Effect of plastic hinge, soil nonlinearity and uplift on earthquake energy in structures

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ABSTRACT: Previous studies have confirmed that nonlinear interaction between soil plastic deformation, foundation uplift and structural plastic hinge can reduce seismic force in structures. However, not much research has been performed to quantify the energy dissipation due to this overall nonlinear soil-foundation-structure interaction (SFSI). In this study, shake table tests were performed to determine the energy induced into the structure. This energy is quantified by the kinetic energy in the structure. Three scenarios were considered: a fixed-base structure without and with plastic hinge development and also a structure with overall nonlinear SFSI. A laminar box was used to simulate a more realistic soil boundary condition. The experimental results revealed that the development of plastic hinges in a fixed-base structure can reduce the induced energy. However, the structure will suffer residual deformations. In contrast, when nonlinear SFSI occurs, the residual deformations can be reduced. When soil deforms plastically, foundation uplift might also take place. Simultaneous occurrence of plastic soil deformation and uplift can dissipate more energy than that in a fixed-base structure with plastic hinges.

1 INTRODUCTION

Some studies have been performed in the past on energy based design principles for buildings subjected to seismic loading. These principles differ from traditional design techniques as they consider energy balance, energy dissipation through viscous damping and energy dissipation capacity of overall structural systems (e.g. Paolacci 2013, Ye et al. 2009). Alongside viscous damping, nonlinear soil-foundation-structure interactions (SFSI) such as foundation uplift and the development of plastic hinges in a structure can be considered for dissipating earthquakes energies.

Foundation uplift occurs when a significant base overturning moment is experienced by a structure, causing momentary and partial separation of the footing from the supporting soil. Many studies on SFSI have reiterated earlier findings such as Huckelbridge and Clough's 1977 shake table tests on multi-storey buildings, which showed the reduced strength requirements in structures when foundation uplift is permitted. More recent studies have shown that combination of structural uplift and soil plasticity can reduce the activated forces and damage to structures during earthquakes (e.g. Pender et al. 2008, Qin et al. 2011). In particular, a study by Qin and Chouw in 2012 focused on the effect of both plastic hinge development and non-linear soil deformation on the response of a scaled-single-degree-of-freedom (SDOF) model structure. In their study, the combined effect of soil nonlinearity and plastic hinge development restricted the development of bending moments in the structure. Consequently, the residual footing rotation was reduced.

This study focuses on quantifying energy dissipated during nonlinear soil-foundation interaction in a structure-footing-soil system. The effects of plastic deformation in the structure are also considered. Structural plastic deformation was simulated by using slip friction hinges controlled by varying bolt pressures and monitored by load cells. The hinge joints were adjusted to simulate both elastic and plastic structural behaviour. Nonlinear soil deformation was simulated with the use of dry sand rained into a laminar box (Cheung et al. 2013). The earthquake motion was simulated based on the Japanese design spectrum for hard soil conditions (JSCE 2000).

2 METHODOLOGY

2.1 Structural model

A SDOF model was constructed by scaling down an equivalent system reflecting the fundamental mode of a four storey prototype. The effective mass (M*) and height (h*) of the equivalent SDOF system of the prototype was obtained, where the base overturning moment of the SDOF system is equated to the prototype structure. The SDOF structure with a scale of 1:15 has a height of 575 mm, a width of 400 mm and fixed on a 475x475 mm foundation. The scale factor of the model was obtained by using the scaling approach proposed by Qin, et al. 2013. The scale factors employed in this study are shown in Table 1. The model was a frame structure consisting of a rigid aluminium beam fixed at both ends by flat rectangular aluminium columns. Both columns were fixed to a Plexiglas footing with artificial plastic hinges (Fig. 1). The plastic hinge system can be fully tightened to simulate a fixed-base condition or loosened to allow plastic hinge development.

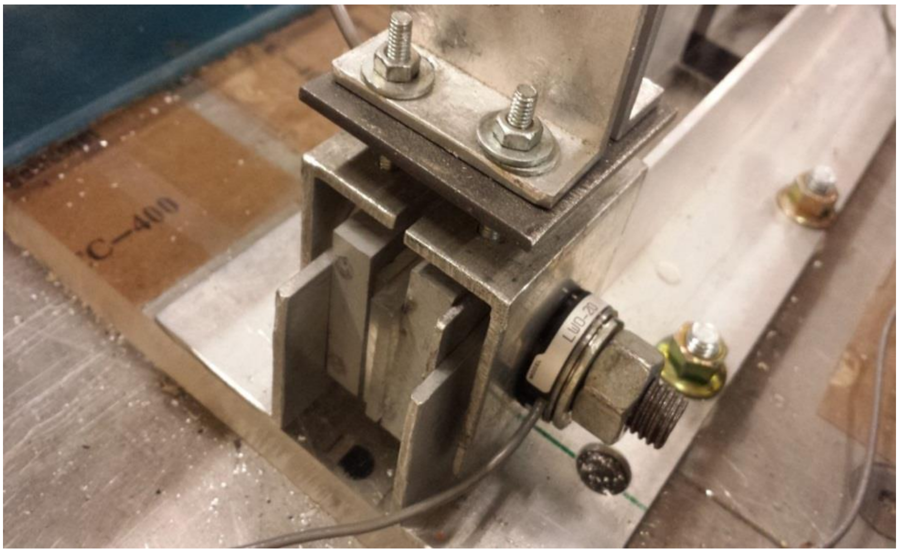

Figure 1. Slip-friction hinge controlled by bolt pressure and monitored by a load cell.

Table 1. Scale factors for the SDOF model

Parameters	**Scale factors**
Dimension	15
Lateral bending stiffness	1200
Mass	1200
Acceleration	15

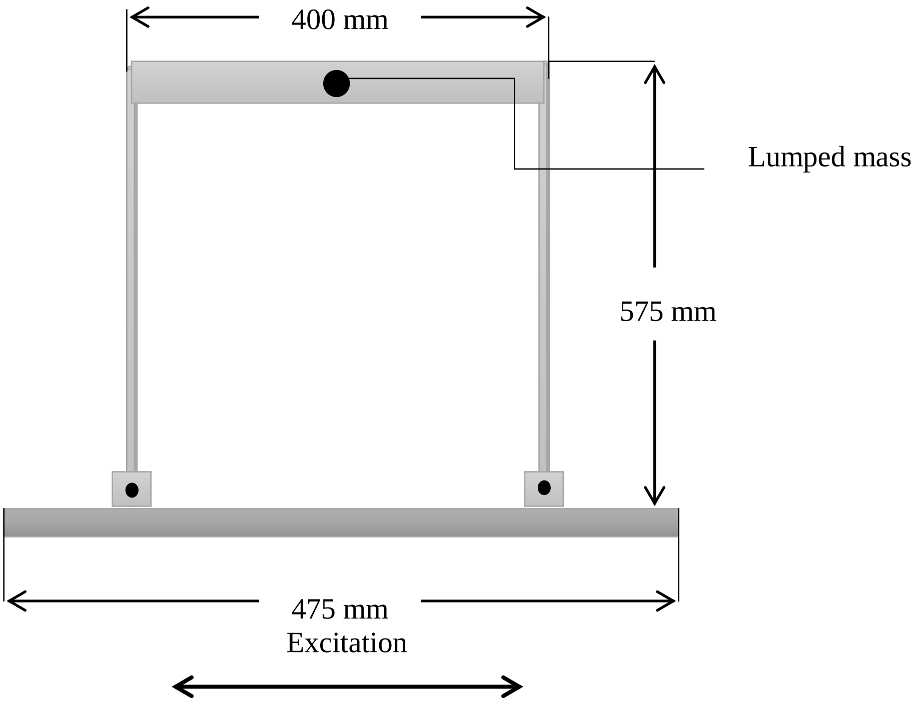

Figure 2. SDOF Model

The lumped mass, M*, of the model was 57kg. The overall system has a damping ratio of approximately 5%. This was calculated from the decay rate of free vibrations. The fundamental frequency of the system was 1.51 Hz, which matched that of the original prototype structure.

In order to achieve a fixed-base condition, steel C sections were used to clamp down the footing of the model on the shake table. Additionally, the bolts of the artificial plastic hinges were tightened, so that they would not be activated and an elastic response was ensured. For the structure with possible plastic deformation, the moment capacity of each plastic hinge was adjusted with the use of a load cell to measure the bolt clamping force. The bolts were carefully tightened to control the initiation of the plastic hinges. By applying a horizontal force to the top of the structure, the bolt pressure for an initiation of the plastic hinges was determined. Each Plastic hinge was adjusted so that it will be activated at 1.25% drift.

2.2 **Laminar box with dry sand**

In order to study the effect of structural uplift and nonlinear soil deformation on the response of the model, a laminar box was used to allow shear deformation at different depths of the soil. The box simulates a more realistic response of the soil to the earthquake excitation (Cheung et al. in 2013). Dry sand was rained into the laminar box from a height of 1 meter to allow particles to reach terminal velocity and obtain uniformly dense sand. Sand paper was placed beneath the footing to reduce sliding on the sand surface. Linear variable differential transformers (LVDTs) were installed to measure the vertical displacement of the edges of the footing. Accelerometers were placed at 50 mm and 150 mm below the sand surface to measure the acceleration within the sand.

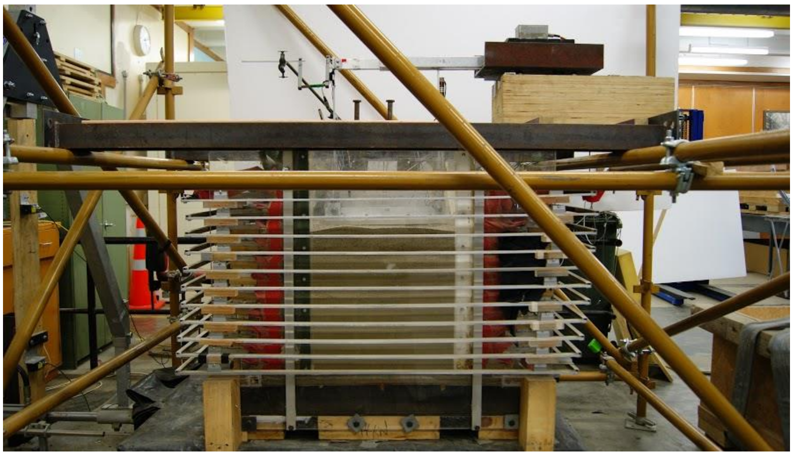

Figure 3. Laminar box set up

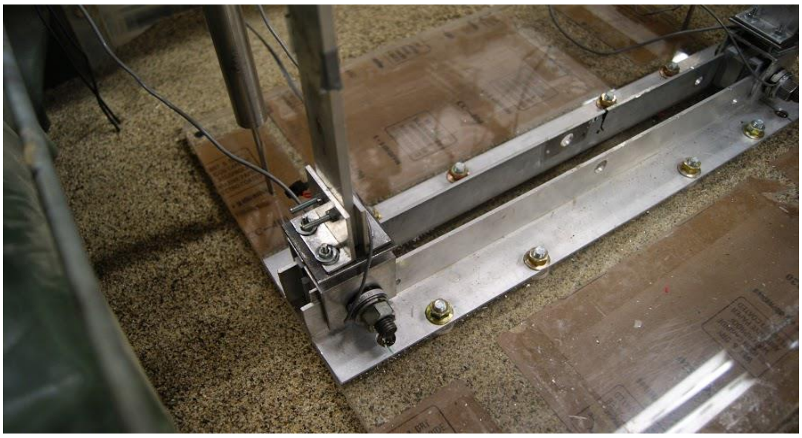

Figure 4. Structure on sand in the laminar box

2.3 Excitation

Excitations were simulated based on the Japanese design spectrum (JSCE 2000) for hard soil conditions. The design spectrum was selected as it contains a distinct frequency content to enable easier interpretation of the results.

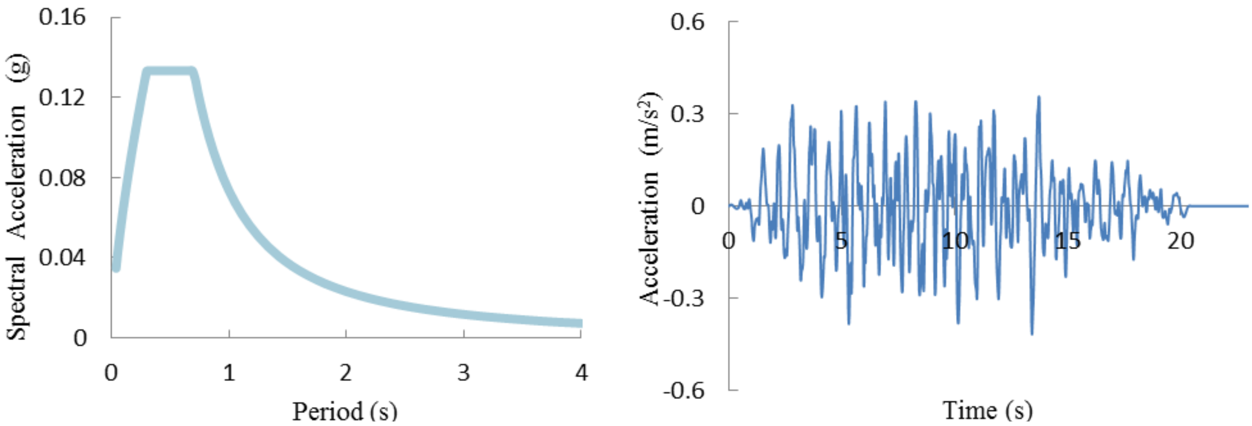

Figure 5. Ground excitation (a) Hard soil Japanese design spectrum in 1:15 scale and (b) applied ground excitation

2.4 Calculation of energy

Energy induced and dissipated within the structural system was calculated by integrating the following equation of motion.

$$\int_0^u m\ddot{u}(t)du + \int_0^u c\dot{u}(t)du + \int_0^u f_s(u)du = -\int_0^u m\ddot{u}_g(t)du \qquad (1)$$

where:

- First term: Kinetic energy (E_K) due to motion of mass relative to the ground.
- Second term: Dissipated energy due to viscous damping (E_D). The damping Coefficient, c, was obtained from free vibration test and is assumed to be constant.
- Third term: Sum of energy dissipated through possible plastic hinge development and recoverable strain energy (E_S) calculated using Equation 2.
- Right hand side of (1): Energy input into the structure by seismic ground excitation (E_I).

$$E_S = E_I - E_K - E_D \qquad (2)$$

3 RESULTS AND DISCUSSION

In order to observe the effects of plastic hinge development and non-linear SFSI on the energy dissipation in the structure, three separate structural conditions were tested:

1. Elastic structure and fixed-base
2. Structure with allowable plastic hinge development and fixed on a rigid base
3. Structure on sand.

3.1 Elastic fixed-base structure

Figure 6 shows the energy in the structure and the displacement-bending moment relationship of the structure under a fixed-base condition. The results show that there was a relatively high amount of kinetic and damping energies within the elastic structure, in comparison to the amount of energy stored in the form of recoverable deformation. The displacement-bending moment relationship also shows a symmetrical form, thus indicating the absence of residual displacement.

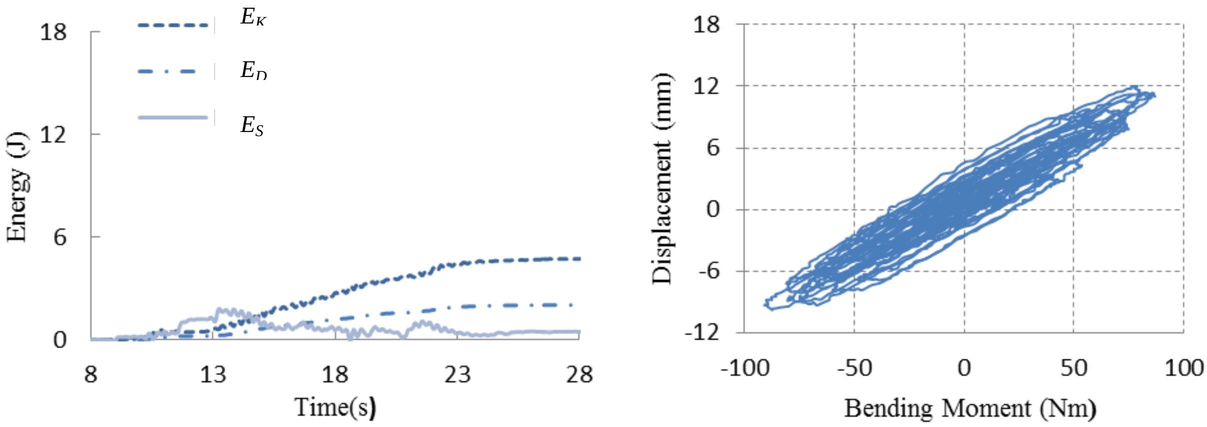

Figure 6. Elastic structure with an assumed fixed-base (a) Energy time history and (b) displacement-bending moment relationship

3.2 Fixed-base with possible plastic hinge

In the corresponding energy time history and displacement-bending moment relationship (Fig. 7) for a fixed-base structure with allowable plastic-hinge development, it can be clearly seen that there was a larger residual displacement recorded, than that of the elastic fixed-base structure. The amount of energy converted into kinetic energy (E_K) (refer to dashed line in Figs. 6(a) and 7(a)) and dissipated damping energy (E_D) (refer to dash-dotted line in Figs. 6(a) and 7(a)) was also reduced. This reduction in kinetic and dissipated energy was accompanied by a substantial increase in energy loss in forming plastic hinges, and stored as recoverable strain energy, E_S. $E_{S,max}$ in the structure with and without plastic hinge development was 8.48 J and 1.30 J, respectively. The residual displacement observed at the end of the excitation was 3.7 mm.

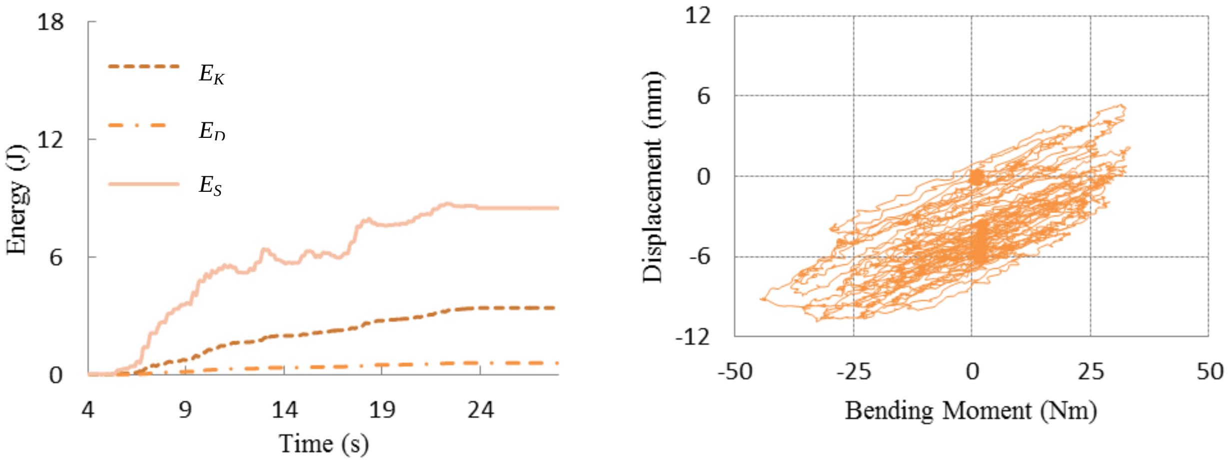

Figure 7. Fixed-base structure with possible plastic hinge (a) Energy time history and (b) displacement-bending moment relationship

3.3 Structure on sand

Examining the displacement-bending moment relationship (Fig. 8b), a clear reduction in the residual displacement was observed compared to the fixed-base case with plastic hinges. A displacement of 0.2 mm was recorded when SFSI was permitted. A comparison of Figures 7(a) and 8(a) shows that an 80% increase in E_S was caused by nonlinear SFSI. Consequently, this resulted in a further decrease in both kinetic (E_K) and damping (E_D) energies. LVDT measurements used to measure the foundation response showed the presence of foundation uplift and settlement at the footing edge. It is concluded that plastic soil deformation increases the energy dissipation in the system and reduces the residual displacement of the structure. Comparing the kinetic energy, E_K, in the elastic fixed-base model structure and that in the structure with plastic hinges and assumed fixed-base, a 28.2% reduction was observed. In the structure with SFSI the energy, E_K, was reduced by 80.3% in comparison with the elastic fixed-base structure. The results confirmed that a simultaneous consideration of structural uplift, plastic hinge development and soil plasticity can greatly reduce the kinetic and dissipated energies experienced by the structure.

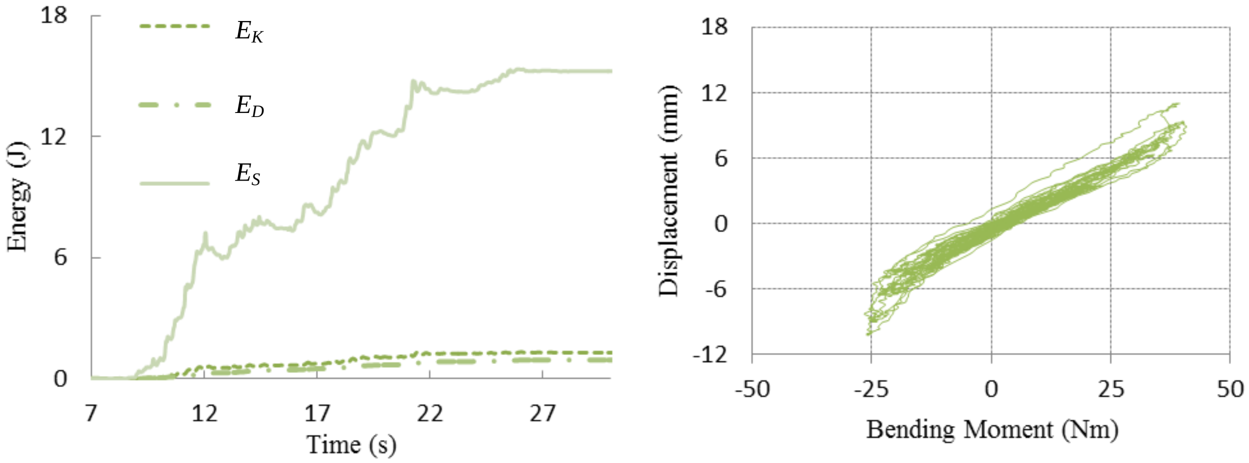

Figure 8. Structure with uplift, non-linear soil and plastic hinge (a) Energy time history and (b) displacement-bending moment relationship

4 CONCLUSIONS

The effect of SFSI was addressed with structural uplift and plastic hinge development on the induced energies and the development of residual displacement in structures. A four storey MDOF prototype was represented by a SDOF model. Plastic hinge development was controlled by adjusting bolt pressure on a slip-friction joint at the support of each column. SFSI was simulated using a shake table by exciting the structure on top of a laminar box filled with dry sand.

Experimental results revealed that:

1. Compared to an elastic structure with an assumed rigid base, plastic hinge development reduces the kinetic energy, E_K within the system. The energy dissipated through damping, E_D, is also reduced. However, a residual displacement is observed.

2. Kinetic energy, E_K, and damping energy, E_D, are further reduced by the combined effect of soil nonlinearity and foundation uplift. This is also accompanied by a reduction in the residual displacement at the top of the structure, in comparison to a structure with rigid base and possible plastic hinge development.

5 ACKNOWLEDGEMENTS

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