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EXPERIMENTAL STUDY OF INFLUENCE OF SOIL-PILE-STRUCTURE INTERACTION ON DYNAMIC BEHAVIOR OF HIGH-RISE BUILDINGS

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Abstract

The soil-foundation-structure interaction can have a detrimental or beneficial effect on the seismic performance of superstructures. This study evaluates the influence of foundation configuration, as one of the components of these interaction systems, on the dynamic performance of piled structures. To this end, a 15-story reinforced concrete building with special moment resisting frames was designed for a site with poorly graded sandy soil located in Los Angeles, CA, with two types of pile foundations, using solid (i.e., rigid) and strip (i.e., flexible) pile caps. For the purpose of experimental testing, this superstructure was simplified to a 5-story building in a way that the dynamic characteristics of the main structure was accurately preserved for the first three contributing modes of vibration. Considering a geometrical scale factor of 1:22, all components of the prototype building were scaled down, according to the scaling relations, to establish the properties of the test specimens. In this study, a set of shake table tests was conducted on three test units using the shake table facility of California State University, Fresno. These units include a fixed-base structure, in which the soil-pile-structure interaction was ignored, as well as two structures sitting on pile foundations with solid and strip pile caps, respectively. In order to minimize the boundary effects on the soil deformation and properly simulate the free-field motion during the shake table testing, a laminar soil box was designed and fabricated for the last two test setups. Each test specimen was subjected to six multiple intensity ground motions, ranging from frequent to maximum considered events, to monitor the seismic performance of superstructures. The results showed that the soil-pile-structure interaction enhances the inter-story drifts of piled structures in comparison with those of the fixed-base structure. In addition, using the strip pile caps resulted in a reduction in the inter-story drifts of structures. The results can be used to improve the seismic performance of superstructure by designing appropriate pile caps.

Keywords: soil-pile-structure interaction; shake table test; pile cap; seismic performance; laminar soil box

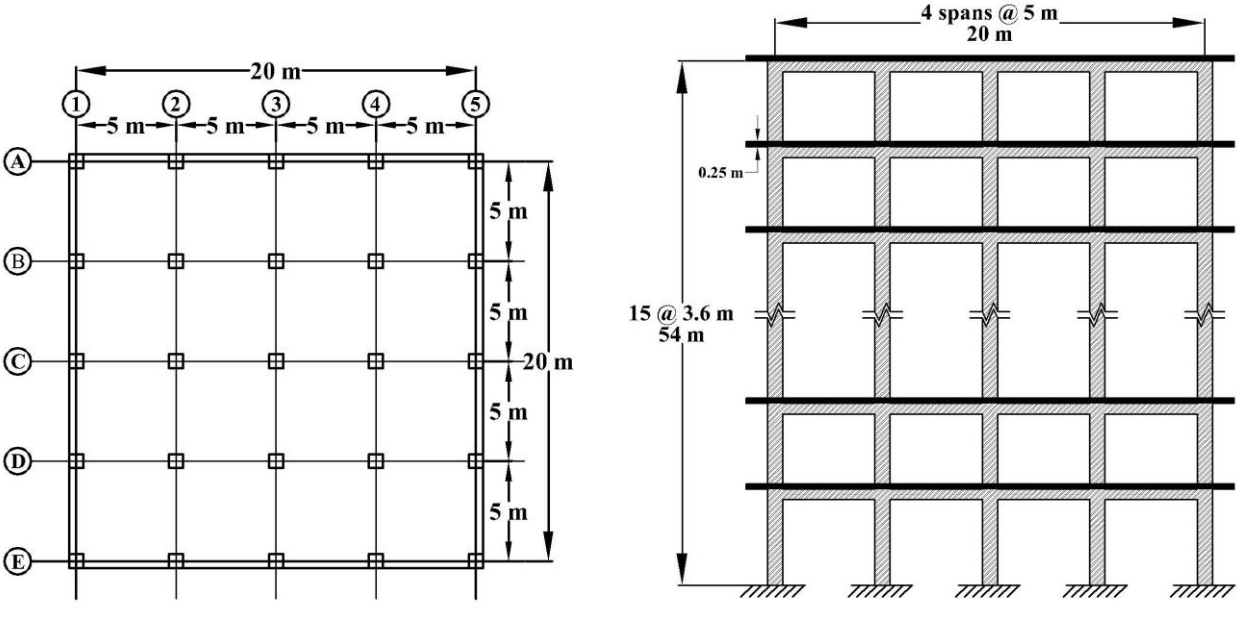
1. Introduction

Soil-foundation-structure interaction (SFSI) analysis is the assessment of the overall response of three linked systems (i.e., soil, foundation, and structure) during earthquakes [1]. Due to the differences in the stiffness of soil and foundation, the foundation experiences a modified excitation rather than free-field motion. This phenomenon, which is referred to kinematic interaction, is independent of properties of superstructure. Simultaneously, the earthquake-induced inertial forces in the superstructure are transmitted to the soil and create extra deformation in the base. This interaction is known as inertial interaction and depends on the mass of structure. There are several factors that influence both inertial and kinematic interactions, including dynamic properties of soil and superstructure as well as the foundation type and layout. Tang and Ling [2] studied the effect of soil liquefaction on the failure mechanism of reinforced concrete piles during a strong shaking event through conducting shake table tests. They showed that earthquakes with lower frequency and higher amplitude result in larger bending moments in the piles. These researchers also showed that the critical failure mode of the piles was bending type. Nguyen et al. [3] assessed the influence of size and load bearing mechanism of piles on the seismic performance of superstructures using numerical modeling. These researchers modeled a 15-story moment resisting frame that was supported by differently sized end-bearing and floating pile foundations. They indicated that increasing the length of floating piles leads to an increase in the maximum lateral deformation of structure. Moreover, using longer piles reduces the rocking motion of the piled structures compared to those having shorter piles. This is due to the higher energy absorbance of longer piles during earthquakes. They also made a few suggestions about selecting the appropriate size and type of pile foundations to improve the seismic performance of superstructures. Yeganeh et al. [4] studied the influence of the SFSI on the seismic performance of a high-rise building adjacent to deep excavation. These researchers showed that the adjacent excavation resulted in an increase in the pile deformation, maximum bending moments induced in the piles, and probable damages in the superstructures. Many other researchers have investigated the effect of different factors on the response of SFSI systems and they have shown that SFSI may improve/deteriorate the seismic performance of the structures. These include Bakhshi et al. [5], Bagheri et al. [6], Dutta et al. [7], and Behnamfar et al. [8]. The foundations were all set to be rigid in these studies. However, the layout and flexibility of foundation can play an important role in the seismic performance of structures, specifically piled structures, according to the results of the analytical studies conducted by the authors previously. In this study, a series of shake table tests were developed to assess the influence of properties of foundation on the seismic response of high-rise buildings. To this end, a 15-story reinforced concrete moment resisting structure was designed as the prototype building. Along with the fixed support, two types of pile foundations with solid and strip pile caps were designed for the prototype building. Meeting the scaling requirements, the test units were fabricated and mounted on the shake table facility of the structural lab at California State University, Fresno (Fresno State).

After Installing the measuring instruments, the scaled models were subjected to the scaled ground motions and the lateral displacement of stories were measured and their inter-story drift ratios were calculated. The outputs were used to evaluate the influence of SFSI and pile cap layout on the dynamic response of superstructures.

2. Prototype

A 15-story reinforced concrete moment resisting frame building was designed as the prototype building according to the requirements of ACI318-14 [9] and ASCE07-16 [10] using a specified concrete strength of 30 MPa and ASTM A706 Grade 60 reinforcement. The prototype building was 54 m high and 20 m wide and it consisted of 4 spans (i.e., span width of 5 m). Figs. 1(a) and (b) show the plan and elevation view of prototype structure, respectively. In addition, the dominant frequency of the prototype structure was 0.5092 Hz.



(a) (b)

Fig. 1 – (a) Plan (b) Elevation view of prototype structures

In order to prepare the shake table testing requirements, a geometric scale factor should be derived according to the scaling criteria. There are a few reasons that the scale factors used to develop the scaled model of SFSI systems are usually small for tall buildings, including: (1) limitations in the size of shake tables, (2) larger size of SFSI models due to simultaneous modeling of soil, foundation, and structures, (3) impracticability of providing moment resisting connections in small scaled models due to the small size of structural elements.

In order to select the optimum geometric scale factor by considering the abovementioned limitations, an equivalent structure was designed. This equivalent structure preserves the dynamic properties of original structure, including first three mode shapes of the original structure and their corresponding natural frequencies. In addition, the dimensions of cross sections of the elements of the equivalent structure are larger than those of the original structure. Therefore, it is feasible to provide the moment resisting connections of the elements of the scaled model of the equivalent structure by welding. To this end, a 5-story equivalent structure was developed as follows [11,12]:

1. Every three stories were represented by an equivalent story, with a modified mass (M_i) and stiffness (K_i).
2. M_i is the mass of ith story of equivalent structure that is sum of the masses of three stories of the original structure. This lumped mass was located at the same level with the middle mass of every three masses.

$$M_i = \sum_{j=0}^{2} m_{3i-j} \tag{1}$$

Where m is the mass of floors in the original structure.

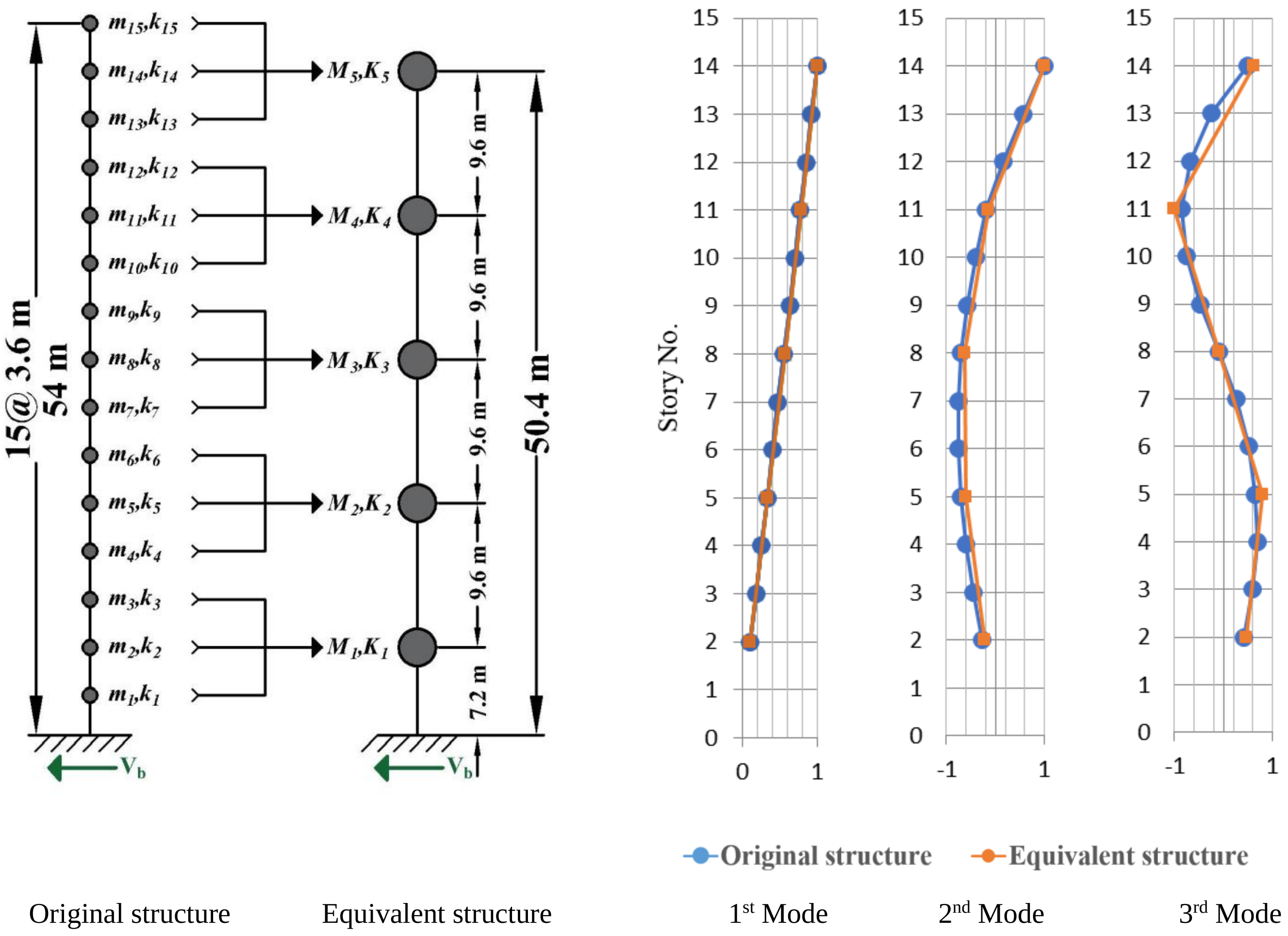
3. Every three stories were combined in series, with an equivalent stiffness of K_i, so that the deformation of these three stories be equal to that of the corresponding story in the equivalent structure.

$$K_i = \begin{cases} \dfrac{1}{k_1} + \dfrac{1}{k_2}, & i = 1 \\ \displaystyle\sum_{j=1}^{3} \dfrac{1}{k_{3i-j}}, & i = 2, \dots, 5 \end{cases} \tag{2}$$

Where k is the lateral stiffness of stories in the original structure.

4. The yielding strength of each story in equivalent structure was estimated by computing the average of yield strengths of the corresponding three stories in the original structure.

Fig. 2(a) illustrates the summary of steps followed to derive the equivalent structure. As well, Fig. (b) shows the first three mode shape of equivalent and original structure. Moreover, the natural period of the first three mode of vibration of original and equivalent structures are presented in Table 1. According to the negligible differences in the dynamic properties of the equivalent and original structure, the equivalent structure was selected to represent the original prototype building.



(a) (b)

Fig. 2 – (a) The steps followed to develop the equivalent structure (b) The first three normalized mode shape of original and equivalent structure

Table 1 – The first three natural period of original and equivalent structure

Mode	**Period (sec)**	
	Original structure	**Equivalent structure**
1st Mode	1.9637	1.807
2nd Mode	0.7794	0.6902
3rd Mode	0.4587	0.3751

Two pile foundations with solid and strip pile caps were designed for the superstructure according to the recommendation of ACI 318-14 [9], the Canadian Foundation Engineering Manual [13], and API [14]. The solid pile caps were 1.5 m thick and 22 m wide. As well, the strips of strip pile cap were 2 m-high and 1.4 m-wide and they were covered by two 0.3 m-thick slabs. Fig. 3 shows the strip pile caps designed for the pile foundations.

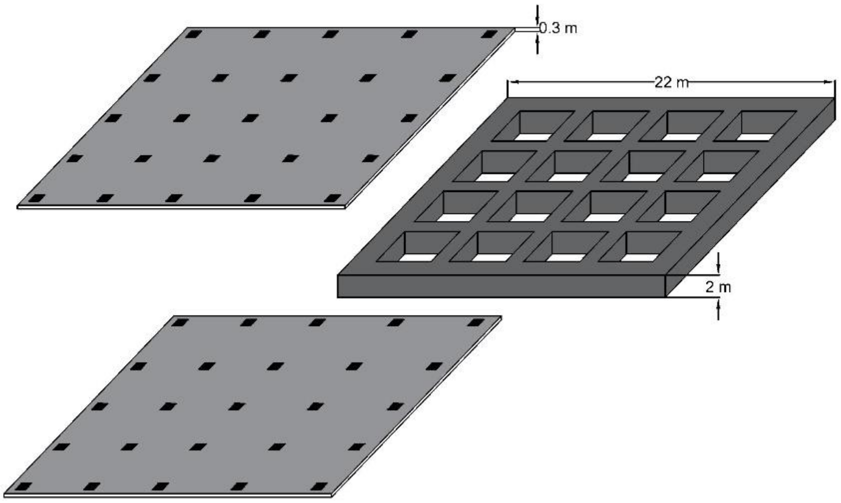


Fig. 3 – Pile foundation with strip pile caps

Both pile foundations consisted of a 5×5 pile group and they were embedded in a sandy soil with an average shear wave velocity of 250 m/s and density of 1650 kg/m^3. The piles had circular sections with a diameter of 1.2 m and they were 18 m long that gives a length over diameter ratio (L/D) of 15. The center-to-center spacing (S) of the piles is 5 m (S/D=4.16) and they are sitting on the bedrock to represent the end-bearing piles. Along with these two pile foundations, a fixed-base structure was considered to be used as a benchmark to study the influence of SFSI on the seismic performance of superstructures.

3. Scaling relations

The scaling relations were derived from the requirements of dynamic similarity between the prototype and scaled model. Meeting the requirement of dynamic similarity, the scaling relationships were obtained in terms of geometrical scaling factor (λ) [15,16]. Table 2 shows these scaling relations. The geometric scaling factor λ was calculated according to specifications of shake table facility and limitations explained in Section 2. This factor was equal to 1/22.

Table 2 – Scaling relations for different parameters of prototype in terms of geometrical scaling factor

Parameter	Scale factor	Parameter	Scale factor	Parameter	Scale factor
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

4. Scaled model

Using the geometrical scale factor and scaling relations shown in Table 2, different parameters and dimensions of scaled model were obtained and they are presented in this section.

4.1 superstructure

Using the scale factor of 1/22, the height and width of the superstructure were 2.45 and 0.9 m, respectively. As well, its dominant frequency of vibration was 2.39 Hz. Considering the dimensions of the scaled model, it was not feasible to fabricate the model using reinforced concrete; thus, A36 steel was used for this purpose. Moreover, the size of the steel elements had to be selected in a way that they could be weldable without making weak points in welding regions. Considering the required dimension and weldability of elements, square steel bars were used to build the model. As well, the lateral stiffness of the frames was provided with three columns in each frame to provide the same stiffness as the five columns that should be considered indeed (i.e., similar to the prototype structure). This modification led to a less than 0.5 percent change in the dominant frequency of vibration of the superstructures (i.e., from 2.39 to 2.38 Hz.). Fig. 4 illustrates the dimensions and elements of the scaled model.

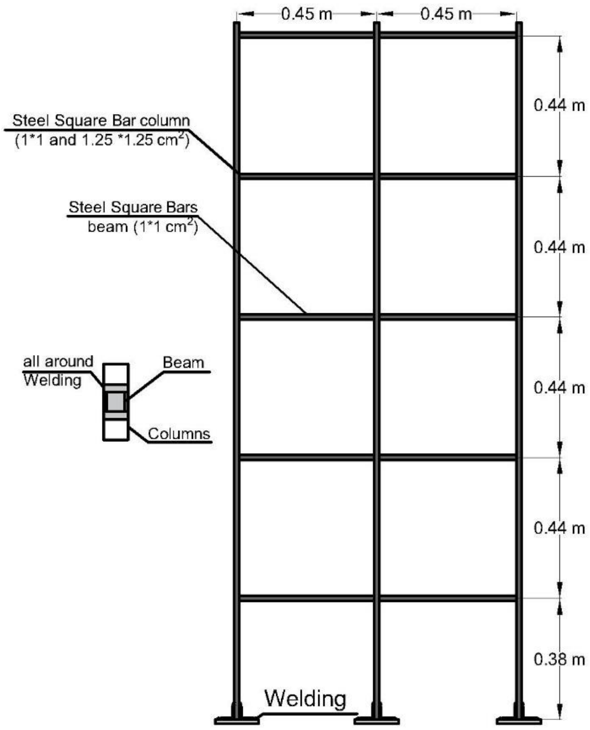


Fig. 4 – Schematic elevation view of scaled model

4.2 Foundation

The solid pile cap was modeled using a thick steel plate. In addition, the strip pile cap was fabricated using square steel tubes that were covered by thin steel sheets, as shown in Fig. 5. Considering the scaling relationships, the Acrylonitrile Butadiene Styrene (ABS) pipes were used with the diameter of 56.2 mm. and wall thickness of 3.91 mm. to provide the required flexural stiffness of the scaled piles. In order to prevent filling the pipes with soil, ABS caps were used to block the open end of the pipes. Moreover, the center-to-center spacing of the piles to their diameter ratio (S/D) is an important dimensionless factor that should be preserved in the scaled models to simulate the performance of pile groups accurately.

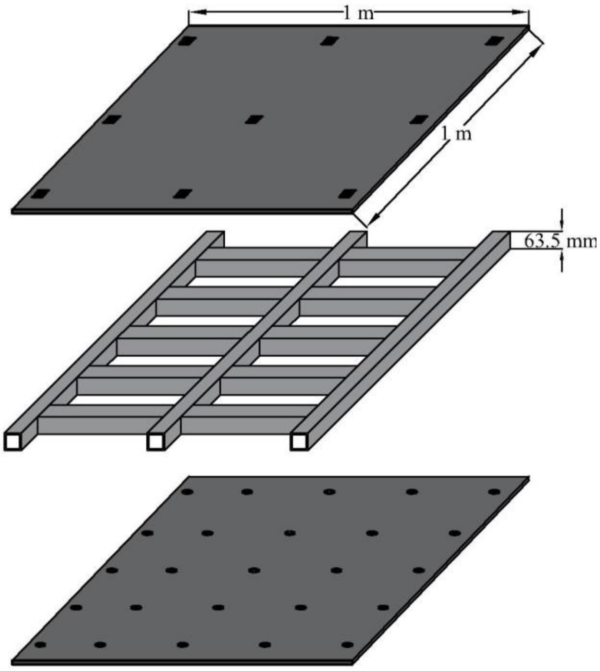


Fig. 5 - Plan of scaled strip pile cap

4.3 Laminar soil container

In order to simulate the infinite soil medium in a small-scale model, a laminar soil box was designed using OpenSees [17]. The dimensions of the designed soil box were 2.1×1.63×1 m (length×width×height) and it was designed such that the dominant frequency of the soil container was similar to that of the soil deposit. The dominant frequency of soil deposit was calculated as follows [18,19]:

$$f_s = \frac{V_s}{4H_s} \tag{3}$$

Where V_s is the shear wave velocity of soil deposit (i.e., 250 m/s in the prototype and 53.3 m/s in the scaled model) and H_s is the thickness of soil deposit (i.e., 1 m in the scaled model). Therefore, the dominant frequency of soil deposit was 13.32 Hz. Using the aluminum tubes and rubber strips, the dominant frequency of the soil container was set to be the same as that of the soil deposit through a trial and error method. Moreover, the soil box should experience the same deformations as the soil layers do when it is subjected to the similar ground motions. All of these considerations were taken into account to provide a realistic boundary condition for the model and prevent the propagating shear waves from reflecting back into the soil medium. To this end, the aluminum tubes of laminar soil box were modeled using the *NonlinearBeamColumn* elements of OpenSees. Furthermore, *nDMaterial PressureDependMultiyield02*, element *stdBrick*, and *BeamContact3D* were used as the soil material, soil element, and soil-pile/soil-aluminum tubes interface, respectively (see Fig. 6). According to the design outputs, the laminar soil box was fabricated using thirteen laminae made of 50.8×50.8×3.2- mm square aluminum tubes. There was a 25.4 mm gap between the laminae that was filled by rubber strips of specific lengths to provide the required natural frequency. The styrene-butadiene rubber (SBR) strips with a hardness of 70-durometer were employed and cut to size for this purpose. The aluminum laminae and rubber strips were attached together by high-strength impact-resistant two-component epoxies that provides a shear strength of 18.3 MPa to keep the soil box integrated during the base excitations. Then, the fabricated laminae were bolted to the timber board made to simulate the bedrock. Fig. 7 shows the different components of the fabricated soil box. Furthermore, a thin layer of coarse material (i.e. sand and gravel) were glued to the timber board to make enough friction between the bedrock and other soil layers. As well, the polystyrene foam sheets were used to minimize the reflection of propagating waves back into the model as well as simulating the viscous boundary condition. In addition, the polyethylene sheets were used to cover the interior sides of the soil box to prevent the loss of soil particles through the gaps between the laminae and also reduce the friction between the soil layers and walls of soil container.

Furthermore, the free-field motion of the soil deposit, as well as the maximum deformation of empty and filled soil container subjected to Kobe ground motion, was derived from the analytical outputs to validate the performance of soil container (see Fig. 8). The results show negligible differences between the deformations of soil container and free-field motion.

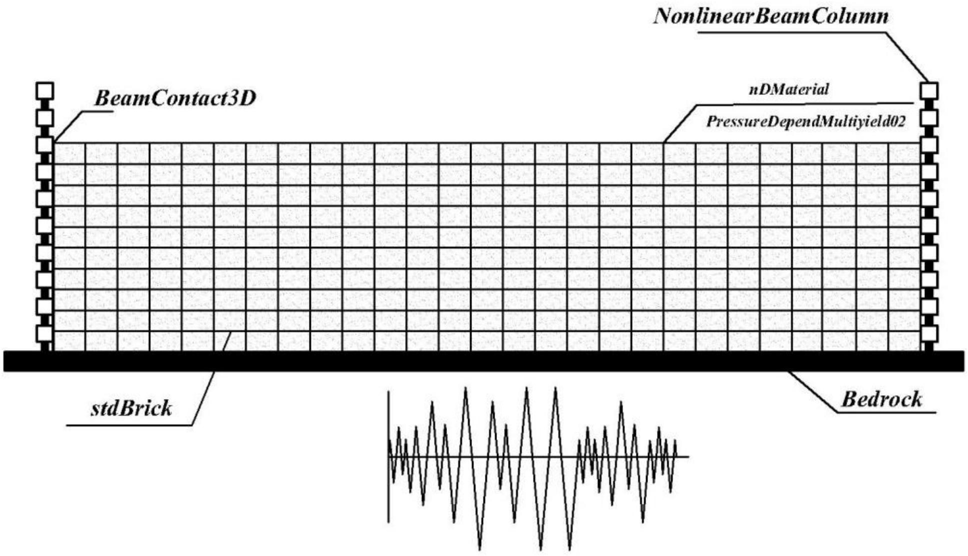
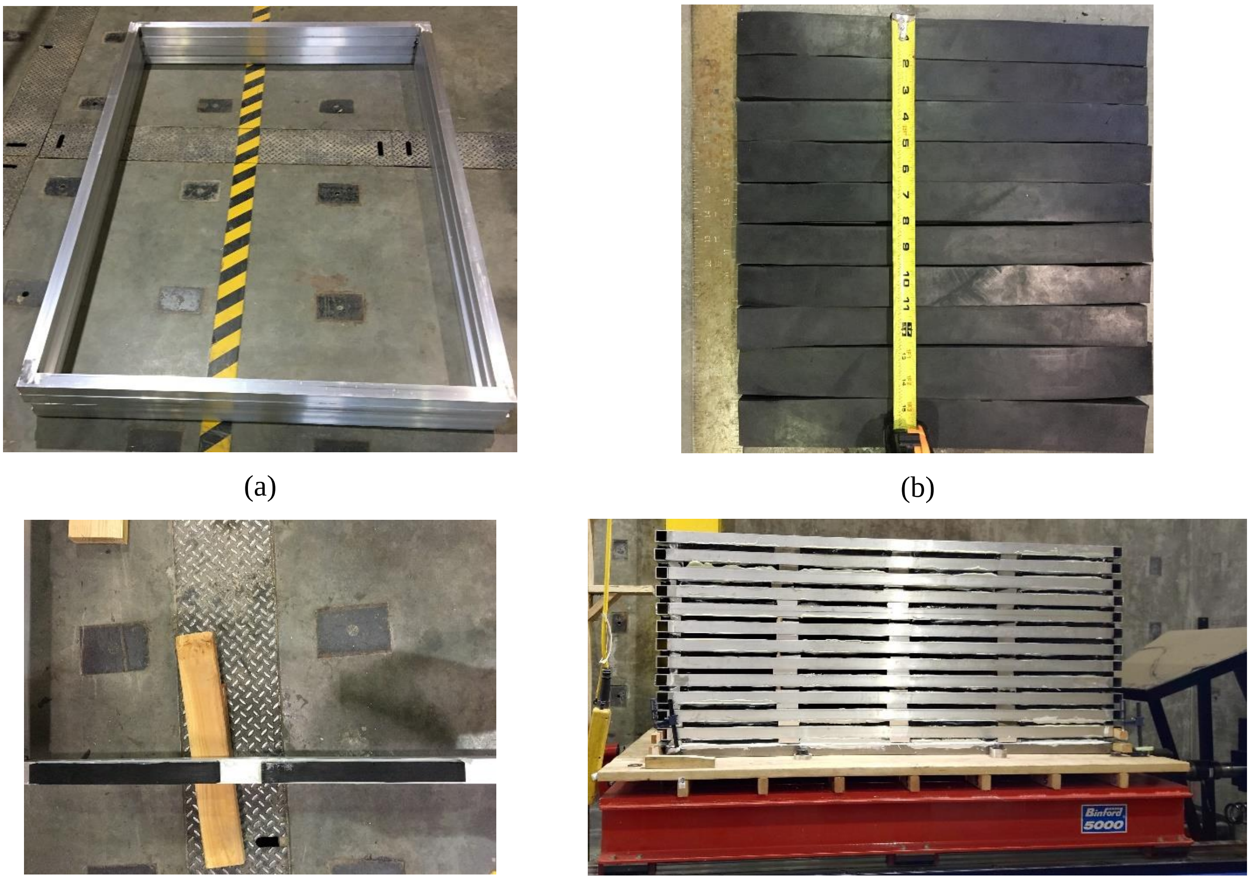


Fig. 6– Elements used in OpenSees software



(a) (b)

(c) (d)

Fig. 7 – Components of laminar soil container (a) Laminae (b) rubber strips (c) rubber strips glued to laminae (d) Fabricated laminar soil container

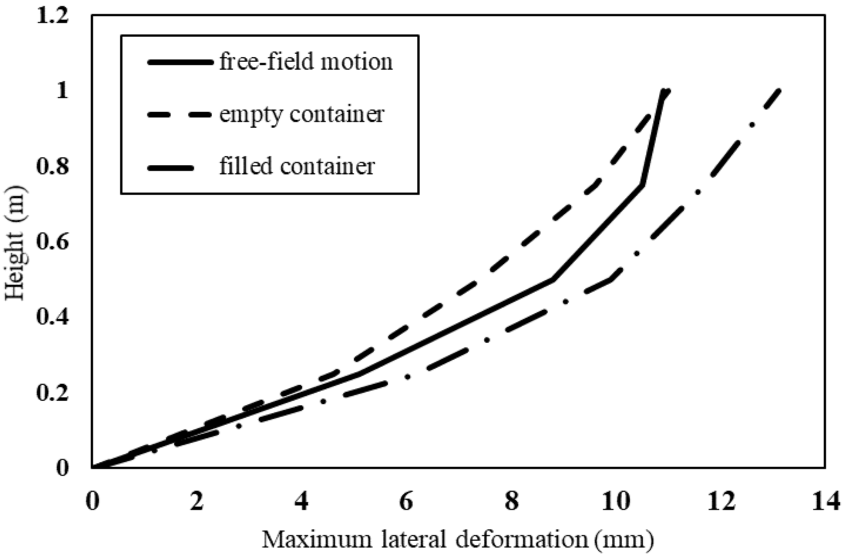


Fig. 8 – Free-field motion and deformation of the soil container

4.4 Soil

The scaled foundations should be embedded in the soil deposit prepared according to the scaling requirements. To this end, poorly graded silica sand was selected to simulate the soil aggregates and fill the soil box. Table 3 shows the properties of the soil. The soil container was filled in 10 layers and each layer was compacted to reach to the desired density. As well, a 25.4 mm gap between the pile cap and the surface of the soil deposit was provided to prevent the piled-raft behavior.

Table 3- Soil properties

Parameter	**Value**
Specific Gravity, G_s	2.60
Uniformity coefficient, C_u	1.60
Effective size, D10	0.3 (mm)
Friction angle, Ø	35 (degrees)
Desired density, ρ	1650 /m^3)

5. Results

Each test unit was subjected to six uniaxial scaled base excitations (i.e., Duzce, Hector mine, Irpinia, Kobe, Manjil, and San Fernando earthquakes) and the lateral displacement of stories of the scaled equivalent structure was measured. Fig. 8 shows the average of inter-story drift ratios of the piled structures during these base excitations. The SFSI effects increased the inter-story drift of the superstructure compared to that of the fixed-base structure. The piled structures experienced larger lateral deformations than the fixed-base structures. As shown in Fig. 8, using the strip pile caps decreased the inter-story drift ratios of the second to fifth stories of the scaled equivalent structure compared to those of piled structure with solid pile caps.

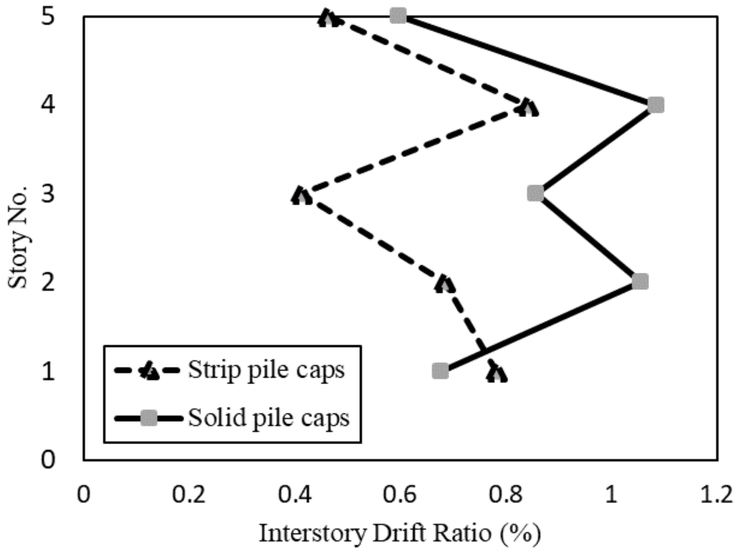


Fig. 9 – The average inter-story drift ratios of piled structures subjected to six base excitations

6. Conclusions

In this study, a series of shake table tests were conducted to assess the influence of SFSI on the seismic performance of the superstructures. As well, pile cap layout was one of the key variables that was investigated in this paper. To this end, a 15-story building was designed and selected as the original structure. Considering the feasibility of fabrication of the scaled models, an equivalent 5-story building was designed that preserved the dynamic properties of the original structure and represented the original prototype structure. Three different types of foundations were designed for the prototype building, including: (1) fixed-base (2) pile foundation with solid pile cap (3) pile foundation with strip pile cap. The two latter types of foundations were embedded in the loose sand. In order to simulate the free-field motion, a laminar soil container was designed using 3D analytical OpenSees models and fabricated in the structural lab of California State University, Fresno. The scaled models were then mounted on the platform and 1-g shake table testing was conducted. The models were instrumented to measure the seismic response of the superstructures during the base excitations. The results showed that the SFSI affect the seismic performance of superstructures significantly. The inter-story drift ratios of the superstructures were increased by considering the SFSI, which shows the importance of considering the soil medium in the seismic assessment of buildings. The inter-story drift ratios of the piled structures with strip pile cap were less than those of piled structure with solid pile cap, which means that using strip pile caps improved the seismic performance of the superstructure.

Therefore, it can be concluded that ignoring the influence of SFSI in the performance-based design of the structures may cause errors in the design process and it is necessary for engineers to take this phenomenon into account when they are designing the structures. Furthermore, selecting the appropriate layouts for the pile caps can improve the seismic performance of superstructures. The findings of this paper help the engineers to select the appropriate type of foundation for the high-rise buildings that they design.

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