Centrifuge modelling of the rocking response of shallow building foundations on dense sand

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ABSTRACT: The rocking response of shallow foundations has been proposed as a potential source of reducing seismic actions on structures so supported. At least one multi-storey building on a shallow raft foundation in Christchurch was observed to have suffered less structural damage than might have been expected from the Christchurch Earthquake of February 22, 2011. Centrifuge experiments have been undertaken at the University of Dundee, Scotland, using a range of equivalent single degree of freedom (SDOF) building models resting on a layer of dense, dry sand to investigate the energy dissipation characteristics of such rocking foundations. Reported in this paper are preliminary results from tests of equivalent 3, 5, and 7 storey building models resting on the ground surface. The models were excited with Ricker wavelet motions, the predominant frequency of which matched the natural frequency of the structure, to measure the free vibration response. The peak input accelerations of the Ricker motions ranged between 0.1 and 0.75g. Analysis of the recorded data revealed that uplift of the foundation was observed for the majority of experiments and had an influence on structural response. Nonlinear soil deformation was also influential for the higher amplitude Ricker motions. The equivalent SDOF period of the response was found to be greater than that of the elastic fixed-base model, indicating nonlinear structure-foundation interaction. Equivalent viscous damping values in the 8 to 20% range were also inferred from the responses. The paper will discuss the significance of these preliminary results in the earthquake resistant design of multi-storey buildings on shallow foundations.

1 INTRODUCTION

Rocking of buildings on shallow foundations during earthquake loading has been proposed as a potential source of reducing the forces transmitted to the structure. Kelly (2009) states that many new and existing buildings have insufficient self-weight to resist uplift of the structural elements during an earthquake and thus rocking can be initiated. Observed, experimental and numerical evidence suggests a building that uplifts and goes through cycles of rocking will have significant energy dissipation capacity as the fundamental period of the system is increased and total horizontal acceleration, overturning moment and relative lateral displacements of the structure are reduced (Housner 1963; Huckelbridge 1977; Priestley et al. 1978; Psycharis 1983). The rocking response of a number of multi-story buildings on shallow foundations in the Christchurch central business district may explain why they have suffered less structural damage than might have been expected during the Christchurch Earthquake of February 22, 2011 (Storie et al. 2014). These buildings generally had large raft foundations resting on a thick layer of competent gravel so had a high static bearing capacity factor of safety (FoS). This meant that uplift was likely the dominant nonlinear soil-foundation-structure interaction (SFSI) mechanism during earthquake loading, rather than nonlinear soil deformation, presenting an interesting case to further investigate the energy dissipation characteristics of these rocking foundations.

Centrifuge experiments were conducted at the University of Dundee, Scotland, to investigate the rocking response of a range of multi-storey buildings on raft foundations resting on a dense sand. Centrifuge modelling is important when investigating soil-foundation systems because confining stresses play an important role in soil behaviour (Taylor 1995). Equivalent elastic single degree of freedom (SDOF) building models were used in the experiments since the focus was the nonlinear mechanisms at the soil-foundation interface and how those mechanisms influenced overall building response. Equivalent 3, 5, and 7 storey building models with identical sized square raft foundations were designed for the experiments and were placed on the surface of a prepared layer of dense, dry sand. The sand represented an idealisation of a non-liquefiable cohesionless deposit. The combination of large raft foundation and dense sand meant that the static bearing capacity FoS for the models was large, simulating the scenario observed in Christchurch. The models were excited with Ricker wavelet ground motions, which were used to simulate a pushover/snapback type experiment, in order to measure the free vibration response of the rocking structures. By applying a range of Ricker wavelet amplitudes the energy dissipation characteristics of the building models expected to rock and uplift by differing amounts could be ascertained.

2 CENTRIFUGE MODELLING

In centrifuge modelling a 1:*N* scale model is rotated at a constant speed so that a centripetal acceleration of *N*g acts on the model, creating an artificial gravitational field and enabling stress distribution in the model soil to be the same as the prototype being modelled (Taylor 1995; Muir Wood 2004). For example, the stresses at a depth of 200mm in a model soil spun at a centripetal acceleration of 50g will be the same as that at a depth of 10m of the same soil in Earth's gravity (i.e. at prototype scale). This is particularly important in geotechnical modelling as the mechanical behaviour of soils is strongly related to stress state. The centrifuge at the University of Dundee that was used for the experiments discussed in this paper is a beam type centrifuge that spins model experiments at the end of a 3.5 metre arm to develop centripetal accelerations of up to 80g when a mechanical shaker is attached. The servo-hydraulic mechanical shaker (or Earthquake Simulator, EQS) is specially designed to apply dynamic motions to the model while it is being spun by the centrifuge. By undertaking this dynamic centrifuge modelling, accurate soil-foundation behaviour is able to be captured in scale model experiments and the rocking response of shallow foundations can be accurately observed and analysed.

3 EXPERIMENTAL CONFIGURATION

Three centrifuge experiments are reported here on equivalent SDOF models of generic 3, 5, and 7 storey buildings with identical square raft foundations. Generic frame structures representative of the buildings that performed well in Christchurch were developed using assumptions made regarding overall building dimensions and mass distribution. Cross sectional drawings of the prototype generic frame structures are presented in Figure 1a. Procedures outlined in Chapter 3 of Priestley et al. (2007) were then followed to develop equivalent SDOF substitute structures for the generic buildings at prototype scale, which were then used to design and construct scale models for centrifuge experiments conducted at a centripetal acceleration of 50g. Cross sectional drawings of the three structure-foundation models used in the centrifuge experiments are presented in Figure 1b. The models were comprised of a 160mm square raft foundation (8m square at prototype scale), a suitable height column, and a 140mm square deck at the top of the column with additional masses to achieve the calculated lumped mass. The fixed base natural period of the generic buildings were assumed to be 0.1s times the number of storeys (i.e. a natural period of 0.3s, 0.5s, and 0.7s for the 3, 5 and 7 storey buildings respectively) and the column dimensions in the SDOF models were chosen to achieve this period given the size of lumped mass at the top of the column.

In each case the model structures were placed atop a layer of dry Congleton silica sand (ρ_{dmin} = 1487 kg/m^3, ρ_{dmax} = 1792 kg/m^3, D_{60} = 0.14mm, ϕ_{crit} = 32 degrees (Lauder, 2010)), which was prepared uniformly by air pluviation to have a density ratio of about 83%. The deposit of sand was 200mm deep, equivalent to 10m at prototype scale given the centripetal acceleration of 50g, and was prepared within an equivalent shear beam container that minimises dynamic boundary effects (Bertalot, 2013). Instrumentation consisted of 9 type ADXL78 MEMS accelerometers (±70g range) within the soil and 7 on each structure-foundation model, along with two pairs of FLA-3-23 strain gauges at the base of the column of each of the equivalent SDOF models to measure bending moments about the two orthogonal axes of bending. Linear Variable Differential Transformers (LVDTs) were connected to the foundation to measure vertical, horizontal and rotational displacement. The layout of the experiments is presented in Figure 2, with the 7 storey model shown for reference.

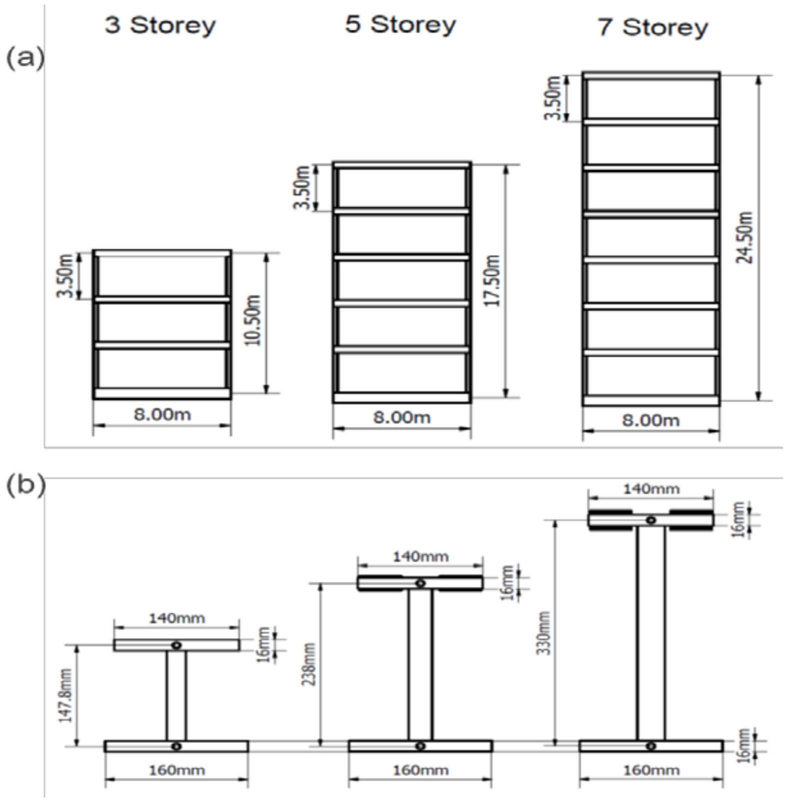

Figure 1. Cross sections of (a) the three generic frame buildings (dimensions at prototype scale), and (b) the three equivalent building models used in the experiments (dimensions at model scale).

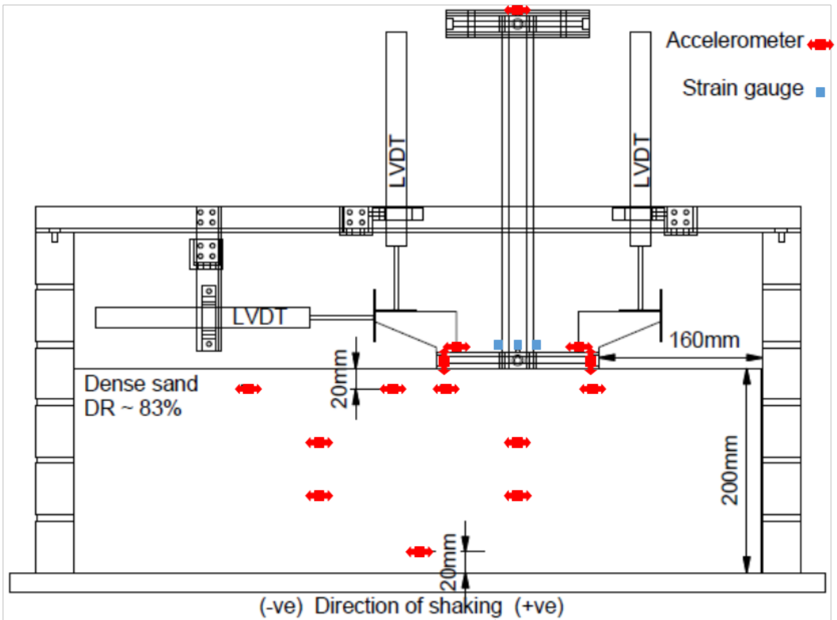

Figure 2. Layout of centrifuge experiment for 7 storey building model (dimensions at model scale).

3.1 Ricker wavelet input motions

Ricker wavelets provided a dynamic means to undertake a pushover/snap-back type of test in the centrifuge experiments. A typical snapback test involves the model being pulled back and then released instantaneously to vibrate freely. However, while the centrifuge is “in flight” it is difficult to undertake this type of test multiple times on a single model set up. Loli et al. (2014) were successfully able to use Ricker wavelets to undertake snapback-type tests and their results found that they could determine foundation moment-rotation and structure-foundation free vibration response for models on shallow foundations. An example of a prototype scale Ricker wavelet acceleration time history used in the centrifuge experiments is presented in Figure 3, along with the 5% damped acceleration response spectra for that wavelet.

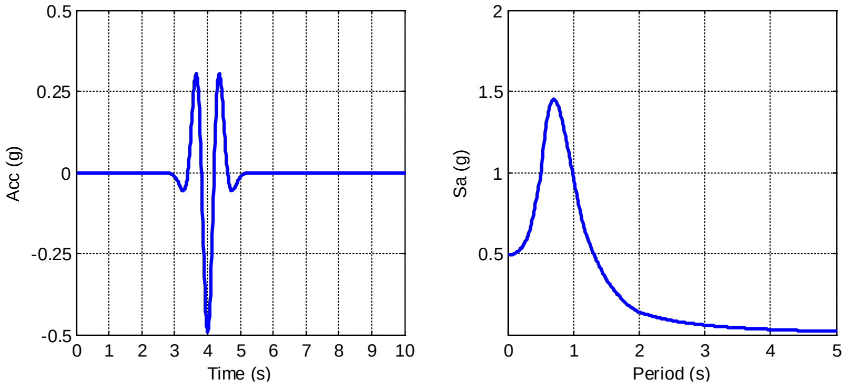

Figure 3. Acceleration time history and 5% damped response spectra for a representative Ricker wavelet (prototype scale) used in the centrifuge experiments.

The characteristics of the Ricker wavelets used for the experiments were chosen to be able to investigate varied SFSI responses of the three generic building models. The predominant frequency of the wavelet was chosen so that the peak in the acceleration response spectrum occurred at the fixed base natural period of each building modelled, so as to maximise structural response. The peak amplitude of the Ricker wavelets were then varied from 0.1g to 0.75g and were applied in succession from smallest to largest amplitude in order to capture a range of SFSI responses of the structure-foundation models. Once suitable prototype Ricker records were chosen they were scaled and filtered so that they could be applied in the centrifuge experiments.

4 RESULTS

The centrifuge experiments provided a range of data regarding the overall response of the soil, foundation, and structure for the three generic building models. Specific preliminary results are presented in this paper and focus on the rocking response and energy dissipation characteristics of the system. Data direct from the centrifuge experiments was scaled and filtered to provide appropriate information on the rocking response of the prototype buildings that were modelled and all the results presented here are at prototype scale.

4.1 Static bearing capacity FoS and elastic foundation settlement

As mentioned previously, the structure-foundation models designed for the centrifuge experiments simulated a scenario observed in the Christchurch Earthquake where buildings on large raft foundations resting on a competent layer of cohesionless soil performed well. Before the centrifuge experiments were undertaken, the static bearing capacity FoS for the three model structures on raft foundations resting on the surface of the layer of dense sand was calculated using the standard formulas that are outlined in the New Zealand Building Code Verification Method B1/VM4 (MBIE, 2008), and the values are given in Table 1. Also given in Table 1 are the elastic vertical settlement values for each of the soil-foundation models, calculated using the small strain shear modulus of the soil and the vertical stiffness of the foundation derived using procedures outlined by Gazetas (1991).

The static bearing capacity FoS values are high due to the large raft foundation on dense soil, and this also results in small static elastic settlement values. Using these static calculations, conclusions could be drawn regarding the uplift and permanent soil deformation response during dynamic Ricker wavelet motions.

Table 1. Static bearing capacity FoS and elastic settlement values for the structure-foundation models.

Model	Static bearing capacity FoS	Static elastic foundation settlement (mm)
3 storey	26	0.9
5 storey	19	1.2
7 storey	15	1.5

4.2 Foundation uplift and permanent soil deformation

The range of amplitudes of Ricker wavelet motions applied in the centrifuge experiments meant that a range of SFSI responses could be observed. Uplift of the foundation from the supporting soil was observed in the majority of experiments undertaken and permanent soil deformation was more evident when higher amplitude Ricker wavelets were used. The extent of foundation uplift was more significant for the 7 and 5 storey models compared to the 3 storey model. This is evident by the extent of positive displacement in Figure 4, which presents the vertical displacement of opposite edges and the middle of the assumed rigid foundation for the 3 storey (a) and 7 storey (b) models subjected to Ricker wavelets of 0.3g and 0.75g peak amplitude. However, the extent of permanent soil deformation under a given size of wavelet was similar across all of the models. In all cases, larger Ricker input motions resulted in greater permanent settlement of the foundation. The difference in foundation uplift response of the different sized models influenced overall structural response (see next section) but the influence of permanent soil deformation also had a role in structural behaviour during large shaking.

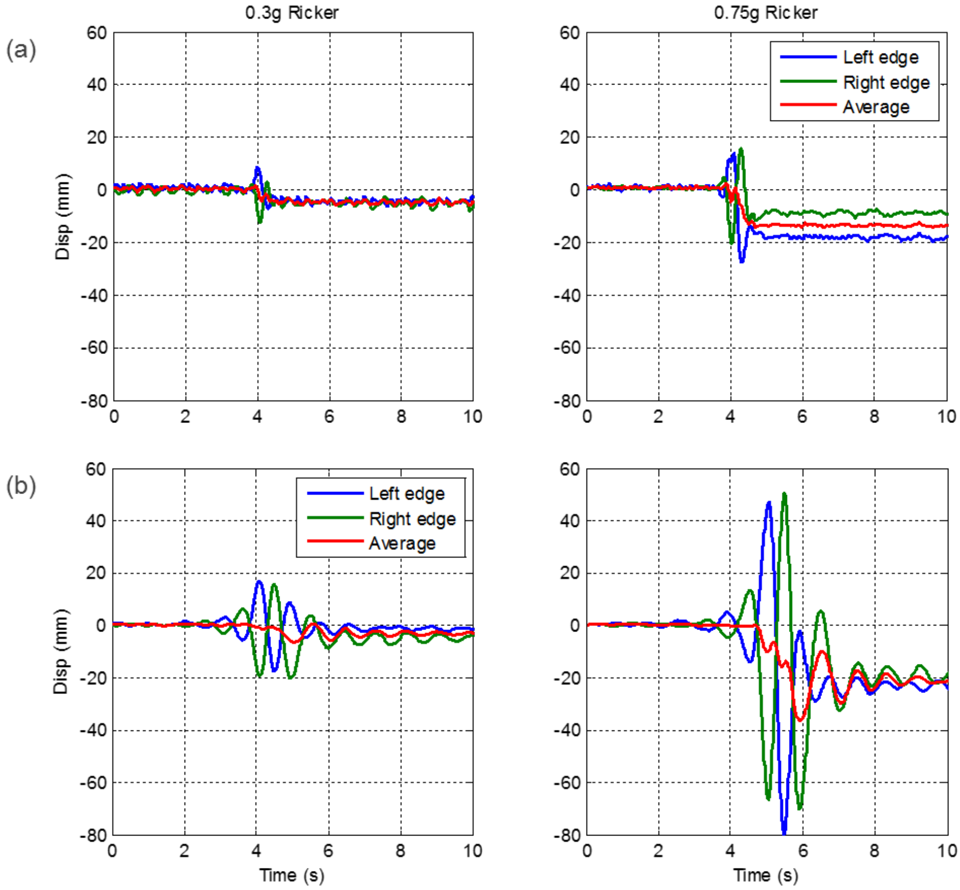

Figure 4. Foundation vertical displacement of the (a) 3 storey model and (b) 7 storey model subjected to Ricker wavelets with a peak amplitude of 0.3g (left) and 0.75g (right).

4.3 Acceleration response

Acceleration was recorded within the soil and at points on the structure as outlined by the accelerometer locations in Figure 2. Structural response was recorded by an accelerometer placed at the centre of the lumped mass of the models and soil response was measured at a range of depths within the soil profile. By comparing the acceleration in the soil with that on the structure, insight could be gained regarding the influence of nonlinear SFSI on the response of the structure. Figure 5 shows comparisons of acceleration time histories at the base of the soil, in the soil just beneath the foundation, and on the top of the structure for the 3 storey (top) and 7 storey (bottom) models each subjected to a 0.75g amplitude Ricker wavelet. The Ricker pulse propagated from the base of the dense soil layer to just beneath the foundation with a slight amplification in both cases but the structure response was quite different. For the 3 storey model the full amplitude of the Ricker wavelet was transferred to the structure and then acceleration of the structure decreased over a few seconds whereas only approximately one-third of the magnitude of the Ricker input was transferred to the structure for the 7 storey model and the response damped out very rapidly. It was observed in Figure 4 that the extent of uplift for the 7 storey model was significantly larger than that of the 3 storey model for the same magnitude Ricker input but in absolute terms the uplift was small compared to the size of the foundation. However, it appears that even a small extent of uplift can significantly reduce the forces transmitted to the structure. Furthermore, a small extent of nonlinear soil deformation also influences the overall damping in the system.

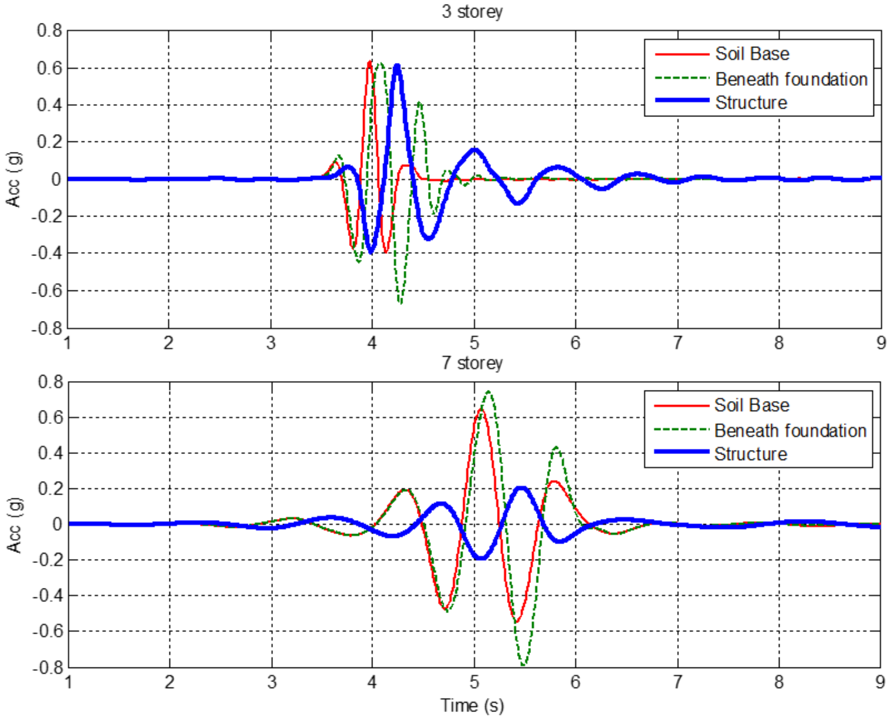

Figure 5. Acceleration time history comparison of soil and structure response for the 3 storey and 7 storey models subjected to the 0.75g amplitude Ricker wavelet.

4.4 Equivalent SDOF period and damping

To gain further understanding of the dynamic behaviour and energy dissipation characteristics of the three generic building models, the equivalent SDOF period and damping ratio were calculated for the Ricker input motions by employing a transfer function. In the frequency domain the acceleration response of the structure (output) was related to that in the soil just below the foundation (input) to calculate the transfer function between these two records, and then an equivalent SDOF period and damping value was calculated to achieve a best fit to the transfer function data (see Thomson, 1993). A linear approximation of a nonlinear system is made by using this transfer function method but it does provide insights into the comparative behaviour of the models.

Results for selected Ricker amplitudes applied to the 3, 5, and 7 storey building models are presented in Figure 6, with the fixed-base period and damping shown for comparison. In all cases the equivalent SDOF period of the structure-foundation systems was greater than that of the fixed-base model. This indicates that rocking and nonlinear SFSI has resulted in period lengthening, which has been shown in the literature to generally have a beneficial effect on structural response (see Kelly 2009). Equivalent SDOF damping ranged between about 8 and 20% across the model responses. This is considerably higher than the 5% damping suggested for structures in many design codes and is primarily due to nonlinear interaction at the soil-foundation interface. As the peak magnitude of the Ricker input increased, the damping ratio increased indicating that a greater extent of SFSI meant higher damping, even when the absolute extent of uplift and permanent soil deformation appeared to be small. Interestingly, the damping ratio is quite high for the 3 storey structure-foundation system even though uplift was not as extensive as was observed for the 5 and 7 storey models. It appears that even with competent soil, the combination of foundation uplift and nonlinear soil deformation has a significant influence on structural response but uplift may be more significant for taller structures with a higher height-to-foundation width ratio.

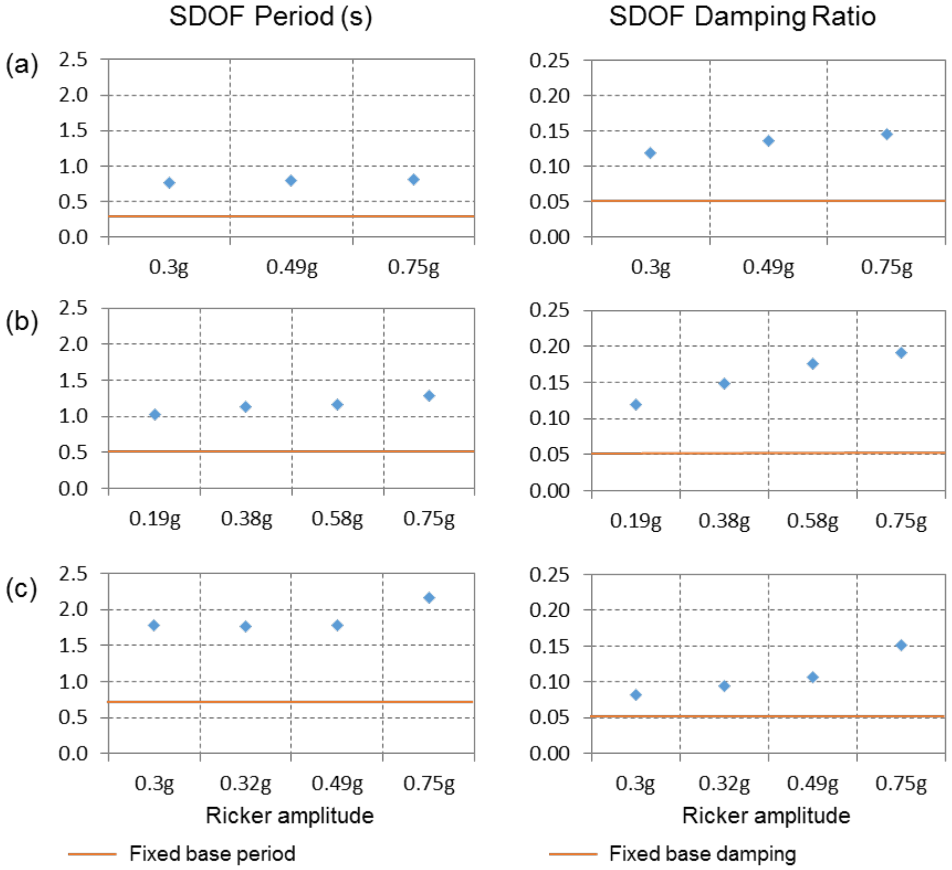

Figure 6. Equivalent SDOF period (left) and damping ratio (right) calculated using a transfer function method for selected Ricker wavelet amplitudes for (a) 3 storey, (b) 5 storey, and (c) 7 storey models.

5 CONCLUSIONS

Centrifuge modelling of the rocking response of buildings on shallow raft foundations resting on dense sand was undertaken at the University of Dundee, Scotland. Centrifuge modelling is important for appropriately capturing interaction between the soil and foundation in scale model experiments because identical soil stress distribution is able to be developed in the model as would be experienced at prototype scale. This is significant because soil behaviour is strongly related to its stress state. Models of equivalent SDOF 3, 5, and 7 storey buildings on raft foundations were developed to represent multi-storey buildings on shallow raft foundations that performed well in the Christchurch

Earthquake. Ricker wavelet ground motions were applied to the models while they were spun in the centrifuge as a dynamic means of undertaking snapback-type experiments and the results presented in this paper highlighted the influence of foundation uplift and nonlinear soil deformation on the dynamic response of buildings.

Uplift of the foundation from the supporting soil meant that the seismic actions transmitted to the structure were reduced. The absolute extent of uplift relative to the size of the foundation did not need to be significant for it to have a large effect on structural response. Permanent soil deformation occurred predominantly for larger input motions, resulting in settlement of the structure-foundation models and further influence on the overall behaviour. However, due to the large raft foundations resting on a competent soil resulting in a large static bearing capacity FoS, even when the bearing area was reduced because of uplift the settlement was of a small magnitude. Nonlinear SFSI in the form of foundation uplift and permanent soil deformation resulted in an increased equivalent SDOF period for all the models and a large amount of damping. These results show that a rocking shallow foundation on a competent soil having a high static bearing capacity FoS will be beneficial for structural performance during earthquake loading. Also, uplift of tall multi-storey buildings on shallow raft foundations might have helped in their good performance during the Christchurch Earthquake, with minimal permanent settlement of the foundations.

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