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SHAKE TABLE STUDY OF SOIL STRUCTURE INTERACTION EFFECTS ON SEISMIC RESPONSE OF SINGLE AND ADJACENT BUILDINGS

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SUMMARY

The objective of this paper is to evaluate the Soil-Structure-Interaction (SSI) effects in dynamic response of single and adjacent building structures. For this purpose, Experimental testing have been carried out using a ground model specimen made of relatively soft soil and four steel building models of 5, 10, 15, and 20 stories. The combined system of Soil-Foundation-Structure models subjected to horizontal component of two real earthquake records generated by shaking table. From the test results it can be concluded that the effect of kinematic interaction is negligible in comparison with inertial interaction. In lower buildings, the horizontal and rocking motions of foundations are the main causes of soil-structure interaction. By increasing the height of buildings, a major manifestation of SSI is a contribution of the rocking motion of the foundation. The cross-interaction has not significant effect in changing of resonance frequency of adjacent buildings.

INTRODUCTION

In the resent decades, it has been recognized that Soil-Structure-Interaction (SSI) effects alters the response characteristics of a structural system [1-4]. The seismic excitation experienced by structures is a function of the earthquake source, travel path effects, local site effects, and SSI effects. The result of the first three of these factors is a "free field" ground motion. Structural response to free field motion is influenced by SSI.

Soil Structure Interaction (SSI) can affect significantly in the seismic demand and capacity of structures. Existing engineering models for considering these effects are required for rational evaluation of seismic demand and capacity of such systems. Simplified provisions of ATC-1978, and NEHRP-1997, consider

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only the effects of seismic demand (base shear) [5, 6]. New findings show that SSI can affect in the seismic capacity of such systems [7].

In the present study, the authors attempt to evaluate the seismic response characteristics of single and adjacent model buildings using experimental tests on the shaking table.

INERTIAL AND KINEMATIC INTERACTION

Two physical phenomena that comprise the SSI interaction mechanisms are: Inertial interaction and kinematic interaction. The inertial interaction is due to structural vibrations gives rise the horizontal and rocking motion of the foundation relative to the free field. Frequency dependant of foundation impedance functions describes the flexibility of the foundation support as well as the damping associated with foundation-soil interaction.

The kinematic interaction is deviation of stiff foundation motions as a result of ground motion incoherence, wave inclination, or foundation embedment. These effects are described by a frequency dependent transfer function relating the free-field motion to the motion that would occur on the base slab if the slab and structure were mass less. An explanation of the kinematic interaction due to translational excitation of a rigid mass less foundation slab so called "τ-factor" described in ref. [3]. This factor is defined as the ratio of the amplitudes of the harmonics in the rigid-base translational motion to the corresponding free field amplitudes.

A system commonly employed in simple field analyses of inertial interaction is shown in Fig. 1, consists of a single-degree-of-freedom structure of height h, mass m stiffness k and damping c on a flexible foundation medium. The base flexibility including translation (u_f) and rotation (θ) is represented by complex stiffness $\bar{k}_u$ and $\bar{k}_\theta$. The real static stiffness K_u and K_θ of a rigid disk on a half space defined by:

$$K_u = \frac{8}{2-\nu} G r_u \tag{1}$$

$$K_\theta = \frac{8}{3(1-\nu)} G r_\theta^3 \tag{2}$$

Where G is the soil dynamic shear modulus, ν is the soil Poisson ratio, r_u and r_θ are the foundation radii corresponding translation and rotation deformation modes to match the area A_f and moment of inertia I_f of the actual foundation $\left(\text{i.e., } r_u = \sqrt{A_f/\pi}, r_\theta = \sqrt[4]{4 I_f/\pi}\right)$.

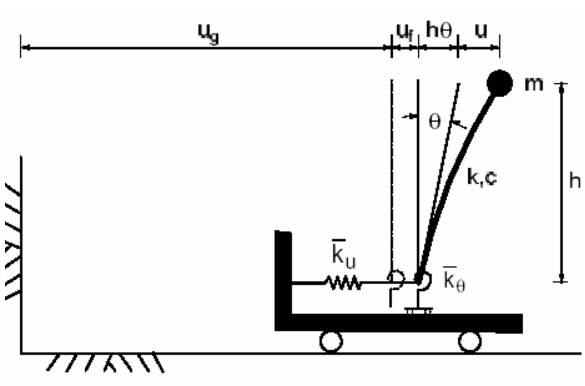

Fig.1: Experimental model of SSI system [1]

The flexible base parameters including effective period ($\overline{T}$) and effective damping ($\overline{\beta}$) are evaluated as follows:

$$\frac{\tilde{T}}{T} = \sqrt{1 + \frac{k}{k_u} + \frac{kh^2}{k_\theta}} \tag{3}$$

$$\overline{\beta} = \beta_o + \frac{\beta}{\left(\tilde{T}/T\right)^3} \tag{4}$$

Where $T = k/m$ is the fixed base period, β is the fixed base period and damping ratio, and $\beta_\circ$ is foundation damping factor. Simplified SSI provisions are included in ATC-1978 and NEHRP-1997 codes based on the above equations [5, 6].

Based on the new seismic design practices, the system performance is represented by a lateral force-displacement relationship. The capacity (S_d) and reduced demand (S_a) spectra's meet at the performance point as shown in Fig. 2. The SSI affects both in demand and capacity spectra's and so in performance point [7]. The objective of this paper is to evaluate the SSI effects in dynamic response (demand spectra) of building structures.

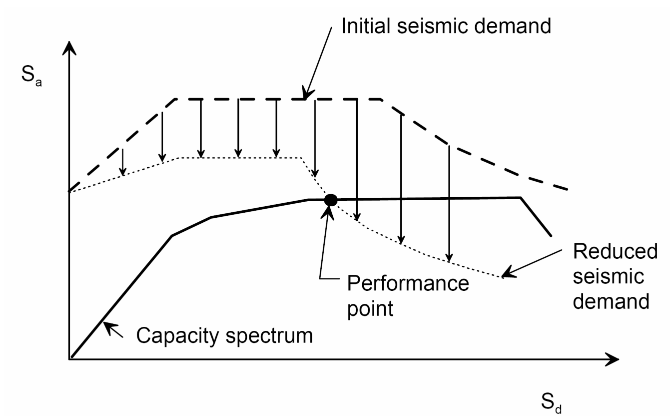

Fig.2: Capacity-Demand spectra to define performance point [7]

EXPERIMENTAL APPROACH

Dimensional analyses are the framework for the scale model similitude in this test program. Three principle test conditions established for scaling parameters are as follows:

1. Testing is conducted in a 1-g environment, which defines model and prototype accelerations to be equal.
2. A model soil with similar density to the prototype soil is desired, which fixes another component of the scaling relations
3. The test medium is primarily composed of saturated clay, whose undrained stress-strain response is independent of confined pressure thereby simplifying the constitutive scaling requirements.

Four structural models of 5, 10, 15 and 20 stories high and two relatively soft soil models were designed for the laboratory tests. The foundation system of structural models was considered as square rigid mats.

In all building models, the height of each storey is 3 cm and the dimension of square rigid surface mats is 20×20 cm. A geometrical scaling of 1/100 is considered for both soil and structure models[8].
A special cylindrical flexible-wall container was designed and constructed to support the soil model with special emphasis on easy connection to the shake table. This container also provided sufficient environment to allow for the elastic half space of the soil. The diameter of ground specimen is 120 cm and the thickness of homogeneous single soil layer from the base rock is 60 cm. General view of structural models, single SSI models, adjacent SSI models, and very low mass accelerometers for vibration recordings are shown in fig. 3 to fig. 6 respectively[8].

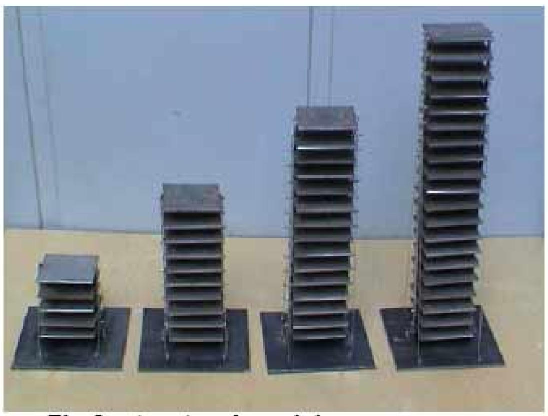

Fig.3: structural models

Fig.4: Single structure on the soil

Fig.5: adjacent structures on the soil

Fig.6: accelerometers for recording

Horizontal component of scaled motions of Elcentro1940 (USA) and Tabas1981 (Iran) earthquakes with different Peak Ground Accelerations (PGA) was used as the inputs for the shaking table. Experimental tests have been carried out on the International Institute of Earthquake Engineering and Seismology (IIEES) one-component shaking table in Iran [8]. The dimension of this table is $120 \times 140 cm$ and the capacity of hydraulic jack is 50 kN.

The complete shaking table test program including six steps is summarized as follows. These steps repeated in two phase for two soil types III and II as defined in Iranian seismic code (standard 2800) [9]. The distance of adjacent structures defined by the ratio d/a, where d is the clear distance between adjacent foundations and 2a is the dimension of foundation.

1. Fixed base structural models.

2. Free field response of soil models.
3. Kinematic interaction of single foundation.
4. Kinematic interaction of adjacent foundations (d/a=1, 2, 3, 4).
5. SSI tests for single structure models.
6. SSI tests for adjacent structure models for different arrangements and distances (d/a=1, 2, 3, 4).

Before the main tests program, some preliminary tests considered to evaluate the shaking table performance. A typical test series for an individual model consisted of a hammer blow test, a sine sweep test, the Elcentro motion, the Tabas motion, another sine sweep test, and a final hammer blow test.

TEST RESULTS

A comparison between command signals and the shaking table shows that the table response match to the command signal is good and repeatable. So the results obtained from several model tests are comparable. Some important test results are as follows. These results are presented in the model scale.

Free field response

Based on the soil dynamic laboratory tests and shaking table tests, the soil properties determined at small amplitude strains. In accordance to ASTM standard the soil type classified as Silty clay (CL-ML). The results of shear wave velocity (V_s), resonant frequency (f_n), and damping ratio (D) in small excitations are summarized in table 1. This frequency is very close to that obtained from the analytical equation determined for a homogeneous soil layer of thickness H_s underlain by a rock or rocklike material [10].

$$f_n = \frac{(2n-1)V_s}{4H_s} \tag{5}$$

Where n is the nth mode and (V_s) is the shear wave velocity that can be determined from shear modulus (G) and density of soil (ν) as follows:

$$V_s = \sqrt{\frac{G}{\nu}} \tag{6}$$

Table 1: Frequency content and damping ratio of soil model in small excitations

Soil type	V_s (m/sec)	Vibration mode	Test freq.(f_s) (Hz)	Anal. freq. (f_s) (Eq. 5)	D (%)
III	31.0	1	13.0	12.91	3.8
		2	35.0	38.75	4.5
II	43.0	1	18.0	17.91	3.9
		2	50.0	53.75	4.8

Transfer function of the free field response for soil type III subjected to Elcentro record is presented in Fig. 7. It can be concluded that the amplification factor of soil in earthquakes with small peak ground accelerations (PGA=0.03g) is about 10; but in stronger earthquakes with PGA≈0.1g and PGA≈0.3g the amplification factor reduces to 6 and 4 respectively.

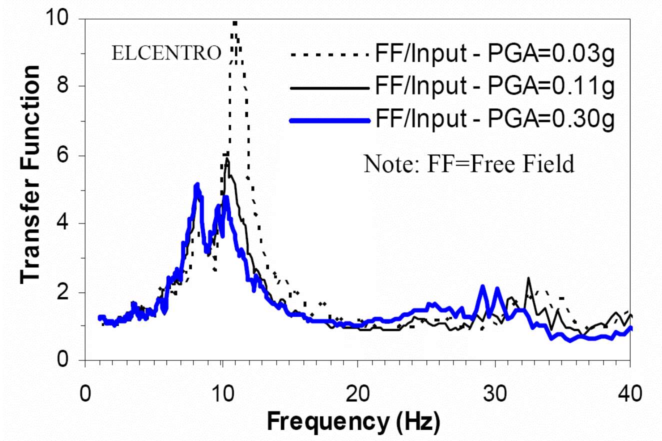

Fig.7: Transfer function of free field response for soil type III

Kinematic interaction of foundations

The main response quantities of a two dimensional foundation including horizontal (H), vertical (V), and rocking(R) Vibration modes have been shown in Fig. 8. Transfer function of H and R components of a single surface foundation on a soil type III subjected to Elcentro record with PGA=0.13g is presented in Fig. 9. It can be concluded that the horizontal motion of foundation and free field response are very similar up to 32 Hz. Also there is no significant effect of rocking motion up to 22 Hz. Similar results have been obtained in the case of adjacent foundations. From these results it can be concluded that the Kinematic effects are negligible in the low frequencies or in the dominant frequencies of building models.

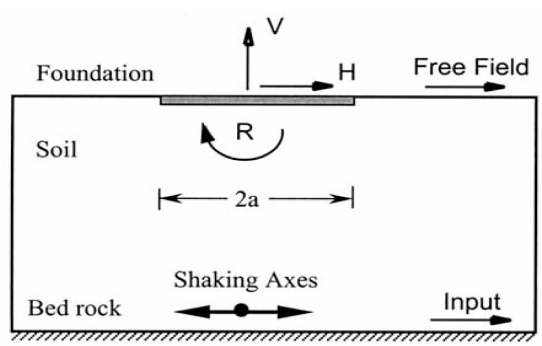

Fig.8: Foundation vibration modes

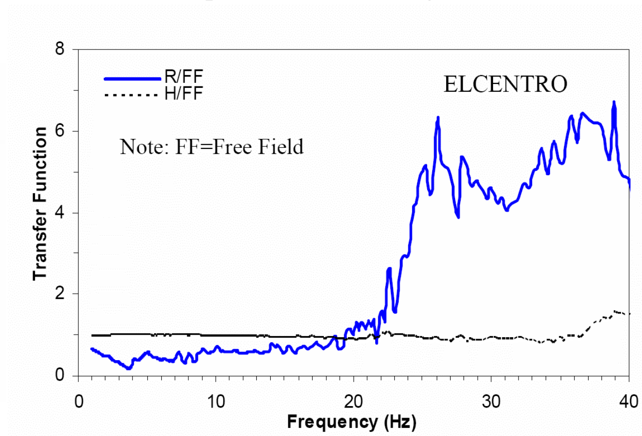

Fig.9: Transfer function of H and R components

SSI effects in single structures

The transfer function of horizontal response at top (roof level), and the horizontal and rocking responses at the foundation level demonstrated in Fig. 10. The effect of SSI in vibration frequencies (or periods) and damping ratios, summarized in Table 2. It can be concluded that the SSI effect increases the first mode period and damping ratio of the structural models, and the higher modes are not affected considerable.

A major parameter in SSI effects is the aspect ratio $(\bar{h}/r)$ of structural models, where $\bar{h}$ is the height of center of mass (approximately 0.7 of total height of structure) from the base, and r is the foundation radii. Variations of effective period $(\bar{T}/T)$ and effective damping $(\bar{\beta}/\beta)$ whit respect of $(\bar{h}/r)$ have been shown in fig. 11. Also, a comparison of test results with ATC and NEHRP requirements presented in this figure. It is clear that by increasing of $(\bar{h}/r)$, the SSI effects are increasing. Analytical studies show that the contribution of horizontal and rocking motions in SSI effects are similar in the case of $(\bar{h}/r) \leq 1.0$. But by increasing of this parameter the rocking motion was the dominant. The contribution of horizontal motions calculated when $K_\theta = \infty$ and the contribution of rocking motions calculated when $K_y = \infty$.

Table 2: Effective period and damping of SSI system

Building type	Mode No.	Without SSI		With SSI		$(f/\bar{f})$ or $(\bar{T}/T)$	$(\bar{\beta}/\beta)$
		f (sec)	β (%)	$\bar{f}$ (sec)	$\bar{\beta}$ (%)		
5 Story	1	15.30	0.33	15.23	0.35	1.005	1.06
10 Story	1	7.60	3.40	7.40	3.50	1.027	1.03
	2	21.00		20.50		1.024	
15 Story	1	5.20	1.17	5.00	2.00	1.040	1.71
	2	19.20		19.00		1.00	
	3	32.00		32.00		1.00	
20 Story	1	3.70	1.30	3.50	2.10	1.057	1.62
	2	12.60		12.60		1.00	
	3	22.50		22.50		1.00	

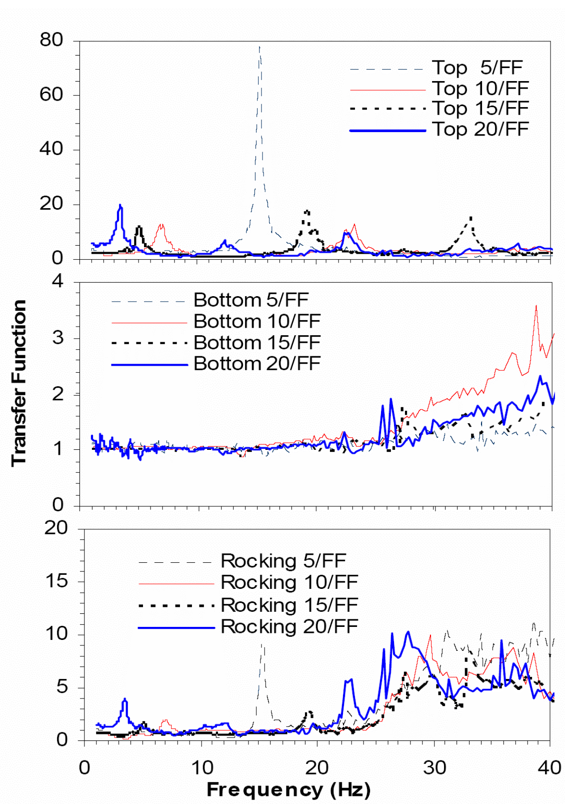

Fig.10: single structure responses with SSI subjected to Elcentro.

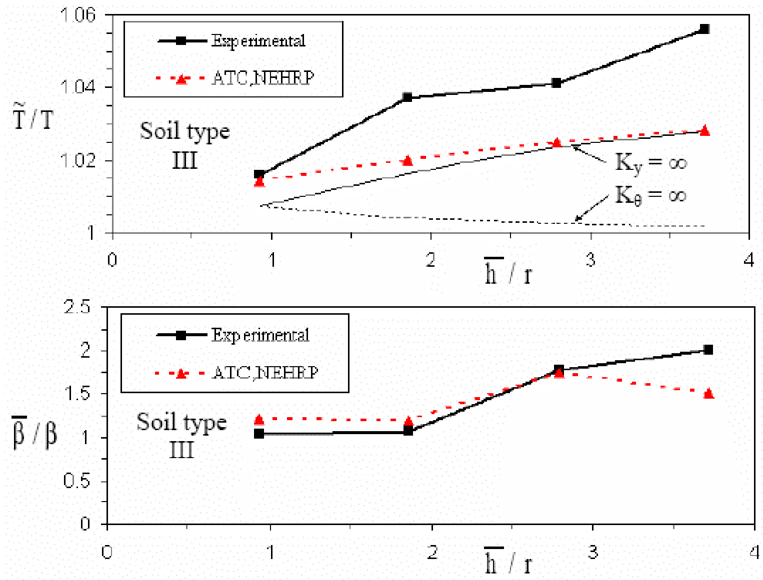

Fig.11: Variation of effective period and damping whit $(\bar{h}/r)$.

SSI effects in adjacent structures

An example of transfer functions for top, Bottom, and rocking modes in adjacent 15 and 20 story building models have been shown in Fig. 12. The results are presented for several distance ratio of adjacent structures (d/a). It can be concluded that the adjacent structures have not significant effect in changing the resonance frequency in comparison with single structures. Similar adjacent buildings have more effect on each other compared to the different adjacent buildings.

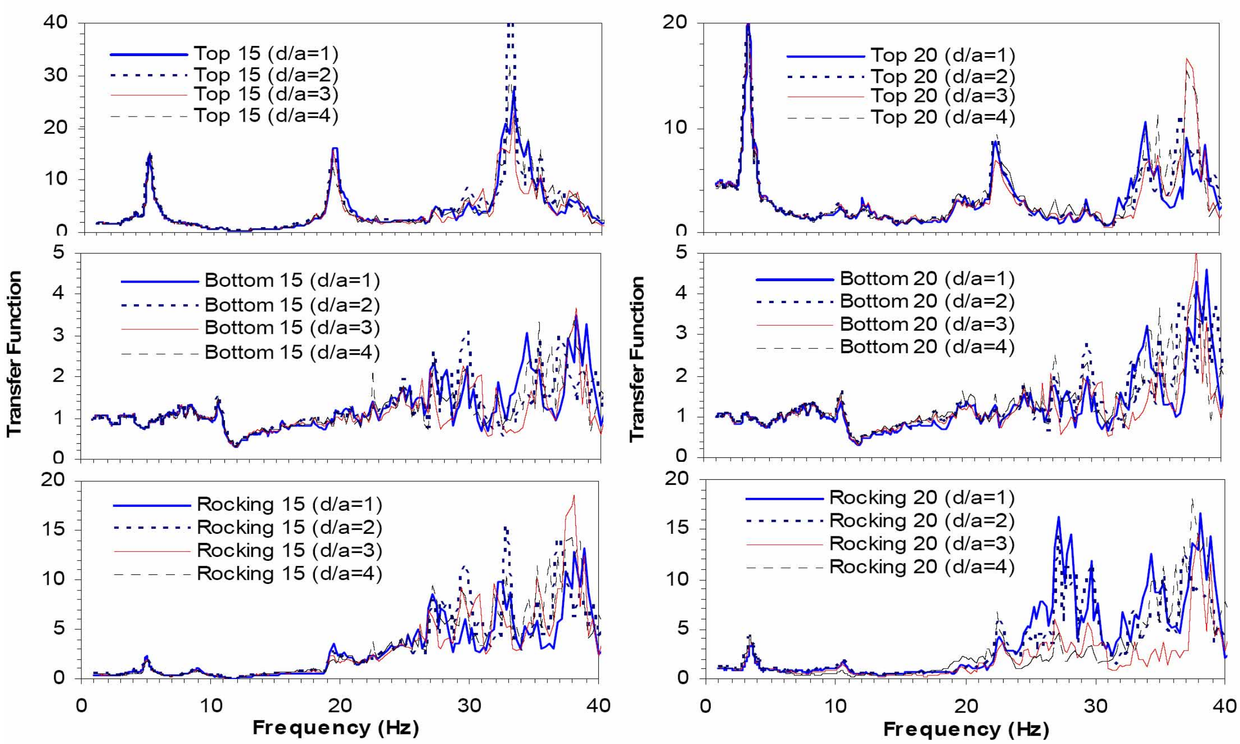

Fig.12: Responses of adjacent 15 and 20 story models with different distances (d/a).

COMPARISON OF TEST AND ANALYSES RESULTS

The computer program FLUSH have been used for finite element analyzes (FEA) of single and adjacent SSI test models [4]. A comparison between test and analyses results for free field response and 10 story SSI model response presented in Fig. 13. A good agreement between test and analyses results can be seen in the time domain.

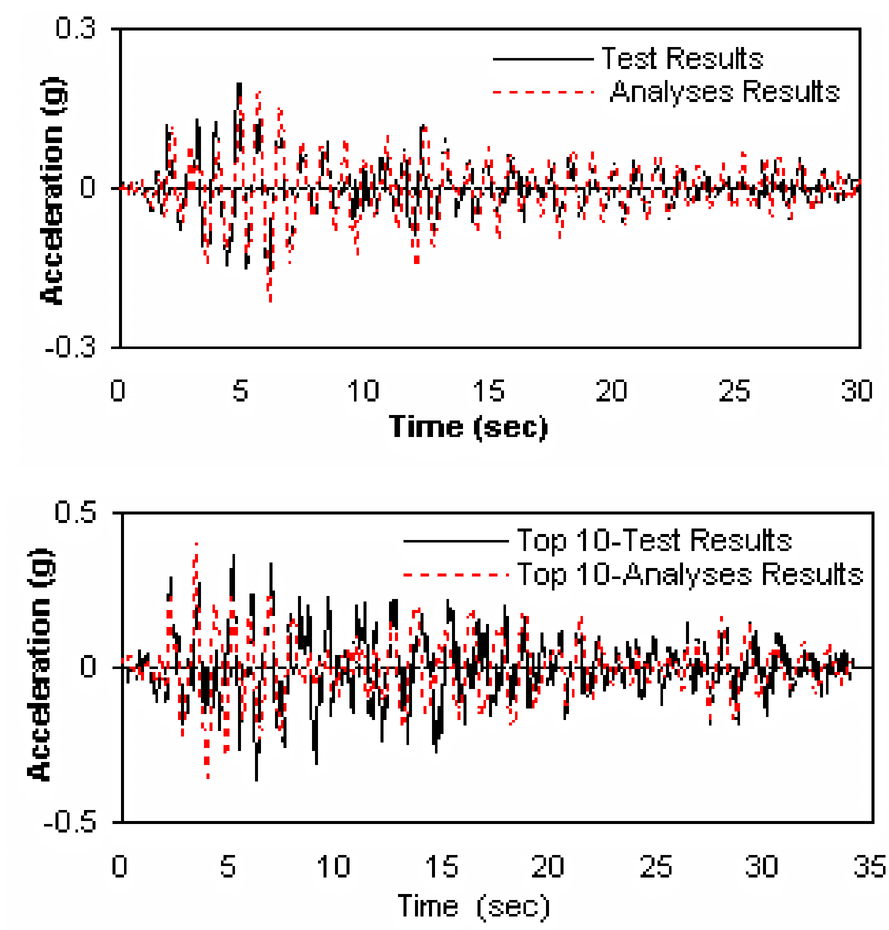

Fig. 13: Comparison between test and analyses results for free field and 10 story model

CONCLUSIONS

Shaking table tests and finite element analyses of four steel building models with 5, 10, 15, and 20 stories have been studied in this paper for accounting the SSI effects in the case of single and adjacent buildings. Successful results of shaking table model tests show the feasibility of 1-g scale modeling technique. Also, a good agreement has been shown between shaking table test results and finite element analyses. Based on the test results it can be concluded that:

1. The amplification factor of soil model in small earthquakes with small peak ground accelerations (PGA=0.03g) is about 10; but in earthquakes with PGA≈ 0.1g and PGA≈0.3g the amplification factor reduces to 6 and 4 respectively.

2. From experimental results, it can be concluded that the effects of kinematic interaction is negligible in comparison with inertial interaction.

3. The effect of SSI was found to be increasing the first mode period and damping ratio of the structures. A major parameter in this relation is the aspect ratio $(\bar{h}/r)$ of structure. By increasing of this parameter (i.e. in taller buildings) the rocking motion was the dominant.

4. Adjacent structures have not significant effect in changing of resonance frequency in comparison with single structures. Similar adjacent buildings have more effect on each other compared to the different adjacent buildings

5. The rocking mode of foundation can change the capacity of buildings in some cases such as frame-shear wall systems.

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