An experimental study of structural plastic hinge development and nonlinear soil deformation

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Abstract

In this study, a two storey steel structure was represented by a scaled single-degree-of-freedom model. The moment capacity and the plastic hinge development in the structure were simulated using an artificial plastic hinge. To investigate the interaction between structural ductile behaviour and soil plastic deformation, shake table tests were performed. The excitation was a ground motion stochastically simulated based on the Japanese design spectrum. The nonlinearity of the foundation soil was incorporated using sand in a sand box. The outcome reveals that an increase of plastic hinge development in the structure, by lowering the moment capacity, reduces the footing permanent rotation due to nonlinear soil footing-structure interaction.

Keywords: Nonlinear soil-foundation-structure interaction, uplift, soil plastic deformation

1. INTRODUCTION

During a strong earthquake when the base overturning moment exceeds the available overturning resistance, resulting from the weight of the structure, a portion of the footing may intermittently separate from the supporting soil. Several examples of towers and oil tanks uplifting from the underlying soil were observed during the 1952 Arvin Tehachapi earthquake, the 1964 Alaskan earthquake, and the 1979 Imperial Valley earthquakes (Psycharis, 1983). It is recognised that soil nonlinearity can reduce damage to the structure. This observation has led to a number of research developments, aiming to capitalize the nonlinear structure-foundation-soil (SFS) interaction in seismic design. Gajan et al. (2005) performed a series of centrifuge tests to study the nonlinear load-deformation behaviour of a shallow foundation including plastic soil deformation. The tests were performed to replicate shallow foundations on moderately dense sand and saturated clay. In the centrifuge the foundations were vertically or laterally loaded. The vertical load tests were performed to measure the vertical static bearing capacity. A comparison of the experimental and numerical results was presented by Cremer et al. (2001) and Houlsby and Cassidy (2002). Another series of centrifuge tests was conducted by Algie et al. (2009) to study the nonlinear SFS interaction and the effect on bridge structures. To extend the current state of knowledge the experiment involved pseudo-dynamic testing of various footing sizes resulting in plastic hinge development of bridge piers. The results showed that a smaller bridge footing size could result in larger plastic soil deformation but with less permanent drift from plastic hinge development in the bridge pier.

Early shake table tests on the effect of structural uplift on a multi-storey building were performed by Huckelbridge and Clough (1977a and 1977b). They concluded that allowing structures to uplift could reduce the required strength and ductility of the super-structure. A further series of shake table experiments was carried out by Paolucci et al. (2008) to replicate highway bridges founded on shallow foundations on sand. Accelerometer sensors were attached to the shake table, in the sand, and to the structure, while load cells were placed at the soil-foundation interface to measure contact force. Results showed that at the point of peak rotation of the footing, the soil-footing contact pressure is maintained in the surroundings of the edge of the footing. This results in a zone of plastic soil response near the edge of the footing. More recently, the effect of nonlinear SFSI on the induced vibrations of structure has been investigated by Qin et al. (2012).

In this study, the interaction between plastic deformation of soil and plastic hinge development at the support of the column was investigated. A single-degree-of-freedom (SDOF) model of a two storey prototype was considered. The nonlinearity of soil was simulated using dry sand in a box, and the permanent deformation of a column was simulated by constructing a slippage rotation joint at the column footing. The moment capacity of the joint was controlled by adjusting the bolt pressure applied to the joint via a load cell. With an applied bolt pressure, the slippage rotation of the column joint is resisted by the friction. The greater the friction is, the larger the rotation resistance. A shake table test was performed to simulate an earthquake, based on the Japanese design spectrum for hard soil condition (JSCE, 2000).

2. METHODOLOGY

2.1 Experimental model

The prototype structure considered was a two storeys office building. The inter-storey height was 3 m, and the total area of each level was 25 m^2. Following NZS3404 (2009), the structure was constructed using 250UC72.9 and 360UB50.7 for columns and beams, respectively. Because of the interior arrangement, the structure had a single bay with a column spacing of 2.8 m. For simplicity a foundation size of 2.8 m x 2.8 m and a cantilever beam of 1.1 m on both sides were assumed. According to NZ1170.5 (2004) the structure had a seismic mass of 50900 kg with 25600 kg for the first floors and roof, respectively. With these properties, the structural prototypes had a fundamental frequency of 1.97 Hz.

The structure was characterised by a SDOF system. By matching the base shear and bending moment of the prototype to the SDOF system, the equivalent mass (m^*) and height (h^*) of the SDOF system can be determined to be 74400 kg and 4.25 m, respectively. In order to obtain the same fundamental frequency, the lateral stiffness of this SDOF system was adjusted. It was found that the effective mass of the SDOF system represented 97.1% of the total mass. The effect of a second mode on the overall structural response was small and thus can be considered as negligible. The properties of the SDOF system are presented in Table 1. The dimensions of the system are scaled with a factor of 10, according to the similitude law and the reformulated Cauchy number developed by Qin et al. (2012). In the reformulated Cauchy number, Qin et al. have demonstrated a scaling approach using the ratio of the inertia force to the elastic restoring force resulting from the structural lateral deformation. If this ratio of the scaled model and that of the prototype is the same, then the response of the prototype can be represented by the small scale model. The properties in Table 1 are scaled according to the scale factors in Table 2.

Table 1: Equivalent SDOF structure parameters

Structure parameter	**Values**
Height (m)	4.25
Width (m)	2.8
Top mass (kg)	74400
Lateral stiffness (kN/m)	12051
Natural frequency (Hz)	1.97

Table 2: Scale factors

Quantity	**Symbol**	**Scale Factor**
Length	L	10
Lateral Stiffness	K	7438.8

Mass	M	7438.8
Time	T	1

2.2 Shake table test

A shake table test was performed on the scaled structure. The nonlinear deformation of soil due to structure-footing-soil interaction was simulated using sand in a box (Figure 1(b)). The box contained sand fill with a depth of 400 mm. Figure 1(a) shows the artificial plastic hinge constructed at the support to simulate a possible permanent deformation of the structural column. The moment capacity of the artificial plastic hinge was controlled by applying different bolt pressures. In this study, three different levels of moment capacity were considered: while one level of moment capacity represented the structure with elastic behaviour, two moment capacities were considered to quantify the plastic hinge development. In the case of elastic structural behaviour, 10 kN bolt pressure was applied. When a plastic hinge development is permitted, two different moment capacities are considered, i.e. 4 kN and 3 kN bolt pressures to simulate a high moment capacity and a low moment capacity, respectively.

The ground excitation in Figure 2 was simulated based on the Japanese design spectrum for a hard soil condition (JSCE, 2000). This spectrum was selected because of the clearly defined frequency content (Chouw and Hao, 2005).

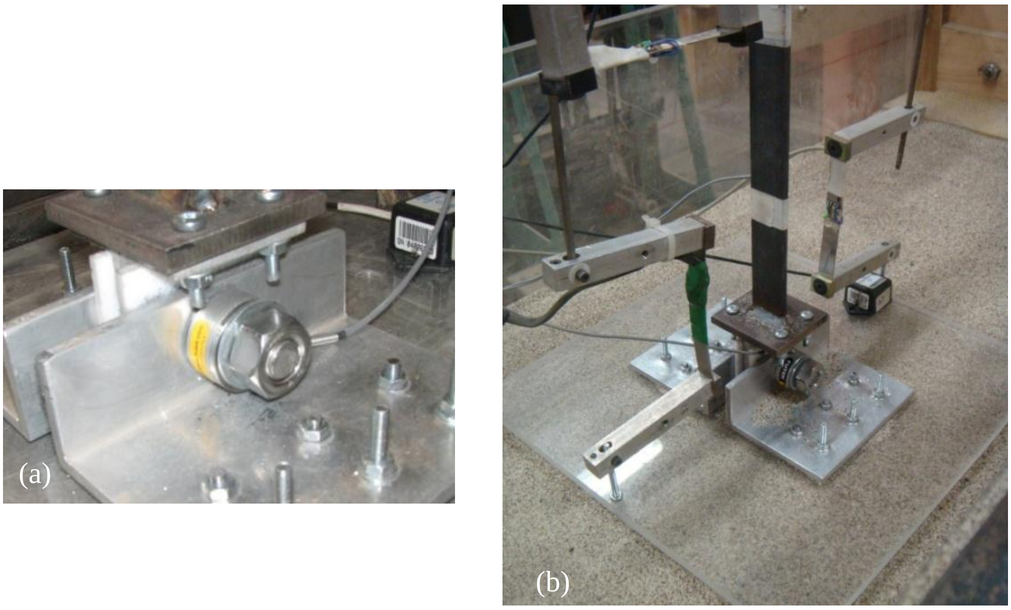

Figure 1: Experiment setup. (a) Artificial plastic hinge and (b) model on sand

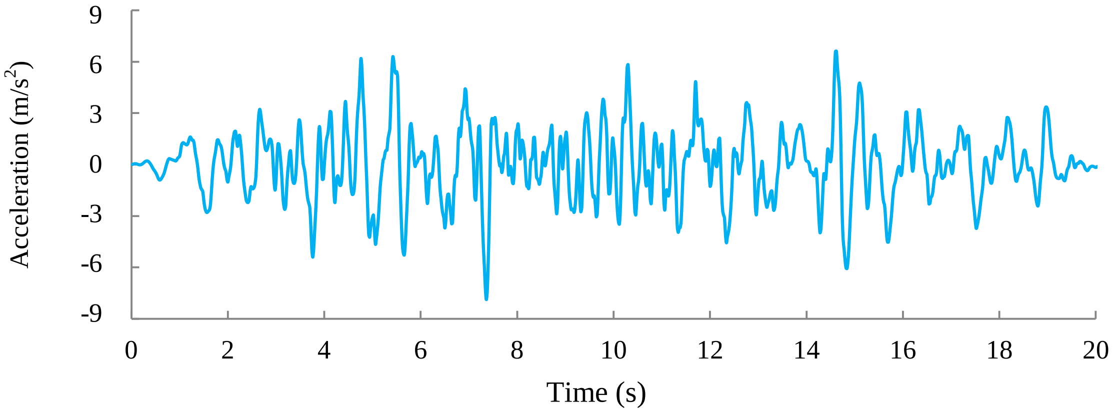

Figure 2: Simulated ground accelerations for hard soil conditions

3. RESULTS AND DISCUSSION

To investigate the interaction between nonlinear foundation soil, structural uplift and plastic hinge development in the structure, columns with different yield strengths were considered. The moment capacity of the structure was controlled by varying the bolt pressure applied onto the artificial plastic hinge at the column footing. To avoid any hinge slippage a bolt pressure of 10 kN was applied. A 4 kN bolt pressure was applied to enable a plastic hinge and thus a permanent rotation to develop. Figure 3 shows the relative horizontal displacement (u) at the top of structure. When a plastic hinge development is tolerated, the residual horizontal displacement in the structure is higher than when an elastic structural behaviour is assumed. In the case of an elastic structure, the residual top horizontal displacement can only be induced by the footing rotation due to soil plastic deformation. In contrast when a plastic hinge in the structure is permitted, the development of the plastic hinge can significantly increase the permanent top horizontal displacement. At the end of the excitation, the residual top horizontal displacement increased from 1.67 to 7.81 mm (0.39% drift to 1.84%) due to permanent deformation of the structural column.

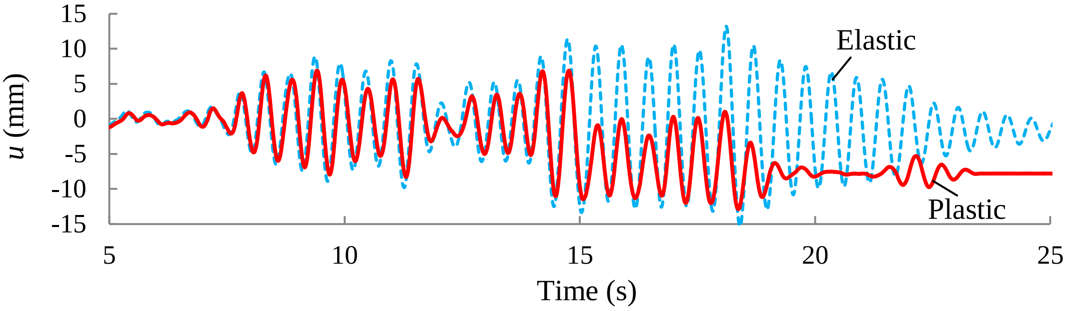

Figure 3: Influence of plastic hinge development on the top horizontal displacement

Although the combined influence of the foundation soil and structural plastic deformation on a structure will increase the structural residual displacement, this interaction can reduce the bending moment in the structural system during earthquakes. Figure 4 shows the time history of bending moment development at the column base of a structure with (solid line) and without (dotted line) plastic hinge development. A reduction of the maximum bending moment in the structure, due to the interaction between nonlinear soil and structural plasticity can be clearly seen. In comparison with the maximum bending moment of 9.7 Nm in an elastic structure, the maximum bending moment in the structure with a plastic hinge development reduced to 7.3 Nm.

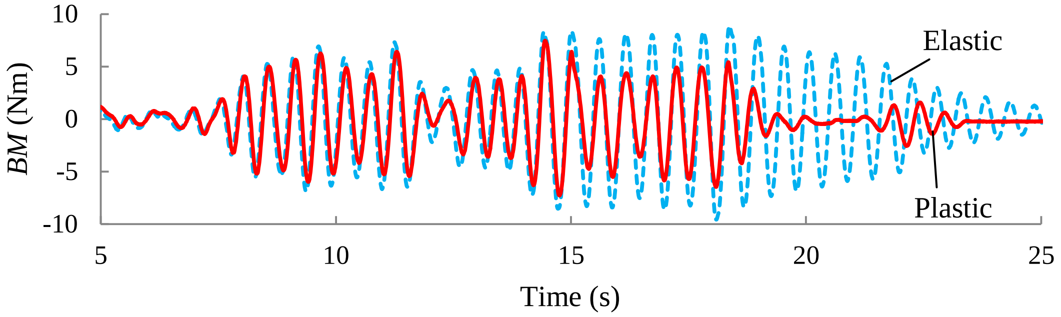

Figure 4: Influence of plastic deformation in soil and structure on the bending moment

Because of the reduction of the bending moment in the structure due to nonlinear SFSI, the footing response could be reduced. Figure 5 shows the time history of footing rotation (*r*) during the excitation. While the dashed line represents the model with elastic behaviour, the solid line illustrates the model with a plastic hinge development. The rotation in the structure with a plastic hinge eliminated the strong and frequent footing rotation that had been observed in the structure with an elastic behaviour. At the end of the excitation, for structures with elastic and plastic behaviour, the residual rotation of the footing caused by soil plastic deformation was 0.36 degree and 0.26 degree, respectively.

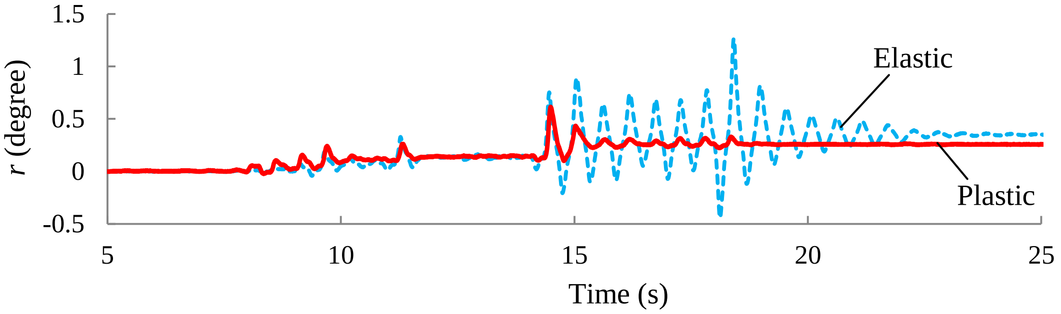

Figure 5: Influence of plastic hinge development on the footing rotation

To reveal the effect of the structural moment capacity on the performance of nonlinear SFSI, the bolt pressure applied to the artificial plastic hinge was reduced from 4 kN to 3 kN. Figure 6 shows a comparison of the footing rotation (*r*) with the two column moment capacities. With a lower column moment capacity, the footing rotation was further reduced. As shown in Figure 6 at about the 15th second of the excitation, a significant footing rotation could still be observed in the model with high moment capacity. On the other hand, no significant footing rotation was evidenced in the model with low moment capacity after the 10th second of the excitation. At the end of the excitation, the residual rotation of 0.26 degree in the model with high moment capacity was 0.11 degree greater than that observed in the model with low moment capacity. The result obtained confirmed that a low moment capacity can reduce the footing response and soil plastic deformation. Reducing the moment capacity of a structure can reduce the design action of the foundation.

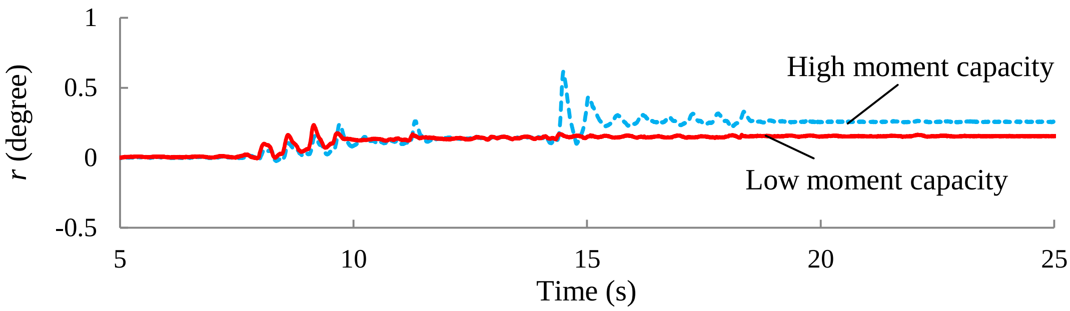

Figure 6: Influence of yield strength on the footing response

4. CONCLUSIONS

In this study, the interaction between foundation soil, structural uplift and column plastic deformation was investigated. A scaled SDOF model of a two storey prototype was considered. The permanent deformation of the column was simulated by constructing a slippage rotation joint at the support of the column. The moment capacity of the joint was controlled by using a load cell. The nonlinearity of soil was simulated using dry sand. A shake table test was performed. The applied excitation was simulated based on the Japanese design spectrum (JSCE, 2000).

This study has revealed that:

1. Soil nonlinearity with structural plastic hinge development can reduce the bending moment in the structure.

2. The interaction between the structural and soil plastic deformation can reduce the residual rotation of footing.

3. The lower the moment capacity of the structure, the less uplift of footing on soil was observed. However, this observation depends on the soil plastic deformation. For obtaining a general conclusion further studies are necessary.

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