Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1545

SHAKE TABLE STUDY OF SOIL- FOUNDATION-STRUCTURE INTERACTION (SFSI) EFFECTS IN ROCKING AND HORIZONTAL MOTIONS OF THE BUILDING STRUCTURES

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ABSTRACT

In the resent decades, it has been recognized that Soil-Foundation-Structure-Interaction (SFSI) alters the response characteristics of structural systems. Two physical phenomena that comprise this interaction mechanism are: Inertial interaction due to mass inertia, and kinematic interaction due to stiff foundation constraint on the soil. Generally, the effects of SFSI were found to increase the period of the first mode and also the damping ratio of the building structures. Therefore, these effects can significantly affect the seismic demand and capacity of structures. In this paper, four structural models of 5, 10, 15 and 20 stories and a relatively soft soil model were designed and constructed for the laboratory tests. The foundation system of structural models was considered as square rigid mats. Soil-Structure models subjected to Elcentro1940 (USA) record on the shaking table. Also, Finite Element Method (FEM) Analyzes results compared with experimental results. Based on the experimental study, in buildings lower than 5 stories, the horizontal and rocking motion of foundation is the main causes of the SFSI effects. In buildings higher than 10 stories, a major manifestation of these effects is a contribution of the rocking motion. Also, good agreement can be seen between test and analyses results

Introduction

It has been recognized that Soil-Foundation-Structure-Interaction (SFSI) alters the response characteristics of a structural system (Stewart, Seed, Fenves, 1998, Wolf, 1985). Two physical phenomena that comprise this interaction mechanism are: Inertial interaction due to mass inertia, and kinematic interaction due to stiff foundation constraint (Clough, Penzien, 1993). 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. kinematic interaction is deviation of stiff foundation motions as a result of ground motion incoherence, wave inclination, or foundation embedment. These

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effects are described by a frequency dependent transfer function relating the Free Field (FF) motion to the motion that would occur on the base slab if the slab and structure were mass less.

A system commonly employed in simple field analyses of inertial interaction is shown in Fig. 1 (Stewart, Seed, Fenves, 1998). The base flexibility including translation (u_f) and rotation (θ) is represented by complex stiffness $\bar{k}_u$ and $\bar{k}_\theta$. The flexible base parameters including effective period ($\bar{T}$) and effective damping ($\bar{\beta}$) are evaluated as follows:

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

$$\bar{\beta} = \beta_o + \frac{\beta}{\left(\tilde{T}/T\right)^3} \tag{2}$$

Where T and β are the fixed base period and damping ratio, and β_o is foundation damping factor.

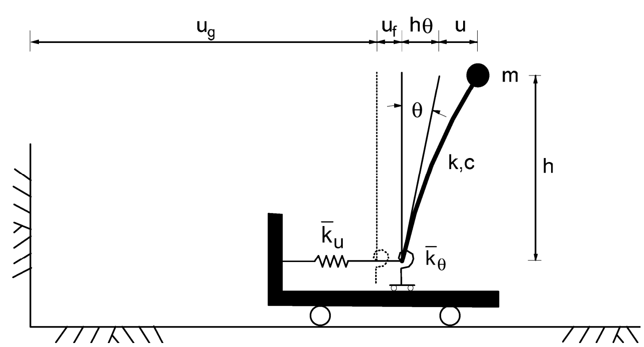

Figure1. Simple analytical model of inertial SFSI (Stewart, Seed, Fenves, 1998)

There are limited criteria in building code requirements for investigation of Soil–Structure Interaction effects. For example, the ATC and NEHRP recommendations are based on the first dominant mode of vibration (ATC, 1978, NEHRP, 1995). Therefore, comparison of Soil–Structure Interaction effects between building code requirements and shake table study is an important research issue. The objective of this paper is to evaluate the SFSI effects in dynamic response of building structures specially translation and rotation of base using shake table test results. Only Inertial interaction has been studied in this paper.

Experimental Approach

Four structural models of 5, 10, 15 and 20 stories in high and a relatively soft soil model were designed for the laboratory tests. The foundation system for structural models was considered as square rigid mat. A geometrical scaling of 1/100 is considered for both soil and structure models. 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 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. Horizontal component of Elcentro1940 (USA) record was considered as input motions for shaking table tests (Hosseinzadeh, 2002).

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.

A general view of structural models is shown in Fig. 2. Completed SFSI model installed on the shaking table is shown in Fig. 3. Also, accelerometers installed on the top and bottom level of 5 story structural model is shown in Fig. 4. Experimental tests have been carried out on the International Institute of Earthquake Engineering and Seismology (IIEES) one-component shaking table in Tehran, Iran. The dimension of this table is $120 \times 140 cm$ and the capacity of hydraulic jack is 50 kN (Hosseinzadeh, 2002).

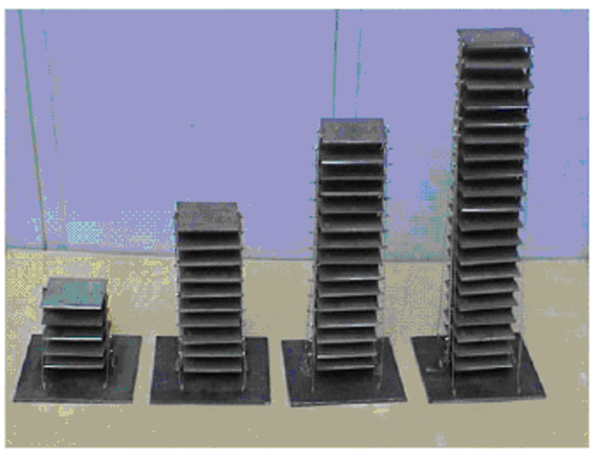

Figure2. Structural models of 5, 10, 15, and 20 story

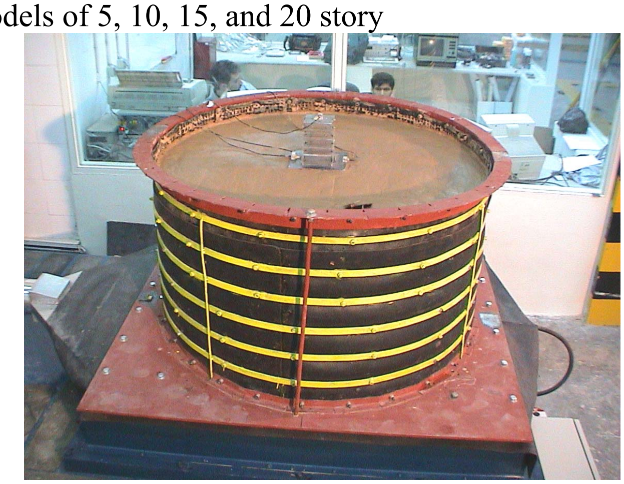

Figure3. Experimental SFSI model installed on the shaking table

Figure4. Accelerometers arrangement on the top and bottom level of 5 story structural model

Test Results

Free Field response

Successful results of shaking table model tests show the feasibility of 1-g scale modeling technique. Based on the geotechnical and shaking table test results, the soil properties at small amplitude strains (linear range) in real scale are as follows:

- Soil type based on the Iranian code (Standard 2800):Type III, Silty clay (CL-ML),
- Shear wave velocity: Vs=310 m/sec,
- Damping ratio: D=4%,
- Natural free field period obtained from shaking table test results: $T_\circ = 0.77\,\text{sec}$

The results of shear wave velocity (V_s), resonant frequency (f_n), and damping ratio (D) in low amplitude excitations (linear range) are summarized in Table 1. As shown in this table, the Free Field (FF) experimental 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 as follows (Das, 1993):

$$T_\circ = \frac{4H_s}{(2n-1)V_s} = \frac{4\times 60}{1\times 310} = 0.774\,\text{sec} \tag{3}$$

Table 1: Frequency content and damping ratio of soil model tested on the shaking table in small excitations (linear range)

Shear wave velocity Vs (m/sec)	Vibration mode	Test frequency f_n (Hz)	Analytical frequency f_n (Hz)	Damping ratio D (%)
31.0	1	13.0	12.91	3.8
	2	35.0	38.75	4.5

Fast Fourier transfer (FFT) function of the Free Field (FF) response for single soil layer subjected to Elcentro1940 (USA) input record is presented in Fig. 5. 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=0.11g and PGA=0.3g the amplification factor reduces to 6 and 4 respectively. The reason of this reduction is nonlinear behavior of soil material by increasing of earthquake PGAs.

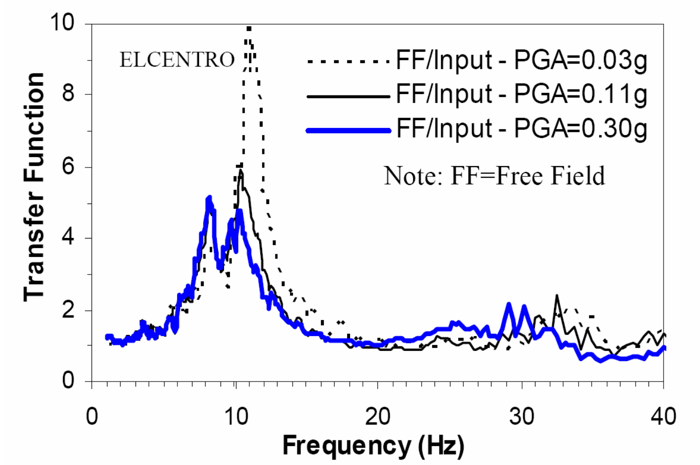

Figure5. Transfer function of Free Field (FF) response of soil model subjected to Elcentro1940 (USA) input record on the shaking table

SFSI model responses

Transfer Function of test results for horizontal response at top (roof level), and the horizontal and rocking responses at the foundation level for 5, 10, 15, and 20 story structural models subjected to Elcentro1940 (USA) input record is demonstrated in Fig. 6. Peak values in this Figure indicate the modal frequencies (or modal periods) of structural models with SFSI effects.

A major parameter in SFSI 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 $(\tilde{T}/T)$ and effective damping $(\tilde{\beta}/\beta)$ whit respect of $(\bar{h}/r)$ have been shown in Fig. 7. Also, a comparison of test results with ATC and NEHRP requirements has been presented in this figure. It is clear that by increasing of $(\bar{h}/r)$, the SFSI effects are increasing.

From the above results, it can be concluded that the variation of effective period ratio $(\tilde{T}/T)$ is under estimated in ATC and NEHRP requirements, but a good agreement is obtained for effective damping ratio $(\tilde{\beta}/\beta)$.

Experimental studies on shaking table show that the contribution of horizontal and rocking motions in SFSI effects is similar in the case of $(\bar{h}/r) \leq 1.0$. However, by increasing of this parameter, the rocking motion was the dominant. The contribution of horizontal motions calculated when K_θ increases to infinity ($K_\theta = \infty$) and the contribution of rocking motions calculated when K_u increases to infinity ($K_u = \infty$)

Summery of test results of building models including periods and damping ratios in the case of without SFSI and with SFSI at the prototype scale presented in Table 2. As shown in this table, the effective period and damping of test models have been increased in the case of SFSI effects.

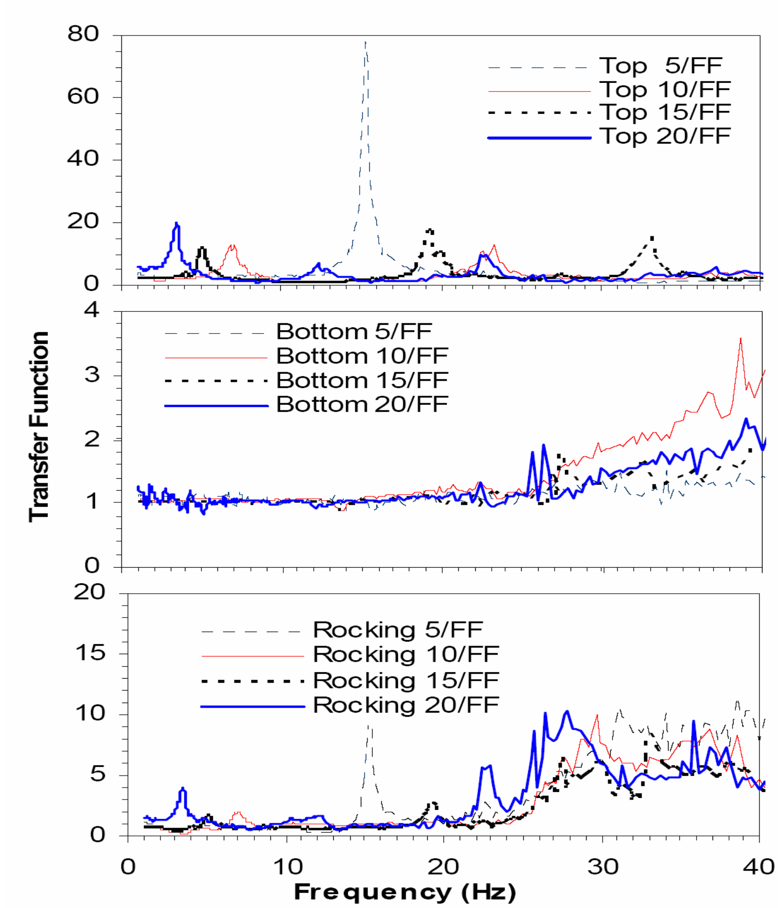

Figure6. Structural model responses with SFSI subjected to Elcentro 1940 (USA) record.

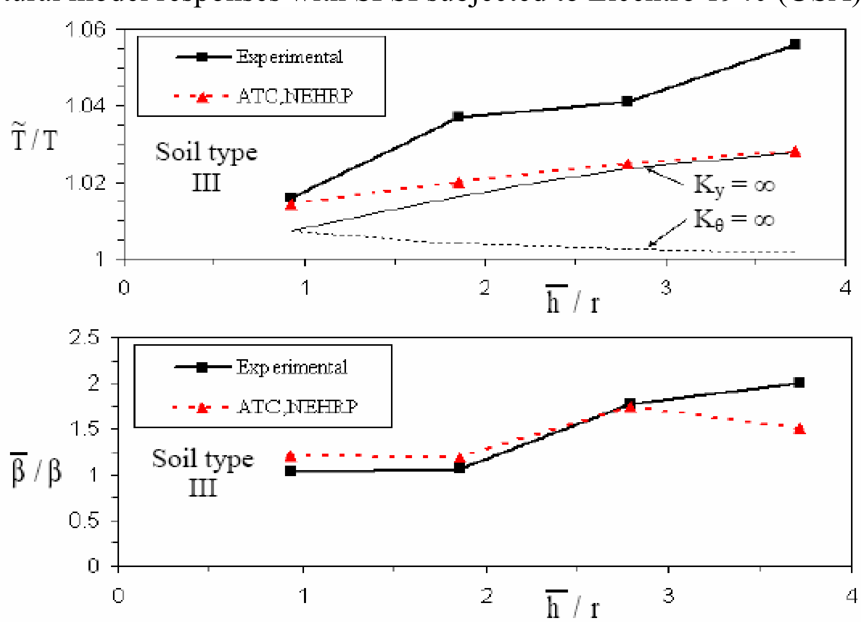

Figure7. Variation of effective period and damping whit $(\bar{h}/r)$

Table 2: Effective period and damping ratios of SFSI system

Building type	Without SFSI		With SFSI		$(\bar{T}/T)$
	T (sec)	β (%)	$\bar{T}$ (sec)	$\bar{\beta}$ (%)	
5 Story	0.685	0.33	0.694	0.35	1.013
10 Story	1.287	3.40	1.299	3.50	1.010
15 Story	1.927	1.17	2.000	2.00	1.038
20 Story	2.597	1.30	2.786	2.10	1.073

Comparison of Test and Analyses Results

The computer program FLUSH has been used for Finite Element Method (FEM) Analyses of single SFSI test models (Lysmer, Ukada, Tsai, Seed, 1975). A comparison between test and analyses results for free field response presented in Fig. 8. Similar comparison is shown in Fig. 9 for 10 story structure with SFSI effects. Good agreement can be seen between test and analyses results in the time domain.

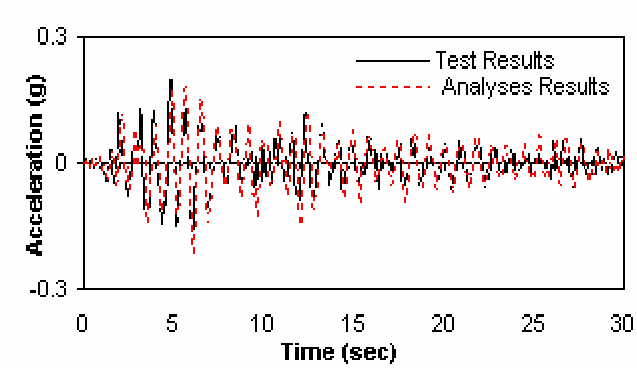

Figure 8. Comparison of test and analyses results for free field response

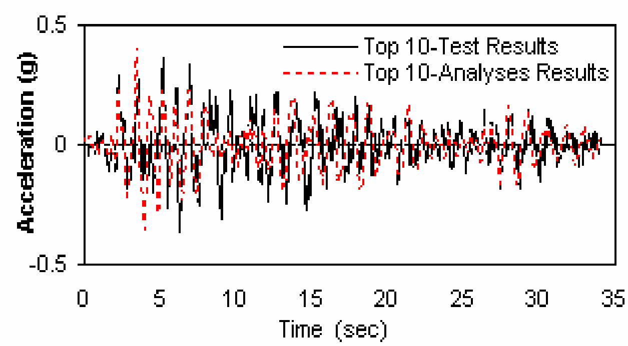

Figure 9. Comparison of test and analyses results for 10 story model with SFSI effects

Conclusions

Based on the shaking table test results and analytical studies performed on the Soil-Foundation-Structure-Interaction (SFSI) in this research, the following conclusions have been obtained:

1. Very good agreement has been shown between shaking table test results and Finite Element Method (FEM) Analyses results.
2. Successful results of shaking table model test results show the feasibility of 1-g scale modeling technique.
3. One major effect of SFSI was found to be increasing the first mode period and damping ratio of the structures. Higher modes has negligible effect in SFSI systems
4. The horizontal and rocking mode of foundation was known to be the main causes of SFSI in buildings lower than 5 stories in high; but in taller buildings, the rocking mode was the dominant.
5. Natural Free Field (FF) period obtained from shaking table tests is very close to that obtained from the analytical equation
6. The amplification factor of studied soil in earthquakes with small peak ground accelerations (PGA=0.03g) is about 10; but in stronger earthquakes with PGA=0.11g and PGA=0.3g the amplification factor reduces to 6 and 4 respectively.
7. Aspect ratio $(\bar{h}/r)$ of structural models is a key parameter in SFSI. By increasing of this ratio, SFSI effects are increases.
8. It can be concluded that the variation of effective period ratio $(\bar{T}/T)$ is under estimated in ATC and NEHRP requirements. However, good agreement is obtained for effective damping ratio $(\bar{\beta}/\beta)$ between codes and shaking table test results.

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