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Structure-soil-structure interaction in a group of buildings using 3D nonlinear analyses

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Abstract. The current study compares the effect of structure-soil-structure interaction (SSSI) on the dynamic responses of adjacent buildings and isolated structures including soil-structure interaction (SSI) with the responses of fixed-base structures. Structural responses such as the relative acceleration, displacement, drift and shear force were considered under earthquake ground motion excitation. For this purpose, 5-, 10- and 15-story structures with 2-bay moment resisting frames resting on shallow foundations were modeled as a group of buildings in soft soil media. Viscous lateral boundaries and interface elements were applied to the soil model to simulate semi-infinite soil media, frictional contact and probable slip under seismic excitation. The direct method was employed for fully nonlinear time-history dynamic analysis in OpenSees using 3D finite element soil-structure models with different building positions. The results showed that the responses of the grouped structures were strongly influenced by the adjacent structures. The responses were as much as 4 times greater for drift and 2.3 times greater for shear force than the responses of fixed-base models.

Keywords: structure-soil-structure interaction; soil-structure interaction; adjacent structure; direct method; nonlinear dynamic analysis

1. Introduction

In engineering, the seismic performance of structures that are assumed to be fixed at their base is determined in isolation (Naeim 2001), but the effect of the soil-structure interaction (SSI) as well as the interactive effects of adjacent buildings are considered less frequently. In practice, however, many structures in urban areas are located on soft soil and are built adjacent to one another. Studies on soil-structure interaction have shown that the dynamic response of structures on soft soil can differ significantly from fixed-base structures (Chopra and Gutierrez 1974, Luco and Wong 1987, Wolf and Hall 1988, Ganjavi *et al*. 2018, Mahmoudabadi *et al*. 2019). Structure-soil-structure interaction (SSSI) is also called site-city interaction and relates to the dynamic interaction between several structures and the underlying soil. The presence of several structures on the medium can lead to interference of the structural responses under seismic excitation through the soil and cause cross-interaction among multiple structures (Lou *et al*. 2011). Also building density and city configuration play a crucial role in the energy distribution inside the city (Kham *et al*. 2006). Under such circumstances, it is inadvisable to ignore the dynamic interaction between adjacent structures (Vicencio and Alexander 2018); and even adjacent foundations that were appeared as rocking and sliding (Ngo *et al*. 2019). Lee and Wesley (Lee and Wesley 1973) were the first to report on the influence of SSSI when investigating the seismic response of several adjacent nuclear reactors. Subsequently, Luco and Contesse (Luco and Contesse 1973) proposed a SSSI designation for this field of study that evolved from the through-the-soil coupling of foundations.

SSSI focuses on the seismic performance of structures in an urban environment by considering the influence of the adjacent structures along with the interaction of the sub-soil under dynamic disturbances. These dynamic disturbances can be either externally applied loads or seismic waves (Lou *et al*. 2011). Recent investigations of the SSSI problem have employed numerical analysis or scale-model shaking table tests on the interaction of two or three adjacent buildings (Kitada *et al*. 1999, Hans *et al*. 2005, Aldaikh *et al*. 2015, Aldaikh *et al*. 2016, Li *et al*. 2017). Also, the necessity to integrate urban environment in hazard analysis, simple and applied relation proposed to estimate the expected efficiency of the site-city interaction effects for any city (Guéguen *et al*. 2002).

The distance between two structures plays a key role; It has been shown that a decrease in the peak response occurs for closely spaced structures (Liang *et al*. 2017). A parameterized study by Zongda (Zongda 1998) found that, when the distance between two structures is less than 2.5 times the width of the foundation, structures will interact and, if the distance is less than the width of the foundation, the response of the structures may increase or decrease markedly. Studies have reported that, in a group of three adjacent structures, the central structure will have a more noticeable interaction than when there is only one adjacent structure (two structure model). These studies also reported

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that the interaction effects can be amplified when the central structure is flanked by two taller adjacent structures and attenuated when flanked by two shorter structures (Aldaikh *et al*. 2015, Aldaikh *et al*. 2016).

Different methods have been used for soil-structure interaction analysis, including the direct, substructure and hybrid methods (Wolf and Hall 1988, Stewart *et al*. 1998, Wolf and Song 2002). Most previous studies have reduced the computational time of analysis by assuming that the superstructures have a single degree of freedom (DOF) in a lumped mass simulation (Alexander *et al*. 2013, Aldaikhn *et al*. 2015, Aldaikh *et al*. 2016, Vicencio and Alexander 2018) or use a 2D system composed of beams and columns (Behnamfar and Sugimura 1999, Liang *et al*. 2017, Dhar *et al*. 2019). Such studies simulate the soil medium through a spring, mass, and damper or an equivalent impedance function (Wolf 1994) or assume a homogeneous, isotropic and linearly elastic half-space (Mulliken and Karabalis 1998). This excessive simplification process tends to ignore the complex geometry of the cross-section and the wrapping and secondary torsion, especially in complex and massive structures (Lou *et al*. 2011), which could cause underestimation of the seismic response and is potentially risky for accurate seismic analysis of SSI (Liang *et al*. 2018); also the efforts to estimate the effects of SSI on buildings shouldn't be ignored (Mirhosseini 2017). Domain-truncation techniques for seismic soil-structure interaction were studied and formulation of absorbing boundary condition modified (Guddati and Savadatti 2012).

The current study employed a 3D model of a group of structures and soil media. The results of fully nonlinear time history analysis on the acceleration, displacement, drift and shear force of 5-, 10- and 15-story buildings has been broadened to include the SSSI effect. The direct method has been applied for SSI and soil-structure nonlinear time-history analysis in OpenSees software for different types of adjacency. Since in this study the effect of SSSI has been studied, the distance between the buildings according to Iranian Seismic Code (Standard No. 2800-05 2014) has been chosen so that there is no pounding between structures.

2. Structure-soil-structure finite element model

Fig. 1 shows the 3D SSSI model of the soil and three structures that were subjected to the direct method of nonlinear analysis.

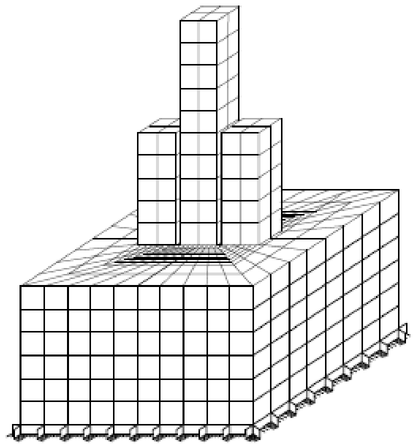

Fig. 1 SSSI model for a group of three structures

2.1 Super structure model

The 3D model examined 5-, 10- and 15-story structures with reinforced concrete frames and shallow foundations having two 5-m spans in the X direction and two 4-m spans in the Z direction (X and Z directions are in the plan). Each structure was designed without considering the effects of SSI or SSSI in order to compare the results of analysis with SSSI cases. Fig. 2 is a sample of the finite element model of the frame and foundation of one structure from OpenSees finite element analysis (McKenna, Fenves *et al*. 2000). -

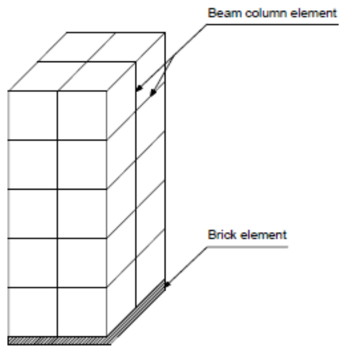

Fig. 2 Superstructure model

OpenSees is a proprietary object-oriented, software framework created at the National Science Foundation sponsored Pacific Earthquake Engineering Center. Due to the high processing speed of this software, being open source, various elements defined in its library, it has been used in studies related to geotechnics, structures and earthquakes, including the SSSI effect (Trombetta *et al*. 2014, Ghandil *et al*. 2016, Farahani *et al*. 2019).

The beams and columns of the structures were modeled as nonlinear elements with plasticity distributed along the length of the elements. Concrete behavior has been modeled as a uniaxial material object with tensile strength and linear tension softening (Concrete02) (Yassin 1994). In compression, it is defined using maximum compressive strength f_{pc} for strain ε_{co} and residual strength f_{pcu} at ultimate strain ε_{cu}. The tensile behavior is determined by maximum tensile strength f_t and the slope coefficient that determines the decrease of tensile strength E_{ts}. Concrete02 features the typical hysteresis behavior shown in Fig. 3. The steel behavior is represented in a uniaxial Giuffre-Menegotto-Pinto model (Steel02).

2.2 Substructure model

Shallow foundations composed of eight-node mixed volume/pressure brick elements were modeled using a trilinear isotropic formulation. The material formulations for the elastic isotropic objects were 3D, plane strain, plane

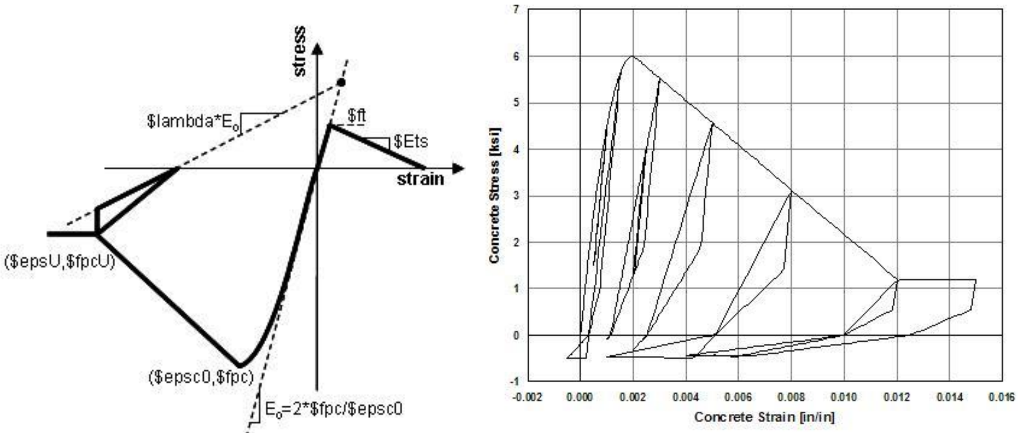

Fig. 3 Graph of stress-strain (left) and hysteresis behavior (right) in Concrete02

Table 1 Major modeling properties of medium soft clay (V_s = 270 m/s) (Rayhani and El Naggar 2008)

Model parameters	Value	Model parameters	Value
ρ = mass density $(\frac{\text{kg}}{\text{m}^3})$	1.595	K = bulk modulus (kPa)	9.37×10^4
G = shear modulus (kPa)	15.9×10^3	ν = Poisson's ratio	0.42
E = elastic modulus (kPa)	4.5×10^4	c = cohesion intercept (kPa)	90
φ = friction angle (deg)	24	c_{sb} = interface cohesion (kPa)	50
k_n = normal stiffness $(\frac{\text{kPa}}{\text{m}})$	7.6×10^4	k_s = shear stiffness $(\frac{\text{kPa}}{\text{m}})$	8×10^2

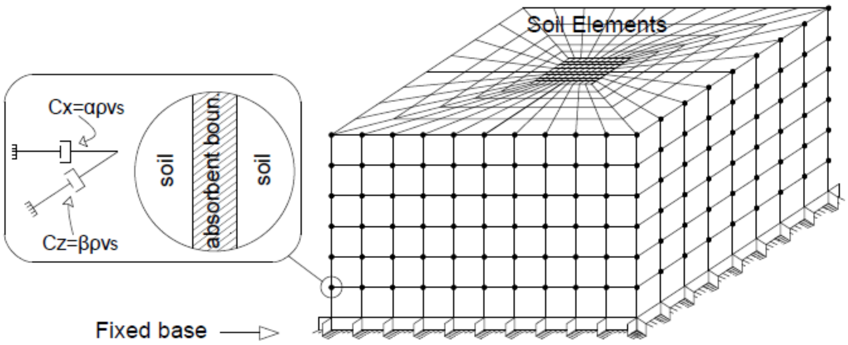

Fig. 4 Substructure model

stress, axisymmetric and plate fiber.

In the models, semi-infinite soil media plays a key role in SSI. Fig. 4 shows the soil media modeled as an assembly of soil elements using the direct method, the fixed support conditions at the bedrock level and the appropriate viscous boundaries around the soil body. The soil was modeled as described by Rayhani and El Naggar with a shear wave velocity of 270 m/s to represent moderately soft soil (Table 1) (Rayhani and El Naggar 2008).

2.3 Soil-foundation interface model

The effects of SSI on the seismic response of the structures were examined by employing interface elements. The interfaces between the foundation and soil were modeled as linear spring-slider systems and zero-length contact 3D elements with interface shear strength as defined by the Mohr-Coulomb failure criterion. The relative interface movement was controlled by interface stiffness values in the normal (k_n) and tangential (k_s) directions (Fig. 5) The rule-of-thumb estimates were used for the maximum interface stiffness values as recommended by Itasca Consulting Group (Itasca 2002) (Itasca 2002) and the magnitudes of k_n and k_s were refined to avoid intrusion of adjacent zones and prevent excessive computation time. Table 1 lists the values for the interface stiffness properties used (Rayhani and El Naggar 2008).

3. Static and Dynamic Analysis and Ground Motion Data

Because the rates of strain softening and seismic response depend on the initial state of the material and its properties (Høeg *et al*. 2000, Asgari *et al*. 2014), the first step applies static analysis under gravity loading and the

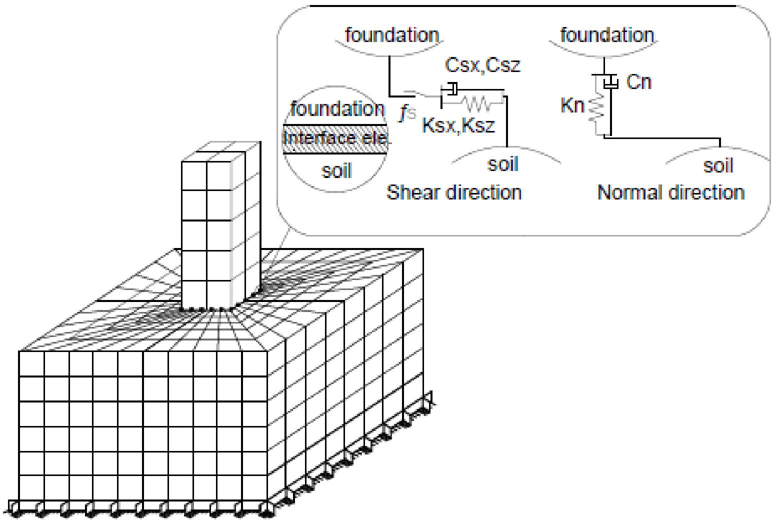

Fig. 5 Soil-structure interaction model for isolated structure

Table 2 Earthquake data for parametric analysis

Earthquake	Station	Year	Soil shear velocity (m/s)	Magnitude (Mw)	Peak ground displacement (m)
Iwait	Minase, Yuzawa	2008	655.45	6.90	0.043
Loma Prieta	Gilroy, CA Array #6	1989	663.31	6.93	0.051
Taiwan SMART1(45)	SMART1 E02	1986	671.52	7.30	0.067

second step is dynamic analysis. Direct method 3D nonlinear dynamic time-history analysis was carried out using three earthquake ground motion records (Table 2). All ground motions were recorded on high rigid soil in these regions to comply with type I soil rigidity according to the Iranian Seismic Code (Standard No. 2800-05 2014). Thus, the recorded displacements were equivalent to the bedrock records. Ground motion records were scaled separately according to the Iranian Seismic Code and applied to the systems horizontally in two directions using both SSI and SSSI models. The scaled ground motion records were applied directly to the lowest soil level in combination with the soil and structure. In the case of fixed-base models, free-field earthquake records that were obtained from ground response analysis were applied to the fixed-base models.

4. Validation of soil and structural molding and method of analysis

Although simulation of structural dynamic responses relies on the use of computer models, verification and validation are the primary means of assessing accuracy, confidence and credibility in modeling. In order to verify the trends and the accuracy of the soil and structure model, the current study employed the method described by Tabatabaiefar and Massumi (Tabatabaiefar and Massumi 2010). A 10-story, 3-bay moment-resisting frame resting on a shallow foundation having the same soil type at 30 m in depth that represents type III according to the Iranian Seismic Code classification (Standard No. 2800-05 2014) was selected. As shown in Fig. 6, they modeled the soil and structure using the direct method in SAP2000 software by applying soil media with 90 m horizontally and 30 m vertically. They used four ground-acceleration records to analyze the structure in fixed-base and flexible-base models using non-linear elastic time-history analysis. They derived the ratio of story deflection and obtained the average of the models.

Table 3 Natural vibration periods in fixed- and flexible -base structures

Building Type	Base Condition	T_x	T_z
5-story	fixed-base	0.53	0.55
	SSI	0.63	0.64
10-story	fixed-base	0.89	0.90
	SSI	1.23	1.25
15-story	fixed-base	1.21	1.23
	SSI	1.65	1.70

In order to verify the model in the current study, all aspects of the 10-story structure and materials of the soil and structure were remodeled (Fig. 7). Time-history dynamic analysis was applied in 3D OpenSees and the average ratio of story deflection of the flexible-base to the fixed-base were compared with the results of Tabatabaiefar and Massumi (Tabatabaiefar and Massumi 2010). Fig. 8 shows a maximum difference of about 13% in the first and second stories. The differences in the other stories were negligible. Thus, the analysis of the SSI models in the

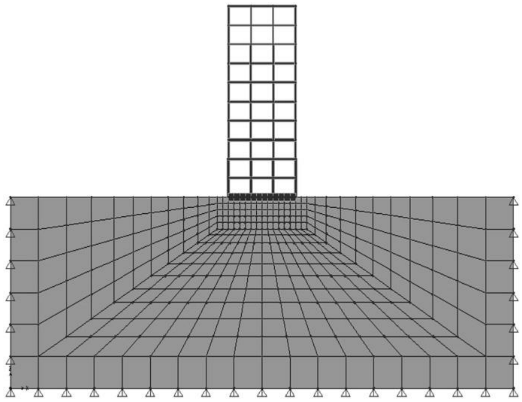

Fig. 6 Model of flexible-base in Tabatabaeifar and Massumi (Tabatabaiefar and Massumi 2010)

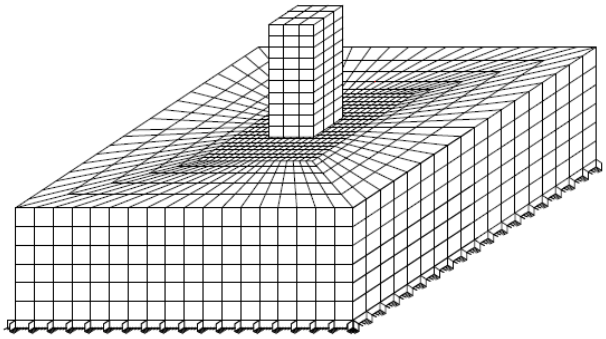

Fig. 7 Current remodeling of flexible-base with the same characteristics and materials for soil and structure used in Tabatabaeifar and Massumi (2010)

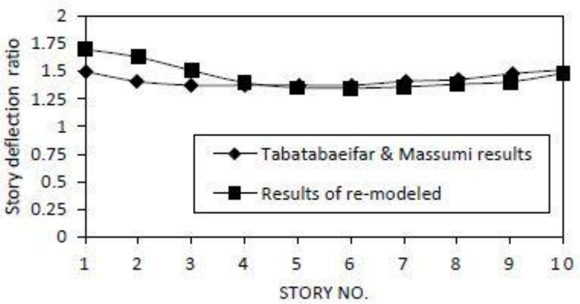

Fig. 8 Average ratio of story deflection of flexible-base to fixed base in Tabatabaeifar and Massumi (2010) and this study

current study can be considered reliable.

5. Natural vibration characteristics of structures

Table 3 compares the natural vibration period of systems in the SSI and fixed-base models in two horizontal directions.

6. Structure-soil-structure interaction

The SSSI models were used to study the seismic performance of the central building as: (1) surrounded by two structures as a SSSI model; (2) an isolated structure (single structure) as a SSI model and; (3) a single fixed-base model. The ratio of relative acceleration, lateral deflection, drift and shear forces of the stories of the central building in the group of three, in the isolated model and in the fixed-base model (without soil) were analyzed separately for each earthquake and the maximum ratios were applied. The different cases, including the 5-, 10- and 15-story structures as shown in Fig. 6, were analyzed under horizontal excitation from three earthquakes in two directions.

7. Results and discussion

The maximum responses of relative acceleration, displacement, drift and shear force of the stories for models with soil to fixed-base models without soil under three pairs of ground motion records on soil type III are shown in Figs. 10-12. The maximum response of the structure with 5 stories in the SSI model to the fixed-base model is denoted as 5ssi/fix and the maximum responses of the central structure with 5 stories in a group of three buildings (SSSI model) with 10-story adjacent structures to the fixed-base model is denoted as 10-5-10sssi/fix.

Fig. 10 shows that the maximum ratios of the flexible-base responses of the 5-story structure as SSI and SSSI models to the fixed-base model were less than one. The 5-story structure with soil, as the flexible-base, produced responses that were lower than those of the fixed-base model. All SSSI responses increased as the number of stories in the adjacent structures increased. The responses for drift (all stories in Fig. 10(c)) and shear force (most stories in Fig. 10(d)) of the 5-story structure with two 15-story adjacent structures were 15% and 18% higher, respectively, than the responses of the same structure with the 5-story adjacent structures.

For the 10-story structure, the ratio of acceleration as shown in Fig. 11(a) was less than one. The models with soil showed a decrease in the acceleration responses of up to 54% in the SSI model and 35% in the SSSI model. In Figs. 11(b) to 11(d), the maximum ratios of story displacement, drift and shear force were greater than one. For the 10-story structure, the ratios of displacement drift and shear force of the SSI and SSSI models were considerably greater than for the fixed-base responses in Fig. 11(b). The displacement ratio was 3.2 times greater for the SSI and SSSI models with lower adjacent structures and 3.7 times greater for the SSSI model with taller adjacent structures.

In Fig. 11(c), the drift ratios for the SSSI model with taller adjacent structures (15 stories) were 4 times greater and for the SSI and SSSI models with equally sized and lower adjacent structures were 3 times greater. These results indicate that taller adjacent structures result in higher ratios. Fig. 11(d) shows that the shear force ratio was 1.8 times greater for the SSI and SSSI models with lower adjacent structures and 2.2 times greater for SSSI models with equally sized and taller adjacent structures. These large differences in the responses are not negligible; thus, the effects of soil and adjacent structures should not be ignored

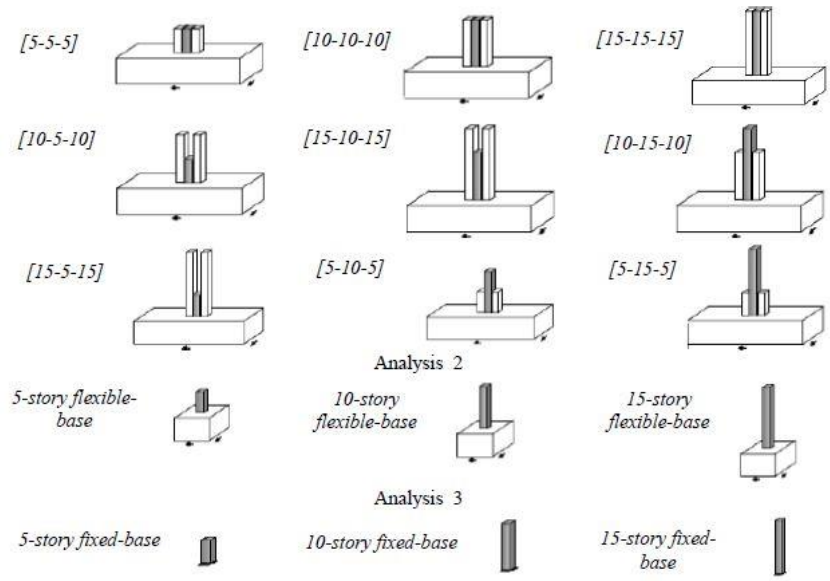

Fig. 9 (1) SSSI models in groups of three buildings (2) isolated soil-structure interaction models (3) fixed-base models

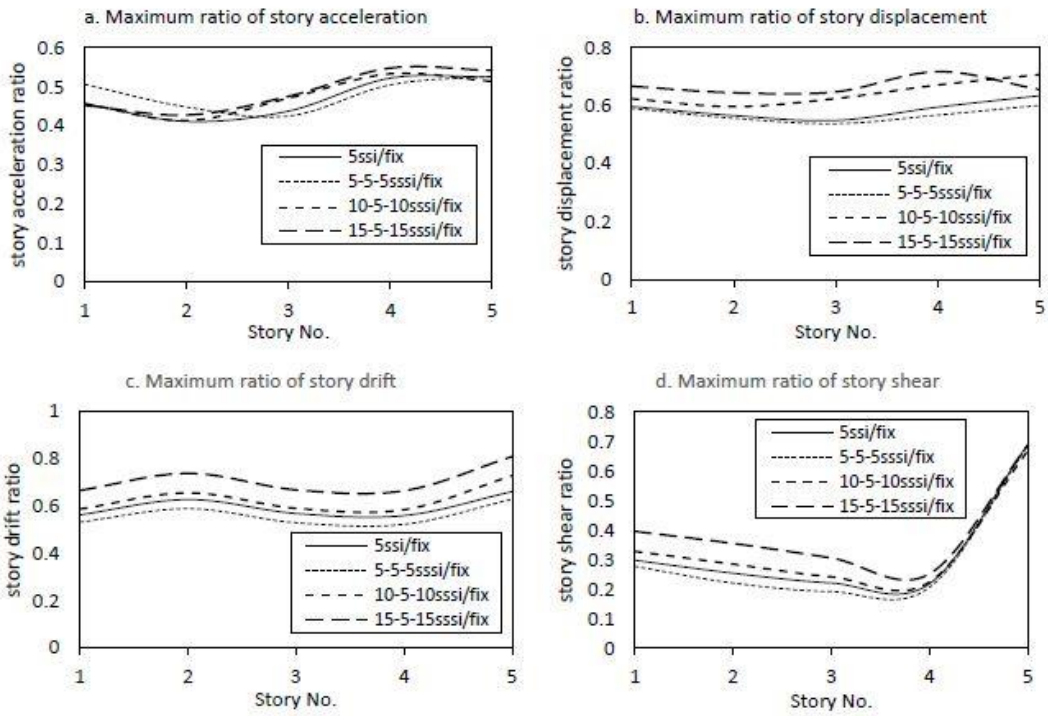

Fig. 10 Maximum ratios of story acceleration, lateral deflection, drift and shear force of flexible-base (SSSI and SSI models) to fixed-base 5-story structures

in dynamic analysis.

Figs. 12(a) and 12(d) show that the maximum ratio s of story acceleration and shear force of the 15-story structure with soil effects was less than one. The result s for the SSI and SSSI models (flexible) decreased 70% for acceleration and 80% for the shear force ratio co mpared to the fixed-base model. The maximum ratios of story displacement and drift (Figs. 12(b) and 12(c)) were significantly greater than one (some more than 2. 5 times greater). The ratios of the 15-story structure for adjacent flexible-base SSSI models increased 20% f or displacement and shear force and 24% for drift over the ratios of the fixed-base model.

The results obtained indicate that the 5-, 10- and 1 5-story structures on soil type III were affected by adj acent structures under the three earthquake records and, in most of the models, showed an increase in the res ponse. These differences in story response occurred bec ause the periods of the SSI or SSSI flexible-base mode ls were longer than those of the fixed-base model and

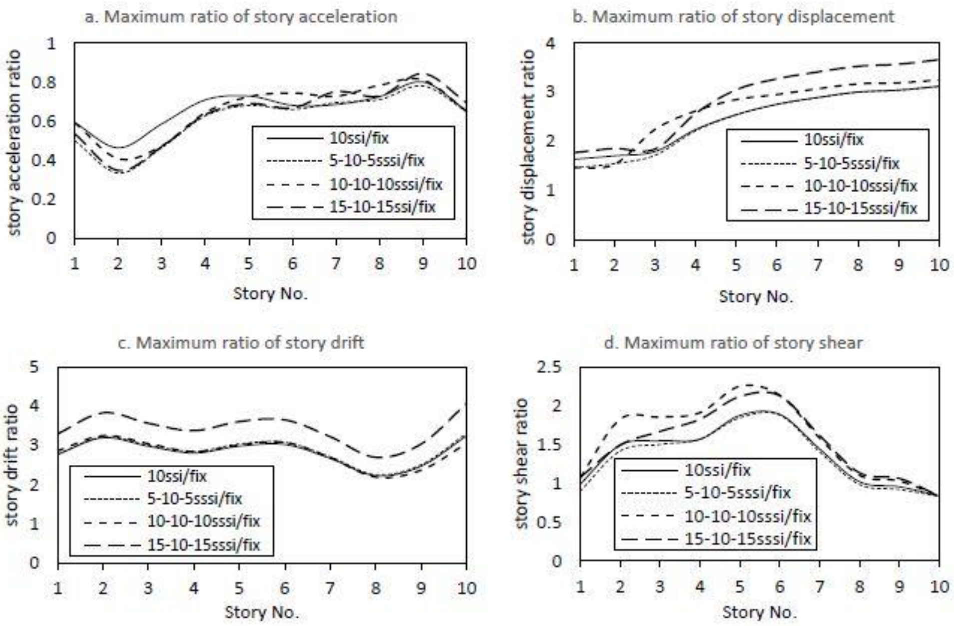

Fig. 11 Maximum ratios of story acceleration, lateral deflection, drift and shear force of flexible-base (as SSSI and SSI models) to fixed-base 10-story structure

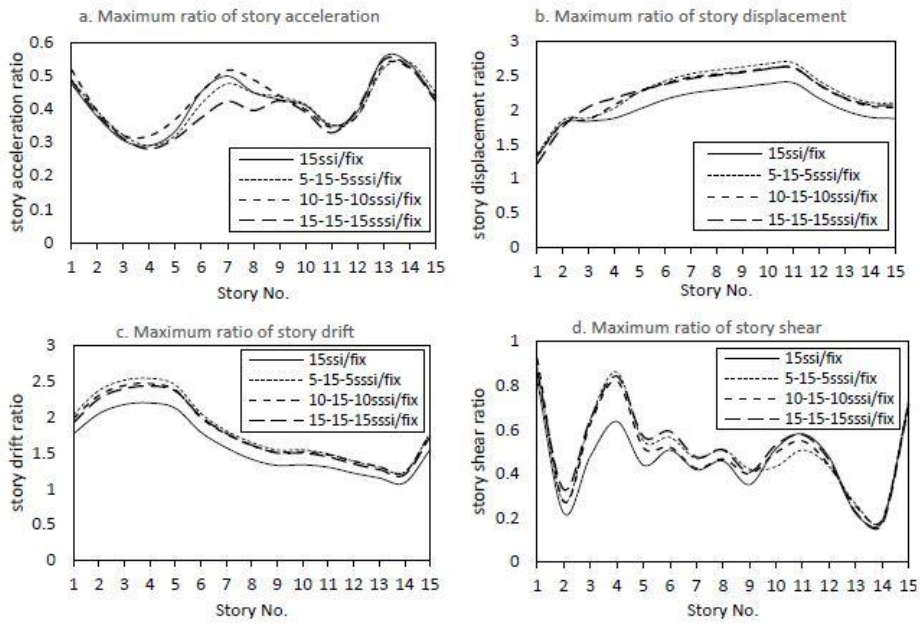

Fig. 12 Maximum ratio for story acceleration, lateral deflection, drift and shear force of flexible-base (SSSI and SSI models) to fixed-base in 15-story structures

also were affected by the adjacent structures. The influence of adjacent buildings in the SSSI flexible-base models for soil type III was considerable.

8. Conclusions

The current study examined the influence of structure-soil-structure interaction (SSSI) on the seismic response of 5-, 10- and 15-story structures and compared the results with those from a fixed-base structure having the same characteristics. In all cases, flexible SSI or SSSI models recorded significantly different responses than the fixed-base models. The results for the 5-story structure indicated that SSI or SSSI can strongly decrease the responses and that two adjacent taller (15-story) structures increased the shear force 18% over the SSI model.

The 10-story structure, unlike the 5- and 15-story structures, was compared with shorter and taller adjacent structures. The results showed that adjacent taller structures caused an increase in the response ratio. For example, the ratios for drift and displacement with two adjacent 15-story structures increased 4 and 3.7 times, respectively. The responses of the 10-story structure with shorter adjacent structures in the flexible-base model did not differ much between the SSI and fixed-base models.

The results for the 15-story structure indicated that the presence of either taller or shorter adjacent structures increased the response ratios when compared with the isolated SSI model. Adjacent structures increased the results for the SSSI model (but not the SSI model) 20% over the fixed-base model for displacement and shear force and 24% for drift.

It can be concluded that adjacent structures should be considered during seismic analysis and design. Especially, structure-soil-structure interaction analysis is advised for tall buildings to avert unsafe designs. Seismic loading could either require reduction or strengthening, depending upon the dynamic characteristics of the structure and frequency content of the seismic loads.

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