Characterising the Snap-back Response of Piles in Stiff Clay

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ABSTRACT: This paper details the results of a series of snap-back field tests of tubular steel piles embedded in stiff clay. Pile head mass and snap-back magnitude were varied throughout testing, with non-linear geometrical effects and damping reported from testing. Free-vibration hammer tests were used to evaluate the change in the natural frequency of the pile-soil system throughout the test series. The dynamic response of the system was modelled using Ruaumoko 3D with discrete spring, dashpot and contact elements to represent the pile-soil interaction. The significant energy dissipation due to the impact between the pile and surrounding soil observed during testing was accounted for in the models using contact members, although this resulted in divergence with test data during the subsequent cycles of the response. Favourable comparisons were obtained with the full-scale response in these subsequent cycles using a model without contact elements.

1 INTRODUCTION

The dynamic response of a pile subject to lateral loading is a complex phenomenon, resulting in interactions between the pile and surrounding soil. This type of loading represents real life scenarios of earthquake, wind, wave and machine vibration forces on a foundation. Extensive research (Matlock, 1970; Reese and Welch, 1975; Matlock et al., 1978; Gazetas and Dobry, 1984; Wotherspoon, 2009; M.Sa'don, 2012) has been carried out in this area, in particular, small scale model testing and the development of analytical and numerical models to simulate pile-soil interaction on the response of a laterally loaded pile. Previous dynamic full-scale testing has been carried out to get an understanding of the response of single piles under different levels of excitation and non-linear soil behaviour, observe gapping effects between the pile shaft and surrounding soil and determine the level of damping and stiffness for the pile-soil system. Most full-scale testing has used forced vibrations to investigate the dynamic response from the pile. However, recently snap-back testing has been shown to be a more economical alternative, whilst still providing similar results to forced vibration tests (M.Sa'don, 2012). From the available data it is still unclear what level of damping and stiffness should be used when considering non-linear soil behaviour.

Details of the set-up and results of snap-back field testing of tubular steel piles embedded in stiff clay are first presented. The test response is then numerically modelled in Ruaumoko using discrete spring, dashpot and contact elements to represent the pile-soil interaction and the response verified with field test data.

2 TEST SET-UP AND METHODOLOGY

2.1 Test site and pile details

Testing was carried out on two 273 mm diameter steel tube piles from an existing 2x2 pile group (centre spacing of 11 pile diameters) driven closed ended to an embedment depth of approximately 24 pile diameters. The site in Albany, Auckland had a stiff residual clay soil profile, with extensive site characterisation using seismic CPT, spectral analysis of surface waves (SASW) and lab testing indicating a variation in small strain shear modulus from 36 MPa at ground surface to 86 MPa at the pile embedment depth. Two of the piles in this group were used as test specimens for this research, with the remaining piles used as reaction piles. Lead masses were added to a steel bracket attached to the pile head to vary the inertial forces during the snap-back response, with four different levels of pile head mass tested during the study. A double acting jack and hydraulic ram were used to provide the static pull-back force, which was measured using a load cell. Linear Variable Displacement Transducers (LVDTs) and strain gauges were used to measure pile head displacement and force respectively.

2.2 Snap-back test procedure

Snap-back tests were carried out by jacking the test pile towards a reaction pile to a target force, and then releasing the test pile to produce the snap-back free-vibration response. The pull-back phase of the snap-back tests defines the static pile lateral response, the results of which are not presented in this paper. The key components of snap-back test set-up are provided in Figure 1, with the dynamic response initiated using a quick-release coupling. Free vibration hammer tests were carried out before and after each snap back, where a low input force from a blow of a cushioned sledgehammer was applied to the top of the pile to excite the elastic natural period of the pile-soil system.

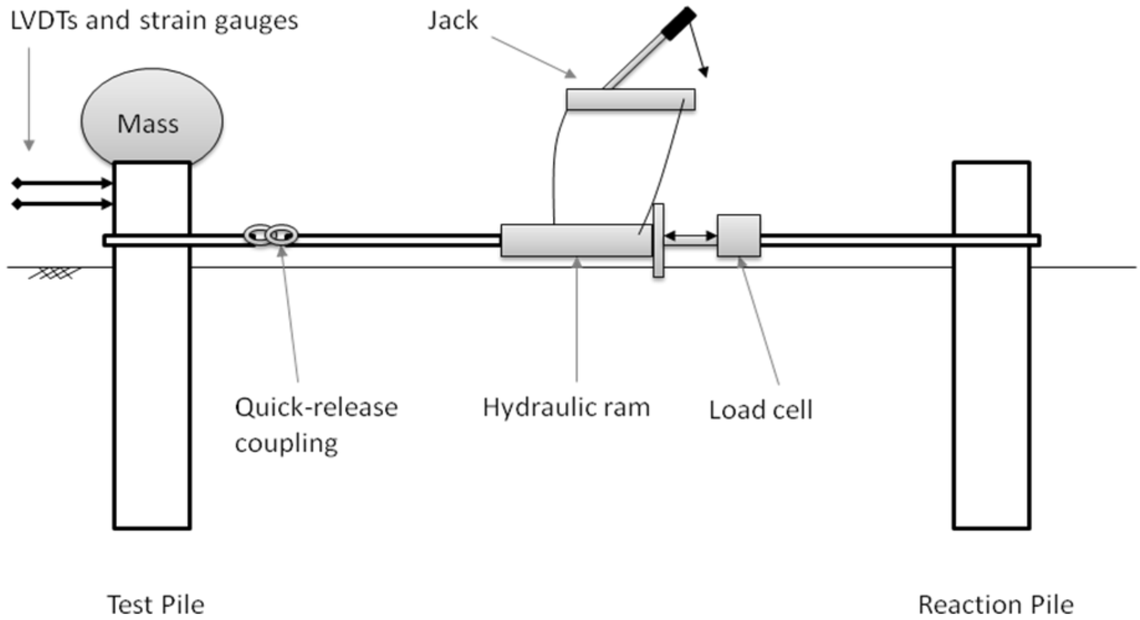

Figure 1. Schematic of snap-back test procedure

2.3 Snap-back test program

The order and magnitude of the pull-back force for the snap-back tests is summarised in Table 1. The variation in pile head mass during the test series is also detailed. Hammer tests were carried out before and after each snap-back test (details provided in Table 1), with gap depth and ground level gap width measurements carried out to track any geometric non-linearity that developed during testing. Hammer tests 12 and 13 are identical, and are duplicated for the purposes of data presentation.

Table 1. Snap-back test program including hammer test details

Snap-back test details Pile 1	Hammer test number before/after snap-back
10 kN 324 kg pile head snap-back 1	1-2
10 kN 609 kg snap-back 1	3-4
10 kN 1275 kg snap-back 1	5-6
120 kN 324 kg snap-back 1	7-8
120 kN 609 kg snap-back 1	9-10
120 kN 1275 kg snap-back 1	11-12
120 kN 1275 kg snap-back 2	13-14
120 kN 609 kg snap-back 2	15-16
120 kN 324 kg snap-back 2	17-18

3 DYNAMIC PILE RESPONSE FROM FULL-SCALE FIELD TESTS

3.1 Change in natural frequency

The variation in the natural frequency of the test pile is presented in Figure 2, with the three different levels of pile head mass used during testing highlighted. The natural frequency was determined using the Fast Fourier Transform (FFT) of the hammer time domain LVDT response. Frequency is plotted against the hammer test number, with hammer tests carried out before and after each of the snap-back tests listed in Table 1. There is a negligible change in natural frequency before and after each of the 10 kN snap-back tests, supporting the visual observations indicating no gap development between the pile and surrounding soil during these tests. The variation in the natural frequency between these first three snapback tests (hammer tests 1-6) results from the addition of mass to the pile head. The soil gapping that developed during the 120 kN tests is evident through a reduction in natural frequency for each pile head mass, where a reduction has occurred between bars of the same colour, or mass. A maximum gap depth of approximately four pile diameters was measured during testing.

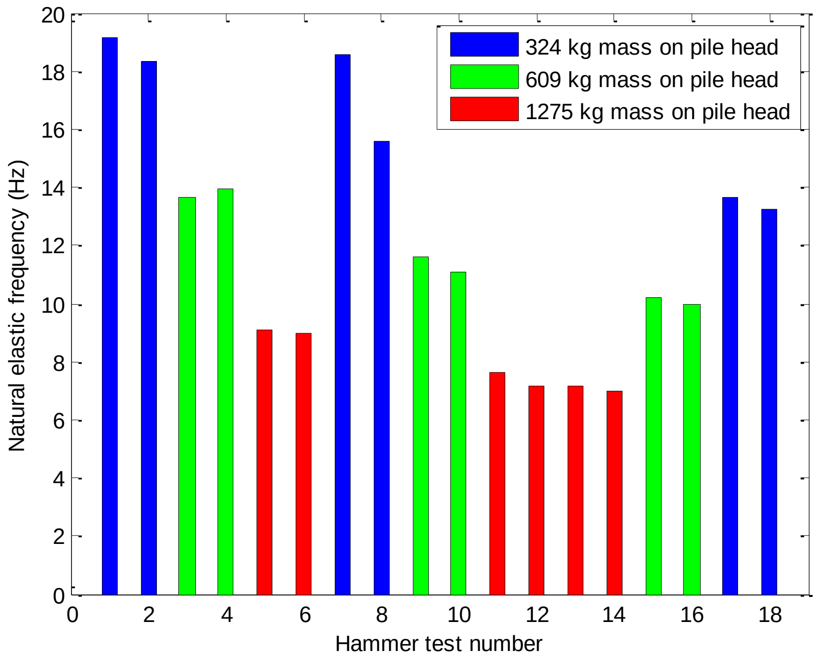

Figure 2. Natural elastic frequencies of the test pile determined from FFT hammer response

3.2 **Damping**

3.2.1 *Damping ratio collection techniques*

Two techniques are used to calculate the level of damping associated with the test response. Each involves idealising the different forms of energy dissipation into the damping ratio; for a Single-Degree-Of-Freedom (SDOF) structure:

$$\zeta = \frac{c}{2\sqrt{m * K}} \tag{1}$$

where ζ = damping ratio (usually expressed as a percentage); c =damping coefficient; m = mass and K = stiffness. The logarithmic decrement method (Thompson, 1988) utilises the relative magnitude of two adjacent peaks of the free vibration response to determine a value of damping for the pile-soil system response:

$$\zeta = \frac{\ln\left(\frac{x_1}{x_2}\right)}{2\pi} \tag{2}$$

where x_1 and x_2 = displacement amplitudes of successive peaks. This damping is referred to as *logarithmic damping*.

The second damping collection technique is defined by exponential envelopes corresponding to the displacement solution for an equivalent viscously damped SDOF system (Chopra, 2006):

$$u(t) = e^{-\zeta.\omega_N.t}\left[u(0)\cos(\omega_D.t) + \frac{u'(0)+\zeta.\omega_N.u(0)}{\omega_D}\sin(\omega_D.t)\right] \tag{3}$$

where *u(t)* = displacement at time *t*; *u'(0)* = initial velocity; ω_N = natural frequency of the system in rad/s, and ω_D = damped frequency. The exponential term on the right hand side of the equation defines what is referred to herein as *system damping*.

Significant energy dissipation effects due to impact between the pile and surrounding soil led to two distinctly different portions of the response. Impact energy dissipation occurs during the early cycles of the test, resulting in a heavily damped response ('impact response'). In the absence of this impact, a response with a lower level of damping is present during later cycles ('cyclic response'). Thus two separate pairs of exponential envelopes are fitted to each portion of the response to provide a measure of the system damping during the 'impact' and 'cyclic' response of the system. The 10 kN snap-back tests had negligible impact effects and hence the impact response was not defined for these tests.

3.2.2 *Damping ratio data*

Using the approaches explained above, one value of system damping is obtained for each test, while multiple values of the logarithmic damping are obtained as a value is calculated for each cycle of oscillation in the test. Damping ratio data from all the low input force hammer tests is presented in Figure 3. Damping ratios are generally in the order of 5 – 10%. Exponential system damping appears to account for the varied nature of the response, which is evident through the range of logarithmic damping values computed. Damping ratio trends are assessed using Equation 1. Therefore larger damping is expected for lower mass levels and for later tests where a reduction in stiffness has occurred due to pile-soil gap depth growth. There is a general agreement with this trend in Figure 3, with some inconsistencies evident for lower mass levels, particularly the 324 kg pile head mass. There is also varied damping produced between consecutive hammer tests for the 609 kg pile head mass. At lower pile head mass levels the greater contribution of distributed pile mass to the overall pile response may move the response away from the SDOF assumption.

Impact and cyclic response exponential system damping for all snap-back tests is shown in Figure 4. Since the impact response system damping is based on the logarithmic decrement method, results for 10 kN tests are not presented. Cyclic response system damping is more varied than those computed for hammer tests, as it is difficult to identify trends using Equation 1 due to the higher forces involved in snap-back tests. Impact response system damping is shown to increase as pile head mass increases, a consequence of larger masses increasing the impact energy dissipation effects as the pile impacts with the surrounding soil following the initial pull-back peak release. The maximum impact response system damping computed is 50% from the 1275 kg pile head.

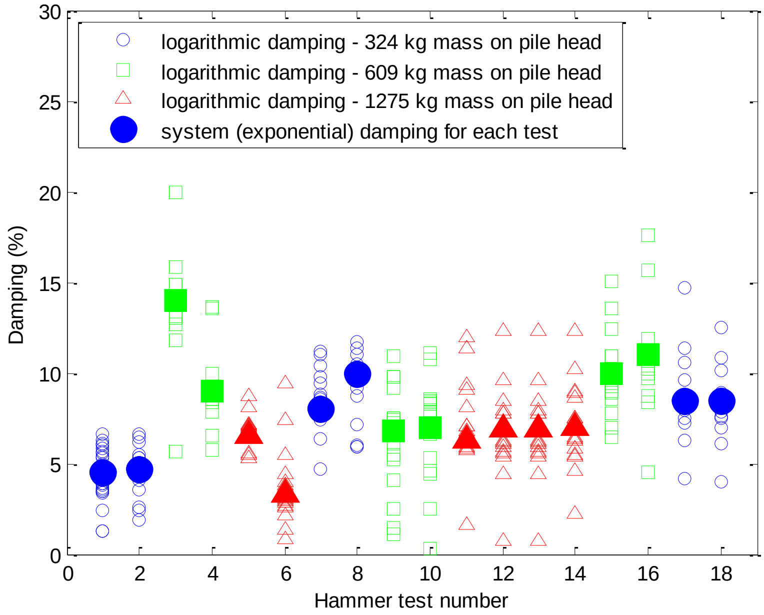

Figure 3. Damping ratios computed from hammer tests using the logarithmic decrement method and exponential system damping envelopes.

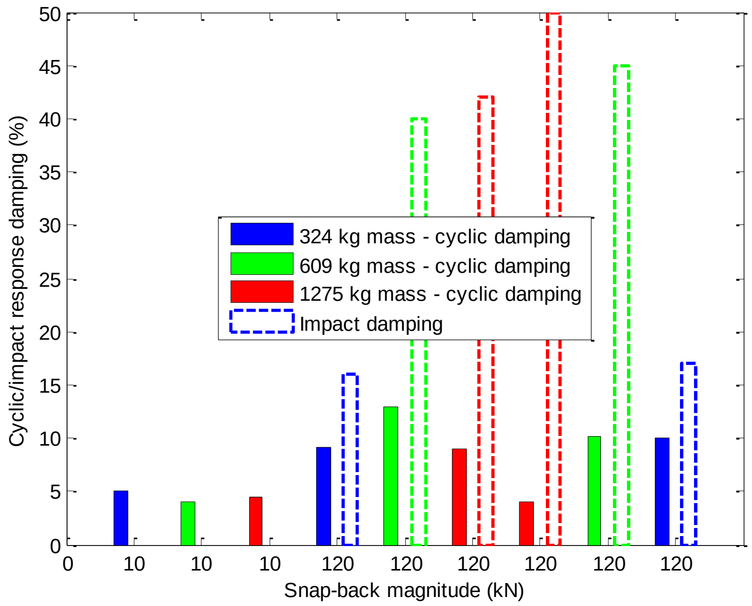

Figure 4. Exponential system damping for all snap-back tests, illustrating snap-back order.

4 NUMERICAL MODELLING OF LATERAL PILE RESPONSE

The dynamic test response is compared with those predicted by the numerical Winkler spring model (Vesic, 1961; Matlock, 1970; Reese and Welch, 1975; Matlock et al., 1978; Gazetas and Dobry, 1984; Wotherspoon, 2009) developed in Ruaumoko 3D (Carr, 2004). A generic overview of the Winkler spring model developed for this research is provided in Figure 5. Discrete horizontal spring and dashpot elements were used to represent soil pile-soil interaction, connected to pile nodes at a spacing of 0.05m on both sides of the pile, with pile mass lumped at these nodes. At each depth these elements were arranged with a non-linear spring attached to the pile node, in series with an elastic spring and dashpot in parallel. The key components of the model are as follows:

- Spring members were used to represent soil stiffness.
- Bi-linear hysteresis rule with slackness utilised to model the inability of soil to support tensile stresses and the development of residual gapping around the pile. A bi-linear response was used to account for compressive soil yield and soil hysteretic damping.
- Soil radiation damping was represented using dashpot members.
- Contact members were introduced into the model to account for effects of pile-soil impact energy dissipation during the initial stages of the snap-back.

The model was able to capture the pull-back static response, the natural period and the hammer test dynamic response. The results of the snap-back test modelling are presented in the following section.

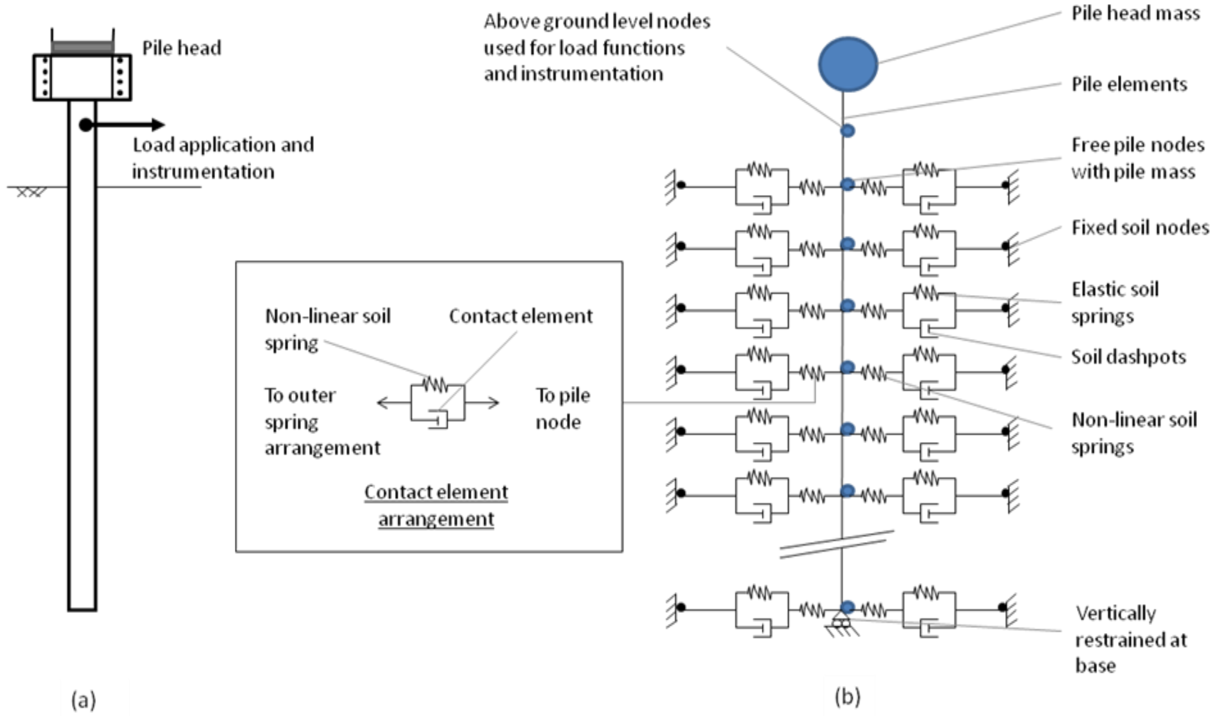

Figure 5. (a) Field testing set-up; (b) Numerical Winkler Spring model representation.

4.1 Dynamic response comparison with field data

The series spring model developed to predict the dynamic response is only capable of capturing the test response at later cycles where the inelasticity evident in the response is not dominated by impact effects. Contact members were incorporated to account for impact energy dissipation developed in the initial stages of the snap-back. Figure 6 compares the model and test results for the 120 and 7.5 kN snap-back test on Pile 2. The series spring model (Fig. 6 (c)) is released from the third peak of the 7.5 kN snap-back response where impact effects are not significant and produces a good comparison with the snap-back test beyond this point. Although damping is well represented there is a slight stiffness shift which is attributed to the reduced pull-back peak of the model compared with the original pull-back peak during testing. This results in a stiffer model response due to a reduction in gap growth.

The models with contact elements (Figs 6 (a), (b)) achieve the necessary energy dissipation developed during testing over the first few peaks, however it diverges with the test data during later cycles where there are no impact effects. The arrangement of the contact member means that a high level of energy dissipation is provided throughout the response and cannot be removed from the response after several cycles, where pile-soil impact effects become negligible during testing. The 120 kN snap-back contact model (Fig. 6 (a)) contains a greater level of forces than the corresponding 7.5 kN snap-back (Fig. 6 (b)), so divergence with test data is more prominent. The only difference between the contact model and series spring model is the addition of the contact elements. Further research with some modification of the contact element model is required to account for the overall test response.

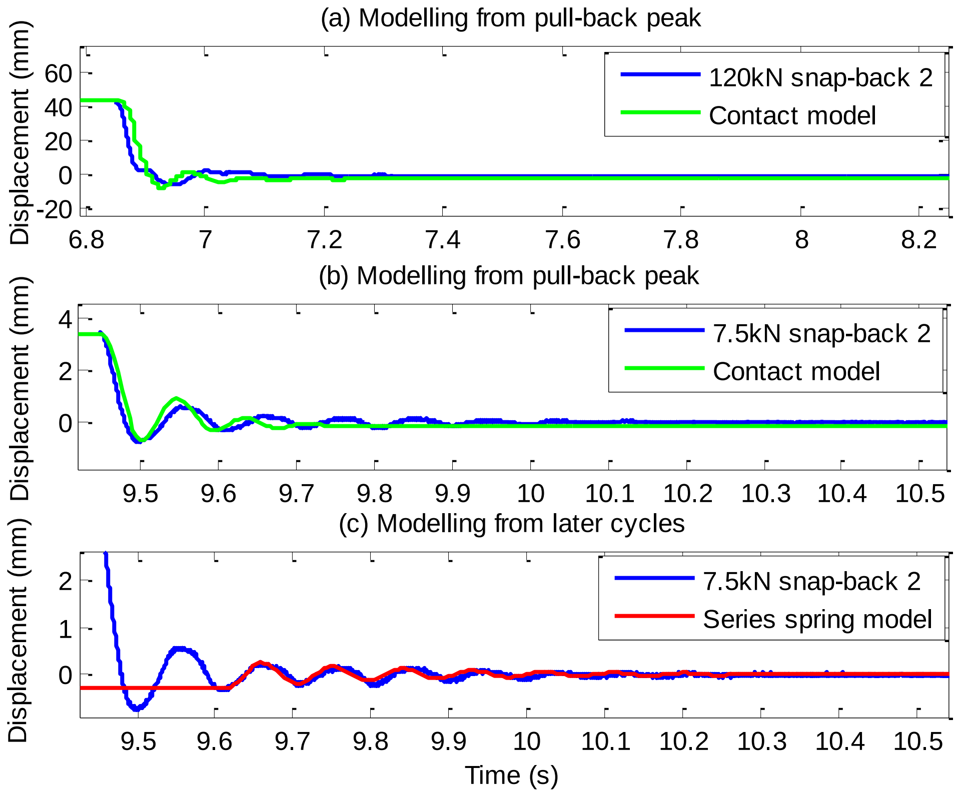

Figure 6. Ruaumoko contact and series spring model comparison on Pile 2 with (a) 120 kN snap-back from start of test; (b) 7.5 kN snap-back from start of test; (c) 7.5 kN snap-back from third peak.

5 CONCLUSIONS

A series of full-scale snap-back field tests on a 273 mm diameter tubular steel pile was performed at a stiff residual clay site in Albany with varying pile head masses. This paper presented the computation of changes in the natural frequency and damping throughout the test series. The test response has been captured with reasonable accuracy using a discrete spring model in Ruaumoko. The following key points are summarised from this paper:

- A reduction in pile natural frequency determined from free-vibration hammer tests has been observed during testing due to increased gap growth around the pile. A maximum gap depth of four pile diameters was measured during testing.
- Fitting exponential damping envelopes to the response based on a SDOF approach has yielded the most consistent damping ratio results, giving a system damping for the entire response.

- Damping determined from hammer tests is typically in the order of 5 – 10%, and in agreement with the mathematical definition of the damping ratio.
- Impact energy dissipation developed near the pull-back peak for snap-back tests has resulted in two distinctly different portions of the response at the start and for the later cycles. Separate envelopes were fitted to give an ‘‘impact’ and ‘‘cyclic’ response system damping for the respective portions. Unsurprisingly, impact response system damping increased as the pile head mass increased. A maximum impact response system damping of 50% was computed for the largest mass level.
- Modal, pushover and dynamic responses were represented reasonably well in Ruaumoko using a Winkler spring model (Millin, 2012). Contact members were introduced into the dynamic model to account for contact damping developed near the pull-back peak of snap-back tests. A limitation identified in the modelling approach is that the contact model is unable to account for the later cycles of the test response where contact damping is no longer present during field testing.

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