Effect of Earthquake Dominant Frequencies on Nonlinear Structure-Foundation-Soil Interaction

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SUMMARY:
In current practice of earthquake-resistant design, the structural and geotechnical components are considered separately. Since it is difficult to incorporate the effect of nonlinear foundation behaviour on structural response, for simplicity linear foundation behaviour is often assumed in the analysis. If earthquake energy can only be dissipated by ductile structural members, damage to a structure may be severe. Although fatalities can be avoided, the downtime of the structures may have severe subsequent impact. On the other hand, by permitting a minor plastic deformation of soil while structure, foundation and subsoil interact, the earthquake energy induced into the structure could be decreased. Thus, damage to the structure could be significantly reduced or even avoided. In this work, the effect of dominant frequencies of ground excitations on nonlinear structure-foundation-soil interaction (NSFSI) was investigated. Plastic deformation in soil and temporary separation between footing and soil were considered simultaneously. The ground excitations were applied using shake table, and the soil was represented by a box of dry sand.

Keywords: Nonlinear structure-foundation-soil interaction, earthquake dominant frequency, footing uplift

1. INTRODUCTION

Lateral force activated in structures during an earthquake can cause structural uplift and foundation soil deformation. In current design understanding, these phenomena are considered as potential for overturning structures and thus should be avoided. However, observations in the past earthquakes have shown that even a structure with a properly designed foundation still suffered this nonlinear structure-foundation-soil interaction (NSFSI). On the other hand, it was reported that structures performed better if footing uplift and soil plastic deformation took place during earthquake (Housner, 1963, Gazetas et al., 2003). Although the current design codes state that any possible footing uplift and soil nonlinearity should be avoided, research shows that this practice will lead to over-conservative structures. Although a possible beneficial effect of NSFSI on seismic performance of structures has been identified several decades ago (Housner, 1963, Pecker, 1998, Apostolou and Gazetas, 2005, Qin and Chouw 2010), only very few structures has been constructed with uplift potential. The reason is that people are still uncomfortable with the idea of letting the structure to move without an absolute assurance of safety. One of implementations was the Rangitikei Railway Bridge (see Fig. 1.1) built in New Zealand (Chen et al., 2006).

Because of the complexity of the structure-foundation-soil system investigations in the past often assumed that the structure is rigid, e.g. Taniguchi (2002) and Apostolou et al. (2007). Gajan et al. (2010) discussed a numerical model that can be used to incorporate sliding. Also in the recent work conducted by Kelly (2009), proposing design guidelines for rocking structures, a rigid structure is assumed, although it is confirmed that structural flexibility can significantly affect the dynamics of structure (e.g. Kodama and Chouw, 2002 and Anastasopoulos, 2010). The effect of footing size on the structural response including uplift had been illustrated, and a significant contrast between the uplift behaviour due to various footing lengths has been discussed by Qin and Chouw (2010).

Figure 1.1. The South Rangitikei Railway Bridge

In this work a flexible structure subjected to different excitations is considered. The influence of earthquake dominant frequency on NSFSI will be investigated. The ground excitation was simulated by a shake table. The single-degree-of-freedom (SDOF) model was scaled using a reformulated Cauchy Number. It is assumed that the structure stands freely on a rigid base, and the effect of the foundation soil was also investigated by using a box of sand. The uniformity of sand prior to each experiment was ensured by raining the sand into the box. The selected ground excitations were simulated based on two Japanese Design Spectra (JSCE, 2000). For the structure considered, the HS spectrum contains a larger spectral value, and produces an excitation with higher frequency than that of the MS spectrum. The relationship between bending moment development and vertical displacement at the footing will be discussed.

2. SHAKE TABLE TEST

2.1. SDOF Prototype

For a two storey structure with uniformly distributed mass and stiffness, the mass of the equivalent SDOF model represents over 90 % of the structural mass. Thus, the inertia force activated in the structure due the earthquake can be well predicted using a SDOF model with a total height and top mass of 4.25 m and 61370 kg, respectively. In order to obtain a fundamental frequency of 2.2 Hz, the lateral stiffness of the prototype was selected to be 12,051 N/m. The prototype structure stands freely on a rigid base or sand. The influence of earthquake characteristic on structural responses with different support conditions is investigated.

2.2. Model Scaling

Because of laboratory facilities constraint, the prototype structure must be scaled down. For this purpose Buckingham's π theorem (Buckingham, 1914) and dimensional analysis were utilised. Based on this approach, one dimensionless group known as Cauchy Number was developed to fulfil the scaling requirement of engineering mechanics. In this work, this dimensionless group is applied in order to obtain the scale factor for shake table test. The scale factor for dimensions of the model and applied ground acceleration was pre-defined to be 10. The scale factor for mass was 7438.8. Because SFSI is significantly affected by the duration of the foundation uplift, the effect of time scale on the overall structural behaviour was unknown. Therefore, physical quantity time is not scaled. It is generally considered to be very difficult to scale all material properties in model scaling. Duffey et al. (1984) suggested that the material scaling could be achieved using the same material of the prototype structure to construct the model.

Table 2.1. Scale Factors and Model Parameters

Physical parameters	SDOF system	Scale factor	Scaled model
Mass	61370 kg	7438.8	8.25 kg
Lateral stiffness	12051 N/m	7428.8	1.62 N/m
Total height	4.25 m	10	0.425 m
Frequency	2.2 Hz	1	2.2 Hz
Applied acceleration	PGA g	10	PGA/10 g

The final scale models had a lumped mass of 8.25 kg. The total height was scaled down to 0.425 m, and the footing was constructed using 0.28 m x 0.28 m rigid plate (Fig. 2.1). Free vibration tests were performed on the model with a fixed base showing a fundamental frequency and damping ratio of 2.2 Hz and 4 %, respectively. Development of the acceleration at the top of the structure, bending moment and vertical displacement at the footing will be measured.

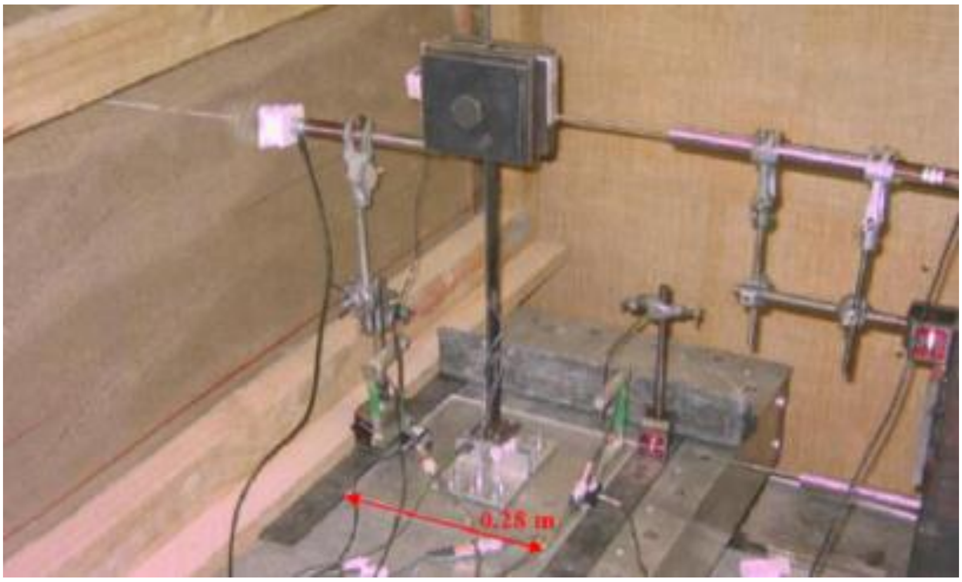

Figure 2.1. Scaled SDOF model on shake table with uplift capability

2.3. Subsoil

A sand box of 400 mm depth with 1000 mm x 450 mm surface area was used to investigate the effect of soil deformation. Sponges were placed at both sides of the box to simulate the extension of sand. Sandpaper was used to minimise possible slippage at the base of the box. Dry sand with a unit weight of 15.5 kN/m^3 was used. This unit weight was consistently achieved by raining the sand from a consistent drop height between 500 mm to 600 mm (Fig. 2.2 (b)). The sand was tested according to NZS4402 (1986) and was found to have a coefficient of uniformity of 1.86. The final setup of the shake table test with structure on sand is shown on the Fig. 2.2(a). Foundation vertical displacement is measured using portal gauge. The horizontal acceleration at the top and bending moment at the column support were recorded using accelerometer and strain gauge, respectively. These measurements were compared with the results obtained from the test of models on a rigid base (Fig. 2.1).

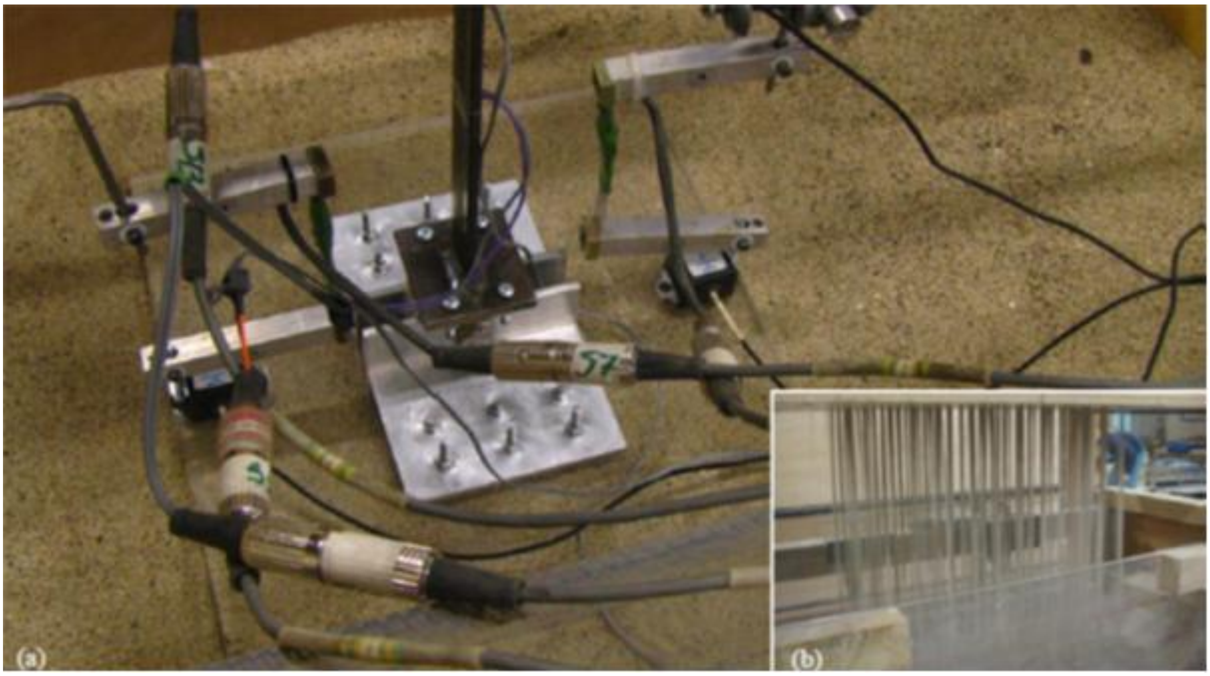

Figure 2.2. Experiment setting using sand box. (a) Footing on sand and (b) sand raining process

2.4. Earthquake Excitations

The applied ground excitations were simulated based on Japanese design spectra (Fig. 2.3(b), JSCE, 2000, Chouw and Hao, 2005). They were selected because of their clear defined frequency content. In this study ground excitations with two different dominant frequency contents were considered (indicated as HS and MS motions Fig. 2.3). It should be noted that for simplicity in the investigation of NSFSI the same sand is used. At this early-stage of the investigation the different soil stiffness ground motions are selected only for considering different dominant frequency contents of ground motions. From the response spectra (Fig. 2.3(b), the spectrum value of the HS excitation at the modal fundamental period of 0.46 s is larger than that of MS excitation.

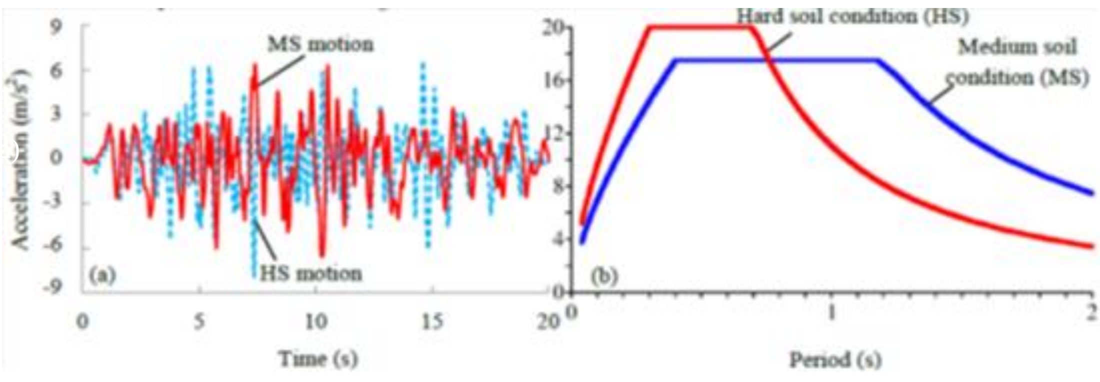

Figure 2.3. Simulated ground accelerations and the corresponding Japanese design spectra

3. DISCUSSION OF RESULTS

3.1. Effect of Earthquake Dominant Frequency on Uplift Behaviour

When the moment at the footing exceeds the structural overturning moment resistance due to gravitational force, the footing can temporary separate from the support. The vertical displacement of the footing was measured using portal gauges while the moment on the footing was recorded by a strain gauge (Fig. 2.1). According to the actual spectrum value, it is anticipated that HS ground motion will develop a stronger acceleration in the structure compared to the MS ground motion. Therefore, the resulted moment should be greater. However, if an uplift of the footing is permitted, a prediction of the moment development using spectrum value can lead to a different conclusion. Fig. 3.1 shows the relationship between moment and vertical displacement (*v*) at the centre of the footing. The result shows that although the MS acceleration spectrum value is smaller than that of the HS acceleration, the bending moment at the footing induced by MS excitation (5.1 Nm) was greater than that induced by HS excitation (4.5 Nm). Similarly, the maximum vertical footing displacement caused by MS excitation (0.22 mm) is higher than that due to HS excitation (0.17 mm). The results suggested that time history analyses is necessary to properly predict the overall performance of structures including uplift. Although the reduction in bending moment due to the uplift benefits the structural performance (Qin et al. 2011), measurement obtained from this work suggests that a larger magnitude of uplift does not necessary lead to a greater deduction of the structural force.

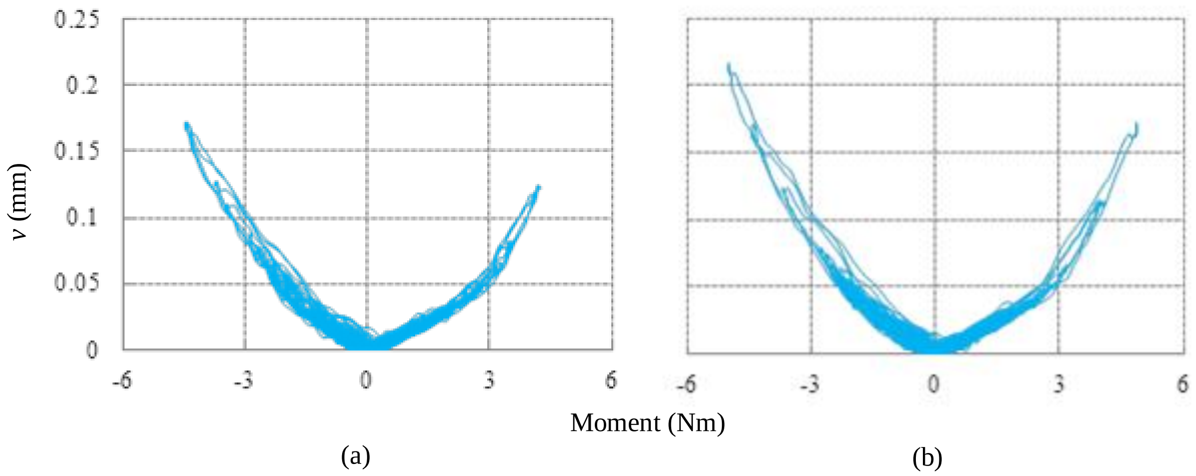

Figure 3.1. Moment-vertical displacement relationship of model on rigid base due to (a) HS excitation and (b) MS excitation

3.2. Effect of Earthquake Dominant Frequency on Soil Nonlinearity

To investigate the influence of earthquake dominant frequencies on footing response with soil deformation, the model was placed on the sand surface as shown in Fig. 2.2(a). When footing actions applied to the soil reaches the bearing capacity of foundation soil, settlement and permanent rotation of the footing can be accumulated. Although the ground motions for different soil conditions were considered, the supporting sand was assumed to be the same. Fig. 2.3(b) shows a larger acceleration spectrum value induced by HS ground excitation, compared to MS ground excitation, suggesting that the HS excitation will cause a greater action on the footing and possibly result in stronger plastic deformations of the supporting soil. Fig. 3.2 shows the bending moment at the support and the vertical displacement (*v*) of the footing. In this work, the footing settlement is equivalent to the magnitude of negative vertical displacement. After the HS and MS excitations, the model settled up to 0.76 mm and 0.63 mm, respectively.

On the other hand, a comparison of the bending moments at the footing on rigid (Fig. 3.1) and flexible base (Fig. 3.2) suggested that plastic deformations of the soil can reduced the force development in the structure. The average maximum moment due to both excitations of 4.8 Nm was observed in the model on rigid base, while only 3.6 Nm was recorded when the model was placed on sand. Although soil nonlinearity had taken place during the excitation, the structure did not overturn. The results revealed that NSFSI can reduce the moment development in the structure and consequently reduced the forces to be considered in the design. However, soil plastic deformations can induce a residual settlement and possible an incline of the structure. Nevertheless, these experimental results illustrate that this residual displacement increases with a larger spectrum value.

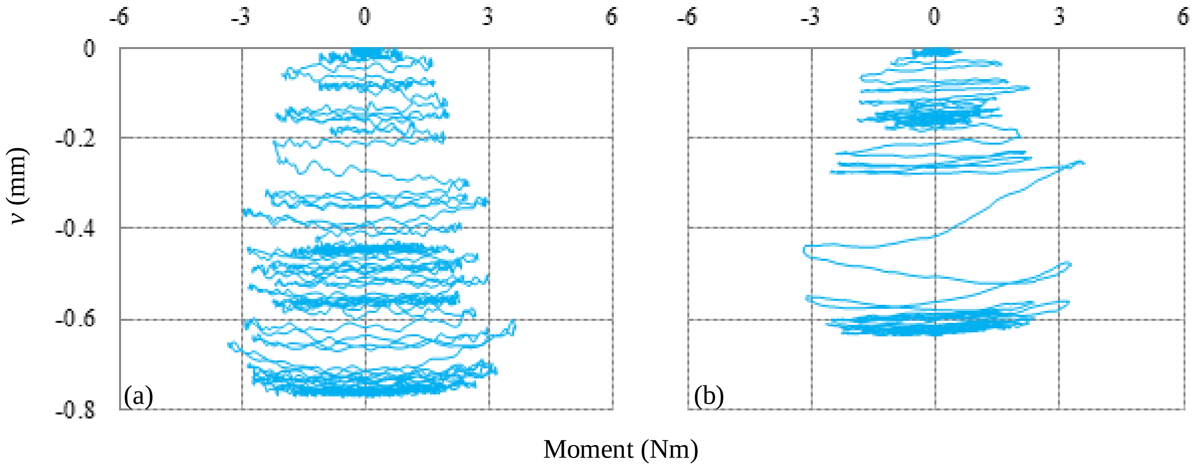

Figure 3.2. Moment-vertical displacement relationship of model on sand due to (a) HS excitation and (b) MS excitation

3.3. Effect of Soil Plastic Deformation on Footing Uplift

Figs. 3.3(a) and (b) show the vertical displacement (*v*) time histories of the foundation with different support conditions due to HS and MS excitations, respectively. When considering a rigid base, only footing uplift can take place (solid line). In comparison to the case where the model was placed on sand, although uplift can still take place, the footing settles (dashed line). Only a very small magnitude of uplift was observed (marked by dotted circles). The results from this experiment with both excitations conclude that soil nonlinearity can reduce the footing rotation due to uplift. It was confirmed that footing rotation due to uplift can increase the horizontal displacement at the top of structure relative to ground (Qin and Chouw, 2010). Reducing foundation uplift can decrease the horizontal relative displacement in the structure due to structural rigid body motion.

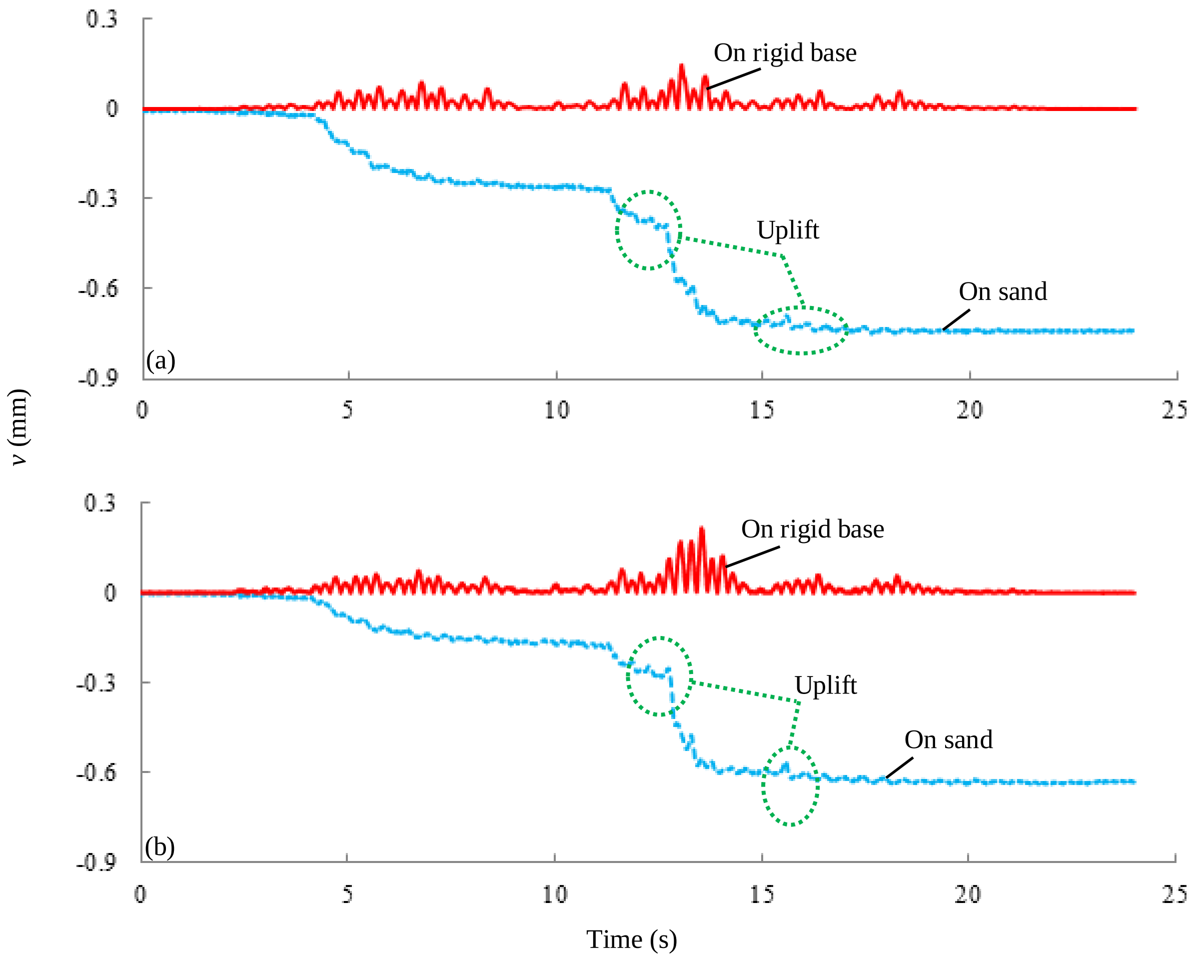

Figure 3.3. Time history of footing vertical displacement with different support conditions due to (a) HS and (b) MS excitations

4. CONCLUSIONS

The influence of earthquake dominant frequencies on NSFSI was investigated. Shake table test was performed on a small scaled SDOF model. The foundation soil performance was considered using a sandbox with 400 mm sand fill. The uniformity of sand for each experiment was achieved by raining the sand into the box. The uplift behaviour of structure under different excitations was studied by a free standing model on a rigid base or on sand. Japanese Design Spectra ware applied for simulating ground excitations.

The investigation reveals:

1. A larger footing uplift does not necessary cause a greater reduction in footing moment development. In order to predict the beneficial effect of uplift behaviour on structures, a time history analyses is needed.

2. In the considered case when soil plastic deformation is permitted, the performance of footing and soil during different earthquakes can be estimated using the corresponding spectrum values. With NSFSI, the bending moment development at the support is reduced. To obtain a general conclusion further investigations are required.

3. Soil plastic deformation can reduce the uplift amplitude, and thus the relative horizontal displacement in the structure due to structural rigid body motion can be reduced.

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