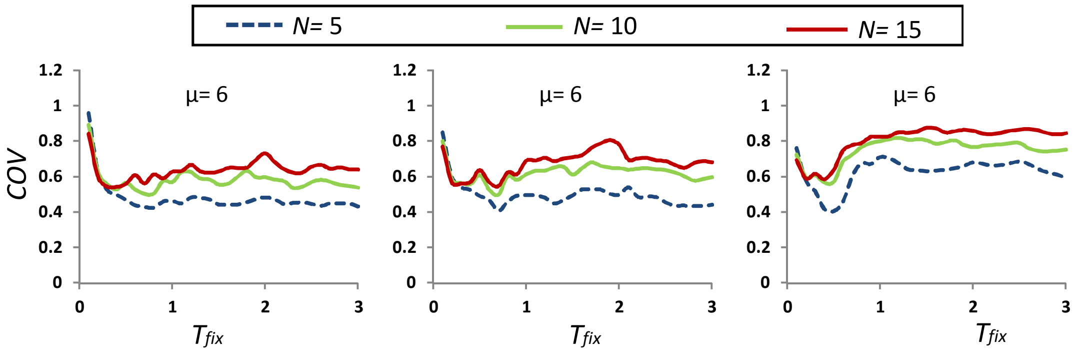
$a_0 = 3$

Figure 5: Effect of number of stories on the average elastic and inelastic strength demand of fixed-base and soil-structure systems for $\bar{H}/r = 3$



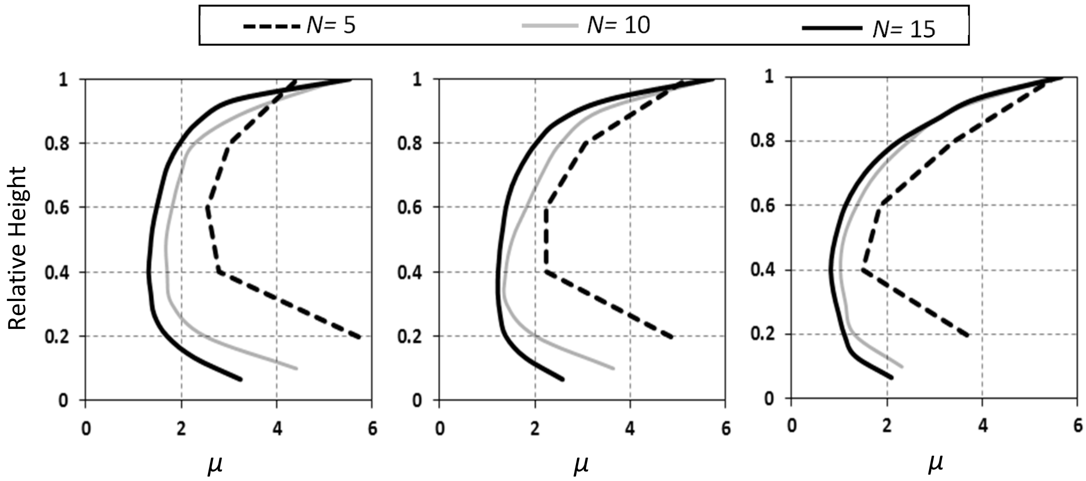
$\bar{H}/r = 1$ $\bar{H}/r = 3$ $\bar{H}/r = 5$

Figure 6: The ratio of elastic and inelastic strength demands in 10-storey building to those in the corresponding E-SDOF system



Fixed base a_0 = 1 a_0= 3

Figure 7: COV of storey ductility demands for 5, 10 and 15-storey MDOF soil-structure systems

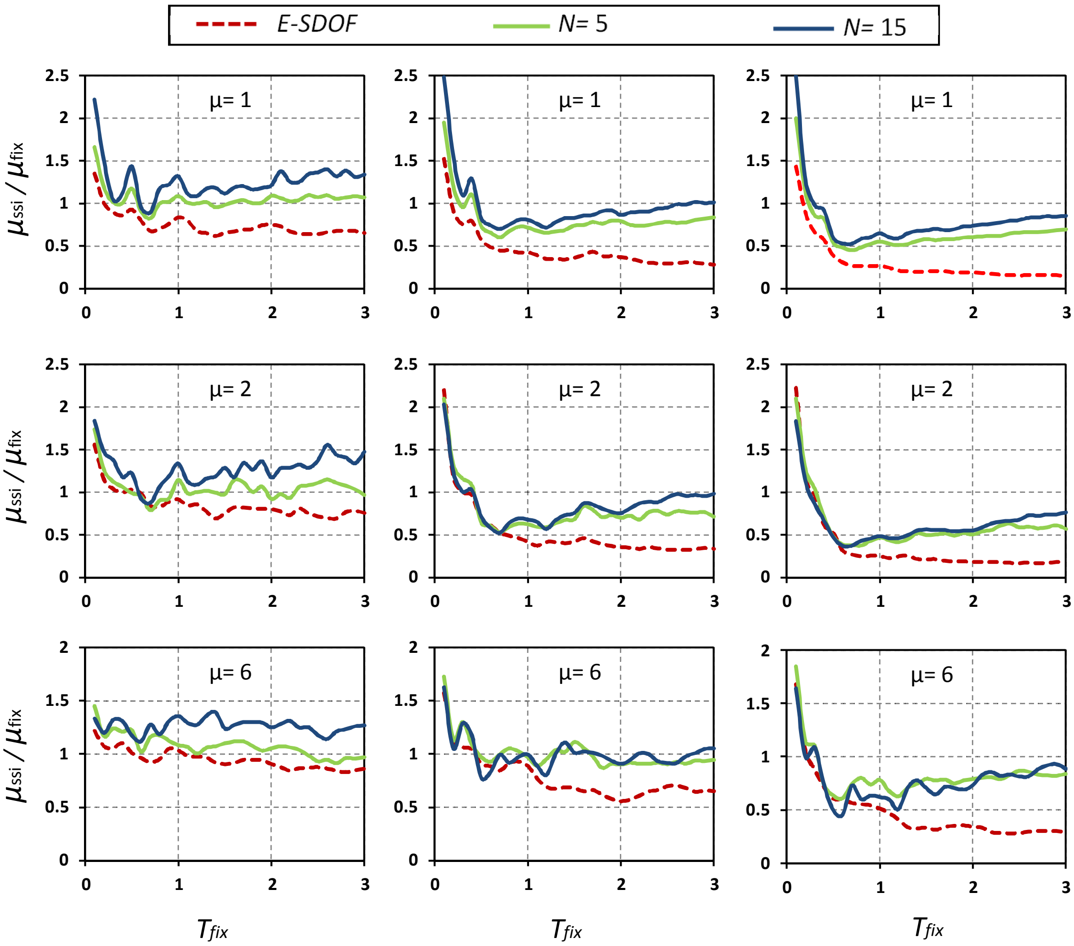


Fixed base

a_0 = 1

a_0= 3

Figure 8: Height-wise distribution of average ductility demands for systems with T_{fix} = 1.5 and μ= 6



a_0 = 1

a_0 = 2

a_0= 3

Figure 9: Average ductility demands for different E-SDOF and MDOF soil-structure systems for $\bar{H}/r = 3$

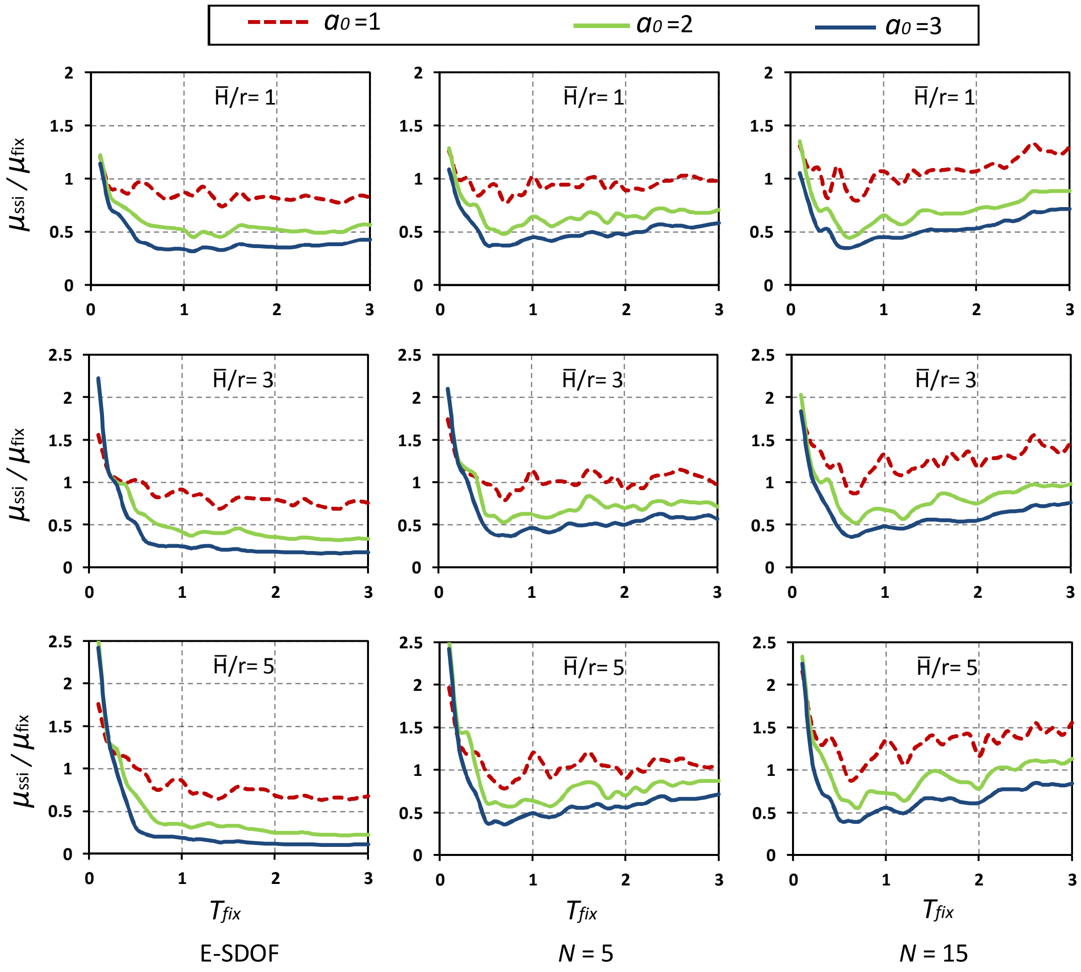


Figure 10: Average ductility demand for different E-SDOF and MDOF soil-structure systems, μ=2

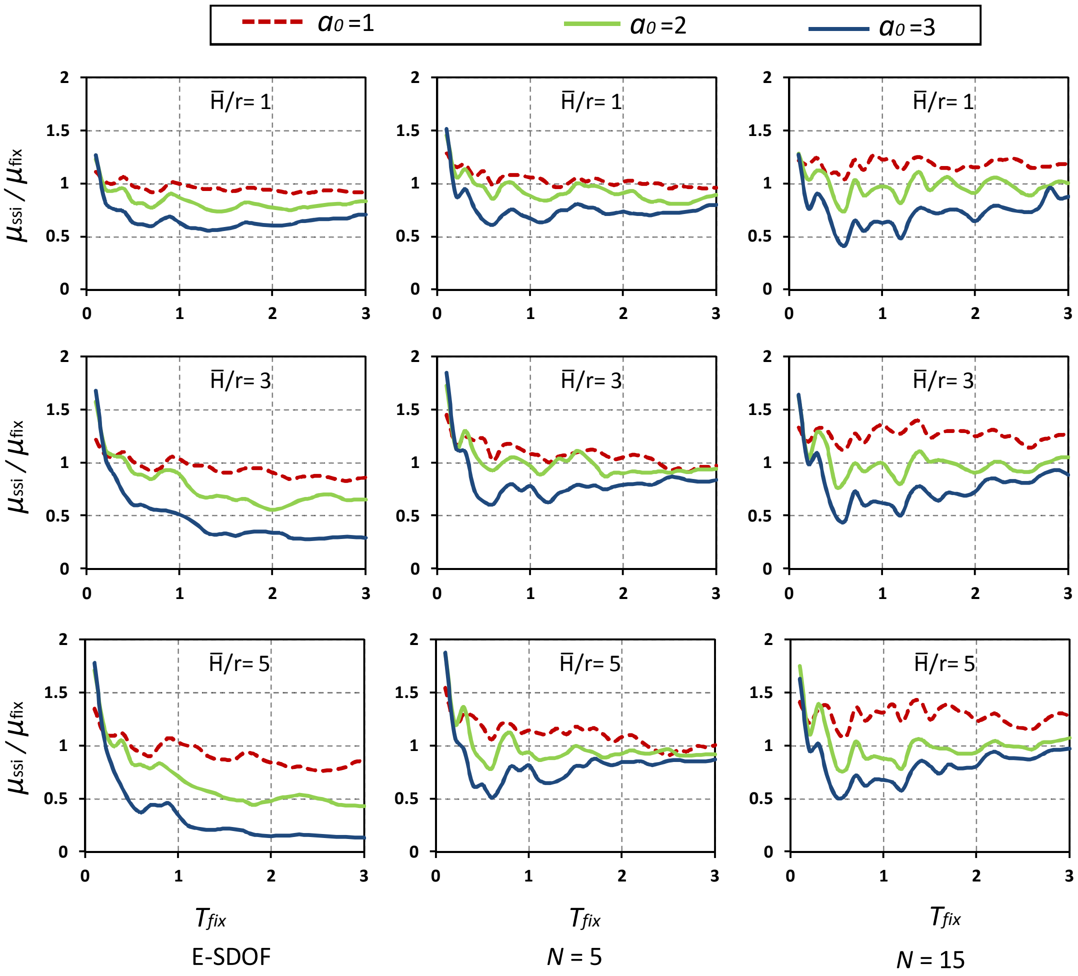


Figure 11: Average ductility demand for different E-SDOF and MDOF soil-structure systems, μ= 6