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Centrifuge Modelling of the Energy Dissipation Characteristics of Mid-Rise Buildings with Raft Foundations on Dense Cohesionless Soil

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ABSTRACT

The nonlinear behaviour of shallow foundations on competent soil during large earthquakes provides a mechanism for energy dissipation and improved performance of buildings. To investigate this, centrifuge experiments were 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. The models were comprised of shallow raft foundations of identical size, and superstructures sized to give equivalent 3, 5, and 7 storey buildings. Ricker wavelets were applied as a ground motion to capture the free-vibration responses of the soil-structure systems. Representative recordings from the Christchurch Earthquake of February 22, 2011 were also applied to the models in separate tests. It was found that significant energy was dissipated between the soil, foundation and structure, particularly when the models were subjected to high amplitude input motions. The dominant energy dissipation mechanism appeared to be uplift of the foundation from the supporting soil. The large raft in conjunction with dense sand meant significant energy could be dissipated through nonlinear soil-foundation-structure interaction (SFSI) without the detrimental effects of significant permanent soil deformation. Ricker wavelets were found to be suitable in determining the SFSI parameters appropriate for use in earthquake analysis.

Introduction

The energy dissipation characteristics of rocking shallow foundations during earthquake loading have been of interest to engineers for many years (Housner, 1963; Priestley et al., 1978). Experimental and analytical studies have found a reduction in the forces transmitted to structures whose foundations are able to uplift from the supporting soil but highlight the possibility of detrimental settlement due to permanent soil deformation (Harden et al., 2005; Kelly, 2009; Pecker & Chatzigogos, 2010). However, shallow foundations are often only viable for multi-storey buildings when the foundation soil is competent because of static settlement requirements, and consequently raft foundations are often used to limit overall and differential settlement. During dynamic earthquake loading these buildings will be able to uplift and reduce overall bearing area for short periods of time with limited permanent soil deformation due to a large reserve of bearing strength that results from having a large raft foundation on a competent soil. The centrifuge modelling discussed in this paper was undertaken to investigate the energy dissipation characteristics of this kind of soil-foundation-structure scenario and assess the influence of nonlinear soil-foundation-structure interaction (SFSI) on the performance of multi-storey buildings on shallow foundations

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during earthquake loading.

Centrifuge experiments were conducted 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. Centrifuge modelling is important when investigating soil-foundation systems because confining stresses play an important role in soil behaviour (Taylor, 1995). Equivalent elastic SDOF building models were used in the experiments since the focus was on 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 competent, non-liquefiable, cohesionless deposit. The models were excited with Ricker wavelet ground motions, which were used to simulate snapback type experiments, in order to measure the free vibration response of the rocking structures. In separate tests, the models were also subjected to representative earthquake records from the event in Christchurch on 22 February, 2011 (see Cubrinovski et al., 2011), to investigate the response of these types of buildings to earthquake loading. 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 and the results appear to be appropriate for determining SFSI parameters for use in earthquake analysis.

Centrifuge modelling

In centrifuge modelling a 1:N scale model is rotated at a constant speed so that a centripetal acceleration of Ng 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). 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, which 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 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.

Experimental Configuration

Centrifuge experiments on equivalent SDOF models of generic 3, 5, and 7 storey buildings with identical square raft foundations are reported in this paper. Generic frame structures were developed using assumptions regarding overall building dimensions and mass distribution. Then procedures outlined in Chapter 3 of Priestley et al. (2007) were followed to develop equivalent SDOF substitute structures for the generic buildings. The calculated prototype scale lumped mass, effective height, and assumed fixed base natural period of the three building models are presented in Table 1 and these were used to develop scale models for the 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 1. 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 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. The mass of the foundation at prototype scale could also be determined using the dimensions of the model and the combined mass of the foundation and structure was then used with the properties of the soil to determine the static bearing strength factor of safety (FoS), also presented in Table 1. As can be seen, the static bearing capacity FoS values were quite large due to a large raft foundation on a competent soil.

Table 1: Prototype scale parameters of the three equivalent building models.

Building Model	Lumped Mass (T)	Effective Height (m)	Fixed Base Natural Period (s)	Foundation Mass (T)	Static bearing capacity FoS
3 Storey	111.7	7.4	0.3	175.9	28.8
5 Storey	190.9	11.9	0.5	177.8	21.2
7 Storey	264.1	16.5	0.7	175.6	16.8

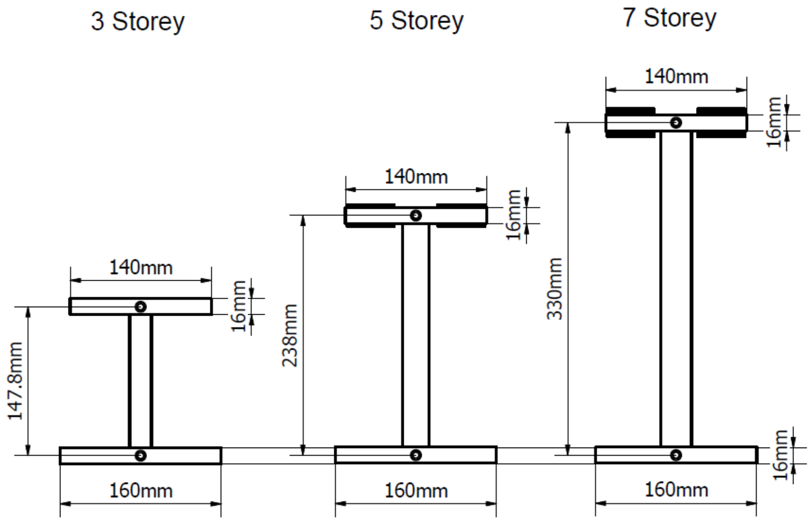

Figure 1: Cross sections of the three equivalent building models used in the centrifuge experiments (dimensions at model scale).

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), 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 accelerometers (±70g range) within the soil and 7 on each structure-foundation model, along with two pairs of strain gauges at the base of the column of each of the equivalent SDOF models to measure bending moments. 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.

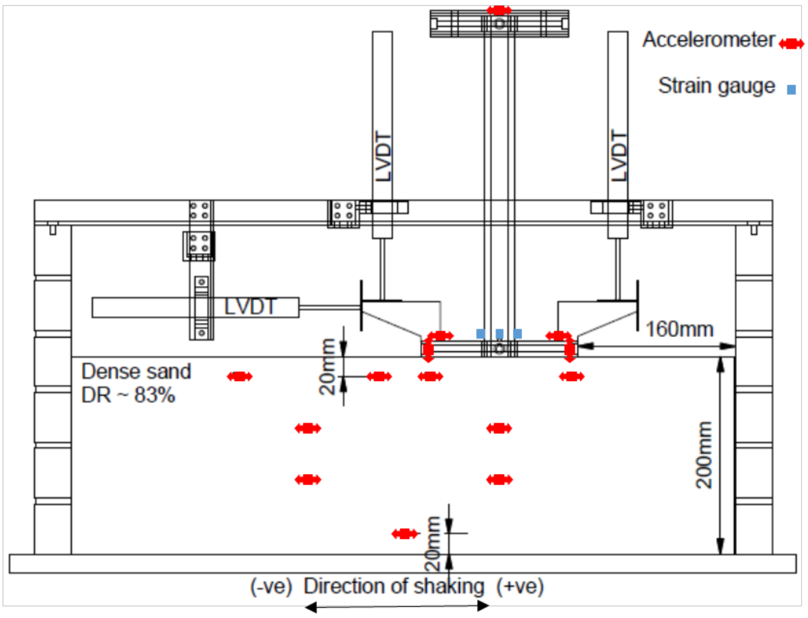

Figure 2: Layout of centrifuge experiment for 7 storey model (dimensions at model scale).

Input motions

Experiments were conducted using a range of amplitudes of Ricker wavelets to provide a dynamic means to undertake snap-back type tests in the centrifuge experiments. 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 3a, along with the 5% damped acceleration response spectra for that wavelet.

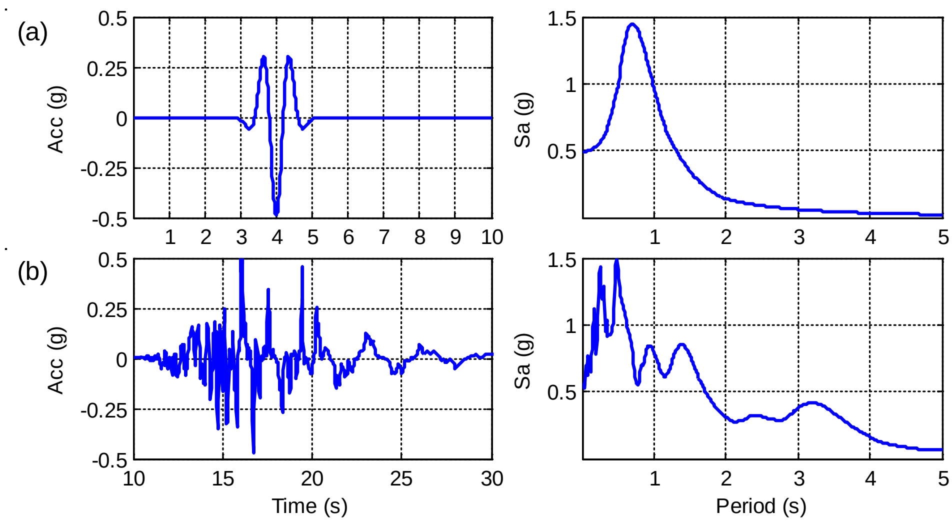

Figure 3: Acceleration time history and 5% damped response spectra for (a) representative Ricker wavelet and (b) CBGS Christchurch Earthquake record (prototype scale).

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 highest amplitude in order to capture a range of SFSI responses. Once suitable prototype Ricker records were chosen they were scaled and filtered so that they could be applied in the centrifuge experiments.

Experiments were also conducted using representative ground motion records from the Christchurch Earthquake on February 22, 2011 (see Cubrinovski, et al., 2011). These experiments enabled observations to be made regarding the response of the building models to earthquake loading and provided comparison with Ricker wavelet snapback type experiments. Results from analysis using the record from the CBGS station near the Christchurch central business district are presented in this paper and the time history and 5% damped response spectra of this record are presented in Figure 3b. Again, these records were scaled and filtered so that they could be applied in the centrifuge experiments.

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 energy dissipation characteristics of the systems. 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 of the results presented here are at prototype scale.

Structure-foundation response

Direct measurements from the centrifuge experiments provided insights into the structure-foundation response and the influence of nonlinear SFSI. Acceleration was recorded within the soil and at points on the structure as outlined by the accelerometer locations in Figure 2. On the left side of Figure 4, comparisons are made between 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 7 storey building model. Figure 4a presents the results for a Ricker pulse with a peak amplitude of 0.49g and Figure 4b presents the results for the CBGS Christchurch Earthquake record. The input motions propagated from the base of the dense soil layer to just beneath the foundation without substantial change but only approximately 30-40% of the peak magnitude of the input was transferred to the structure for this building model. A similar but less significant reduced response was observed for the 5 storey model and the full peak magnitude of the input motion was transferred to the structure for the 3 storey model. Nonlinear interaction at the soil-foundation interface appeared to have a more significant beneficial effect on the taller building models in terms of the magnitude of forces transmitted to the structure. However, across all of the models, and particularly noticeable in the Ricker plot in Figure 4a, the response of the structure damped out fairly rapidly once peak response was reached.

Nonlinear interaction between the foundation and soil was observed in the displacement measurements of the foundation during dynamic loading. Vertical displacements of the foundation are presented on the right side of Figure 4 for the two input motions specified.

Uplift was considered to be occurring when positive displacement of the edges of the foundation occurred at a magnitude greater than the static elastic settlement plus any average permanent settlement during dynamic loading because soil, particularly dry sand, is considered to have no tensile capacity. Uplift of the edges of the foundation occurred for the majority of the experiments undertaken and increased in magnitude as the amplitude of the Ricker wavelet increased. The extent of uplift of the edges of the foundation ranged from only a few millimeters up to 50 mm in the Ricker wavelet experiments and averaged around 10 mm in the Christchurch Earthquake experiments. These extents of uplift were only small relative to the size of the foundation, which was 8 metres square for each model (≤ 0.6% for the largest Ricker cases and ≤ 0.13% in the Christchurch cases). However, this small extent of uplift over a number of cycles was able to contribute to significant reductions in the peak response of the taller structures relative to the input motion and also contributed to damping observed during excitation. Residual settlement of the foundation could also be observed at the end of the experiments and indicated permanent soil deformation had occurred. This was observed for the larger Ricker wavelet motions and all of the Christchurch motions across all of the building models but, as with uplift, was small compared to the size of the foundation, with a maximum settlement of about 20 mm across the experiments. Differences in settlement of opposite edges of the foundation resulted in very small residual rotations, with a maximum value of 0.1 degrees across the experiments. The combination of relatively small extents of uplift and permanent soil deformation still influenced the dynamic properties of the structure-foundation models and provided a mechanism for energy dissipation.

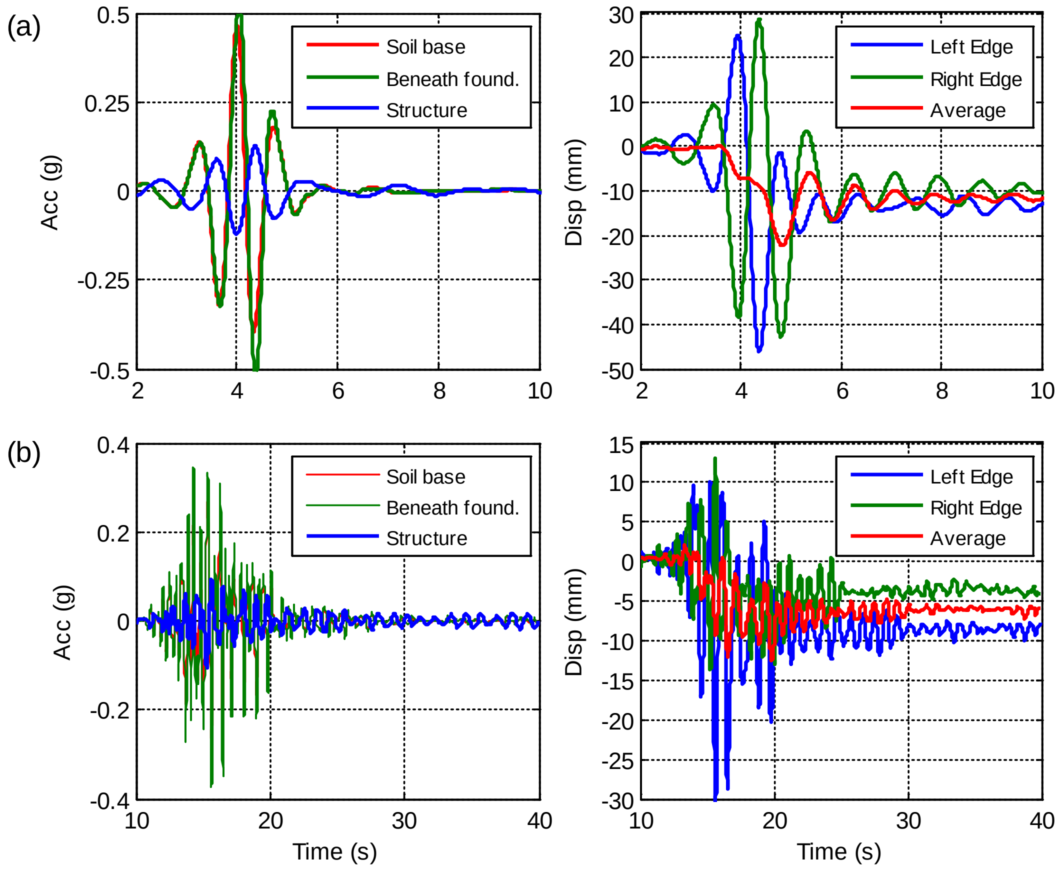

Figure 4. Acceleration time history comparison of soil and structure response (left) and foundation vertical displacement time history (right) for the 7 storey model subjected to (a) Ricker wavelet with peak amplitude of 0.49g and (b) CBGS Christchurch Earthquake record.

Equivalent period and damping

To quantify the total energy dissipation in the experiments, the equivalent SDOF period and damping ratio were calculated 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 provides insights into the comparative behaviour of the models.

Equivalent SDOF period and damping results for a range of Ricker wavelet peak input motions are presented in Figure 5 for the three building models. The results for the Christchurch record are included in red and were placed at the peak input amplitude recorded in the centrifuge experiments. In all cases the period of the structure-foundation systems was greater than that of the fixed-base model indicating period lengthening. This means that the response of the structure has moved away from the typically damaging content of an earthquake found at low period. The extent of period lengthening was greater for the 7 storey model than for the 5 storey model, which had a greater extent of lengthening than the 3 storey model. 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 equivalent period and damping ratio increased indicating that a greater extent of SFSI resulted in higher damping, even when the absolute extent of uplift and permanent soil deformation appeared to be small relative to the size of the foundation.

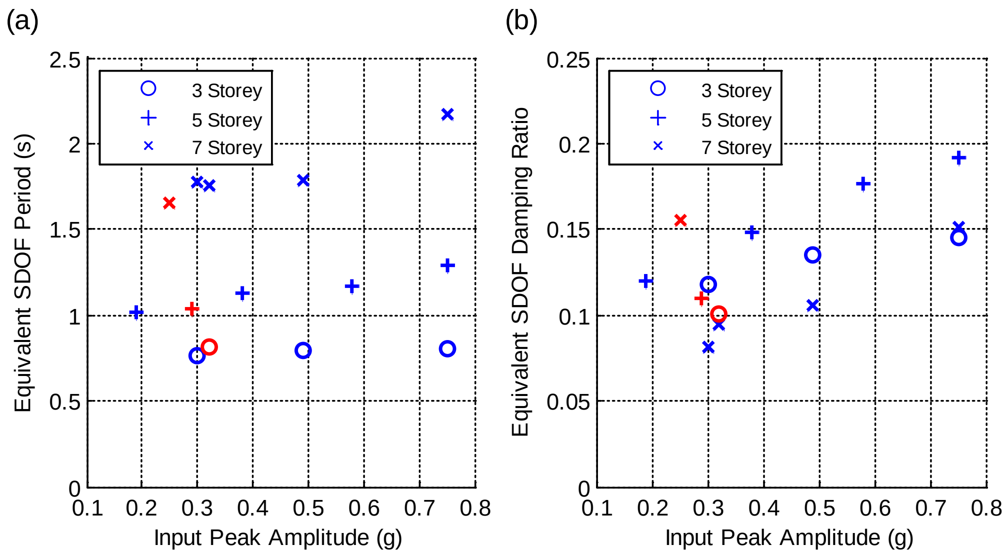

Figure 5: Equivalent SDOF (a) period and (b) damping ratio for selected Ricker wavelet peak amplitudes (blue) and the CBGS Christchurch Earthquake record (red).

The equivalent SDOF period and damping ratio results combined with the structure acceleration results presented in the previous section appear to show that nonlinear SFSI has provided an energy dissipation mechanism for the building models on shallow foundations.

The equivalent period of response of the structure has been lengthened, equivalent damping ratios for the systems are reasonably high, and the forces transmitted to the structure have generally been reduced. When uplift causes the foundation to lose and regain contact with the soil as it rocks and when nonlinear soil deformation occurs energy was able to be dissipated.

Conclusions

Centrifuge modelling of mid-rise buildings on shallow raft foundations resting on dense cohesionless soil has highlighted the energy dissipation potential of nonlinear SFSI in this scenario. Rocking and uplift of the foundation combined with permanent soil deformation had a significant influence on structural response in all of the centrifuge experiments and uplift may have been more significant for the taller structures. The extent of uplift and foundation settlement was not substantial compared to the overall size of the foundation, which is important because there is potential for significant energy dissipation during large earthquake loading without detrimental effects on building serviceability. Nonlinear SFSI resulted in increased equivalent SDOF period and a large amount of damping for all of the buildings subjected to a range of Ricker wavelets and Christchurch Earthquake records. The results showed that a rocking shallow raft foundation on a competent soil, having a large reserve of bearing capacity during uplift, could be beneficial for structural performance during earthquake loading.

Acknowledgments

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References

Bertalot, D. (2013). *Seismic behaviour of shallow foundations on layered liquefiable soils.* PhD Thesis, University of Dundee.

Cubrinovski, M., Bradley, B., Wotherspoon, L. M., Green, R., Bray, J., Wood, C., Pender, M., Allen, J., Bradshaw, A., Rix, G., Taylor, M., Robinson, K., Henderson, D., Giorgini, S., Ma, K., Winkley, A., Zupan, J., O'Rourke, T., DePascale, G., & Wells, D. (2011). Geotechnical aspects of the 22 February 2011 Christchurch Earthquake. *New Zealand Society for Earthquake Engineering Bulletin,* 44(4), 205-226.

Harden, C. W., Hutchinson, T. C., Martin, G. R., & Kutter, B. L. (2005). *Numerical modeling of the nonlinear cyclic response of shallow foundations*: Pacific Earthquake Engineering Research Center (PEER).

Housner, G. W. (1963). The behavior of inverted pendulum structures during earthquakes. *Bulletin of the Seismological Society of America,* 53(2), 403-417.

Kelly, T. E. (2009). Tentative seismic design guidelines for rocking structures. *Bulletin of the New Zealand Society for Earthquake Engineering,* 42(4), 239-274.

Loli, M., Anastasopoulos, I., Knappett, J. A., & Brown, M. J. (2014). *Use of Ricker wavelet ground motions as an alternative to push-over testing*. Paper presented at the 8th International Conference on Physical Modelling in Geotechnics.

Pecker, A., & Chatzigogos, C. T. (2010). Non Linear Soil Structure Interaction: Impact on the Seismic Response of Structures. In M. Garevski & A. Ansal (Eds.), *Earthquake Engineering in Europe* (Vol. 17, pp. 79-103): Springer Netherlands.

Priestley, M. J. N., Calvi, G. M., & Kowalsky, M. J. (2007). *Displacement-based seismic design of structures*. Pavia: IUSS Press.

Priestley, M. J. N., Evison, R. J., & Carr, A. J. (1978). Seismic response of structures free to rock on their foundations. *Bulletin of the New Zealand National Society for Earthquake Engineering,* 11(3), 141-150.

Taylor, R. N. (1995). Centrifuges in modelling: priciples and scale effects. In R. N. Taylor (Ed.), *Geotechnical Centrifuge Technology*. London: Blackie Academic and Professional.

Thomson, W. T. (1993). *Theory of vibration with applications* (4th ed.). London: Chapman & Hall.