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Shaking Table Tests on Soil-Structure System to Determine Lateral Seismic Response of Buildings

H.R. Tabatabaiefar

School of Engineering and Information Technology, Federation University Australia, Mt Helen, Australia

ABSTRACT: In this study, a series of experimental shaking table tests were performed on a physical fixed based model (structure directly fixed on top of the shaking table) and a flexible base model (soil-structure system) under the influence of four scaled earthquake acceleration records (two near field and two far field records) and the results were measured. The soil-structure system includes a 15 storey structural model resting on a synthetic clayey soil mixture consisting of kaolinite, bentonite, class F fly ash, lime, and water. The selected soil model was placed into a laminar soil container, designed and constructed to realistically simulate the free field conditions in shaking table tests. Comparing the measured response of fixed base and flexible base models, it is noted that the lateral deflections of flexible base model have evidently amplified in comparison to the fixed base model. As a result, performance level of the structural model may change extensively (e.g. from life safe to near collapse level), which may be extremely dangerous and safety threatening. Thus, it is experimentally observed that dynamic soil-structure interaction plays a significant role in seismic behaviour of moment resisting building frames resting on relatively soft soils.

1 INTRODUCTION

The Mexico City earthquake in 1985 and Christchurch-New Zealand earthquake in 2011 evidently demonstrate the significance of site local properties on the seismic response of structures. The mentioned earthquakes as well as many other examples clearly depict the significance of amplification of rock motions at the base level of un-braced building structures founding on relatively soft grounds. The problem of Soil-Structure Interaction (SSI) in seismic analysis and design of structures has become increasingly important, as it may be inevitable to build structures at locations with less favourable geotechnical conditions in seismically active regions. In addition, the scarcity of land compels engineers to construct major structures over soft deposits (Massumi & Tabatabaiefar, 2007; Fatahi et al., 2011). During the recent years, the importance of dynamic soil-structure interaction for building structures with shallow foundations founded on soft soils has been well recognised and studied (Samali et al., 2011). Dynamic soil-structure interaction has significant effects on seismic response of building frames resting on soft soil deposits. Considering performance-base design approach, the amplification of lateral deformations due to SSI noticeably changes the performance level of the building frames (Tabatabaiefar et al., 2013a,b). Consequently, the safety and integrity of the building would be endangered. Thus, the conventional design procedure excluding SSI may not be adequate to guarantee the structural safety of building frames resting on soft soil deposits (Tabatabaiefar et al., 2011; Fatahi & Tabatabaiefar, 2014). As a result, there is a strong need to develop novel experimental tools to evaluate seismic response of building structures resting on soft soil deposits under the influence of soil-structure interaction.

2 BACKGROUND

Full-scale field tests or scale model tests are essential to study soil-structure system behaviour during earthquakes. Such tests are also required to validate numerical or analytical models. For such applications, it is necessary to have a set of scaling relations which can relate the observations and predictions. Shaking table test is an experimental technique used in earthquake engineering to simulate ground motions. Since the emergence of shaking tables in the 1920s, large number of earthquake model tests have been performed. Shaking table tests have been considered as 1g modelling, in which the gravity acceleration of the model and prototype are always the same. Shaking table test is relatively cheap and easy to model complex prototypes, although there is a lack of accuracy due to 1g manner (e.g. low confining pressure of model affects test results especially in sandy soils). It should be noted that, in centrifuge tests by increasing the gravity force via rotating the model, it is possible to accurately model the soil stress- strain condition as exists in prototype. In comparison, although centrifuge test models the stress-strain conditions accurately, it is difficult to build complex prototypes, and due to small size of the model, fewer instruments can be installed (Taylor, 1997). During the past few decades, several researchers have carried out shaking table tests on soil-structure systems using various types of soil containers and structural models. In many of the past experiments, the structure model on top of the soil has not been taken into consideration at all. Some of the tests were only performed on the soil inside the container (e.g. Prasad et al., 2004; Lee et al., 2012) in order to investigate dynamic behaviour of the soil under the influence of earthquake loads, while some others were undertaken on soil-foundation system to observe the dynamic interaction of shallow or pile foundation with the underlying soil (e.g. Richards et al., 1990; Stanton et al., 1998). In some of the past mentioned experiments, the structural model has been considered but simplified to SDOF (single Degree of Freedom) oscillator (e.g. Pitilakis et al., 2008; Chau et al., 2009) so as to model and investigate dynamic soil-structure interaction. However, by simplifying the structural model, the behaviour of the soil-structure system may not be completely conforming to reality. Unlike past shaking table experiments which were performed without the structure or employed simplified SDOF (single Degree of Freedom) oscillators, in this study, the adopted structural model will simulate most of the structural properties of the real prototype building such as frequency of vibrations, number of stories, and mass. Therefore, this experiment will be a unique experimental shaking table test considering the structural model in the soil-structure system precisely. As a result, realistic seismic response of a multi-storey frame could be determined.

3 SHAKING TABLE EXPERIMENTAL TESTS

In this study, the dynamic simulation has been carried out on the shaking table with a uni-axial configuration, allowing for one-dimensional input motions. The shaking table is 3 m×3 m table with testing frequency range between 0.1 to 50 HZ, maximum payload of 10 tonnes, and overturning moment of 100 kN-m. The prototype building frame of the soil-structure system (Figure 1) is a fifteen storey concrete moment resisting frame. The building frame height and width are 45 and 12 metres, respectively and spacing between the frames into the page is 4 metres. The building is resting on a footing which is 4 meters wide and 12 meters long. Natural frequency of the prototype building is 0.384 Hz and its total mass is 953 tonnes. Soil medium underneath the structure is a clayey soil with shear wave velocity of 200 m/s and unit weight of 14.40 kN/m3 (soil density of 1470 kg/m3). The horizontal distance of the soil lateral boundaries and bedrock depth are selected to be 60 metres and 30 metres, respectively.

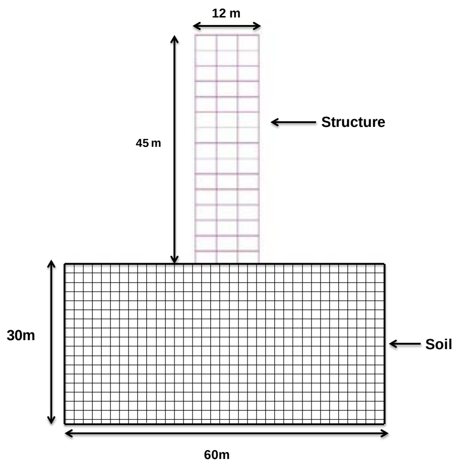

Fig.1. Dimensional characteristics of the prototype

3.1 Scaling Factor for Shaking Table Testing

Scale models can be defined as having geometric, kinematic, or dynamic similarities to the prototype (Sulaeman, 2010). Geometric similarity defines a model and prototype with homologous physical dimensions. Kinematic similarity refers to a model and prototype with homologous particles at homologous points at homologous times. Dynamic similarity describes a condition where homologous parts of the model and prototype experience homologous net forces. The objective of the scale modelling procedure for this test program is to achieve “dynamic similarity”, where model and prototype experience homologous forces. For this purpose, adopted methodology by Meymand (1998) is the framework for scale model similitude in this study. According to this approach, three principal test conditions establish many of the scaling parameters. The first condition is that testing is conducted in 1-g environment, which defines model and prototype accelerations to be equal. Secondly, a model with similar density to the prototype is desired, fixing another component of the scaling relations. Thirdly, the test medium is primarily composed of saturated clayey soil, whose undrained stress-strain response is independent of confining pressure, thereby simplifying the constitutive scaling requirements. In addition to the three principal test conditions, Meymand (1998) pointed out that the natural frequency of the prototype should be scaled by an appropriate scaling relation. By defining scaling conditions for density and acceleration, the mass, length, and time scale factors can all be expressed in terms of the geometric scaling factor (λ), and a complete set of dimensionally correct scaling relations (ratio of prototype to model) can be derived for all variables being studied. The scaling relations for the variables contributing to the primary modes of system response, adopted in this study, are shown in Table 1. The mentioned scaling relations have been utilised by many researchers (e.g. Meymand, 1998; Turan et al., 2009; Sulaeman, 2010; Lee et al., 2012) in soil-structure interaction shaking table test experiments.

Table.1.Scaling relations in terms of geometric scaling factor (λ)

Mass Density	**1**	Acceleration	**1**	Length	λ
Force	λ^3	Shear Wave Velocity	$\lambda^{1/2}$	Stress	λ
Stiffness	λ^2	Time	$\lambda^{1/2}$	Strain	**1**
Modulus	λ	Frequency	$\lambda^{-1/2}$	EI	λ^5

Adopting an appropriate geometric scaling factor (λ) is one of the important steps in scale modelling on shaking table. Although small scale models could save cost, the precision of the results could be substantially reduced. Considering the specifications of the shaking table, scaling factor of 1:30 provides the largest achievable scale model with rational scales, maximum payload, and overturning moment which meet the facility limitations. Thus, geometric scaling factor (λ) of 1:30 is adopted for experimental shaking table tests on the scale model in this study.

3.2 **Soil-Structure Model Components**

In this study, soil-structure model possesses three main components including structural model, laminar soil container, and soil mix. Employing geometric scaling factor of 1:30, height, length, and width of the structural model are determined to be, 1.50 m, 0.40 m, and 0.40 m, respectively. The finalised base plate is a 500×500×10 mm steel plate while the floors consist of 400×400×5 mm plates and four 500×40×2 mm steel plates are used for the columns. The connections between the columns and floors are provided using stainless steel metal screws with 2.5 mm diameter and 15 mm length. After the numerical modelling and design, the structural model was constructed in house. The completed structural model is shown in Figure 2. The mass of the model (mm), without the base plate, was measured to be 104 kg which matches the required structural mass (Table 2). Total measured mass of the structural model considering the mass of the base plate is 115kg. Numerical modelling and design as well as testing and construction procedure of the structural model have been explained by Tabatabaiefar (2012).

Table.2.Required characteristics of the structural model

Total Height (m)	Total Length (m)	Total Width (m)	Natural Frequency (Hz)	Total Mass (kg)
1.50	0.40	0.40	2.11	106

The geotechnical model cannot be directly mounted on shake table because of the requirements of confinement. To model the soil in shaking table tests, a container is required to hold the soil in place. During the past few decades, several studies have been conducted on soil-structure systems using various types of soil containers. Many researchers (e.g. Taylor et al., 1997; Pitilakis et al., 2008; Tang et al., 2009) concluded that laminar soil containers are the most appropriate and efficient type of the soil containers. Based on the conclusions made by the above mentioned researchers, well designed laminar soil containers can better model the free field boundary conditions in comparison with rigid and flexible containers as the lateral deformations in laminar soil containers are almost identical to the free field movements. By selecting 1:30 as the geometric scaling factor, the container should have minimum length, width, and depth of 2.0 m, 1.20 m, and 1.0 m, respectively. Allowing a further 10 mm on each side for construction purposes similar to Prasad et al. (2004), the final length, width, and depth of the laminar soil container are estimated to be 2.10m, 1.30m, and 1.10m, respectively. In terms of choosing the materials to build the soil container, according to the previous conducted research works (e.g. Taylor, 1997; Jakrapiyanun, 2002; Pitilakis et al., 2008), aluminium frames and rubber layers were employed in an alternating pattern. Therefore, the laminar soil container consists of a rectangular laminar box made of aluminium rectangular hollow section frames separated by rubber layers. The aluminium frames provide lateral confinement of the soil, while the rubber layers allow the container to deform in a shear beam manner. The employed laminar soil container in this study, constructed in house, is shown in Figure 3. The natural frequency of the laminar soil container was measured to be 10 Hz in the laboratory and it was noted that it fits the required natural frequency. Detailed explanation of this experimental setup can be found in Tabatabaifar (2012).

Fig.2. Completed structural model

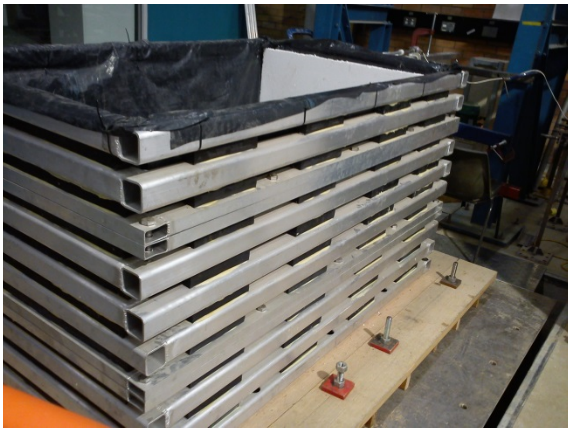

Fig.3. Laminar soil container

In this study, a synthetic clay mixture was adopted as the soil medium for the shaking table testing process. In order to develop the synthetic clay mixture, Q38 kaolinite clay, ActiveBond 23 bentonite, class F fly ash, lime, and water were used as the components of the soil mixture. The proposed mix was prepared three times to control repeatability of the test and each time three cylindrical test specimens of size D=50 mm and h=100 mm were taken. To measure shear wave velocity of the mix over the cure age, bender element tests were performed. The soil specimens were placed between bender elements, and shear wave velocity of each soil specimen was obtained at different cure ages. Based on the laboratory measurements, it is understood that the soil mix produces the required shear wave velocity of 36 m/s (based on the scaling factor in Table 1) on the second day of its cure age. Afterwards, the standard method of soil density determination was performed on the second day of the cure age according to AS 1289.3.5.1-2006 (Methods of testing soils for engineering purposes). Accordingly, soil density in the second day of the cure age was determined to be 1450 kg/m3 which is almost equal to the prototype soil density (1470 kg/m3). Thus, shear wave velocity and soil density values of produced soil mix on the second day of the cure age satisfy the dynamic similarity requirements, explained in Section 3.1.

3.3 **Scaling of Adopted Earthquake Acceleration Records**

Four earthquake acceleration records including Kobe, 1995 (Figure 4a), Northridge, 1994 (Figure 5a), El Centro, 1940 (Figure 6a), and Hachinohe, 1968 (Figure 7a) have been adopted for the shaking table tests. The first two earthquakes are near field ground motions and the latter two are far field motions. These earthquakes have been chosen by the International Association for Structural Control and Monitoring for benchmark seismic studies (Karamodin and Kazemi, 2008 scaling relationship between natural frequency of the model and natural frequency of the prototype is 5.48 while scaling relations between the model and prototype accelerations is 1.0, meaning the earthquake magnitude remains the same as the prototype based on the first principle of "dynamic similarity" which defines model and prototype accelerations to be equal. Scaled earthquake acceleration records are illustrated in Figures (4b-7b).

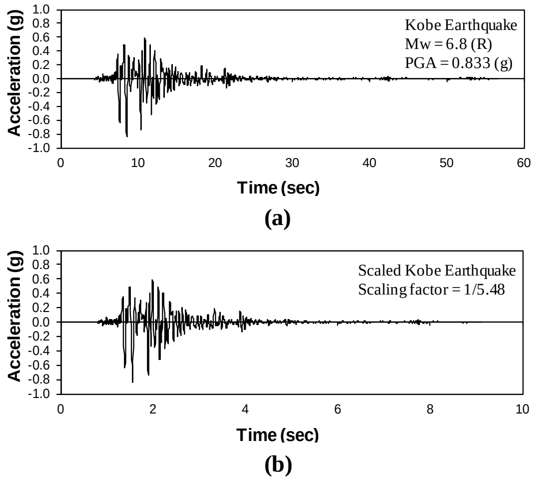

Fig.4. Kobe earthquake (1995)
a) original record; (b) scaled record

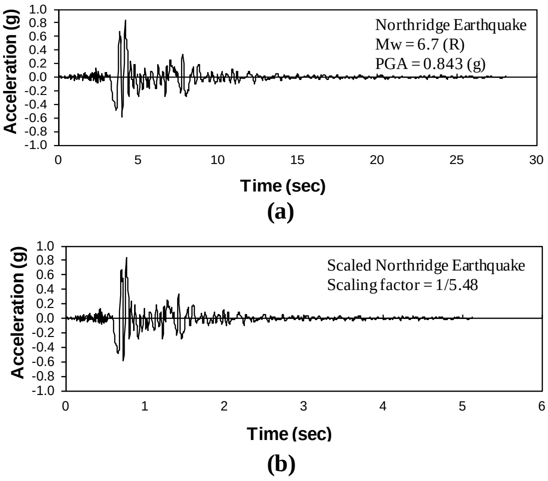

Fig.5. Northridge earthquake (1994)
a) original record; (b) scaled record

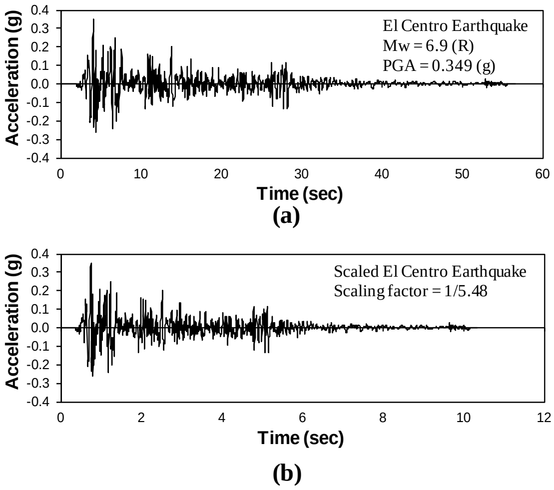

Fig.6. El Centro earthquake (1940)
a) original record; (b) scaled record

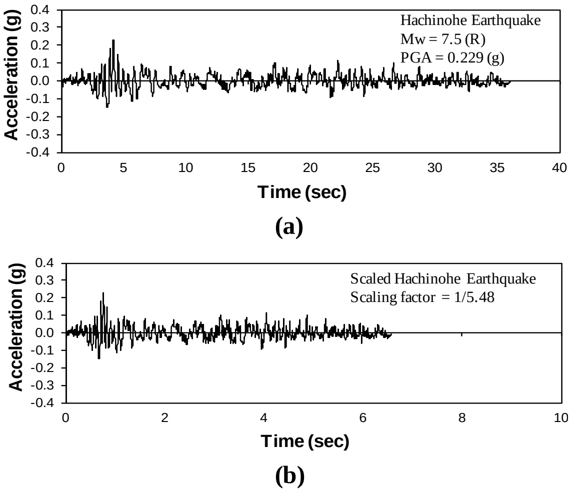

Fig.7. Hachinohe earthquake (1968)
a) original record; (b) scaled record

3.4 **Shaking Table Tests on Fixed Base Structural Model**

Tests were carried out on the constructed structural model as a fixed base model (structure directly fixed on top of the shaking table) in order to ensure the structural model possesses the targeted natural frequency and determine the damping ratio of the structural model (Figure 8). In addition, to verify the numerical model, seismic response of the fixed base model under the influence of the four scaled earthquake records were obtained. After ensuring adequacy of the structural model characteristics, shaking table tests were performed by applying scaled earthquake acceleration records of Kobe, 1995 (Figure 4b), Northridge, 1994 (Figure 5b), El Centro, 1940 (Figure 6b), and Hachinohe, 1968 (Figure 7b) to the fixed base structural model. The results of the performed shaking table tests under the influence of four scaled earthquake acceleration records in terms of maximum lateral deflections are determined and presented in Figure 10. In determination of the lateral deflections, the movement of the shaking table has been subtracted from storey movements. Therefore, all the records are in comparison to the base movements. It should be noted that for the sake of accuracy and consistency, the recorded displacements using displacement transducers, verified against the calculated displacements from accelerometer records, have been presented.

3.5 **Shaking Table Tests on Soil-Structure Model**

Figure 9 shows the final setup of the displacement transducers and accelerometers at different levels of the structural model for the soil-structure system on the shaking table. Details of the tests preparations and various components are explained by Tabatabaiear (2012).

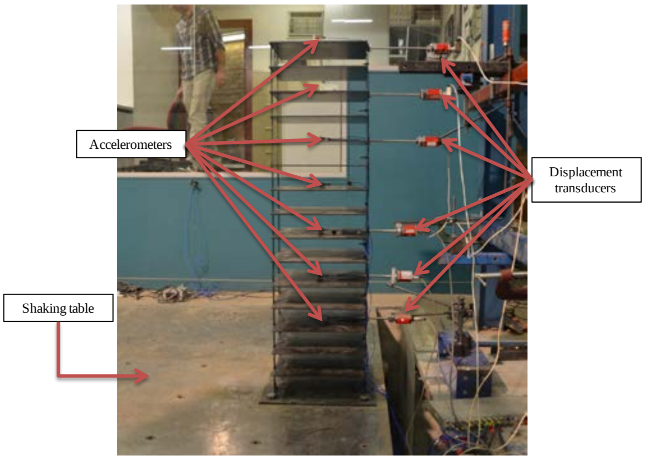

Fig.8. Final arrangement of the measuring instruments of the fixed base model

Before applying the scaled earthquake acceleration records to the flexible base model (soil-structure model), Sine Sweep test was carried out in order to estimate the natural frequency of the flexible base model. During the Sin Sweep test, frequency of the shaking table was raised from 0.1 Hz to 50 Hz to obtain the natural frequency of the soil-structure model. The obtained natural frequency of the soil-structure model from the performed Sin Sweep test was estimated to be 1.60 Hz. It can be noted that as expected, natural frequency of the soil-structure model is considerably smaller than the natural frequency of the fixed base structural model, previously determined to be 2.19 Hz. Afterwards, shaking table tests were undertaken by applying scaled earthquake acceleration records of Kobe, 1995 (Figure 4b), Northridge, 1994 (Figure 5b), El Centro, 1940 (Figure 6b), and Hachinohe, 1968 (Figure 7b) to the flexible base model, with the final setup as shown in Figure 9.

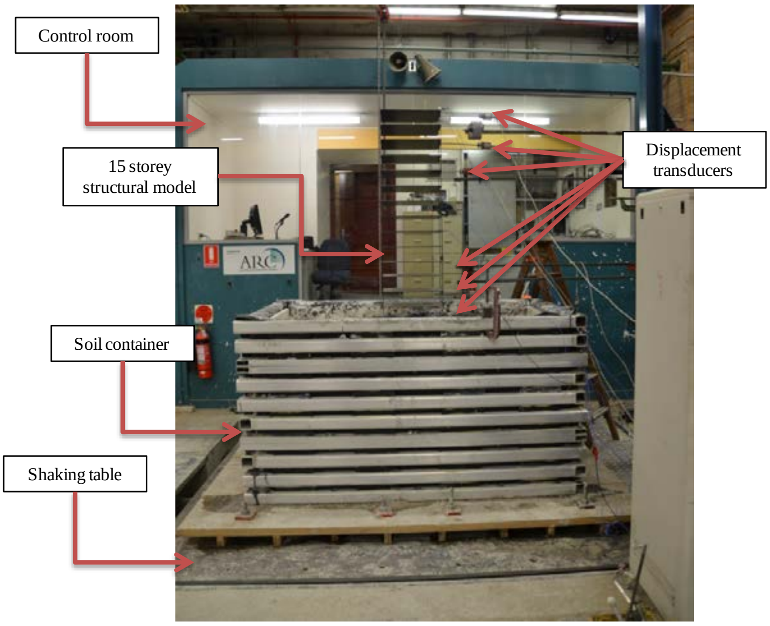

Fig.9. Final setup of the measuring instruments of the soil-structure model

4 RESULTS AND DESCUSSION

The results of the carried out shaking table tests under the influence of four scaled earthquake acceleration records in terms of the maximum lateral deflections of various storey of the structure are illustrated for fixed base model and flexible base model (soil-structure model) in Figure 10a-d.

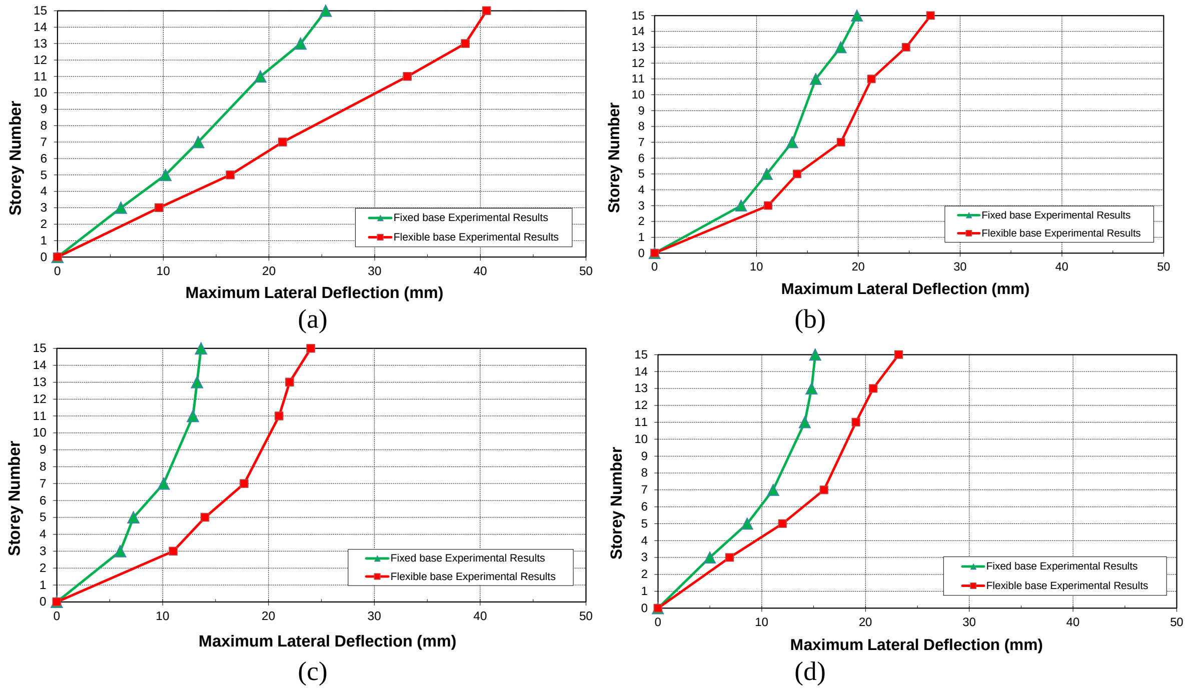

Figure 10: Maximum lateral displacements of fixed base and flexible base models (a) Kobe (1995) earthquake; (b) Northridge (1994) earthquake; (c) El Centro (1940) earthquake; (d) Hachinohe (1968) earthquake

Average values of the experimental values of the lateral deflections of the fixed base and the flexible base models were determined and compared in Figure 11a, while their corresponding inter-storey drifts have been calculated and shown in Figure 11b.

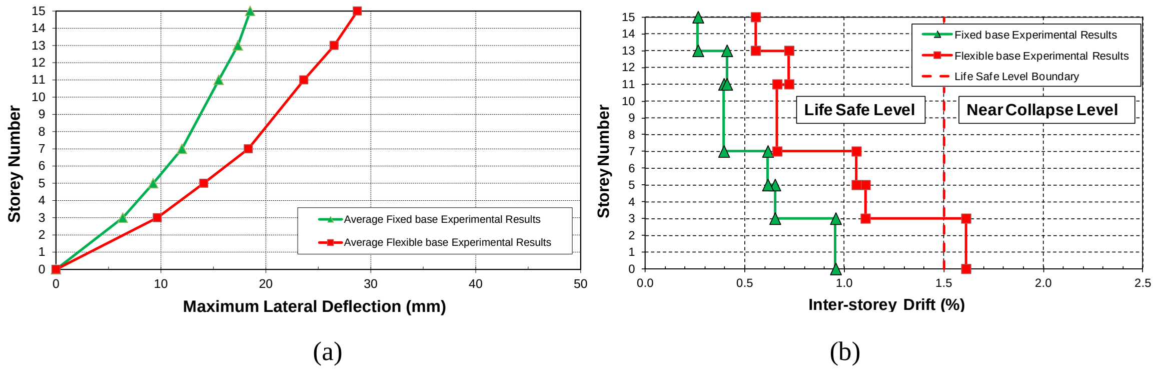

Fig.11. Average experimental results (a) Maximum lateral deflections (b) Inter-storey drifts

Based on the experimental average values of maximum lateral deflections of the fixed base and the flexible base models (Figure 11a), lateral deflections of flexible base models have increased by 55% in comparison to fixed base model which can be led to amplification of P-Δ effect. As shown in Figure 11b, due to amplification of the average values of inter-storey drifts due to SSI, performance level of the structural model changes significantly. As a result of the overall lateral displacement amplifications and consequent P-Δ effect, it is observed in this study that the performance level of the structure changes from life safe to near collapse level. Such a considerable change in the performance level of the model is extremely dangerous and safety threatening. Thus, it is experimentally observed that dynamic soil-structure interaction has profound effects on the seismic response of the structural model resting on relatively soft soil. In addition, increasing the overall drifts will have destructive effects on non-structural components of the system which should be seen and addressed by a safe structural design.

5 CONCLUSIONS AND RECOMMENDATIONS

Based on the experimental investigations conducted in this study, it is understood that the measured lateral deflections of the flexible base model and corresponding inter-storey drifts have noticeably amplified in comparison to the fixed base model. As a result of the overall lateral deflection amplifications, it is observed that the performance level of the structural model changed from life safe to near collapse level which is very dangerous and safety threatening. Thus, it is experimentally observed that soil-structure interaction has considerable effects on the seismic response of moment resisting building frames resting on relatively soft soils and should be taken into consideration in the seismic design. It can be concluded that the conventional design procedure excluding SSI may not be adequate to guarantee the structural safety of mid-rise moment resisting building frames resting on relatively soft soil deposits. As most of the seismic design codes around the globe do not address the soil-structure interaction (SSI) explicitly, considering SSI effects in the seismic designs as a distinguished part of these standards is highly recommended. It is also recommended to engineering companies working in regions located in high earthquake risk zones, to consider dynamic soil-structure interaction effects in the analysis and design of mid-rise moment resisting building frames resting on soft soils to ensure safety of the design.

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