Effect of Soil-Structure-Interaction on Inelastic Displacement Ratios of Existing Structures

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ABSTRACT

The computation of Inelastic Displacement Ratios (IDRs) in different structural types and site conditions has been attracted numerous studies in the past. Those studies usually were performed through a nonlinear time history analysis of a SDOF oscillator, which is assumed to be fixed at its base. There are multitude relations for calculating this ratio denoted by C_R in cases with known values of strength reduction factor or C_μ in cases with known ductility ratios. However, all of them exclude Soil Structure Interaction (SSI) effects. In fact, it should be mentioned that although numerous investigations have been carried out to consider (SSI) in elastic structures, the aforementioned effect in inelastic structures is not enough clear yet. If the structure with nonlinear hysteretic behavior is located on a flexible foundation, the inelastic behavior of the structure will be completely different to from that of fixed at its base. To evaluate this, multiple levels of strength reduction factor or target ductility as well as diverse values of SSI indexes are considered to provide a comprehensive parametric study. It should be noted that the results could be implemented in *Coefficient Method* of FEMA-356, newly modified in FEMA-440 where the effect of SSI in such inelastic structure is under investigation. In fact, a different approach than to FEMA-440 is explained here that exerts SSI effects on IDRs, while the concept of such documents is to convert Soil-Structure System to an equivalent fixed base oscillator and then use IDRs determined for fixed base assumption. The SSI model used in this paper is fundamental lumped parameters based on the concepts of cone models representing the soil with a 3-DOF system, which is capable of involving frequency dependency of soil. All of the analyses are performed in response spectra format. That is, it can be implemented for MDOF systems responding through their fundamental mode of vibration for a wide range of ordinary structures and soil conditions.

KEYWORDS: soil structure interaction, inelastic displacement ratio, strength reduction factor, soft soil site, Nonlinear Static Procedure, Coefficient Method.

1. INTRODUCTION

Current procedures for estimating seismic demands are based on the estimation of maximum displacement demands of inelastic SDOF systems determined by pushover analysis. For instance, FEMA-356 and FEMA-450 are two documents employing nonlinear static procedures so called respectively *Coefficient Method* to estimate the target roof displacement.

IDRs labeled by C_1 are defined in Coefficient Method to relate expected maximum inelastic displacement to displacement computed from linear elastic analysis. This parameter is shown by C_R in some references as well.

IDRs were first studied by Veletsos and Newmark (1960). With considering two approaches: equal-displacement rule (in displacement and velocity sensitive parts of the spectra) which the inelastic displacement is assumed to be its elastic displacement; and equating the strain energy for elastic and inelastic systems, leading to $C_\mu = \mu/\sqrt{2\mu-1}$ where μ is ductility demand of structure. On the other hand, with implementation of statistical analysis over large ensembles of ground motions, numerous investigations were performed for different types of hysteretic behavior of SDOF systems and wider range of periods of vibration. The effect of epicentral distance, earthquake magnitude, and type of firm site classes are investigated later by Chopra & Chintapankdaee (2004) and Ruiz-Garcia and Miranda (2003). More recently elaborate investigations for the C_R coefficients in soft soil sites have been done by Ruiz-Garcia and Miranda (2006), where as the IDRs have a relative minimum values at about their predominant ground motion period (T_g) ranges, the authors proposed that the periods should be normalized by T_g in order to decrease the dispersion of statistical analysis results.

Nevertheless, the effects of Soil Structure Interaction on IDRs have not been investigated yet. In fact, although SSI effects in elastic system have been investigated in the past, its effects in yielding systems have recently been attracted some researchers.

By defining equivalent nonlinear fixed base oscillator for soil structure system, Aviles and Perez-Rocha (2003, 2005) studied in this matter elaborately and proposed a procedure to modify NEHRP standard in the soil structure systems. Also Ghannad and Ahmadinia (2006), and Ghannad and Jahankhah (2007) performed a parametric studies and revealed the importance of SSI on inelastic behavior of structures. In recent aforementioned studies, the authors indicated that the Strength Reduction Factor (R) of structure with fixed base assumption or with including its foundation flexibility has a remarkable difference. However, these investigations were not directly addressed for existing structures where the strength reduction factor of structure is known. Also, no clear regulation or relation was proposed in Nonlinear Static Analysis procedures for soil structure systems.

Back to rehabilitation documents up to FEMA-440, the effect of SSI were confined to replace fixed base foundation with foundation located on springs representing soil stiffness and to perform pushover analysis of this flexible base system. Other parts of the procedure for soil structure systems had no difference to when the structure is assumed fixed at its base. But, some modifications were performed to include the foundation damping in the analysis process in FEMA-440. This modification is based on the formulations of Veletsos and Nair (1975), which were derived from linear elastic assumption of the structure. In Behmanesh (2008), validity and accuracy of FEMA-440 is studied and it was declared that the modification is required when the structure overtakes its inelastic displacements. It was also revealed that the Coefficient Method of FEMA-440 do not lead to acceptable results for soil structure systems in soft soil sites. Indeed, the relation that was proposed for inelastic displacement ratios (C_1) is basically valid for fixed base structure built on firm sites. As it could be implemented from above explanations, traditional approach of standards on including SSI, like FEMA-356,440 and 450 or ATC-40, is to change the soil structure system to an equivalent fixed base oscillator with equivalent dynamic properties and exert all the relations and regulations derived for fixed base type of structures in order to make the computations easier. But, when the inelastic behavior of structure should be considered, this equivalent system seems to be reconsidered, which was done by modifying foundation damping in FEMA-440. The equivalent damping ratio is defined by ductility ratio of an equivalent oscillator as well as period of structure, period of soil structure system, and slender ratio of the building, which are key parameters for determining damping ratio in elastic systems. Therefore, the procedure has a great loop since the ductility is unknown and it is computed at the end of the analysis. On the other hand, in case the soil structure system is converted to its equivalent fixed base oscillator, other parameters like C_1 in Coefficient Method or effective period and effective damping of Equivalent Linearization Method could be used here. The pushover analysis should be performed by flexible base modeling of systems, where it is more difficult than fixed base modeling even for commercial softwares. The displacement computed at the end of the analysis is comprised of soil movements as well; whereas, the structural displacement control acceptance criteria depend on structural displacements.

The approach of this paper is based on evaluating IDRs in a manner that contains SSI effects. Thus by means of solving a linear elastic soil structure system which is accurate enough for engineering purposes (Veletsos and Nair (1975)), inelastic demands will be determined directly with no such a trial procedure proposed by FEMA-440. In addition, the relations could be set in a manner that pushover curves need to be developed for fixed base structures which is easier to model and analysis.

2. SOIL STRUCTURE MODEL

A simplified model shown in Figure-1 is employed to compute exact objective parameters. The structure is an elasto-plastic SDOF system with stiffness k and period T. m and h are lumped mass and height of the structure, which can be extended to the effective mass and height of MDOF structures. The mass moment of inertia is labeled I. Moreover, the foundation is assumed as a circular disk.

The soil beneath the foundation is considered as a homogeneous half space and is modeled by Fundamental Lumped Mass Parameters based on the concepts of Cone Models, extended by Wolf (1994), representing the soil with a three DOF system. This model, with fixed parameters, is capable of including frequency dependency of dynamic soil stiffness.

The response of a soil structure system generally depends on the size of the structure, its dynamic properties, soil profile, and the applied excitation. The influence of these factors can be described by the following non-dimensional parameters; a non-dimensional frequency as an index for structure to soil stiffness ratio defined as $a_o = \frac{2\pi h}{T v_s}$, where T is the period of the structure in its fixed base condition. The practical range of a_o for ordinary building type structures is from zero for the fixed base structures; to about three for cases with dominant SSI affects; aspect ratio of the structure, defined as $S = \frac{h}{r}$; ductility demand of structure $\mu = \frac{u_m}{u_y}$, where u_m and u_y are the maximum displacement due to specific base excitation and the yield displacement, respectively; structure to soil mass ratio index, $\tilde{m} = \frac{m}{\rho r^2 h}$, where ρ is the unit weight of the soil. $\tilde{m}$ is taken to be 0.47; the ratio of the mass of the foundation to that of the structure is defined as $\tilde{m}_f = \frac{m_f}{m}$. We assume it to be 0.1 in all parts of our analysis; poison's ratio of soil, υ, chosen 0.5, in that our time histories were recorded on soft soil sites; material damping of the soil and the structure. We set damping ratio of the structure to 5% as is usual, but the damping ratio of the soil to be zero, mass moment inertia I and I_f taken as $\frac{1}{4} m r^2$ and $\frac{1}{4} m_f r^2$ respectively for simplicity.

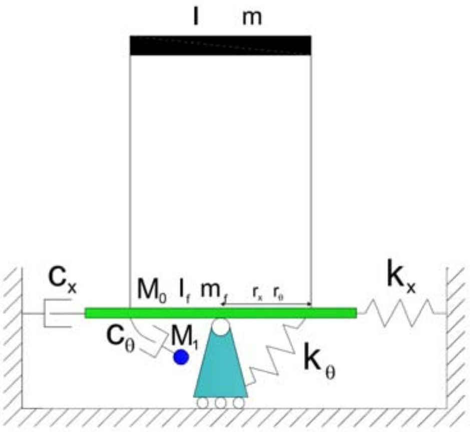


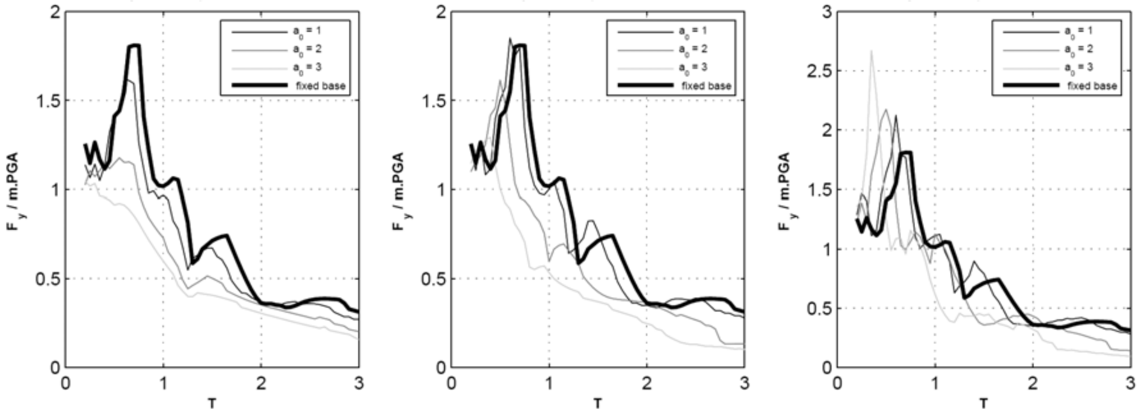
Figure-1 Soil-Structure System

3. GENERAL EFFECTS OF SSI ON INELASTIC STRUCTURAL DEMANDS

Effects of SSI on inelastic demands are investigated on 4 formats; on strength demands of the structure at target ductility level of the structure, on inelastic displacement demands of the structures at target strength reduction factor, and on ductility demands of the structures at constant strength of the structure.

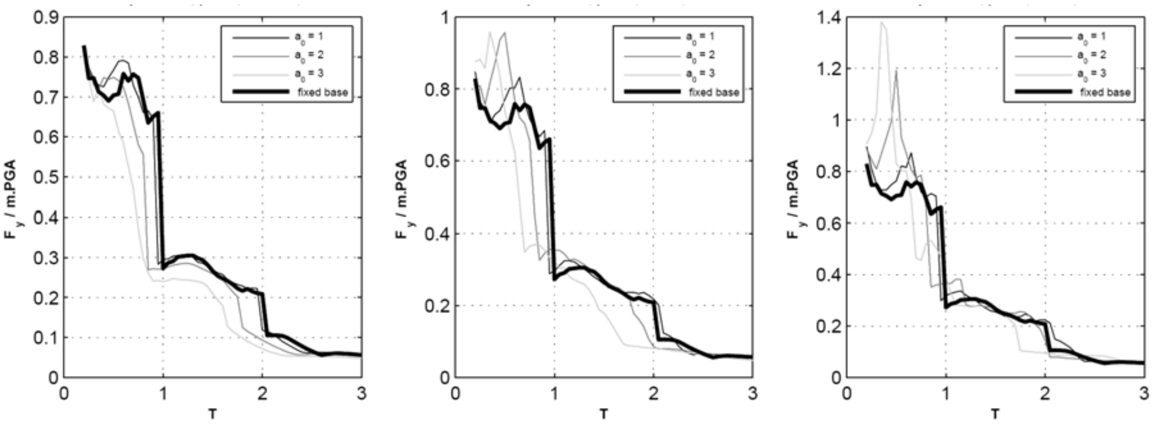
3.1. Effect of Inertial SSI on Strength Demands of Structures at Target Ductility Level

For preassigned ductility level of the structure, the system explained in part 2 is analyzed for its strength demands. The results for earthquake Loma Prieta (1989), recorded at station 58375, at target ductility levels of 2 and 6 are depicted in Figure-2 and Figure-3 respectively.



(a) $S = 0.5$ (b) $S = 1.0$ (c) $S = 2.0$

Figure-2 the effect of SSI on strength demands of the structure at structural ductility level of $\mu = 2$



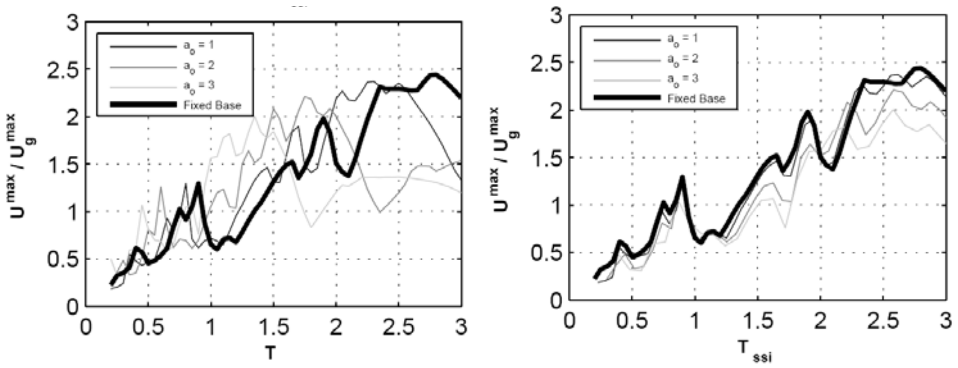
(a) $S = 0.5$ (b) $S = 1.0$ (c) $S = 2.0$

Figure-3 the effect of SSI on strength demands of the structure at structural ductility level of $\mu = 6$

The graphs declare that although SSI decreases the strength demands of the structure in long period ranges, it has detrimental effects for short period ranges especially for higher values of slenderness ratios. Actually for squatty structures, the SSI effects would decrease the strength demand in the whole parts of the spectra. Moreover, not only SSI effects change the demands remarkably especially in short period structure with higher values of slenderness ratios, but also its detrimental effects would be worse by increasing a_o which could be implemented as the influence of SSI in the system's responses.

3.2. Effect of Inertial SSI on Displacement Demands of Structures at Target Strength Reduction Factor

In design procedures, the designer is looking for an appropriate strength and stiffness for the structure to reach and fulfill the ductility and displacement expectations of the structure, while in rehabilitation procedures with known strength and stiffness, the ductility and displacement of the structure determine the performance level of the structure and its corresponding rehabilitation objective. Therefore, to clarify the effects of SSI for existing structures, the displacement demands of the structure with constant strength reduction factor, defined by equation (3.1), are derived for different sets of soil-structure conditions. In equation (3.2), $\tilde{F}_m$ is the maximum force of structure analyzing in flexible base modeling and $\tilde{F}_y$ is the strength or yield force of the structure determined from pushover analysis.



(a) (b)

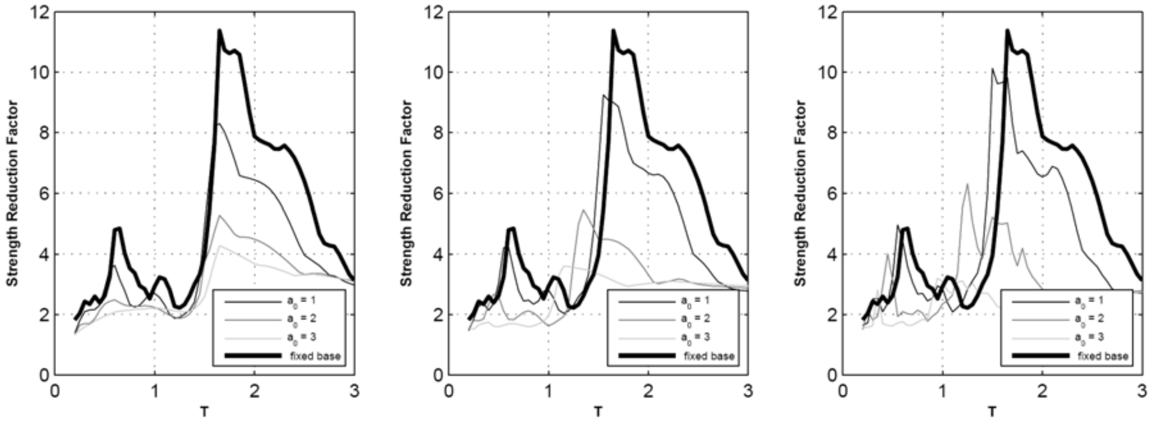
Figure-4 Effect of SSI in the displacement demands for $S = 2$ condition at $R_{ssi} = 4$

Figure-4a shows that SSI effect could increase or decrease the inelastic displacement demands in different parts of the spectra, while when the results would be depicted with respect to soil-structure period derived by relation (4.2) it could be implemented that the SSI almost always has beneficial effects on inelastic displacement demands. The graphs show almost the acceptability of T_{ssi} as the equivalent period for inelastic systems and consequently the equivalent damping that should be determined in order to cover the differences. The parameter U_g^{max} is the maximum ground displacement and U^{max} is the maximum inelastic displacement of the structure.

$$T_{ssi} = T\sqrt{1+\frac{k}{k_x}\left(1+\frac{k_x\bar{h}^2}{k_\theta}\right)} \tag{3.1}$$

$$R_{ssi} = \frac{\tilde{F}_m}{\tilde{F}_y} \tag{3.2}$$

However, it should be mentioned that through the previous studies, Aviles and Perez-Rocha (2005) and also Ghannad and Jahankhah (2007), the SSI has also a notable influence on strength reduction factor that makes the aforementioned conclusion complex. In the other words, it is not true to compare fixed base system and flexible base system at constant R_{ssi}. As depicted in Figure-5 for earthquake Loma Prieta (1989), recorded at station 58472, this parameter is sensitive to the SSI indexes listed in part 2 of this paper; this coefficient would be subsided by increasing soil interaction especially around predominant ground motion period.

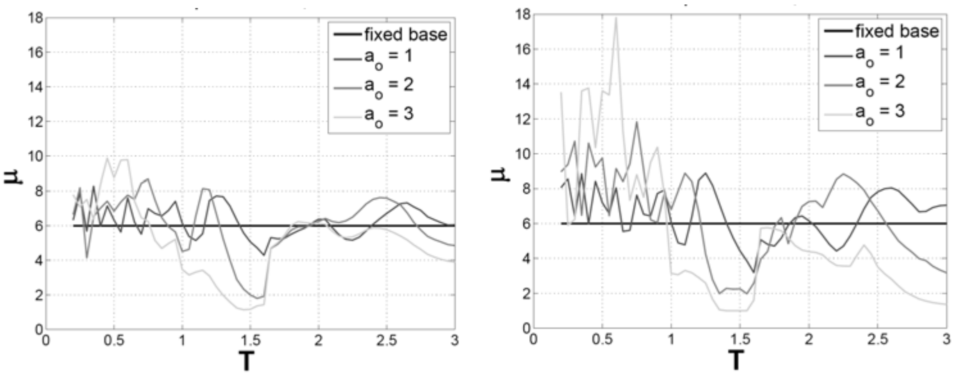


(a) $S = 0.5$ (b) $S = 1.0$ (c) $S = 2.0$

Figure-5 the effect of SSI on strength demands of the structure at structural ductility level of $\mu = 4$

3.3. Effect of Inertial SSI on Ductility Demands of Structures at Specific Strength of the Structure

This is the most enlightening effects of the SSI especially in rehabilitation procedures. The strength or yield force of the structure in its fixed base assumption model is defined the strength of the structure located at flexible foundation with structural dynamic properties as assigned for its fixed base assumption but different soil status. The displacement and ductility demands of such system would disclose the importance of the SSI in the analysis of inelastic systems. The results for earthquake Loma Prieta (1989), recorded at station 58472, at ductility level $\mu = 6$ are depicted in Figure-6. Ignoring SSI would lead to notable unconservative results in short period ranges, conservative at periods near the predominant ground motion period, and moderate influence in other periodic ranges. The situation is going worth with increasing a_o and S. Analysis for other time histories and sets of non-dimensional coefficient were leaded to similar results.



(a) $S = 1.0$ **(b)** $S = 3.0$

Figure-6 Importance of SSI on inelastic displacement demands

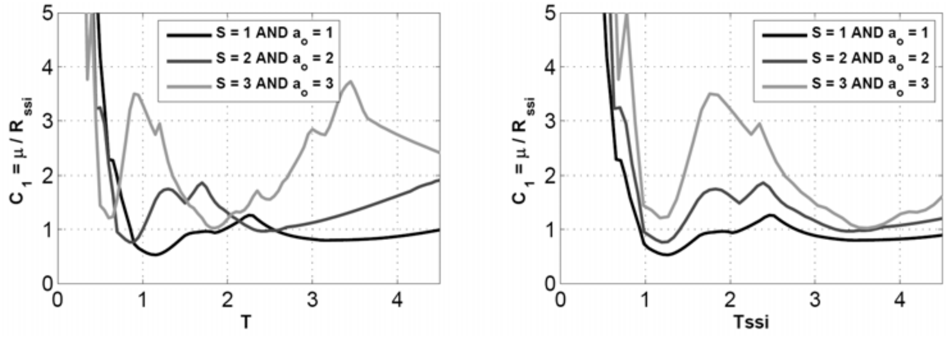
4. EFFCTS OF SSI ON INELASTIC DISPLACEMENT RATIOS OF EXISTING STRUCTURES

As discussed previously in introduction, in current Nonlinear Static Procedures like FEMA-440, or FEMA-356 the so called Coefficient Method is employed in order to calculate the maximum inelastic displacement of the structure. The procedure used in these documents are based on converting the soil-structure system to its relevant fixed base oscillator by pushover analysis of flexible base model and then use the IDRs derived from fixed base assumption. In this part of the paper, the effect of SSI in these values and the importance of key parameters would be discussed. The IDRs of soil-structure system would be defined by equation (4.1). In the equation μ, U^{max}, and U are the ductility, maximum inelastic, and maximum elastic displacement of structure in soil structure system respectively.

$$C_1 = \frac{\mu}{R_{ssi}} = \frac{U^{max}}{U} \tag{4.1}$$

4.1. Importance of Lengthened Soil-Structure Period

In Figure-7a, the values of inelastic displacement ratio for the earthquake Loma Prieta (1989), station 1002 (USGS), are depicted in three configurations displayed with respect to the period of structure. It can be seen that there is no harmony between these graphs. But, if they are depicted with respect to the period of soil-structure system (T_{ssi}), as shown in Figure-7b, the general trend would be identical.



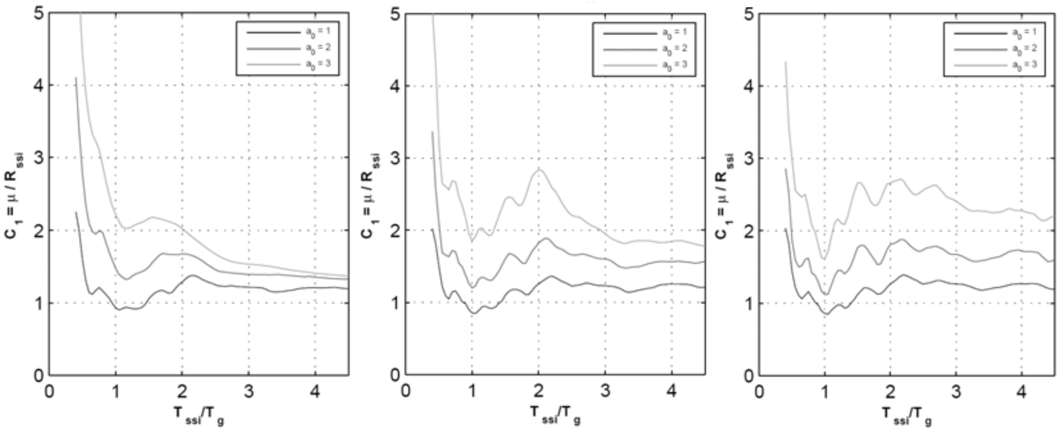
(a) **(b)**

Figure-7 the role of natural soil-structure period on statistical study, $R_{ssi} = 4$

It could be implemented that the IDRs of soil-structure systems are remarkably larger than those derived for fixed base assumption of the structure. Actually the “equivalent displacement rule” proposed for fixed base structure by Veletsos and Newmark (1960) are not valid for soil-structure systems. The other important point of the curve is that through a study by Ruiz-Garcia and Miranda (2006) the IDRs values have a relative minimum around their predominant ground motion period. This relative minimum in soil structure system would occur when the soil-structure period is close to predominant ground motion period. Therefore, in order to propose a general relation for C_1 in soil-structure systems by statistical analysis, the authors believe that the analysis should be performed with normalizing the period of the soil structure system to the predominant ground motion period.

4.2. Importance of Non-Dimensional Frequency, a_o

In order to evaluate the influence of this ratio, which could be inferred as the severity of SSI on system's response, the average values of IDRs over 20 ground motions recorded on soft soil condition is determined at specific strength reduction factors and slenderness ratio. The ground motions are almost those indicated in Appendix-C of FEMA-440 for site class E. Figure-8 show the effects of a_o at three different values of $S = 1, 2, 3$ at $R_{ssi} = 3$. At any periodic ranges the IDRs would increase by increasing a_o. The IDRs are almost always greater than unit even for $a_o = 1$ (except when $T_{ssi} = T_g$) that indicate that the difference between inelastic and elastic displacement in soil-structure system is much more than its difference when the structure assumed fixed at its base. Although caution should be taken that it does not mean that the displacement demands are higher when considering SSI, that is the elastic displacement of the structure which the target inelastic displacement of system is calculated by multiplying it to C_1 is less than when considering SSI. Moreover, the general trends of the IDRs for $S = 2$ and $S = 3$ are more similar to each other that when $S = 1$.

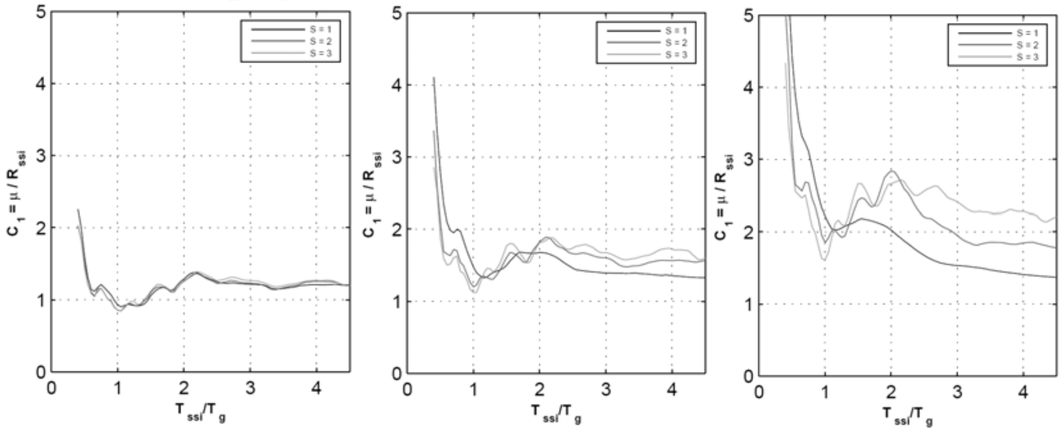


(a) $S = 1$ (b) $S = 2$ (c) $S = 3$

Figure-8 the effect of a_o on IDRs at Strength Reduction Factor of $R_{ssi} = 3$

5.3. *Importance of Slenderness Ratio,* S

The values of IDRs of structures at specific a_o with three different values of S are depicted in Figure-9. In contrast with the Figure-8 trend, there is no such a harmony behavior produced at constant slenderness ratios. Indeed, in some of the periodic ranges, about $T_{ssi} \leq 1.2T_g$, IDRs would decrease with increasing S and conversely for remained parts of the spectra. Furthermore, the sensitivity of the results to S is much less than their sensitivity to a_o; in $a_o = 1$ condition there can be seen no differences between different values of slenderness ratios.



(a) $a_o = 1$ (b) $a_o = 2$ (c) $a_o = 3$

Figure-9 the effect of S on IDRs at Strength Reduction Factor of $R_{ssi} = 3$

8. CONCLUSION

By developing a 4-DOF system, a parametric study is performed to investigate the effect of inertial SSI on inelastic displacement demand and its implementation in current Nonlinear Static Procedures: *Coefficient Method*, which is conceptually derived and extended for structures assumed fixed at their base. The ductility ratios of structure with specific strength when assumed fixed at its base are different from when the flexibility of the foundation is included. This fact revealed the importance of SSI on inelastic displacement demands.

Although current documents on Coefficient Method include SSI effects by defining equivalent period and damping ratio for its equivalent fixed base oscillator and calculate consequently its displacement demands by relations and equations derived for an equivalent fixed base oscillator, the approach employed in this investigation is based on finding inelastic displacement ratios of structures including SSI effects. Proposed procedure is both more accurate and easier to use in practice than the procedure proposed in the last document on this issue: FEMA-440.

The IDRs have significant difference to those determined in firm site classes and soft soil classes when the SSI effects are ignored. The results revealed that equal displacement rule is not valid in Soil-Structure systems and the inelastic displacement of structure is much larger than its relevant elastic displacements in almost whole periodic ranges. It was declared that the sensitivity of the results to a_o is much more than their sensitivity to S. The IDRs would increase with increasing a_o but their behavior for changing the S is depend on the periodic ranges. For system's period about $T_{ssi} \leq T_g$, increasing S leads to decrease IDRs and converse trend for other parts of the spectra.

This idea could be implemented in NSPs of FEMA-440, to refrain from the trial procedure indicated for equivalent damping ratio. Also employing this approach could refrain the engineer from performing pushover analysis of flexible base structure, the procedure of current documents like FEMA-356 and ATC-40. The nonlinear demands could be calculated from pushover analysis of fixed base structure only which is less time consuming and practical.

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