Effects of Soil-Structure Interaction on Nonlinear Seismic Response of Buildings

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SUMMARY
Soil-structure interaction (SSI) may have significant effects on free vibration characteristics and seismic response of some structures. These effects result from the soil inability to fully restrain the movements of structure foundation in addition to soil's large energy dissipation capacities. Soils dissipate vibration energy in two mechanisms: hysteretic "or material" and geometric "or radiation". This research intends to investigate the effect of soil-structure interaction on dynamic properties and seismic response of buildings whose lateral-load resisting system is composed of moment-resisting reinforced-concrete plane frames. This objective is achieved through the analyses of multi-story plan frames via the direct approach of solving SSI problems using OPENSEES program. The results are presented for cohesionless soils with wide range of shear wave velocities; two strong earthquake ground motions (Kobe 1995 and Victoria 1980); two levels of peak ground accelerations: 0.1g and 0.3g, and variable-height buildings (7, 10, 14, and 18 floors).The investigated effects are: fundamental vibration period, spectral acceleration, maximum story shear distribution, base shear, and contact soil stresses. Parametric analyses show that SSI alters the buildings performance essentially for stiffer ones (low-raised) and for stronger earthquakes (higher peak ground accelerations).

Keywords: soil-structure interaction, seismic response, nonlinear, plane frames, time history analysis.

1. INTRODUCTION

Various research demonstrated the important effects that SSI has on the seismic response of buildings (e.g. Ramadan et al. 2009, Preisig 2005, HosseinZadah 2002, and El Naggar et al. 2001); and on other large structures such as bridges (Tongaonkar and Jangid 2003 and Saadeghvaziri et al. 2000); dams (Abouseeda and Dakoulas 1998 and Ramadan and Novak 1992 & 1993); elevated tanks (Livaoglu and Dogangun 2007); and silos (Azadi and Soltani 2010). These studies included two-dimensional and three-dimensional soil-structure models using either the substructure method or the direct approach. A prevailing common conclusion of all studies is that SSI could produce significant effects on the seismic response of structures: both beneficial and detrimental effects were reported. Nevertheless, utilization of the findings of these research efforts in national and international design codes and in routine design calculations is still very rare if not absent.

In this paper, one of the most common lateral-load resisting systems (i.e. moment-resisting reinforced-concrete plane frames) is investigated to quantitatively assess the effects of soil-structure interaction on the system's dynamic properties and seismic response. To this end, many multi-story plane frames are analyzed via the direct approach of solving SSI problems using OPENSEES program. The analyzed frames represent buildings with variable heights (7, 10, 14, and 18 floors) built on soils varying from soft to stiff and subject to earthquakes ground motions with different frequency contents and peak ground accelerations. First, the structural model and the applied seismic ground motions are briefly described. Then, the effects of SSI of building fundamental period and corresponding spectral accelerations are discussed. This is followed by analyzing the effects of SSI on seismic response (e.g. story shear and base shear) of buildings, Finally, variations of the contact soil stresses under various load conditions is addressed. The paper then ends with the major findings of the study.

2. MODEL DESCRIPTION

Figure one depicts the models adopted for the typical RC plane frame for both foundation assumptions, i.e. fixed and elastic. All frames were designed to satisfy the pertinent Egyptian Codes of Practice for residential buildings: ECP-201 and ECP-203. In addition, as the analysis is nonlinear, gravity loads were included from the first analysis step. For more details, refer to Al-Anany 2012.

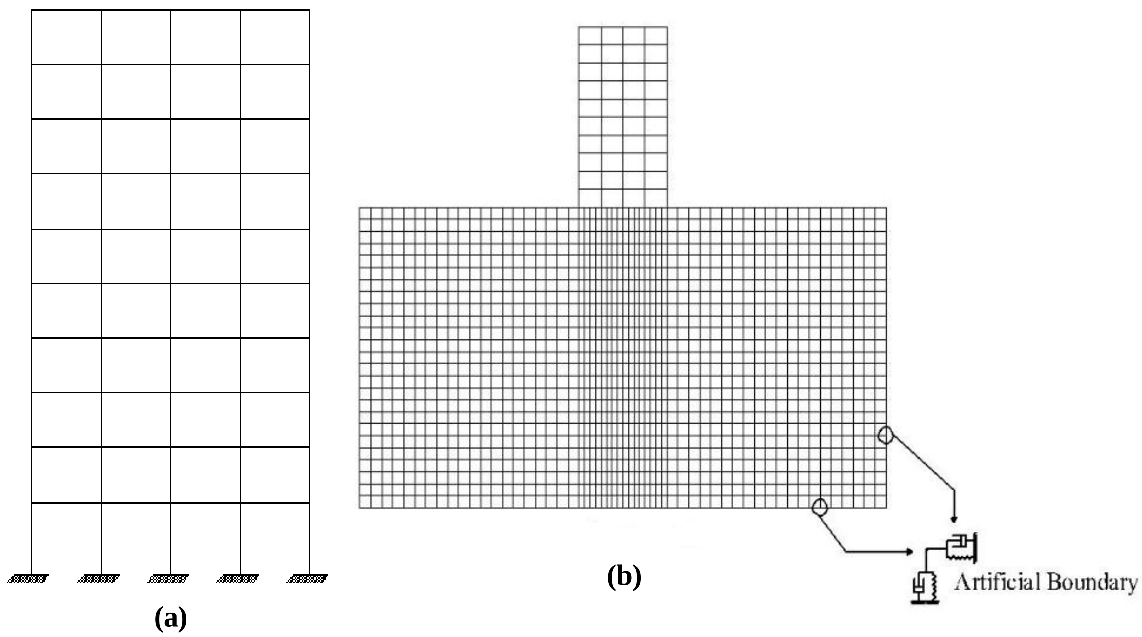

Figure 1. Ten-story building models: (a) Fixed foundation; (b) Elastic foundation

For the plane frame superstructure, the span length is 4m while the floor height is 3m for all floors but 4m for ground floor. The "NonlinearBeamColumn" element from OPENSEES's material library is used to model all structure elements. This nonlinear element is defined by fiber sections. This fiber sections are discretized into smaller regions for which the material stress-strain response is integrated to give resultant behavior (McKenna 2011).

The soil is modeled with four-node quadratic elements forming a (96m × 50m) mesh. The material chosen to represent the soil quad elements is "PressureDependMultiYield" material that defines the nonlinear behavior of soil medium. This material has an elastic-plastic constitutive relation which simulates the essential response characteristics of pressure-sensitive soils under general loading conditions. Model mesh boundaries are constructed using the pre-processor GID software.

3. INPUT SEISMIC GROUND MOTION

Two strong ground motion records: Kobe 1995 and Victoria 1980, were selected as control ground motions. Figure 2 shows that these records have frequency contents that are markedly different in the frequency range (below 8 Hz) that dominates the response of analyzed structures.

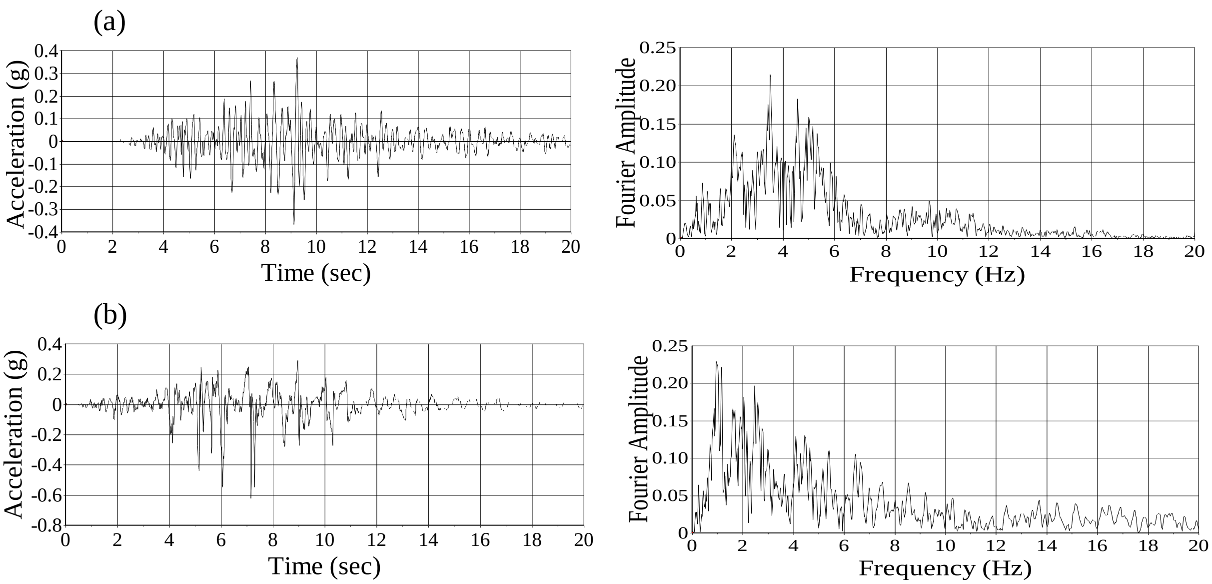

Figure 2. Acceleration time histories and corresponding Fourier amplitude spectra of the applied ground motions: (a) Kobe; (b) Victoria

4. EFFECT OF SSI ON BUILDING FUNDAMENTAL PERIOD

To assess the effect of SSI on the building fundamental period, more than 100 numerical models representing 7-story, 10-story, 14-story, and 18-story buildings were developed and analyzed. For this part of the study, soil material is assumed to be linearly elastic. Figure 3 presents variation of fundamental period of the system including soil elasticity (i.e. with flexible foundation), $T_{a,elastic}$, with soil stiffness for shear wave velocity, V_s, of 60 to 250m/s (shear modulus, G_s= 6.12 MPa to 130 MPa). To furnish tangible results, all values in Fig. 3 are normalized with respect to their corresponding values assuming columns to be fixed at base (i.e. assuming rigid foundation), $T_{a,fixed}$. Also, the empirical values predicted by formulas recommended by ECP-201 and IBC-2006 are indicated on Figs. 3a to 3d for comparison purposes.

From Fig. 3, it is evident that both ECP-201 and IBC-2006 always underestimate the fundamental period of plane frames. Besides, the figure shows that ignoring SSI results in underestimation of the fundamental period by up to 53%, 43%, 33%, and 25% for buildings with 7-story, 10-story, 14-story, and 18-story, respectively. For buildings with 14 or more stories, Figs. 3c and 3d indicate that the effect of SSI on fundamental period becomes insignificant for soils with shear wave velocity of 250m/s or more. However, even for soils with shear wave velocity of 250m/s, ignoring SSI underestimates the fundamental period by about 29% and 22% for buildings with 7-story and 10-story, respectively. It worth noting that underestimation of the fundamental period (as a result of ignoring SSI) alters the earthquake spectral accelerations and, consequently, the seismic design forces as explained below.

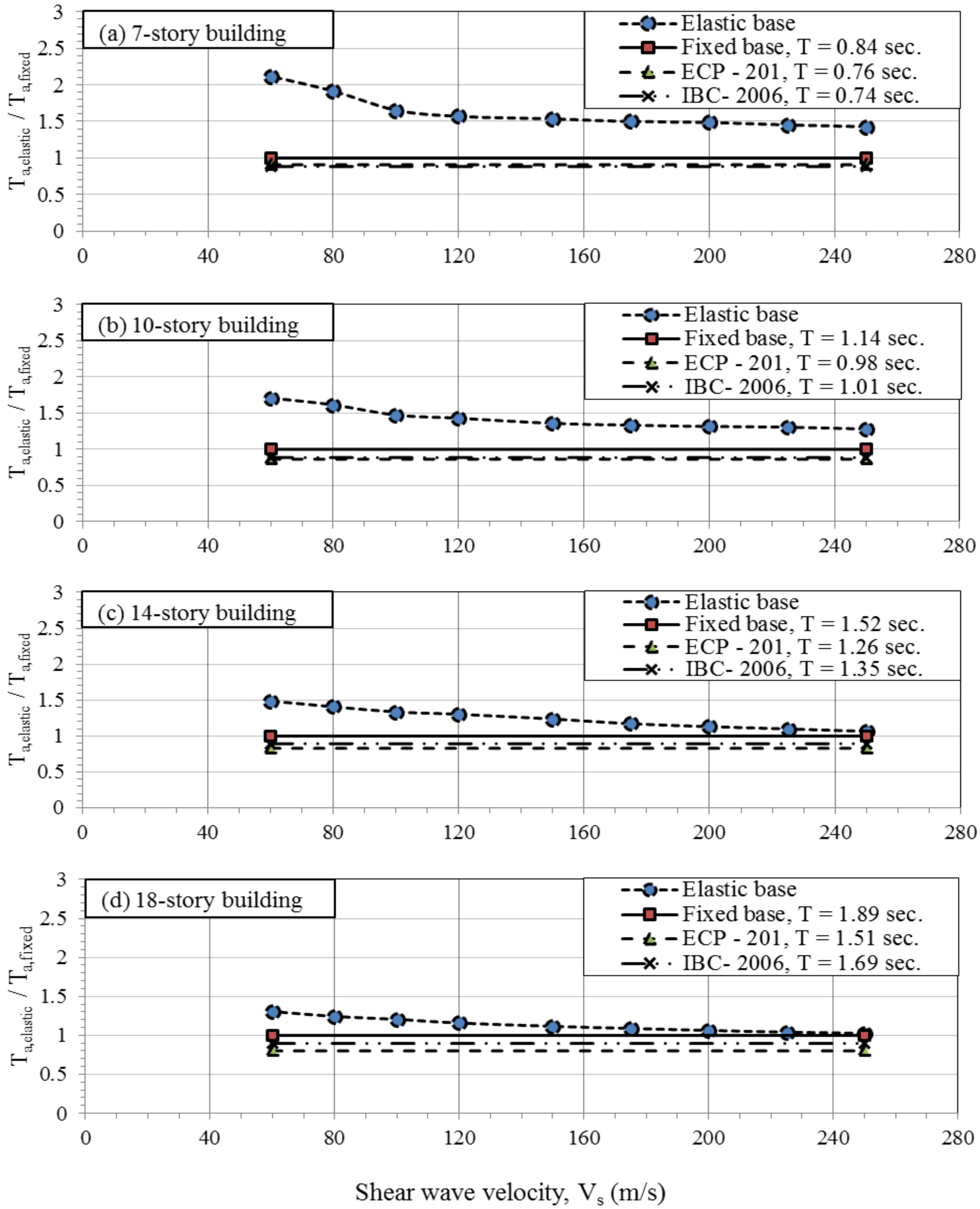

Figure 3. Effect of soil shear modulus (V_s) on fundamental period of buildings with variable heights: a) 7-story; b) 10-story; c) 14-story; d) 18-story

5. EFFECT OF SSI ON SPECTRAL ACCELERATION

In order to investigate the effect of soil-structure interaction on altering building seismic design, the spectral accelerations corresponding to the two conditions of including and excluding SSI effects are calculated and compared. For these purpose, the two elastic acceleration spectra recommended by ECP-201 and depicted in Fig. 4. are used (i.e. spectrum type I and the envelope of spectra types I and II). Two soil classes are considered: class C (medium to dense sand with V_s of 180 to 360m/sec) and class D (loose to medium dense sand with V_s of less than180m/sec). Now, for every number of stories and soil stiffness, the spectral acceleration is calculated twice: first using $T_{a,elastic}$ and then using $T_{a,fixed}$. As $T_{a,elastic}$ is larger than $T_{a,fixed}$, ignoring SSI overestimates the building spectral accelerations with the percentages listed in Table 1 for various building heights, spectrum shapes, soil classes, and soil stiffnesses (V_s= 60 to 250m/s). Results listed in Table 1 shows that ignoring SSI could lead to large overestimation of spectral accelerations for low to medium rise buildings founded on loose to medium dense sandy soils. This would lead to uneconomic designs that can be avoided if SSI is accounted for.

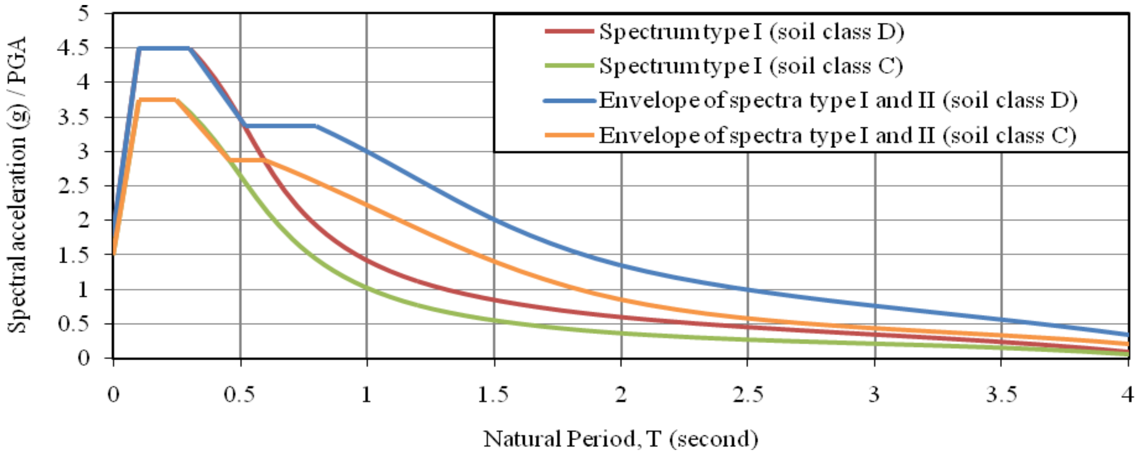

Figure 4. Response spectra types I and II for soil classes C and D as in ECP-201

Table 1. Percentage overestimation of spectral acceleration for buildings with variable height when SSI is ignored based on the elastic acceleration spectra recommended by ECP-201(V_s= 60 to 250m/s)

Building height	Percentage overestimation of spectral acceleration for shown spectrum type and soil classes (%)			
	Spectrum type I		Envelope of spectra types I and II	
	Soil Class C	Soil Class D	Soil Class C	Soil Class D
7 stories	43 to 54	56 to 313	43 to 49	50 to 211
10 stories	56 to 64	68 to 277	28 to 31	34 to 171
14 stories	14 to 27	37 to 222	7 to 13	17 to 68
18 stories	7 to 14	18 to 69	2 to 6	12 to 61

6. EFFECT OF SSI ON BUILDINGS RESPONSE TO EARTHQUAKES

Realizing that the SSI effects are higher for stiffer buildings, the study of SSI effects on building response to earthquakes is limited to two different building heights: ten-story and seven-story. Three values of the soil shear wave velocity are considered: V_s= 60, 100, and 150 m/sec for the seven-story building; and V_s= 100, 150, and 200 m/sec for the ten-story building. The earthquake records, Kobe and Victoria, are normalized to peak ground accelerations (PGA) of 0.10g and 0.30g to model the maximum and minimum PGA values in Egypt.

Figures 5a and 5b show the distribution of maximum story shear for the 10-story and 7-story buildings, respectively, due to Kobe earthquake with PGA = 0.3g while Figs. 6a and 6b present similar data for the Victoria earthquakes. The big differences in maximum story shear distribution between buildings assumed to have fixed base and same buildings on elastic foundation are clearly illustrated in Figs. 5 and 6. Compared to the correct "elastic foundation" response, the maximum base shear obtained when SSI is not accounted for (i.e. for fixed base) is increased by a factor of three for the 10-story buildings and by a factor of four for the 7-story buildings. This is true for both earthquake records. The effect of frequency contents can be appreciated when comparing the base shear of the 10-story and 7-story buildings under different records. For fixed structure condition, the base shear of the 7-story buildings is almost the same under both records but the base shear of the 10-story buildings under the Victoria record is about 70% of its value under the Kobe one. Finally, note that the base shear for the 7-story building is larger than that of the 10-story building for both earthquakes despite having much less seismic weight. This demonstrates the significant effect of structural flexibility on building seismic response.

Time histories of base shear in the 7-story and 10-story buildings due to Kobe and Victoria records (PGA=0.3g) are shown in Figs. 7 and 8 for different values of the soil shear wave velocity as well as for fixed-base cases**.** These figures clearly show that SSI not only reduces the seismic shear forces but also modifies their time histories by altering the frequency content of the building response. Besides, the figures indicate that the same building responds differently when subject to different records with the same PGA depending on the record frequency contents.

Results of the buildings response to earthquakes with PGA of 0.1g showed similar trend as reported above with two observations. First, the effect of SSI was less-pronounced for the smaller PGA due to less soil nonlinearity. Second, the building base shear for PGA=0.1g was about 35% to 42% of the corresponding value for PGA=0.3g. The above discussion confirms that neglecting SSI in seismic response analysis could lead to extremely overestimated actions that would considerably increase the construction costs.

7. EFFECT OF EARTHQUAKES ON SOIL CONTACT STRESS

To demonstrate the effect of earthquake on contact soil stresses, Fig. 9 presents the soil stress beneath the building foundation for three load cases: vertical loads alone; vertical loads plus Kobe earthquake with PGA=0.1g; and vertical loads plus Kobe earthquake with PGA=0.3g. These stress distribution correspond to 10-story buildings and soil shear wave velocity of 150m/s. For cases including earthquake effects, the results are shown for the instant corresponding to the maximum base overturning moment. The flexural flexibility of foundation is evident from the reduction in contact stress at mid-spans. The earthquake loads increased the contact stress under exterior columns (in one side only) by 22% and 27% for PGA of 0.1g and 0.3g, respectively. The peak soil stresses for the different PGA values arbitrary occur on different sides of the foundation and the percentage increase in contact stress is not linear in PGA.

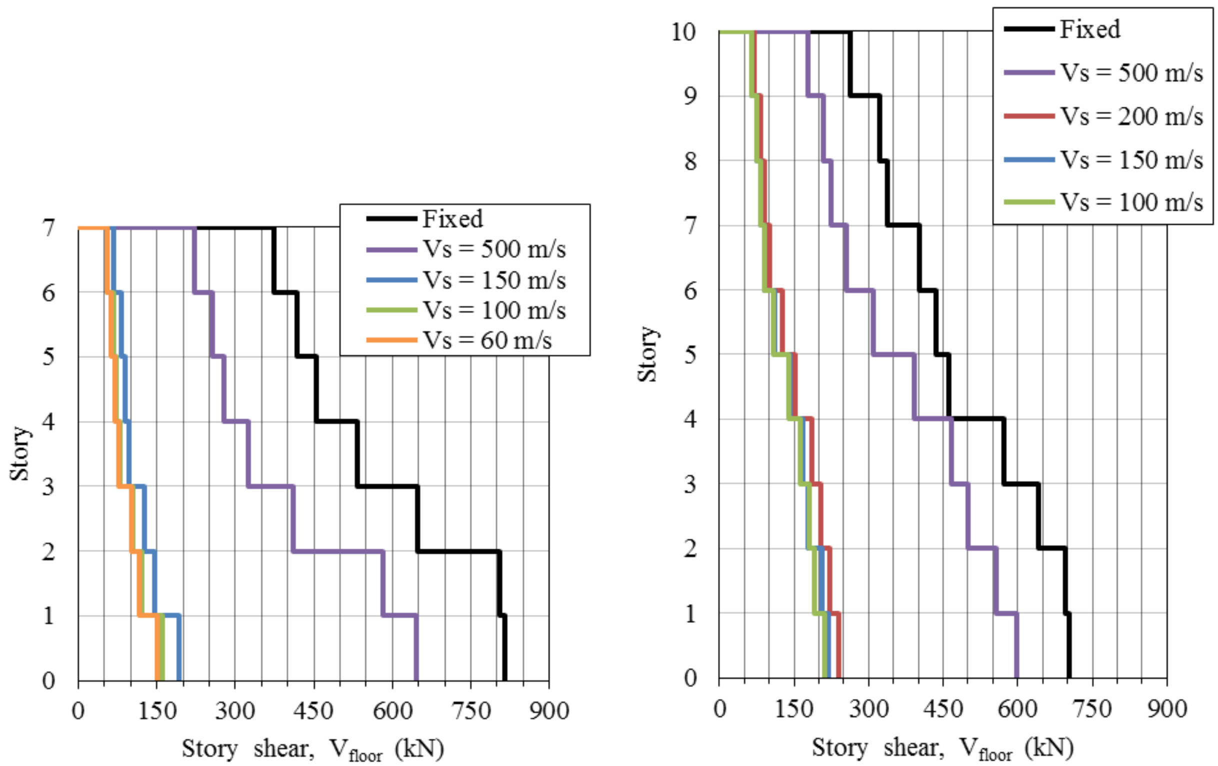

Figure 5. Maximum story shear for buildings due to Kobe earthquake (PGA = 0.3g)

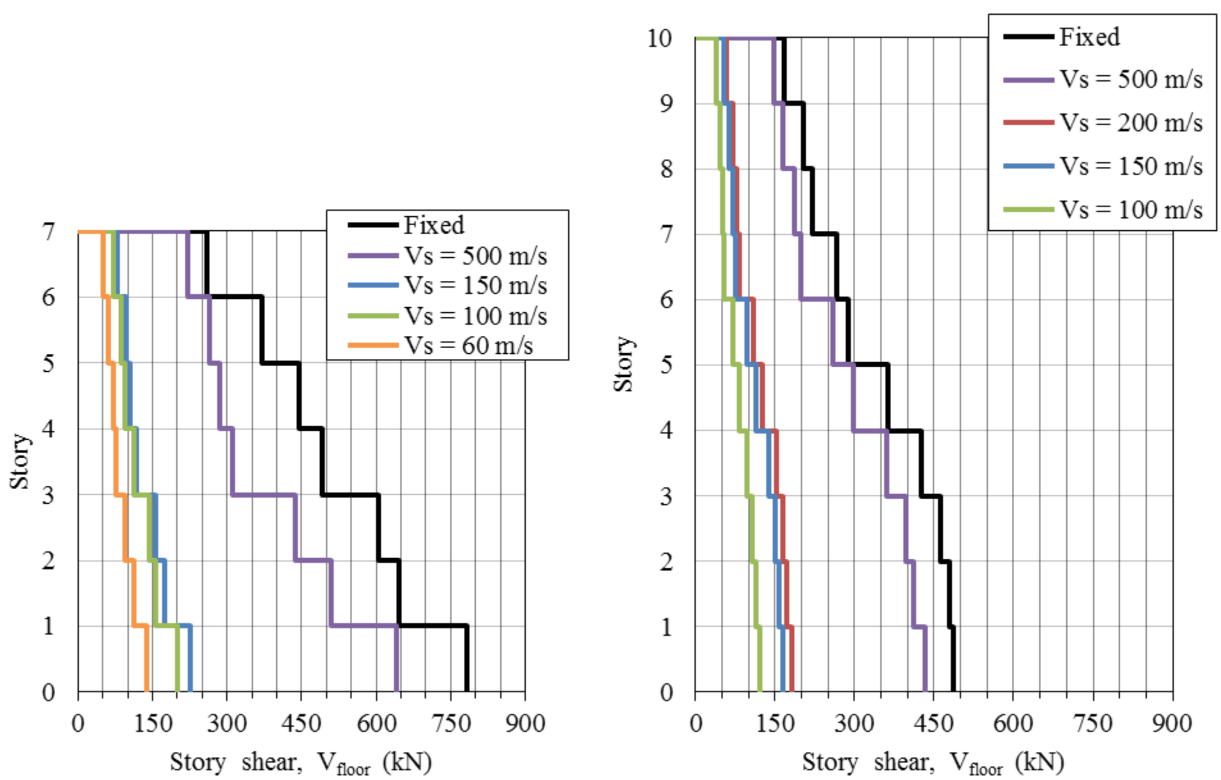

Figure 6. Maximum story shear for buildings due to Victoria earthquake (PGA = 0.3g)

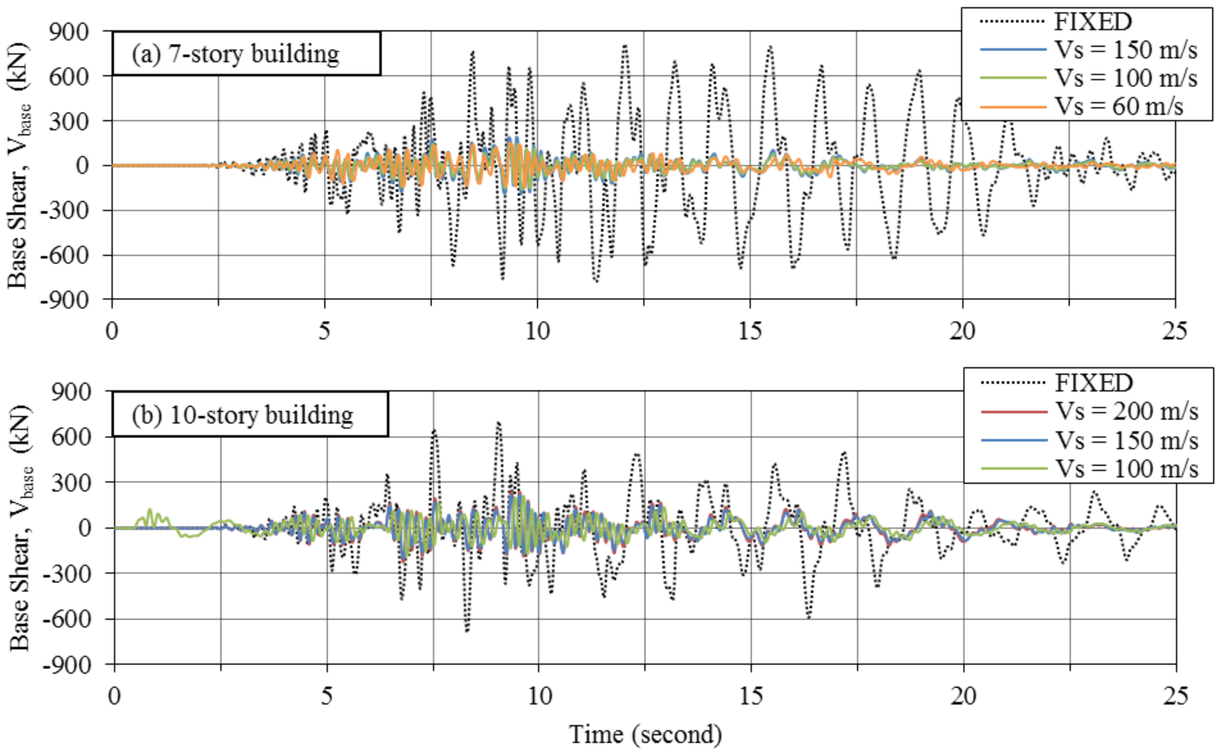

Figure 7. Time history of base shear for buildings due to Kobe earthquake (PGA = 0.3g)

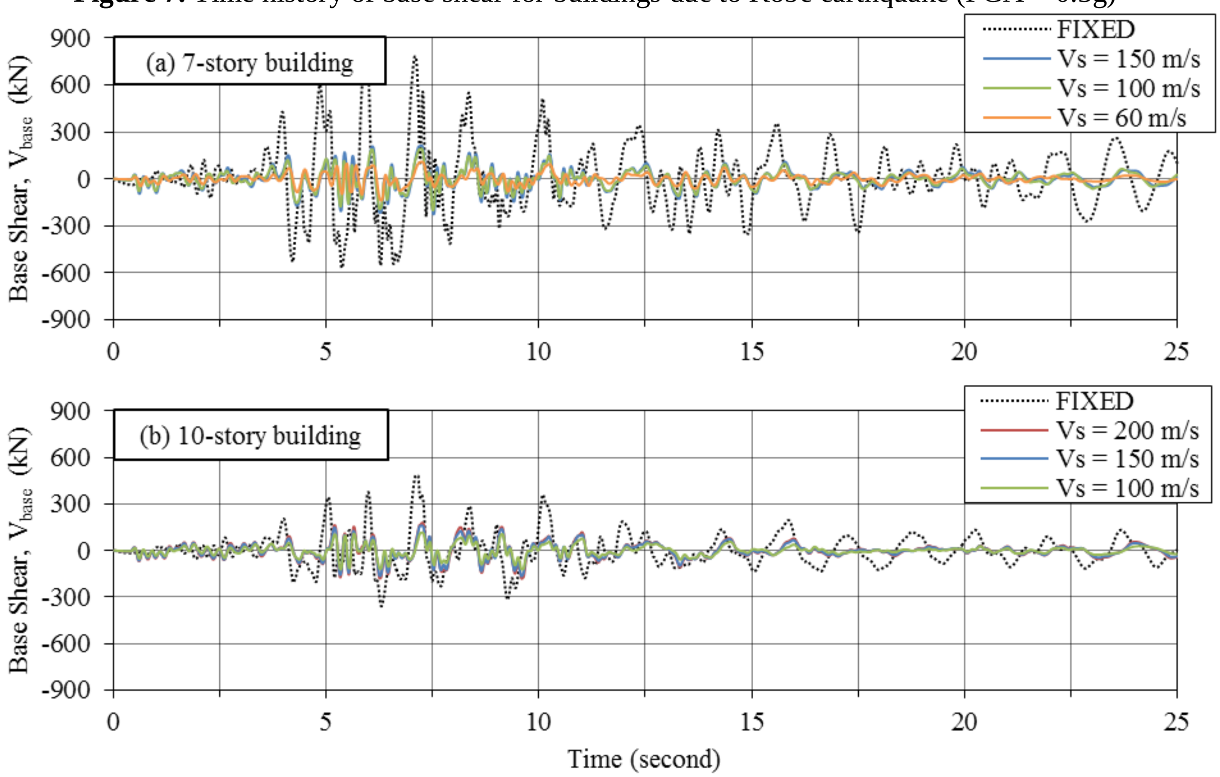

Figure 8. Time history of base shear for buildings due to Victoria earthquake (PGA = 0.3g)

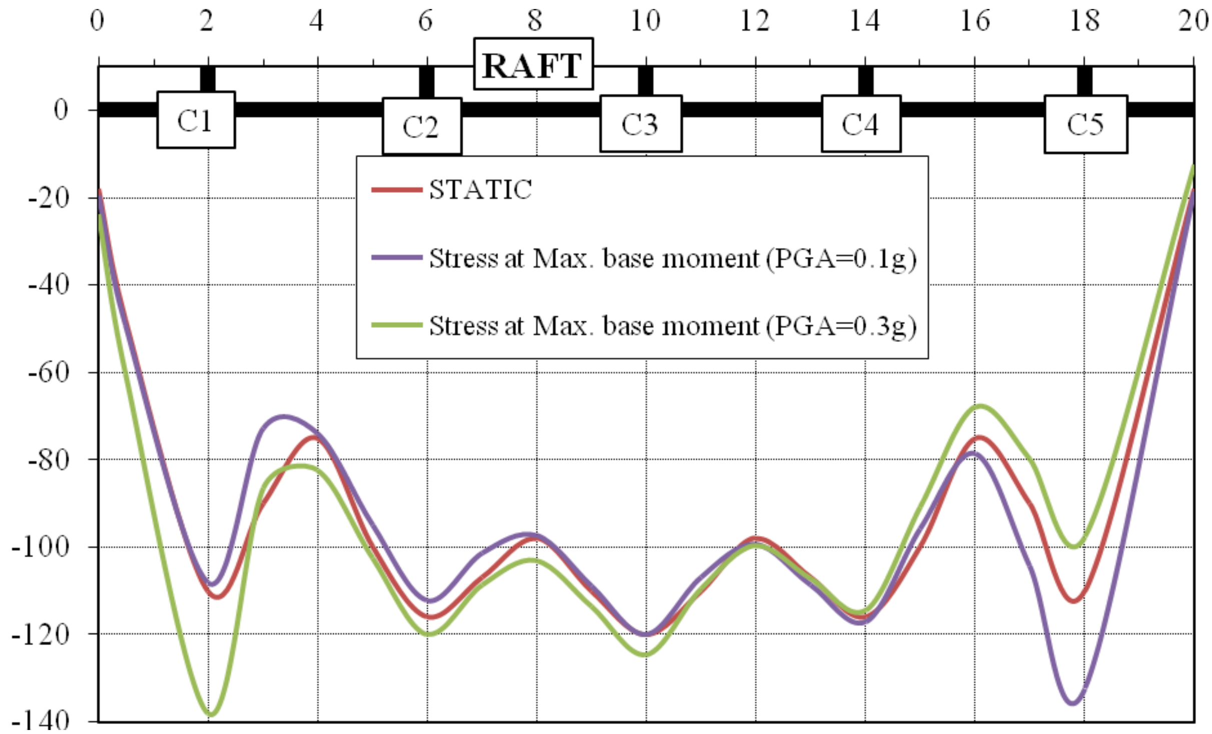

Figure 9. Distribution of contact stresses (kPa) for the 10-story building due to different load cases- Kobe earthquake (V_s=150 m/sec)

8. CONCLUSIONS

According to the performed analyses, the following conclusions are made:

1- For soils shear wave velocity of 60 to 250m/s, ignoring SSI resulted in underestimation of the fundamental period by up to 53%, 43%, 33%, and 25% for buildings with 7-story, 10-story, 14-story, and 18-story, respectively. Nevertheless, for buildings with 14 or more stories, the effect of SSI on fundamental period becomes insignificant for soils with shear wave velocity of 250m/s or more.

2- Underestimation of the fundamental period (as a result of ignoring SSI) alters the earthquake spectral accelerations and, consequently, the seismic design forces. In particular, for the response spectra recommended by ECP-201, the percentage overestimation of spectral acceleration due to overlooking SSI reached 313% and 61% for 7-story and 18-story buildings, respectively.

3- Big differences in maximum story shear distribution are observed between buildings assumed to have fixed base and same buildings on elastic foundation. The maximum base shear obtained when SSI is not accounted for (i.e. for fixed base) can be as large as three multiples and four multiples of its correct “elastic foundation” value for 10-story and 7-story buildings, respectively. In addition to reducing the seismic response, accounting for SSI also modifies the frequency content of building response.

4- Frequency contents of earthquakes have pronounced effects on building seismic response. For the same PGA assuming fixed-base condition, the base shear of the 7-story building is almost the same under both Kobe and Victoria records but the base shear of the 10-story building under the Victoria record is about 70% of its value under the Kobe one.

5- SSI effects become highest for low-rise buildings on soft soils when subjected to earthquakes with large PGA's. For such cases, neglecting SSI in seismic response analysis could lead to extremely overestimated actions and would considerably increase the construction costs.

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