Soil-Structure Interaction Effects on Seismic Behavior of Base-Isolated Buildings

Erfan Alavi
PhD, Structural Engineering Department, Sazeh Consultants Co., P.O. Box 11365-4591,Tehran, Iran; International Institute of Earthquake Engineering and Seismology, IIEES. E-mail: e.alavi@sazeh.co.ir ; e.alavi@iiees.ac.ir

Mojtaba Alidoost
Msc, Structural Engineering Department, Sazeh Consultants Co., Tehran, Iran; Sharif University of Technology. E-mail: m.alidoost@sazeh.co.ir

SUMMARY:
The present study attempts to estimate the effects of SSI on base-isolated buildings founded on the different soil types. Four base-isolated buildings with 2, 4, 7, and 10 stories are selected and designed preliminarily with ignorance of the soil interaction effects. The fundamental period of each base-isolated building (T_D) is taken variable as 1.6, 2, and 2.5 seconds. The super-structure, above the isolators, is modeled as a lump mass with equivalent spring stiffness and damper. The isolators are also modeled in the analysis, based on the stiffness and damping characteristics. Dynamic response spectrum analyses are performed on the fixed and SSI base-isolated models. The results indicate that on the very stiff soil (Vs > 375m/s), the SSI has negligible effects on the responses (< 5%) for the all base-isolated models, however, on the softer soil whatever the base-isolated building is stiffer, less T_D , the soil interaction effects will become larger. Furthermore, on the soft soil (Vs < 200 m/s), the effectiveness of SSI models increases and the responses decrease (> 10 %). By increasing the aspect ratio of H/r, the height to equivalent radius of foundation, the effects of rocking action and consequently SSI on the responses will increase; this matter for relatively tall base-isolated buildings on the soft soil is more significant.

Keywords: soil-structure interaction, SSI, base-isolated, seismic, building

1. INTRODUCTION

Soil-structure interaction, SSI, sometimes plays an important role, especially for massive structures constructed on the relatively soft soil, which may alter the dynamic characteristics of structural responses. In the usual type of structural analysis, soil-structure interaction is neglected and the structural responses are just accounted for. The history of studies on SSI subject returns to the late 1970s, despite, the soil flexibility effects on the vibrating systems like machine foundations had previously attracted the attention of a number of researchers. The first areas, which were seemed to have considerable influence of SSI on the structural response, were nuclear power plants, as studied by Idriss et al. (1979) and Johnson (1981). During the recent decades, extensive researches have been conducted regarding the effects of soil-structure interaction (SSI) on the seismic responses of the structures. It was found that the interaction between soil and structure results in a decrease of the fundamental frequency of the response and a modification in the energy dissipation, which is attributed to radiation and material damping in the soil, Johnston (2003).

The common practice usually ignores effects of SSI on seismic behavior of base-isolated structures, accounting on the flexibility of base-isolated buildings, despite, the recent studies on the base-isolated bridges and structures have shown the effectiveness of SSI on seismic responses of the systems. Hence, not only for the seismic design but also from economical aspects, SSI might be necessary to be considered in the design of a base-isolated building. The coupled effect of SSI and the base isolation on structures has gained the interest of a number of researchers during the recent years. Soil-structure interaction has been mainly considered for base-isolated bridges and liquid storage tanks. In the following, a brief review on the main studies in this field is presented.

Constantinou and Kneifati (1986) proposed an energy method to estimate the damping of seismically isolated structure, taking into account the energy dissipation of the bearing and the radiation damping in the soil. Novak and Henderson (1989) investigated the modal properties of base-isolated structures and concluded that, when the flexibility of soil and isolators are comparable, the contribution of SSI should not be ignored. Kelly (1991) carried out an experimental study concerning base-isolated nuclear facilities founded on soft-sites, led to the conclusion that the isolator design should be taken into the account for significant displacement demands. Spyrakos and Vlassis (2002) assessed the effects of SSI on the response of base-isolated bridges by a parametric study. They derived analytical expressions to demonstrate the significance of SSI phenomena in influencing the response of the isolated system. Tsai et al. (2004) developed a time-domain procedure to investigate the efficiency of isolators to reduce the energy imported in an FPS-isolated building for earthquake motion. Both radiation damping and foundation flexibility were found to be essential in the accuracy of response prediction and safety of the isolated structure. Spyrakos and Maniatakis (2009) studied on effects of soil-structure interaction on the response of base-isolated 4-DOF located on an elastic soil layer overlying rigid bedrock and subjected to a harmonic ground motion. Initially, a four degree of freedom system was developed and the equations of motion were formulated in the frequency domain. Frequency independent expressions were used to determine the stiffness and damping coefficients for the rigid surface foundation on the soil stratum underlined by bedrock at shallow depth.

The present study focuses on effects of SSI on base-isolated buildings founded on the different soil types, to evaluate quantitatively as well as qualitatively the seismic responses of the combined system. In that regard, four base-isolated buildings with 2, 4, 7, and 10 stories are selected and designed preliminarily with ignorance of the soil interaction effects. The fundamental period of each base-isolated building (T_D) is taken variable as 1.6, 2, and 2.5 seconds to cover the common base-isolated buildings and to study the effects of the super structure relative stiffness to soil in the responses. The height of the structures is taken variable to evaluate the dependency of the responses to the aspect ratio and the rocking actions of the buildings. Super-structure, above the isolators, is modeled as a lump mass with equivalent spring stiffness and damper. The isolators are also modeled in the analysis, based on the stiffness and damping characteristics. Dynamic response spectrum analyses are performed on the fixed and SSI base-isolated models and the responses are obtained and analyzed. Several important responses are presented and the results are compared and discussed in the following sections.

2. ANALYTICAL MODELS AND ASSUMPTIONS

Four base-isolated structures with different heights of 2, 4, 7, and 10 stories are selected and preliminary designed according to UBC97 guidelines. Fig.2.1 shows a 4-story building as a sample. Then, the soil characteristics beneath of the buildings are modelled using half-space cone model theory for simulation of the soil behaviour in order to incorporate SSI into the seismic responses of the base-isolated buildings. Three different soil types are chosen as the soil classifications in UBC97, Sc, S_D, and S_E for the site, the analysis has been performed with and without considering the soil effects, and the results are compared to. A mathematical model as shown in Fig. 2.2 is assumed for simulation of the base-isolated structure and the soil system. In this model, parameters m_s, K_s, C_s and h_{eq} are lumped mass, stiffness, damping and equivalent height of structure, respectively. The height and effective weight of each story is taken uniform and equal to 3.3m and 2000 kN, respectively. Each building had a square plan (15m × 15 m) and consisted of 3bays in each direction, with the equal span of 5m. The fundamental periods of the super structures with the fixed bases (not supported on the base isolators) were around 0.1, 0.2, 0.35 and 0.5 sec corresponding to 2, 4, 7, and the 10- story buildings, respectively, to have adequate lateral stiffness in order to act appropriately in a base-isolated system. The structural damping ratio is assumed as about 5% for the first mode and around 10.5% for the isolated system.

The foundation is considered as a spread shallow type and is assumed to be the rigid type; it is also replaced by a lump mass, m_f, which is divided to two and equally appropriated to the top and the bottom levels of the isolation. It is noteworthy that often the two bases are considered in the design of the base-isolated foundation level. The first, which is the foundation of the structure, and the second, is a rigid base on the top of isolators to constrain the movements of the bottom of the columns. Here, the weight of the second base-level is also included in the analyses.

The vertical location of the total effective mass of the super structure, h_{eq}, is assumed to be as 0.55 of the height of a base-isolated building in compliance with the output of the work of Lee et al. (2001), and with considering the nearly rigid body motion of base-isolated structures. The seismic zone of the building site is selected the seismic zone 3 corresponding to UBC97, and the soil types are chosen Sc, S_D and S_E as regards to the soil shear velocities.

The effective period of the isolated structures at the design displacement, T_D, is taken 1.6, 2 and 2.5 sec. for the all systems. And, the minimum effective horizontal stiffness of the isolation system at the design displacement, K_D min, is calculated in accordance with the equation (58-2) of UBC97.Also, the design displacement, D_D, which acts in the direction of the main horizontal axes of the structures, is determined based on the equation (58-1) of UBC97. Based on these data, the minimum equivalent static lateral base shears Vb is calculated for the design of the isolators, using the equation (58-8) of UBC97.

The damping model is assumed to be proportional to the stiffness and is set with including the damping of soil and structure to have about 12.5,14,and 16% damping coefficients in the first modes with respect to the type of soil Sc, S_D, and to S_E, respectively. It can be taken into the account that existence of several damping in the super structure, base isolators, and the soil, has made the combined system as a non-classical system. The soil beneath the foundation is considered as a homogenous half–space model that is approximately simulated by the discrete springs and dampers, with frequency independent dynamic stiffness and damping in the sway,(K_h, C_h) and the rocking (K_r, C_r) degrees of freedom, as shown in Fig.2.2.

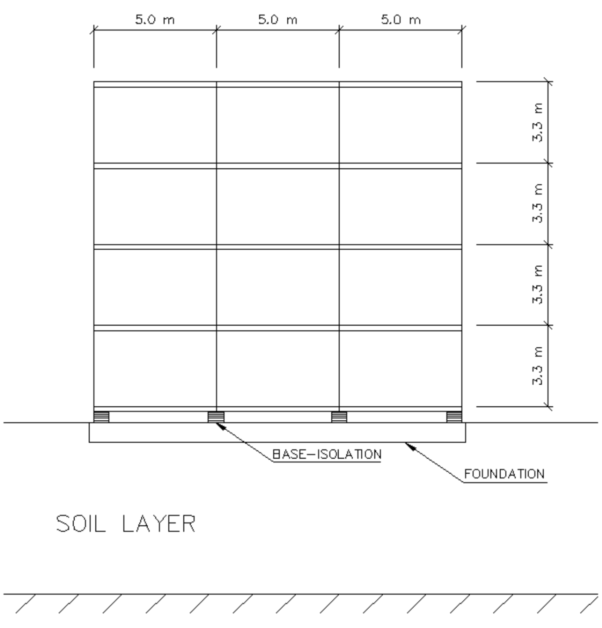

Figure 1. 4-Story Base-Isolated Structure, as a sample

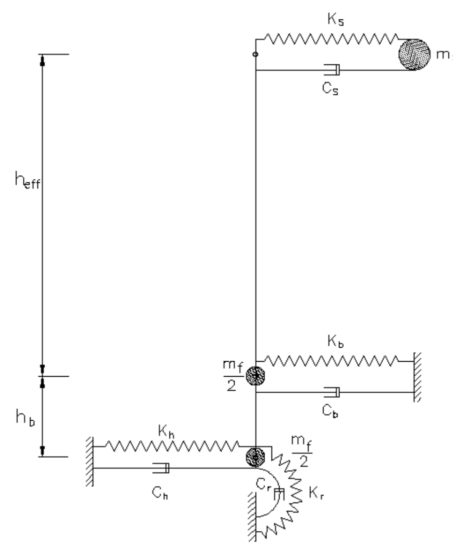

Figure 2. Analytical model for base-isolated structure including soil parameters

2.1. Isolators Design

The multilayered high-damping natural rubber laminated with steel reinforcing thin steel plates is assumed as the base isolators. The maximum shear strain, γ, is taken as 150%, and the shear modulus of the elastomer ,G=0.6 MPa, and the damping ratio of the isolators is β=0.15. Consequently from these assumptions and based on the available equations developed by Naeim and Kelly (1999), Eqn.2.1, the thicknesses of the isolators are designed and resulted as tr=0.3, for the buildings with 2 and 4-story, and 0.4 meter, for the buildings with 7 and 10-story. More details with regard to the isolators design and the analysis methods can be found in the work of Alavi et al. (2010). The total maximum probable displacement, DTM, due to MCE ground motion including the torsional displacement, is also incorporated into the design of the isolators. More details of the isolators are given in Table 2.1 with respect to the buildings, where K_b is the total horizontal stiffness of the isolators.

$$t_r = \frac{D_{TM}}{\gamma} \tag{2.1}$$

Table 2.1. Stiffness and thickness values of the base isolators

Base-Isolated Buildings	T_D=1.6 sec	T_D=2.0 sec	T_D=2.5 sec	T_D=1.6, 2.0, and 2.5 sec
	K_b kN/m	K_b kN/m	K_b kN/m	t_r mm
2-Story	6161.9	3943.6	2523.9	300
4-Story	12323.8	7887.2	5047.8	300
7-Story	21566.7	13802.7	8833.7	400
10-Story	30809.5	19718.1	12619.6	400

2.2. Soil Parameters

The response of soil-structure system mainly depends on the size of a structure, its dynamic characteristics and the soil profile as well as the nature of excitation. The following definitions and dimensionless parameters are introduced through Eqn.2.2 to Eqn.2.5 in order to facilitate the study of effects of SSI on the base-isolated buildings. In the modelling of the soil properties, the half-space theory and the cone model is used to evaluate the equivalent soil stiffness and damping ratios in the horizontal and rotational directions.

$$a_0 = \frac{h_{eff}.\omega_{sb}}{V_s} \quad , \quad \overline{m} = \frac{m_s + m_f}{\rho.r^2.H} \tag{2.2}$$

$$K_h = \frac{8G.r}{2-\upsilon} \quad , \quad C_h = \frac{4.6r^2}{2-\upsilon}\rho V_s \tag{2.3}$$

$$K_r = \frac{8G.r^3}{3(1-\upsilon)} \quad , \quad C_r = \frac{0.4r^4}{1-\upsilon}\rho V_s \tag{2.4}$$

$$G_0 = \rho V_s^2 \quad , \quad \frac{G}{G_0} = 0.75 \tag{2.5}$$

Where, a_0 denotes a stiffness ratio expressing the relative stiffness between the base-isolated structure and soil; this ratio is assumed as zero for the fixed base model and approximates to 2 for very flexible foundations; as a sample, a_0 values are computed for T_D = 2 sec and presented in Table 2.2. It can be seen that whatever the soil type becomes stiffer the a_0 ratio will result in smaller value that leads to the reduction of SSI effects on the system. However, whatever the height or mass of a building increases on the one type of a soil, this index become larger ; this trend can be found out from each row of Table 2.2. The bigger amount of a_0 implies the further effects of SSI on the responses.

In which, h_{eff} and ω_{sb} are the effective height and the circular frequency of the first mode of the base-isolated structure; V_s is the soil shear wave velocity. $\overline{m}$ is the structure-to-soil mass ratio index, the mass ratio is assumed as to be around 0.47 for the structures; ρ is the soil mass density, and H is the total height of the building; r is the equivalent radius of the foundation; G and υ are the shear modulus and Poisson ratio of the soil. G_0 is the primary shear modulus of soil. The value of proportion of G to G_0 depends on the type of soil and the seismicity of the site zone, and varies among 0.5 and 1; therefore, the ratio between G to G_0 is taken the average value between the two abovementioned amounts as 0.75, in Eqn.2.5.

The other parameters, defined in the previous sections, are illustrated in Fig.2.2. The properties of soil for the mentioned structures are computed and summarized in Table 2.3. The following data are also presumed in the calculation of the soil parameters.

$$h_{eff} = 0.55H \qquad \rho = 1800\,Kg/m^3 \qquad \upsilon = 0.33 \qquad V_s = 70,\ 100,\ 200\ and\ 400\ m/s$$

As per the definition, the soil with the shear wave velocities Vs < 200 m/s is considered as the soft soil, the soil with shear wave velocities in the range of 200 m/s ≤ Vs ≤ 375 m/s is assumed as the stiff soil, and the soil with Vs > 375 m/s is taken into the computations as a very dense soil or the soft rock. It is obvious that for the soil profile type with more than 760 m/s shear wave velocity the results would be so close to the fixed-base isolated system.

Table 2.2. Relative base-isolated structure-to- soil stiffness, a_0 , for T_D =2 sec.

Shear Velocity, V_s , m/s	**2-Story**	**4-Story**	**7-Story**	**10-Story**
70	0.16	0.33	0.57	0.81
100	0.11	0.23	0.40	0.57
200	0.06	0.11	0.20	0.29
400	0.03	0.06	0.10	0.14

Table 2.3. Soil parameters in SSI analyses

Shear Velocity, V_s m/s	**G N/mm^2**	**K_h N/mm**	**C_h N.s/mm**	**K_r N.mm/rad**	**C_r N.mm.s/rad**	**Soil Type**
70	6.62	2.69E+05	2.49E+04	1.60E+13	3.88E+11	S_E
100	13.50	5.48E+05	3.56E+04	3.27E+13	5.54E+11	S_E
200	54.00	2.19E+06	7.12E+04	1.31E+14	1.11E+12	S_D
400	216.00	8.77E+06	1.42E+05	5.24E+14	2.22E+12	S_C

2.3. Numerical Analysis Method

The dynamic response spectrum analysis method has been used according to UBC97 in the study of the effects of SSI on the seismic responses of the base-isolated buildings. As previously mentioned, the conditions were defined as the fixed base-isolated and the flexible base-isolated in conjunction with the soil properties beneath the structures. The main structural responses are obtained for comparison of the seismic behaviours of the systems. In that regard, the fundamental period, base shear and the total relative displacements of the structures are compared to, for the different type of the soil and the isolated buildings, with respect to the heights (aspect ratios) and the frequencies. Hence, various types of base-isolated buildings, from short to relatively tall buildings with different design periods T_D, have been analyzed and studied.

3. ANALYTICAL RESULTS

In this section, the obtained results from the numerical analyses are presented and discussed.

3.1. SSI Effects on Design Period, T_D

The effects of SSI on the design period of a base-isolated structure are investigated by evaluation of the fundamental periods of the base-isolated models located on the soil. As a common practice in the base-isolated building design, the design period, T_D, is defined according to the rigid body motion of a SDOF system supported on the isolators. While, the natural period of a real base-isolated system, which is calculated by a dynamic modal analysis that includes the structural stiffness of the super structure, is usually higher than the preliminary design period. Figures 3-3 to 3-5 show the variations of the periods of the base-isolated buildings on the different soil types, corresponding to the different design periods, T_D=1.6, 2.0, and 2.5 sec, respectively. As seen in the graphs, the fundamental periods, which are obtained from the dynamic analysis, are greater than T_D for the all cases. Therefore, it can be pointed out that for a structure, i.e. a 10-story building with T_D =1.6, as provided in Fig.3-3, the fundamental period has increased from 1.74 sec in the fixed-base isolated to 2.19 sec due to SSI effect on the soft soil, which resulted in 26% increase.

The increase in the fundamental period can be found for the all structures on the different soil types and with the different heights. However, the rate of the increase is greater for the structures on the softer soil. Furthermore, whatever, the structures are stiffer, less T_D, the effect of SSI on the increment of the fundamental period increases. For instance, from Fig. 3-5, the fundamental period of the 10-story building with 2.65 sec reached 2.98 sec on the soft soil with Vs=70 m/s, which shows 12% increase in the period. Besides, it is observed that the effect of SSI reduces on the stiffer soil, where, the results on the soil with Vs=400 m/s incline to the fixed-base isolated outcomes.

From the other view, the aspect ratios, H/r, of the buildings shown on top of the figures 3-3 to 3-5 vary from 0.8 to 4. The results show that H/r affects on the influence of SSI, due to the increase of the rocking mode actions on the responses. The all three figures show similar trends towards the aspect ratio changes, and therefore, it can be concluded that the SSI effects increase on the slender structures. Moreover, verification of the structure-to-soil relative stiffness, a_0, from Table 2.2, shows that the results have meaningful relation to a_0; where, for the greater a_0, SSI effects would become more significant.

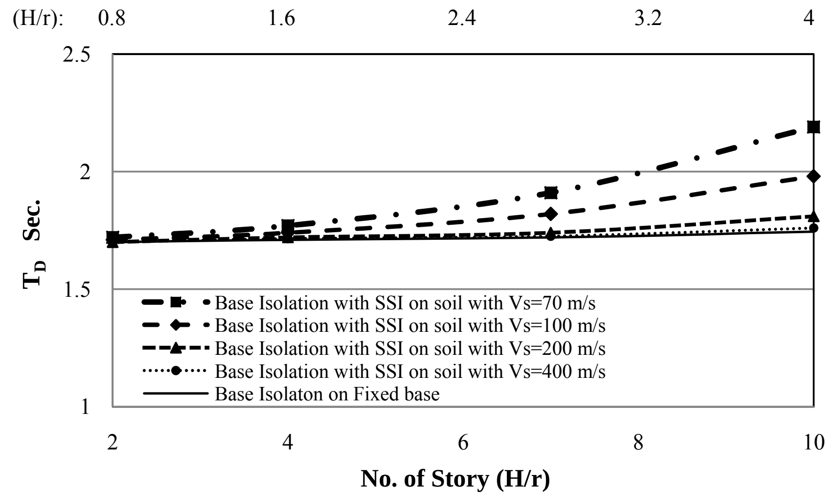

Figure 3. Fundamental periods of the base-isolated buildings with SSI effects, for T_D=1.6 sec.

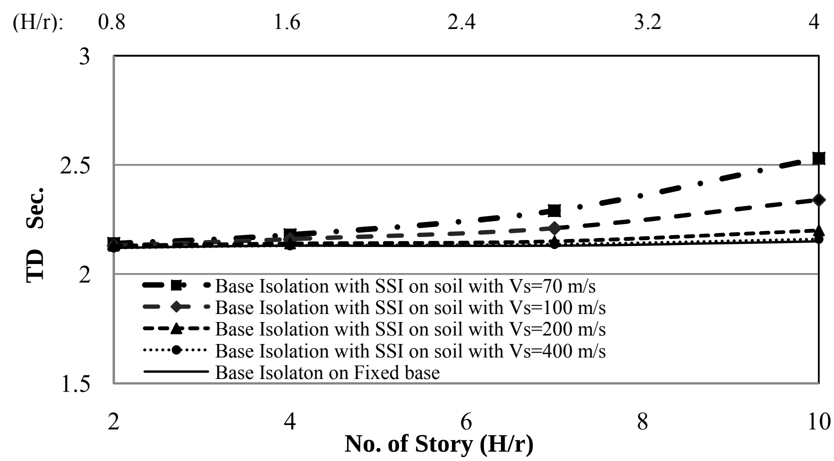

Figure 4. Fundamental periods of the base-isolated buildings with SSI effects, for T_D=2.0 sec.

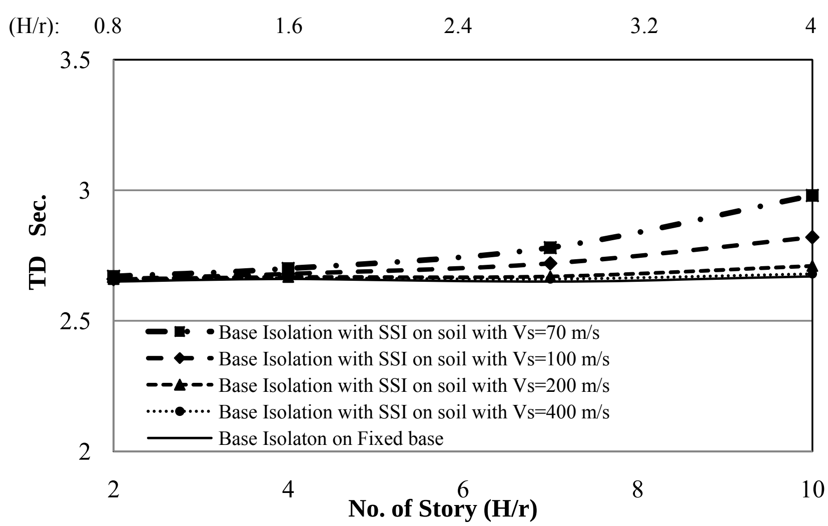

Figure 5. Fundamental periods of the base-isolated buildings with SSI effects, for T_D=2.5 sec.

3.2. SSI Effects on Design Base Shear, Vb

In order to investigate the variation of the design base shear in the two different conditions, the fixed-base isolated buildings and with SSI, the base shears from dynamic response spectrum analysis are obtained and compared to the design base shears, which were estimated for the design of the buildings. The base shear ratios of the combined model with SSI effects to the fixed-base isolated structures are depicted in Figures 3-6 and 3-7 versus different shear wave velocities of the soil for the buildings in the two design periods of 1.6 and 2.5 sec, respectively. It is observed from the two figures that application of SSI on the base-isolated system results in the decrease of the design base shear. The graphs imply that the effect of soil-structure interaction on the structural responses is relatively more considerable when the soil type has been a soft soil, Vs < 200 m/s, than the stiff soil types. This reduction on the base shear for the base-isolated buildings on the soft soil has been more than 10% and even reached 28%. The rate of the reduction of the base shear response decreases when the soil type is stiffer, where, for $200 \leq Vs \leq 375$ m/s the reduction becomes less than 10% , and for the very stiff soil Vs > 375 m/s the reduction rate would be less than 5%. In addition, the comparison between the graphs of Figures 3-6 and 3-7 leads to this point that whatever the structural system has been stiffer, less T_D , rate of the reduction of the base shear has been mostly greater than in the case of a more flexible base-isolated system, placed on a similar soil. For instance, in the 7-story building with T_D = 1.6 and 2.5 sec on the stiff soil with Vs=200 m/s , the reduction rates have been 8% and 4% , respectively. Hence, the SSI effect on reduction of the base shear for very flexible base-isolated systems, i.e. T_D around 2.5 sec, located on the stiff to very stiff soil, is negligible.

3.3. SSI Effects on Relative Total Drift

The sensitivity of the total relative drift is also evaluated in terms of SSI application on the analyses. Fig. 3-8 represents the total relative drift of the 7-story base-isolated building on the different kinds of soil proportioned to the total relative drift of that fixed base-isolated building; T_D of that building has been 2 sec. It can be found that the SSI decreases the total relative drift of the building, where, effect of soil-structure interaction for the building on soft soil is rather substantial and this effect is less in stiff soils. For instances, the deduction in the relative horizontal displacement for the base-isolated building on a soil with shear wave velocity of 70 m/s has been about 0.72 and for a soil with shear wave velocity of 400 m/s has become around 0.95. With reference to Table 2.2, it can be inferred that for the greater a_0 , the SSI effects increase.

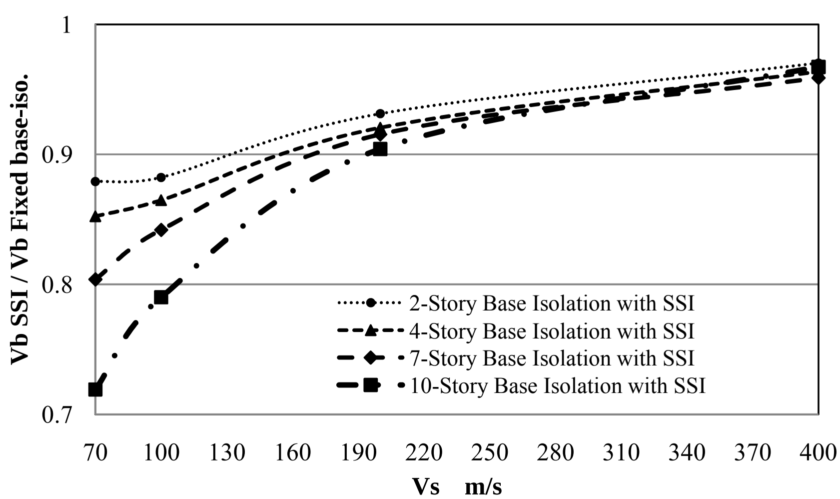

Figure 6. Ratio of base shear of the base-isolated structures with SSI on the different soil types, for T_D=1.6 sec.

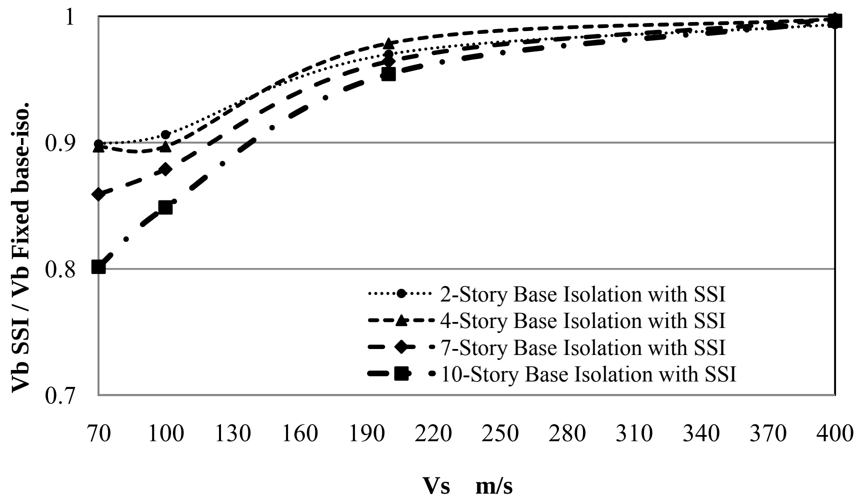

Figure 7. Ratio of base shear of the base-isolated structures with SSI on the different soil types, for T_D=2.5 sec.

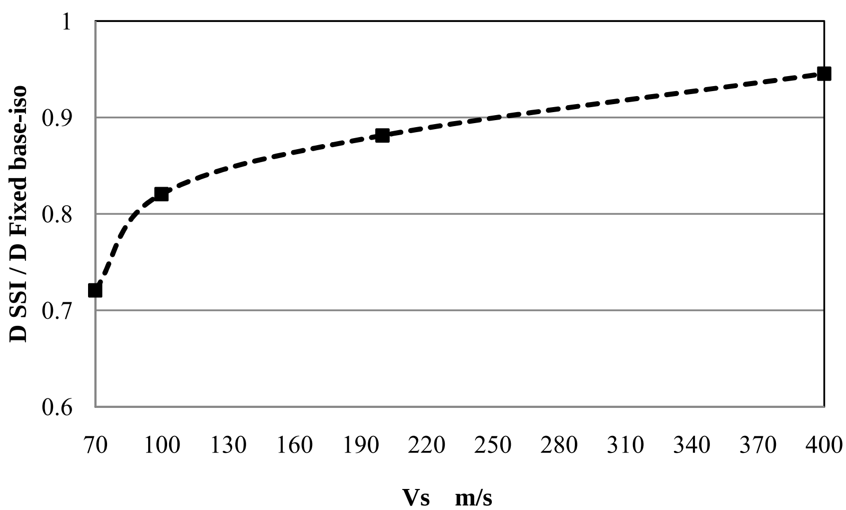

Figure 8. SSI effects on the relative total displacement of the 7-story base-isolated building with T_D =2 sec.

4. CONCLUSIONS

The following points can be drawn as the main conclusions from the analytical studies and the numerical results presented and discussed in this paper.

The soil-structure interaction, SSI, effects on the seismic responses of a base-isolated building can be considerable, depending mainly on the soil profile type, the stiffness and the mass of the super structure, the aspect ratio of the building, and the foundation properties. The results indicate that on the very stiff soil (Vs > 375m/s), the SSI has negligible effects on the responses (< 5%) for the all base-isolated models; and on the softer soil whatever the base-isolated building is stiffer, less T_D, the soil interaction effects will become larger.

SSI causes increase in the fundamental periods of the base-isolated buildings on the different soil types and with the different heights; however, the rate of the increase is significant for the structures on the soft soil (Vs < 200 m/s), while it is negligible for the stiff to very stiff soil, Vs ≥ 200 m/s. This increase for a 10-story base-isolated building on the soft soil reached 26% in comparison to the fixed base-isolated structure results.

The seismic responses as the design base shear and the relative displacements of the base-isolated buildings due to SSI decrease; especially, when the structure is located on the soft soil, the reduction might become greater than 10%. In addition, whatever the relative structure-to-soil stiffness ratio, a_0 , increases, the SSI will become more effective on the seismic responses of the base-isolated buildings.

By increasing the aspect ratio of H/r, the height to equivalent radius of foundation, the effects of rocking action and consequently SSI on the responses will increase; this matter for relatively tall base-isolated buildings on the soft soil is more significant.

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