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Elastic and Inelastic Response of Single- and Multi-Degree-of-Freedom Systems Considering Soil Structure Interaction Effects

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ABSTRACT

Soil structure infraction (SSI) usually is not an attractive subject for civil engineering community due to its complex behaviour. The complex behaviour of SSI together with uncertainties in soil and structure parameters, and in earthquake ground motion result in a significant controversy over the effect of SSI on structural response in both elastic and inelastic states. A few studies considered SSI in inelastic response analysis are mainly based on idealized structural models of SDOF systems. However, it is commonly understood that the structure slenderness and vibration frequencies are closely coupled with the SSI. Therefore an SDOF system might not be able to well capture the SSI and structural response characteristics. In this paper, a comprehensive parametric study is performed to investigate the effect of SSI on global response of structures modelled with both MDOF and its equivalent SDOF (E-SDOF) system. Intensive time-history analyses subjected to an ensemble of 21 earthquake ground motions recorded on alluvium and soft soils were performed to investigate the influences of various soil and structure parameters on its responses. Results show that strength and ductility demands of MDOF soil-structure systems depending on the number of stories, soil flexibility and the level of inelasticity can be very different from those of the corresponding E-SDOF ones.

Keywords: Inelastic behaviours, Soil-Structure Interaction, MDOF systems, Strength and ductility demand

1. INTRODUCTION

Seismic demands of building structures are known to be dependent 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 responses of structures located on soft soils by altering the overall stiffness and energy dissipation mechanism of the systems. 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 (Perelman et al., 1968; Jennings and Bielak, 1973; Chopra and Gutierrez, 1974; Veletsos, 1978). These works led to providing tentative provisions in ATC3-06 (1978), which is actually the foundation of new provisions on earthquake-resistant design of soil-structure systems (NEHRP, 2000). Code-specified 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). 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 (NEHRP, 2000; ASCE/SEI 7-05, 2005). However, the inelastic behavior of the superstructure, inevitable during severe earthquakes, has not been well investigated. 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 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. Rodriguez and Montez (2000) investigated the response and damage of buildings located on flexible soil and concluded that inelastic displacement demand in soil-structure system can be approximated by using an equivalent fixed-base system having an elongated period. The effects of SSI in yielding systems, including both kinematic and inertial interaction, were evaluated by Aviles and Perez-Rocha (2003) through developing the concepts of equivalent elastic soil-structure system to include the nonlinear behavior of the structure. Ghannad and Ahmadnia (2006) assessed the adequacy of ATC3-06 regulation when considering the SSI effect on inelastic response of structures using simplified SDOF system with elastic-perfectly plastic behavior. They concluded that using this provision leads to higher ductility demands in the structure, especially for the case of short period building located on soft soils.

On the other hand, the relationship between MDOF and SDOF system response of fixed-base systems was first studied by Veletsos and Vann (1971) by considering some shear-beam models with equal story masses connected by weightless springs in series from one degree of freedom (DOF) to five DOFs. They concluded that for systems having more than three DOFs the proposed design regulations for SDOF systems were not sufficiently accurate and could lead to unconservative estimates of the required inelastic lateral strength, and that errors tended to increase as the number of degrees of freedom increased. Another study was conducted by Nassar and Krawinkler (1991) on three types of simplified fixed-base MDOF models to estimate the modifications required to the inelastic strength demands obtained from bilinear SDOF systems in order to limit the story ductility demand in the first story of the MDOF systems to a predefined value. More examples of the works conducted on the subject can be found in the reference (Seneviratna and Krawinkler, 1997; Santa-Ana and Miranda, 2000). However, all of the works were performed on fixed-base systems, i.e. based on a presumed assumption that soil beneath the structure is rigid.

As mentioned in the literature, 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 was not investigated in detail. A few studies of SSI effects on MDOF systems are those conducted by Dutta et al. (2004), Barcena and Steva (2007) and Tang and Zhang (2011). However, the lack of clarity in SSI effects on seismic demands of MDOF systems deserved special attention. Here, in this paper an intensive parametric study has been performed to investigate the effect of inertial SSI on both elastic and inelastic seismic strength and ductility demands of MDOF and its equivalent SDOF systems using simplified soil-structure model for surface (shallow) foundation in which the kinematic interaction is zero. This is carried out for a wide range of non-dimensional parameters to demonstrate and define the severity of SSI effects on both MDOF and SDOF systems.

2. SOIL-SHALLOW FOUNDATION-STRUCTUR MODEL

To incorporate the effects of higher modes, the number of stories and lateral strength and stiffness distribution on inelastic response of MDOF buildings interacting with soil beneath them, the well-known shear-beam model 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 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. In all MDOF models, lateral story stiffness is assumed as proportional to story shear strength distributed over the height of the structure in accordance with the IBC load pattern (2009). Five percent Rayleigh damping was assigned to the first mode and the mode in which the cumulative mass participation was at least 95%. For each MDOF building an E-SDOF is also introduced. The properties of these E-SDOF systems are set such that the mass of the SDOF system is the same as the total mass of the MDOF building; similarly, the period of vibration, damping ratio and effective height of the SDOF systems are the same as the fundamental mode properties of the MDOF building. Sub-structure method is used to model 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). A typical soil-structure system for MDOF and also E-SDOF system are shown in Figure 1. 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 motion. 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.

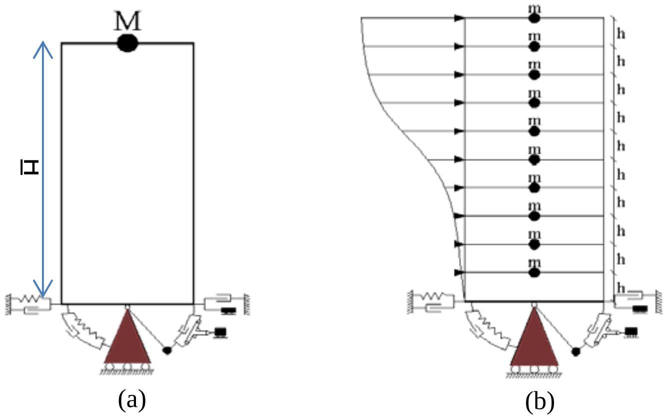

Fig.1. Soil- structure models for sway and rocking motions (a) E-SDOF system (b) Typical MDOF system

3. KEY PARAMETERS

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. It has been shown that the effect of these factors can be best described by the following dimensionless parameters [Veletsos, 1977; Ghannad and Ahmadnia, 2006]:

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} , v_s and $\bar{H}$ are respectively the natural frequency of the fixed-base structure, shear wave velocity and effective height of structure corresponding to the fundamental mode properties of the MDOF building . 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 Ahmadnia, 2006).
2. Aspect ratio of the building defined as $\bar{H}/r$, where r is equivalent foundation radius.
3. Interstory displacement ductility demand of the structure defined as:

$$\mu = \frac{\delta_m}{\delta_y} \tag{6}$$

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 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 υ.

7. Material damping ratios of the soil ζ_0 and 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 Ahmadnia, 2006]. In the present study, the foundation-to-structure 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, damping ratio of 5% is assigned to the soil material.

4. METHODOLOGY FOR ANALYSIS

The adopted soil-shallow foundation-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 are utilized for all MDOF and E-SDOF models. A series of 5-, 10-, and 15-story MDOF shear buildings and also their equivalent SDOF models are considered to investigate the effect of SSI on strength and ductility demands of both MDOF and E-SDOF systems. In this regard, for a given earthquake ground motion, a family of nearly 4300 different soil-structure models including MDOF as well as E-SDOF models and various predefined key parameters are considered. This includes MDOF and E-SDOF models with 30 fundamental periods of fixed-base structures, ranging from 0.1 to 3 sec with intervals of 0.1, two values of aspect ratio ($\bar{H}/r$ =1, 3), four values of dimensionless frequency (a_0 = 0, 1, 2, 3), and three values of target interstory displacement ductility ratio (μ_t = 1, 2, 6) where μ_t =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. For each earthquake ground motion, the total normalized elastic and inelastic shear strength of the MDOF and E-SDOF system are computed by an iterative procedure in order to reach the μ_t in the structure, as a part of the soil–structure system, within a 0.5% error:

To investigate the effect of SSI on the ductility demand of the MDOF and E-SDOF structures the common procedure is utilized. First the elastic and inelastic total shear strength, as representatives of elastic and inelastic strength demands, for each of MDOF and E-SDOF systems without considering the effect of soil beneath them are computed to reach a presumed target ductility ratio, μ_t , when subjected to a designated earthquake ground motion. Subsequently, using the same total shear strength of the fixed-base structure, the ductility demand of the soil-structure system with different values of a_0 is computed to investigate the SSI effects. The effect of SSI on ductility demands of MDOF and E-SDOF systems can then be investigated by comparing the difference between the ductility demand of the fixed-base model and that of the soil–structure system. This comparison reflects the controversial point existing in conventional design methodology such that if a predesigned fixed-base model is to be located on flexible soil, based on reality, what structural behavior maybe expected?

5. EFFECT OF SSI ON STRENGTH DEMANDS OF MDOF AND E-SDOF SYSTEMS

6.1. Strength demands for E-SDOF systems corresponding to different number of stories

A series of different E-SDOF soil-structure systems corresponding to the first-mode shape of 5-, 10- and 15-story buildings are analyzed to compare the elastic and inelastic strength demands of different SDOF soil-structure systems subjected to an ensemble of 21earthquake ground motions with different characteristics recorded on alluvium and soft soils 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). As an example, the average values of strength demand for three different E-SDOF soil-structure systems, i.e. E-SDOF of 5-, 10- and 15-story buildings, are depicted in Figure 2. The results are shown for E-SDOF soil-structure systems with aspect ratios of 1 for dimensionless frequency *a0* = 2 as well as for three values of target interstory displacement ductility ratios (μ_t = 1, 2, 6). The abscissa in all figures is considered to be as the first-mode period of the fixed-base structure, T_{fix} , and the vertical axis is strength demand normalized by the total structural mass times PGA for each earthquake ground motion. It can be clearly seen that the strength demands of E-SDOF systems are independent of the number of stories such that all the strength demand curves for E-SDOF soil-structure systems corresponding to the 5-, 10- and 15-story buildings are completely coincident. The reason of this similarity goes back to the first-mode shape of the shear buildings which is independent of the number of stories as illustrated in Figure 3. The figure is plotted to compare the normalized first-mode shape of the fixed-base shear buildings for three presumed number of stories with two different target periods, T_{fix} =1 and 3 sec. As seen, for each presumed target fundamental period, the normalized mode shapes of all three MDOF shear buildings are completely coincident and hence not dependent on the number of stories. It is important to note that this result is true when (1) total structural mass is uniformly distributed along the height of the structures and (2) lateral stiffness in all MDOF buildings with different number of stories is distributed based on the same specified pattern which here is IBC load pattern.

6.2. Strength demands for MDOF and E-SDOF soil structure systems

Here the effects of SSI on total strength demand for both E-SDOF and MDOF soil-structure systems are studied and compared with each other. Figure 4 is provided to illustrate the difference between the strength demands of E-SDOF and associated MDOF models for both fixed-base and soil-structure systems. The results are provided for E-SDOF and three MDOF systems (*N*=5, 10 and15) with $\bar{H}/r$ = 3, and for two different dimensionless frequencies, a_0 = 1, 3 as well as for fixed-base structures. As seen, for elastic state, i.e. μ_t = 1, except for short periods, the values of strength demands increase as the number of stories increases. This trend is intensified by increasing the value of a_0 such that for the severe SSI effect (a_0 =3), the difference between the strength demands of E-SDOF system and those of the corresponding 15-story building increases remarkably. In the inelastic state, however, the trend is somewhat different in a way that; (1) nearly in all periods, especially for higher level of inelasticity, strength demand increases as the number of stories increases, but the rate of increment becomes smaller with the increase of the number of stories; and (2) as the level of inelasticity increases the difference between the strength demand values of E-SDOF systems and those of the corresponding MDOF buildings for the case with strong SSI effect with a_0 =3 reduces. It should be noted that although for the case of a_0 =3, the growth rate of strength demands with increasing the number of stories reduces as structure undergoes more level of inelasticity, it is still significant particularly when the strength demands of MDOF systems are to be compared with those of the associated E-SDOF systems. In addition, the ductility demand for MDOF systems is conventionally referred to as the greatest value among all the story ductility ratios, hence the values of ductility ratios in all other stories are lower than the presumed target ductility value. This may result in having a greater strength demand when compared to the same MDOF building in which all stories have identical ductility ratio values equal to presumed target value.

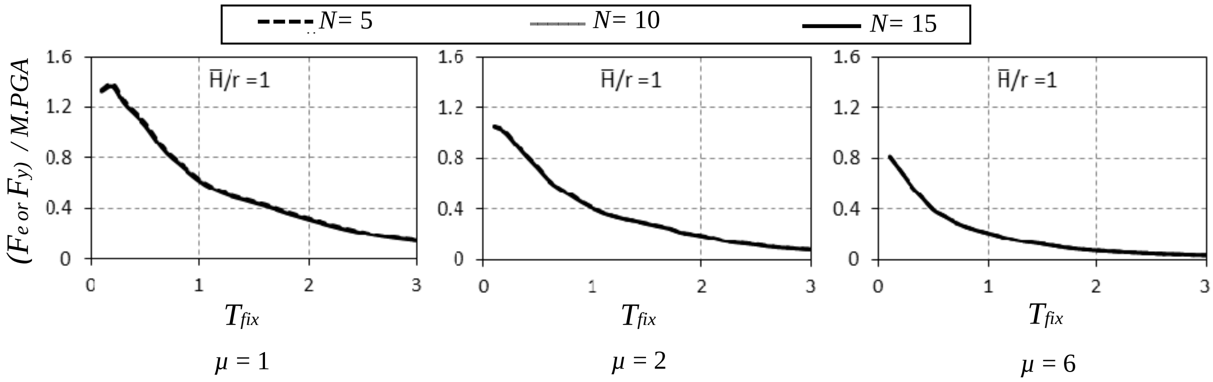

Figure 2. Comparison of the averaged elastic and inelastic strength demand for different E-SDOF system with soil-structure interaction (a0= 2)

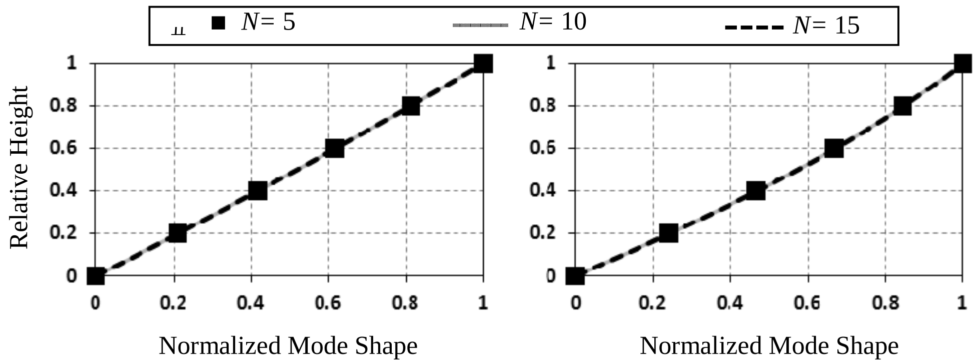

Figure 3. Comparison between first-mode shape for different number of stories: (Left) T=1 and (Right) T=3

6. EFFECT OF SSI ON DUCTILITY DEMAND OF MDOF AND E-SDOF SYSTEMS

The procedure outlined in Section 5 is used here to investigate the effect of SSI on ductility demand of E-SDOF and MDOF building structures. Figure 5 shows the averaged ductility demand spectra of all ground motions used in this study for the structural model with $\bar{H}/r$ = 3. Results include inelastic ductility demand spectra for three values of dimensionless frequency, a_0 = 1, 2, 3, all for both MDOF and E-SDOF soil-structure systems. The vertical axis in all plots is the ratio of ductility demand in flexible-base structures to that of the fixed-based structure. As seen, the results of MDOF structures are different from those of the corresponding E-SDOF systems such that the results can be classified into two parts; first, the set of curves associated with low value of dimensionless frequency (a_0 = 1); second, the curves corresponded to the large amount of dimensionless frequency (a_0 = 2, 3) which are the representatives of the cases with substantial SSI effects. For the E-SDOF systems, irrespective of the dimensionless frequency or the level of inelasticity, there is a threshold period before that the ductility demand of the structure with SSI is larger than that of the fixed-base one; subsequently, this tendency is reversed. The larger is the dimensionless frequency, the greater is the difference between the ductility demands of the fixed- and flexible-base systems. The results for E-SDOF systems are compatible with recent studies carried out in SDOF systems by Ghannad and Ahmadnia (2006), and Mahsuli and Ghannad (2009). The variation of ductility demands for MDOF systems, however, can be completely different from that of the E-SDOF systems depending on the amount of dimensionless frequency as well as the level of inelasticity. It can be observed that for MDOF systems with $a_0 = 1$, i.e., the curves related to the first column in Figure 5, the ratios of ductility demands in almost all periods are greater than unity. Also, this trend is intensified as the number of stories increases, which is more obvious for the case of 15-story building. Looking at the second and third columns of the same figure which are associated to the cases with significant SSI effects ($a_0 = 2, 3$), it can be seen that although like E-SDOF systems there is still a threshold period before and after that the ratios of ductility demands are respectively greater and lower than unity, the trend do not continue for the longer period like E-SDOF systems in a way that for MDOF systems after reaching to a minimum level, the ratio again rises as period increases.

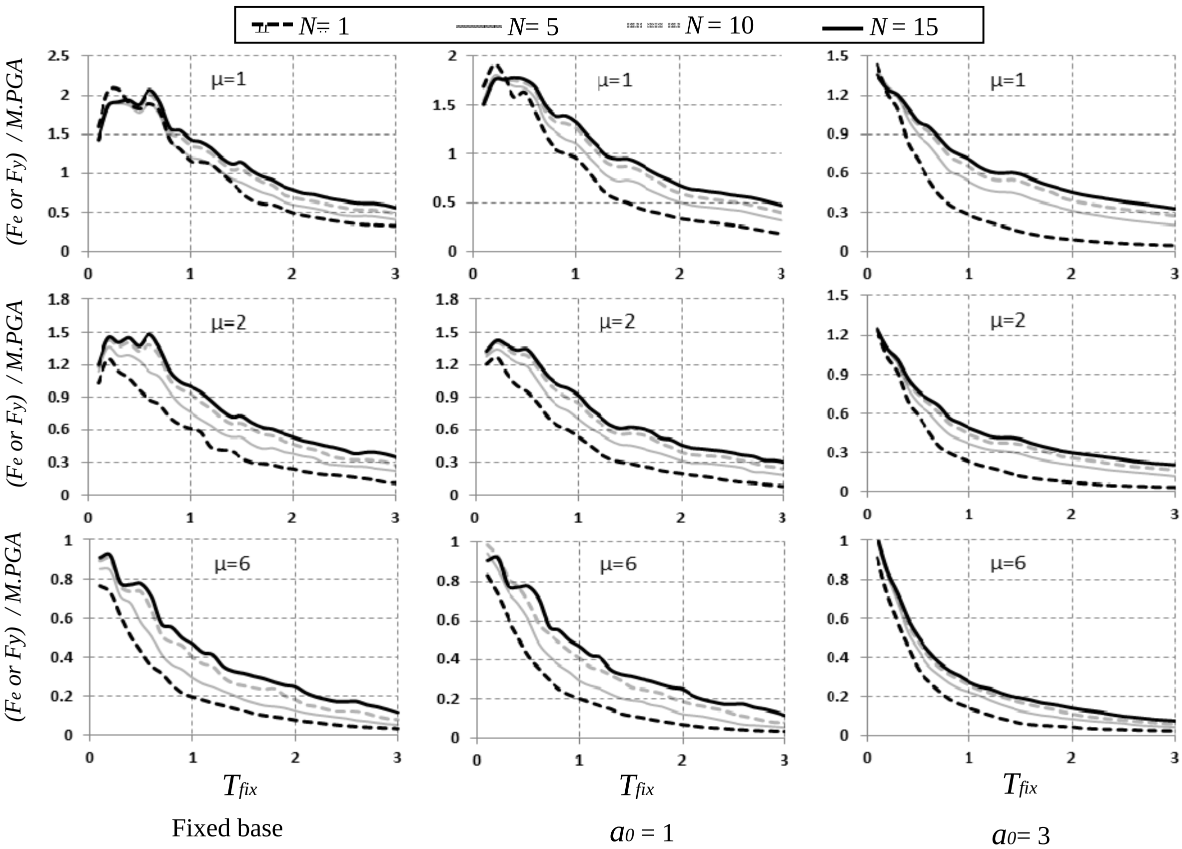

Figure 4. Effect of number of stories on the averaged elastic and inelastic strength demand of fixed-base and soil-structure systems for $\bar{H}/r = 3$

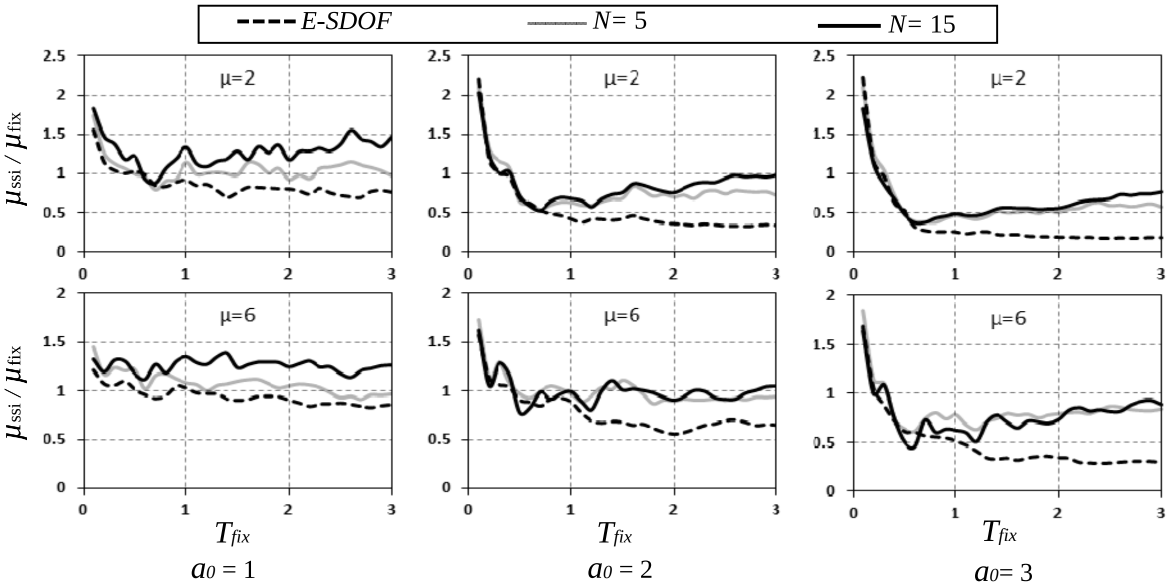

Figure 5. Averaged ductility demand for different SDOF and MDOF soil-structure systems for $\bar{H}/r$ = 3

7. CONCLUSION

An intensive parametric study was carried out to investigate 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. It was demonstrated that strength and ductility demands of MDOF soil-structure systems depending on the number of stories, dimensionless frequency and level of inelasticity can be much different from those of the corresponding equivalent SDOF ones. Results of this study show that E-SDOF systems cannot accurately estimate the strength and ductility demands of MDOF soil-structure systems, especially for the cases of mid- and high-rise building, due to their higher mode and number of DOFs effects. In addition, For the E-SDOF systems, irrespective of the dimensionless frequency or the level of inelasticity, there is a threshold period before that the ductility demand of the structure with SSI is larger than that of the fixed-base one; subsequently, this tendency is reversed. However, for MDOF systems with less SSI effect, i.e., lower dimensionless frequency, the ratios of ductility demands in almost all periods are greater than unity, and will increase for slender structures as the number of stories increases. For the cases of the predominate SSI effects, although like E-SDOF systems there is still a threshold period before and after that the ratios of ductility demands are respectively greater and lower than unity, the trend do not continue for the longer period like E-SDOF systems in a way that for MDOF systems after reaching to a minimum level, the ratio again rises as period increases.

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