Effects of Nonlinear Soil-Foundation-Structure Interactions on a Multi-Storey Building during Earthquakes

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Abstract

During earthquake events, soil and structural plastic deformation can occur. Previous studies focused mostly on the effects of soil nonlinearity on the seismic response of elastic multi degree-of-freedom (MDOF) systems. However, little work has been done on the combined effect of structural plastic hinge development and nonlinear soil deformation. This study focuses on the response of a multi-storey building with nonlinear soil-foundation-structure interaction (NSFSI), i.e. soil plastic deformation, foundation uplift and plastic hinge development in the structure. The development of bending moments, kinetic energy and induced earthquake energy in the structure were investigated. Experiments were performed on a shake table with a scaled MDOF model. The soil plastic deformation was simulated by placing the structure on sand in a laminar box. Plastic hinge development in the structure was permitted. Response of the model under fixed-based conditions was used as a reference case. The response of the structure with NSFSI was compared to that of its fixed-based counterpart. It was found that the maximum bending moments at the column-foundation connection and the kinetic energy in the structure were reduced when NSFSI was considered.

Keywords: Soil-foundation-structure interaction, plastic hinge, plastic soil deformation, multi-storey building.

1. INTRODUCTION:

Current structural design practice estimates earthquake response on structures, using free-field motion records and an assumed fixed base. However, in reality the behaviour of a building under earthquake excitation can be significantly affected by the interaction between the structure and the supporting soil medium. This soil-foundation-structure interaction (SFSI) can reduce the activated forces in the structure and thus reduce damage, which suggests current design practice may be over-conservative. The effects of SFSI on seismic actions in both single degree-of-freedom (SDOF) and multi degree-of-freedom (MDOF) systems have been investigated in the past. There is however, a limited amount of research considering holistic systems which incorporate plastic hinge development and SFSI simultaneously, i.e. non-linear SFSI (NSFSI).

Following the 1999 Kocaeli earthquake (Turkey), unintentional soil failure preventing structural damage in a multi-storey building was observed (Anastasopoulos et al. 2010). Subsequently, Anastasopoulos et al. (2010) carried out numerical modelling and experimental tests, which confirmed the effectiveness of allowing bearing capacity to be exceeded during earthquake loading. Further experiments on a MDOF model found that allowing non-linear foundation behaviour significantly reduced structural drift following earthquake excitations (Anastasopoulos et al. 2012).

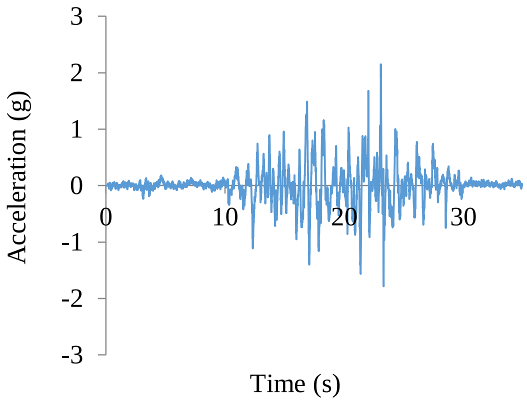
Other studies by Qin et al. (2011, 2013), Qin and Chouw (2012) and Sarrafzadeh et al. (2014) also investigated the effect of SFSI and NSFSI on SDOF structures. The results of these investigations also showed that SFSI could reduce the actions in the structure during seismic loading but caused permanent deformations in the structure.

This study focuses on the response of a multi-storey structure with NSFSI via shake table experiments.

2. METHODOLOGY:

2.1 Overview

A four storey structure was excited on a shake table using ground motions based on the Japanese design spectrum (JDS) for hard soil conditions (JSCE 2000), shown in Figure 1. The JDS was selected due to its distinct frequency content.



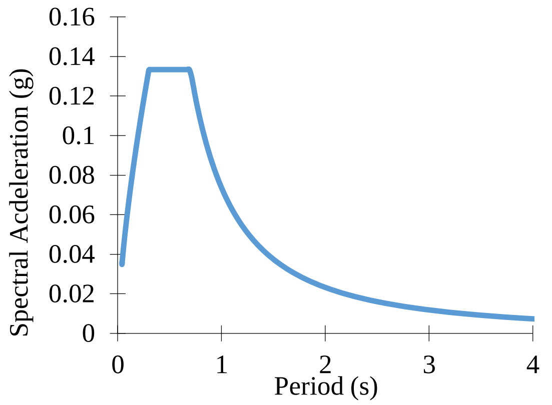


Figure 1 Simulated ground acceleration and the corresponding Japanese design spectra for hard soils

To investigate the effects of NSFSI on the performance of the structure under seismic loading, testing was done for the following conditions:

- Elastic structure with a fixed-base
- Structure with allowable plastic hinge deformation and a fixed-base
- Elastic structure on sand (SFSI)
- Structure with allowable plastic hinge deformation on sand (NSFSI)

For the SFSI and NSFSI tests, the structure was placed on dry sand contained in a laminar box, which was placed on the shake table. The general configurations of the structure with fixed base and on sand are shown in Figure 2.

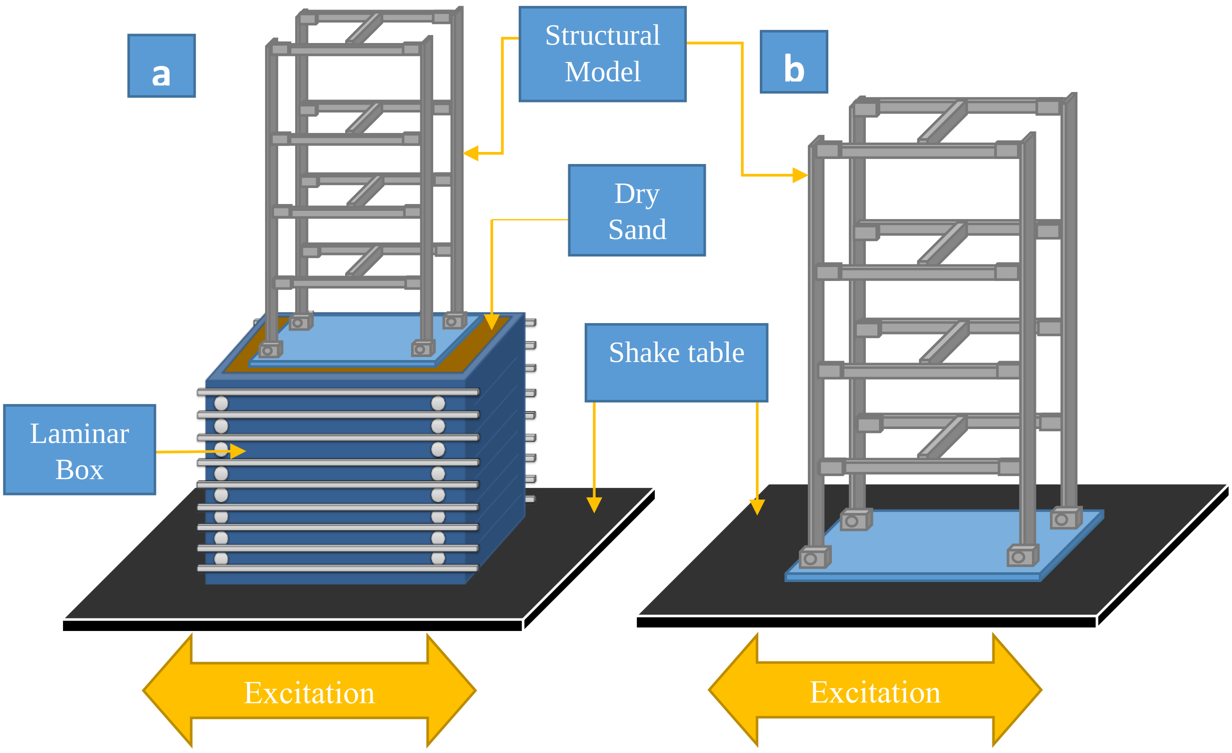


Figure 2 General arrangement for (a) Testing on sand and (b) Fixed base testing

2.2 The Structure

The MDOF structure used in this study was a scaled model of a four storey building prototype. With a scale factor of 1:15, the inter-storey height of the model was 200 mm, with a total height of 800 mm. The total mass of the system was 65.3 kg.

The structure was made of aluminium columns and beams connected with steel plates. The plates were used to simulate plastic hinges in beam column connections. For the plastic hinge formation at the foundation-column connection, slip friction hinge joints were used. In the elastic case, the column-foundation connections were fixed to prevent inelastic behaviour. Free vibration tests revealed the natural frequency of the structure to be 1.515 Hz.

2.3 Laminar Box and Sand

A laminar box containing dry sand was used to allow more realistic shear deformation and response of soil during earthquake excitation (Cheung et al. 2013). The sand was rained into the laminar box from a height of 1 m to ensure that the sand grains reached terminal velocity. Consequently, a uniform density soil profile was achieved. Figure 3 shows the test set up with the MDOF structure on top of the sand in the laminar box.

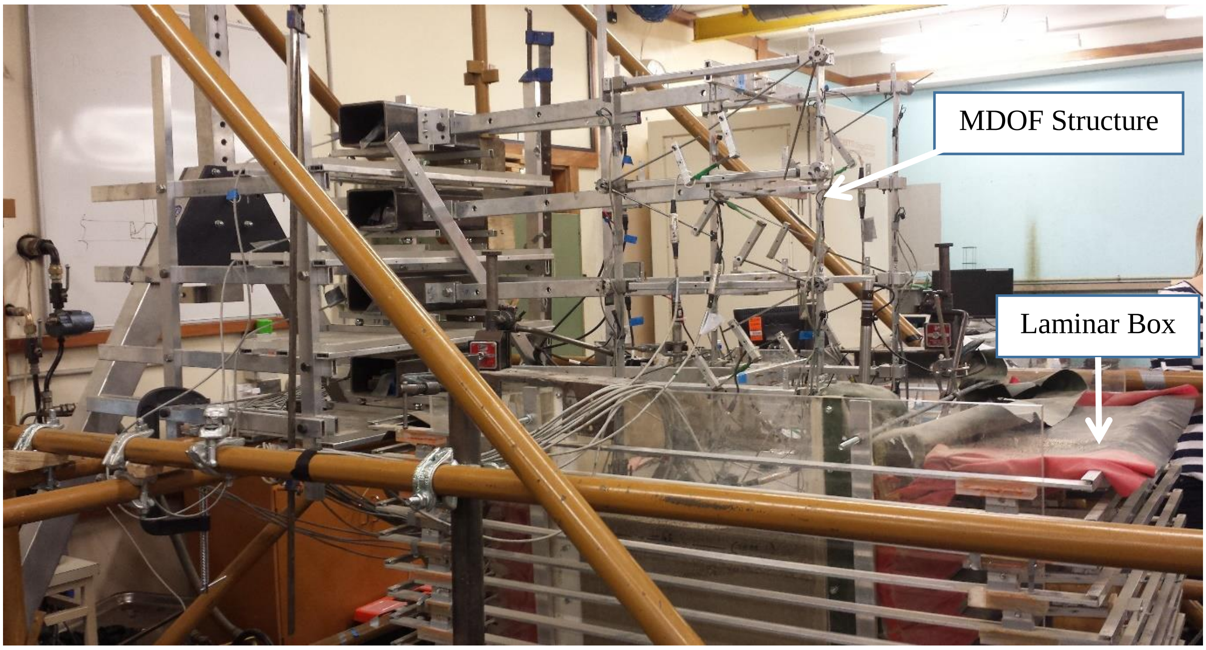


Figure 3 Set up of the laminar box testing

2.4 Plastic Hinges

To simulate the plastic hinge deformation, four slip friction hinge joints were constructed for each column-foundation connection (see Figure 4(b)). Load cells were used to record the pressure applied by tightening the hinges (see Figure 4(c)). The pressures were adjusted to ensure the structure obtained a ductility between 2 to 2.5 when subjected to earthquake excitations. The base connection for the elastic case and the slip friction hinge joints can be seen in Figure 4.

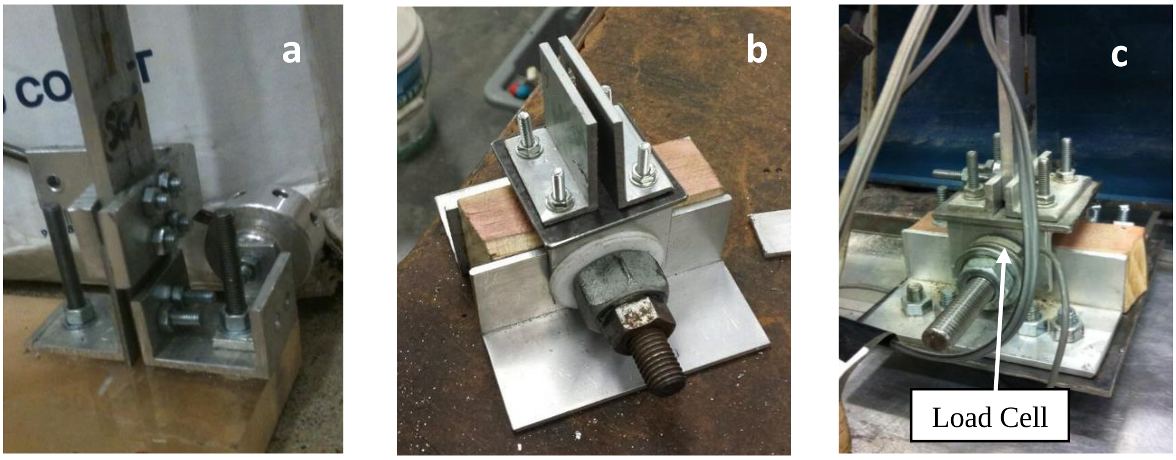


Figure 4 Base connections for (a) Elastic, (b) Plastic (under construction), and (c) Plastic (in use) structures

3. RESULTS:

3.1 Structural bending

As expected, plastic hinge formation limited the bending moment experienced by the structure, in comparison to the elastic structure under fixed base conditions. Incorporation of SFSI showed similar reductions, while NSFSI resulted in the lowest maximum bending moment.

NSFSI resulted in a maximum bending moment of 1.94 Nm at the column-foundation connection, which was a 44.9% reduction of the maximum bending moment of the SFSI case (3.52 Nm). The bending moment time history of these two cases in Figure 5 shows a consistently lower bending moment in the structure with NSFSI.

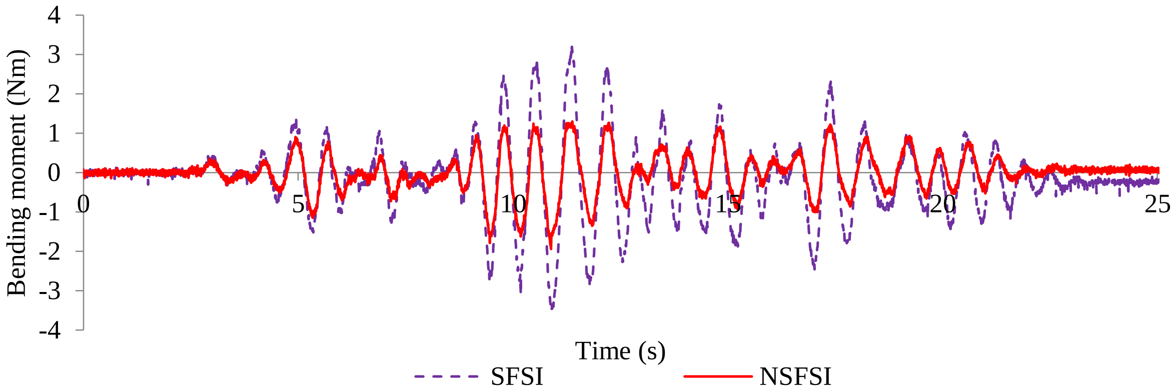


Figure 5 Bending moment comparison between results for the structure with SFSI and NSFSI

The bending moment time history for the NSFSI and plastic fixed base cases can be seen in Figure 6. The maximum bending moment for the plastic fixed base structure was 3.32 Nm, similar to that of the SFSI case. Once again NSFSI conditions resulted in a lower maximum bending moment, with a reduction of 41.6%.

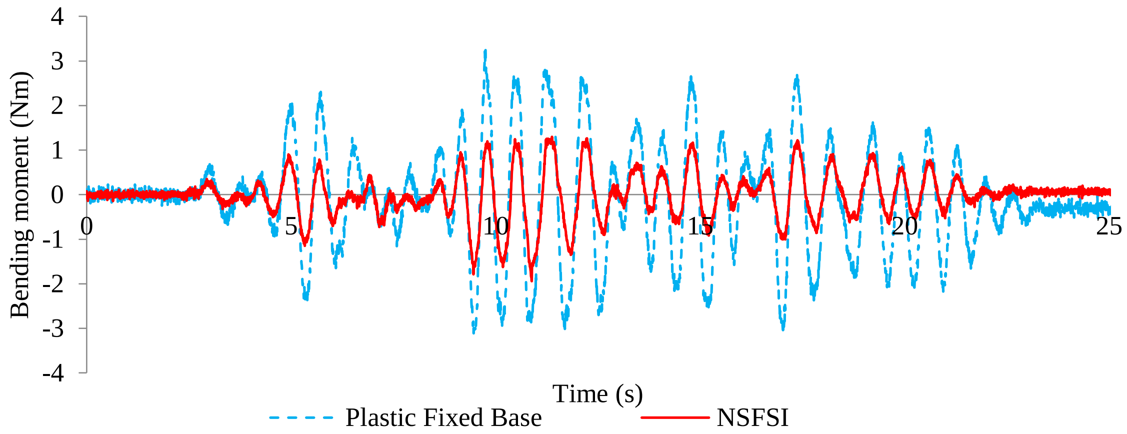


Figure 6 Influence of soil-foundation-structure interaction on a plastic structure

Plastic hinge formation, SFSI and NSFSI result in residual displacements in the structure. In the plastic fixed base structure, a residual displacement of 0.78 mm was recorded, compared to 1.1 mm in the structure with NSFSI and 2.16 mm in the structure with SFSI.

3.2 Energy in the system

Earthquake energy (E_E) and kinetic energy (E_K), under different base conditions at each floor of the structure were calculated. E_E was calculated using Equation 1, which incorporates the total displacements of the floor masses and the acceleration at the foundation of the structure. E_K was calculated using Equation 2, which takes into account the acceleration at each floor of the structure, and the inter-storey displacement at each level.

$$E_{E_i} = \int_0^U m_i . a_g \, dU \qquad (1)$$

$$E_{k_i} = \int_0^u m_i . (a_i - a_g) \, du \qquad (2)$$

where m_i = mass at floor *i*, u = inter-storey displacement, U = total displacement, a_g = ground acceleration, a_i = acceleration at floor *i*.

Figure 7 shows the E_E induced at the top floor of the structure, under different base conditions. Comparison between the structure with SFSI and the elastic fixed base structure shows that the largest amount of energy was induced in the structure with SFSI. The formation of plastic hinges in both the fixed base structure and the structure with SFSI lowered the induced E_E at the top level of the structure. The total energy induced in the nonlinear fixed base structure and the structure with NSFSI was approximately 74% of the fixed base elastic structure and 54% of the structure with SFSI.

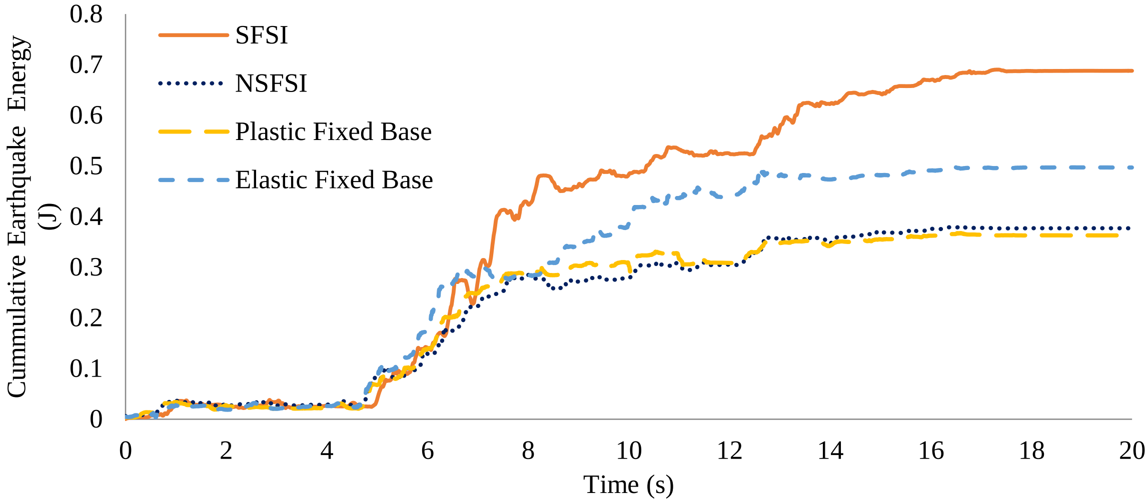


Figure 7 Induced earthquake energy in the top floor of the structure

Figure 8 shows the E_K at the top floor of each structure during the earthquake excitation. The elastic fixed base structure and the structure with SFSI had approximately the same amount of E_K, with 0.15 J. This shows that SFSI had little effect on the development of E_K when the structure was elastic. The plastic fixed base structure had the highest amount of E_K, with 0.19 J. The NSFSI structure had the lowest E_K of 0.066 J, indicating that incorporating SFSI made a significant difference in E_K, when structural nonlinearity was allowed (65.3% decrease).

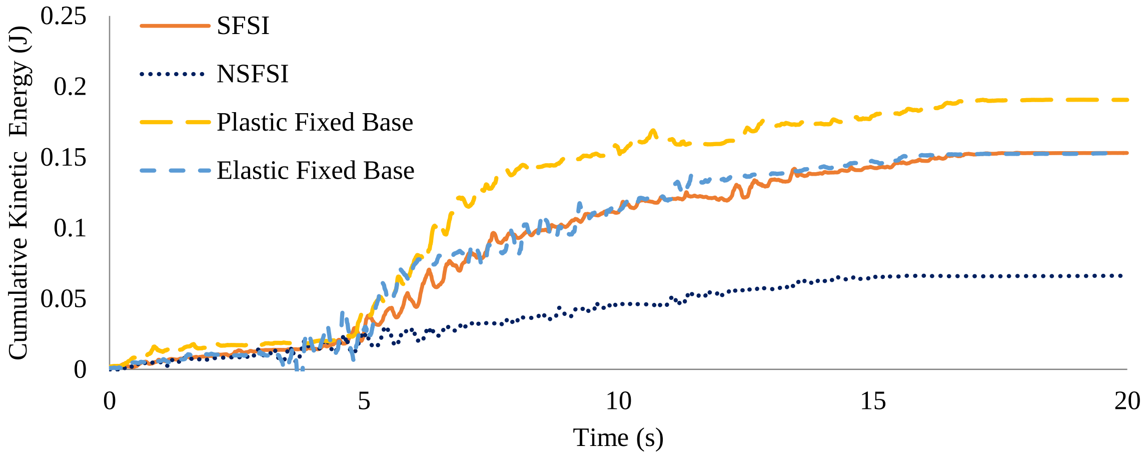


Figure 8 Kinetic energy in the top floor of the structure

4. Conclusions

Experiments on a MDOF structure were performed to understand the effects NSFSI on its seismic performance. The results show:

- As expected, plastic hinge formation in a fixed base structure resulted in a reduction in bending moments. The incorporation of SFSI in an elastic structure, obtained similar bending moment reductions but with a significant increase in residual displacement. NSFSI resulted in lower bending moments than all other cases, with only a slight increase in residual displacement in comparison to the fixed base structure with allowable plastic hinge development.
- Structural plastic hinge formation caused a reduction in E_E, regardless of whether the base of the structure was fixed or on sand.
- For elastic structures, the base conditions showed no significant effect on the induced E_K. However when structural plasticity was allowed, fixed base conditions resulted in an increase of E_K while the structure with NSFSI showed a significant decrease.

5. Acknowledgement

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