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Snap-back testing for estimation of nonlinear behaviour of shallow and pile foundations

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ABSTRACT: We are working on the development of methods for analysing the earthquake response of foundations that make use of Soil-Foundation-Structure-Interaction (SFSI) as a means of incorporating nonlinear soil deformation effects and nonlinear geometrical effects into the earthquake resistant design of foundations. There are three challenges in this work. First, to incorporate adequately the nonlinear response of the soil during the earthquake. Second, to account for geometrical nonlinearity during the earthquake - that is loss of contact between various parts of the foundation and the underlying and/or adjacent soil. Third, to obtain appropriate values for the soil parameters which describe the nonlinear response of the foundations. The main thrust of this paper is to show how snap-back testing is a most effective means of evaluating nonlinear soil behaviour. We consider that snap-back testing is more convenient than using a shaking machine which applies sinusoidal excitation. The results from rocking of a shallow foundation and cyclic lateral loading of a single pile enable damping and stiffness to be estimated at increasing levels of lateral loading.

1 INTRODUCTION

We have performed field experiments at a site in Auckland where both shallow and deep foundations have been subject to cyclic loading, Algie et al (2010), M.Sa'Don et al (2010). The first batch of tests used an eccentric mass shaking machine to excite the foundations with sinusoidal oscillations at a range of frequencies. Although successful we recognise limitations to this approach for the following reasons. First, a given level of excitation force cannot be obtained until the shaker frequency has been increased from zero to the frequency required to generate the force. Second, the response of the system is measured under steady state excitation at a fixed frequency. In this way what is obtained from the use of a shaking machine is not representative of what happens during earthquake excitation.

An alternative, described here, is the use of snap-back testing. This test is simpler than using an eccentric mass shaking machine. It gives the response of the system to one impulsive excitation instead of continuous excitation; it is more representative of what occurs during an earthquake. An added bonus is the static load-deflection curve obtained during the pull-back phase of the test. The initial pull-back can generate a force of comparable magnitude to the maximum force that can be produced by the shaking machine we used.

Below we present results obtained for the nonlinear stiffness and damping of shallow and deep foundations from snap-back testing. Tests were done at a site with Auckland residual clay. The shallow and deep foundations were within about 10 m of each other. A series of snaps from different initial loads shows how the nonlinear behaviour of the foundation develops as the applied load increases. It is found that the damping for the snap-back response of the shallow foundations was generally larger than that of the pile foundations.

Figure 1: Set-up for shallow foundation testing. Figure 2: Set-up for snap-back testing of pile foundations.

2 SITE DESCRIPTION AND LAYOUT OF TESTS PERFORMED

The site used for the tests, in Albany in the northern part of Auckland, consists of a profile of stiff cohesive soil formed by in situ weathering from tertiary age sandstone and siltstone (it is thus a residual soil profile). There were eight shallow foundations, which support the ends of the steel frame shown in Figure 1; these are reinforced concrete 2.0 m in length and 0.4 m square. The steel frame structure is 2 m wide, 3.5 m high and 6 m long. Steel kentledge is strapped to the top of the frame to provide the required vertical foundation load. There were four driven closed-end steel tube piles 273 mm in outside diameter with 9.3 mm walls. The soil profile was investigated with 21 CPT tests between the surface and depth of 5 or 8 m; in some of these the shear wave velocity of the soil was measured. The s_u values obtained from the CPT q_c values are reasonably consistent with depth at about 100 kPa. Hand shear vane testing was also done. The shear wave velocity measurements from the seismic cone penetration tests were supplemented with WAK tests (Briaud and Lepart 1990) and SASW tests (Stokoe et al 1994, Stokoe et al 2004). All of these indicated a reasonably consistent shear wave velocity for the materials equivalent to a small strain shear modulus for the soil of about 40 MPa.

3 SNAP-BACK TESTING PROCEDURE AND EQUIPMENT

The equipment required for snap-back testing is simple. Instrumentation and data logging equipment are, of course, the same as needed for the testing with the eccentric mass shaking machine. To apply the snap-back force a hydraulic jack, load cell, and quick release mechanism are needed. In addition a reaction force has to be mobilized against the cable applying the snap-back force; in our case a crane. The quick release device we used had a working force capacity up to 100 kN. The set-up for the snap-back tests is shown in Figure 1. On the right is the frame supported on shallow foundations. The kentledge on the top of the frame is clearly visible as is the chain containing the hydraulic jack anchored at to the crane. In Figure 2 the set-up for the pile testing is shown. The chain is again anchored to the crane. The eccentric mass shaking machine is attached to the top of the pile providing a mass of 600 kg. For both tests the forces and displacements during the pull-back are monitored. During the cyclic response the displacements and accelerations are measured as well as strain gauge readings on the steel frame and the pile shaft.

4 RESULTS FOR SHALLOW FOUNDATIONS

In Figure 3 are shown the static moment-rotation curves obtained during the application of the pull-back forces for Test 7. It is apparent that there is considerable nonlinearity in the moment-rotation curves and also that the stiffness is degraded from one test to the next during the early pull-backs. For those pull-backs after number 6, which applied the largest moment to the system, there is less degradation. Subsequent 3D nonlinear finite element modelling with Abaqus (Simulia 2010) confirmed that there are two sources of this nonlinearity: geometric effects due to uplift of the foundation and a contribution from nonlinear soil deformation.

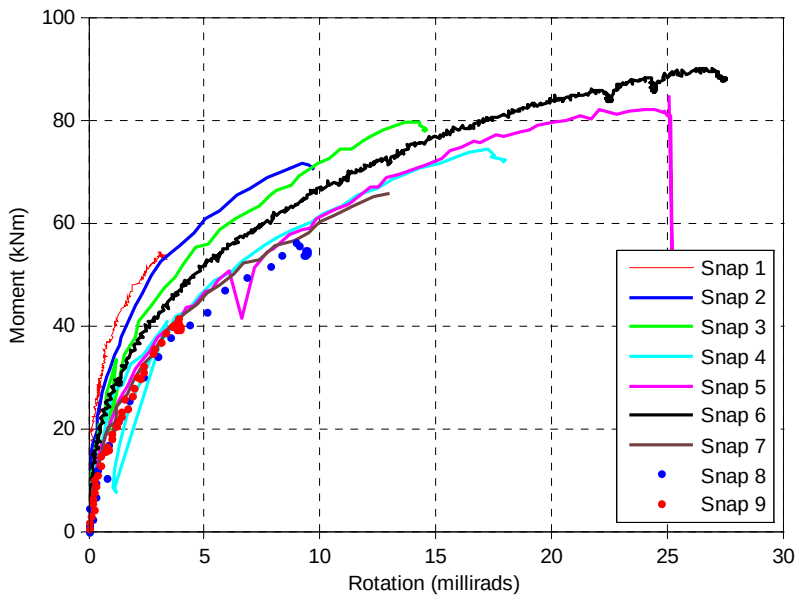

Figure 3: Shallow foundation moment-rotation curves obtained during pull-back.

Figure 4 plots the response of snap-backs 1, 6 and 9 of Test 7. Note that the maximum rotation for snap-back 6 is about an order of magnitude greater than those for the other two. The response for snap-back 6, the middle plot in Figure 4, shows a very small amount of permanent rotation when the dynamic response comes to an end. The damping values, determined by logarithmic decrement during the first half cycles, are 42% for snap-back 1, 32% for snap-back 6 and 34% for snap-back 9. These damping values are large in relation to values usually applied in structural and foundation design. The decrease in damping value from snap-back 1 through to 9 is a consequence of the accumulation of permanent deformation in the soil beneath the foundation, so the effective length of the foundation was decreasing gradually.

Figure 5 presents moment-rotation information calculated from data recorded during two of the snap-back tests. Also included in the diagrams are the data from the initial pull-back parts of the tests. The moments were calculated from data obtained from strain gauges attached to the legs of the steel frame structure. As explained above, the responses of the shallow foundations are consequences of two sources of nonlinearity. If the nonlinearity is purely a consequence of uplift the initial branch of the snap-back response will be close to the loading curve. If, on the other hand, soil nonlinearity is involved the initial unloading branch will not follow the loading curve; clearly the case in Figure 5.

Figure 6 has all the damping values obtained from snap-back testing of the steel frame on the shallow foundations. The most important feature of this diagram is the large values obtained for the damping parameter. The next most significant feature of the diagram is the amount of scatter present. We think a factor contributing to this will be the accumulation of permanent deformation beneath the shallow foundations as the number of snap-back tests on a particular foundation increases. Another reason for the scatter is that the damping values are different for each side of the foundation – the side in the direction of pull-back consistently indicated higher damping; this is clear if the damping values from the two sides of the foundation are plotted separately.

4 RESULTS FOR DEEP FOUNDATIONS

Figure 7 gives the time response after the snap-back release for pile 4 at three different snap-back loads. The damping values determined from the first cycle of free vibration are 4 % from 15 kN, 11 % from 36 kN, and 11 % from 65 kN. After the 15 kN and 36 kN snap-backs the displacement returns to zero. After the 65 kN snap-back there is permanent displacement, which will be a consequence of nonlinear soil deformation accompanied by gapping.

Figure 8 shows the load-deformation loops measured during two of the snap-back tests; one for snap-back force of 60 kN and the other for 15 kN. Using the logarithmic decrement method, the damping is

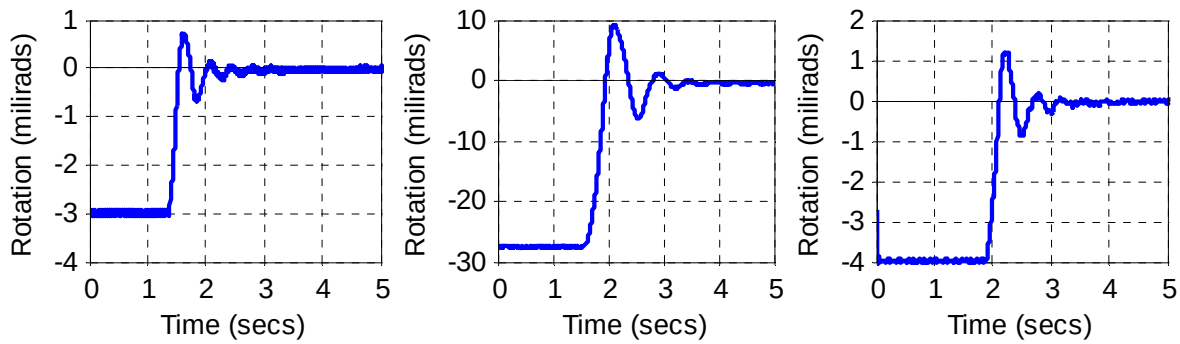

Figure 4: Time histories for three of the responses to the shallow foundation snap-back releases.

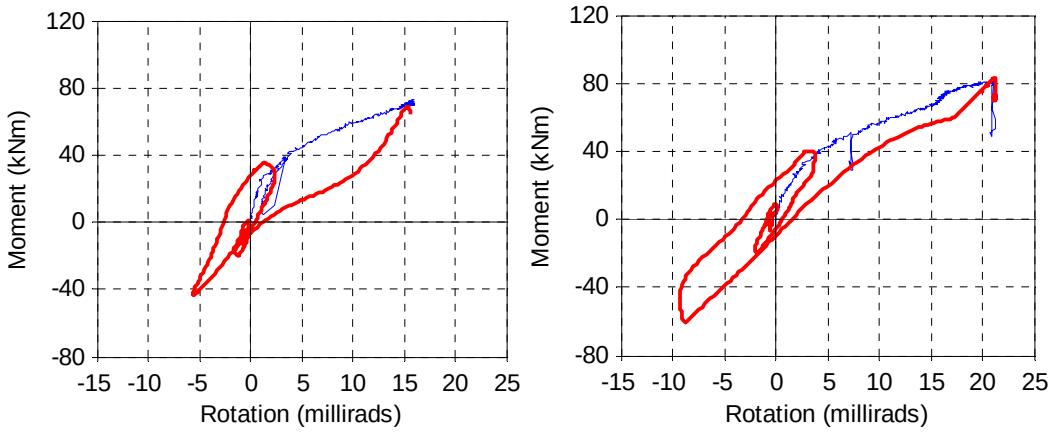

Figure 5: Shallow foundation pull-back and snap-back moment-rotation responses.

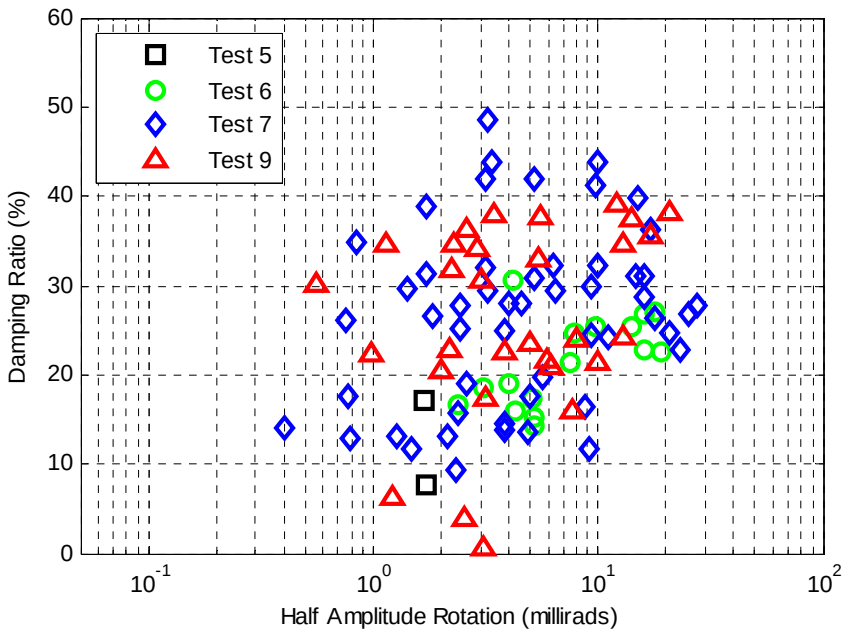

Figure 6: Damping values obtained from the shallow foundation snap-back response.

evaluated at 11% for the 60 kN snap-back force (the maximum value applied) and 4% for the 15 kN snap-back. Marked in this plot is the elastic lateral stiffness of the pile head obtained using the small strain shear modulus of the soil. Clearly this stiffness applies only at very small pull-back loads; at larger loads a reduced "operational" modulus is required. The shape of the load-displacement loops after the 60 kN pull-back force indicates much more damping than those from the 15 kN pull-back.

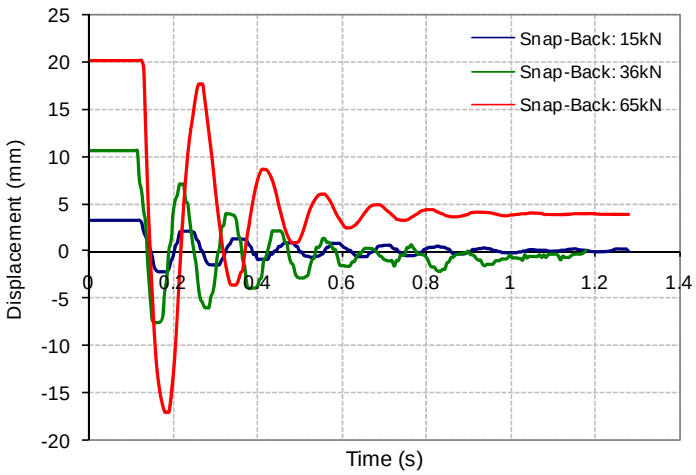

Figure 7: Time histories for three of the responses to the snap-back releases on pile 4

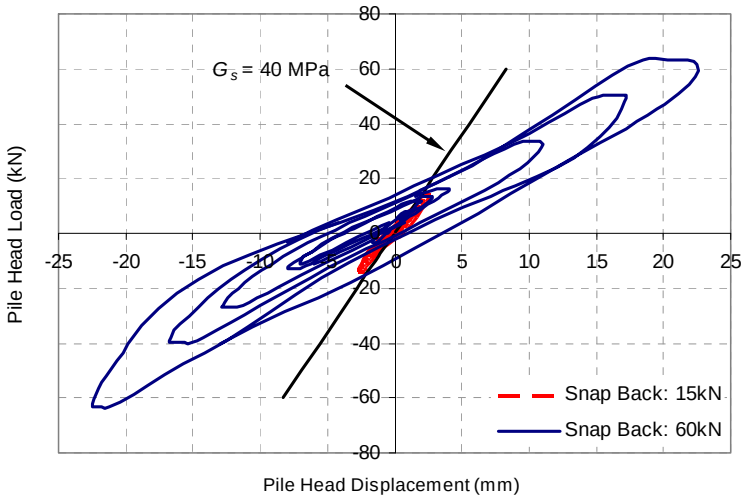

Figure 8: Moment-rotation loops for two of the snap-backs on pile 4

5 APPLICATION OF DATA OBTAINED DURING THE PULL-BACK PHASE

Data obtained during the pull-back phase of the test is just as useful and interesting as that from the snap-back. Figure 3 indicates very clearly the nonlinearity of the shallow foundation moment rotation curves. In Figure 9 further interpretation, using normalised values, of the data in Figure 3 is presented. (The rotation is normalised with respect to the static tilt angle at which the structure in shown in Figure 1 would topple.) First, an hyperbola is fitted around the upper bound of the recorded data – upper bound as the intention was to model the response on initial loading and not the effect of the successive snapbacks. It is clear from Figure 9a that the fitted curve matches the data well and the extrapolation beyond the recorded data is controlled by the moment capacity of the foundation. In Figure 9b the data is plotted as the secant rotational stiffness of the foundation, which decreases rapidly as the rotation increased. A more useful way of looking at this is seen in Figure 9c where a logarithmic scale is used for rotation. Data such as that in Figure 9c can be employed in the design of shallow foundations following the Direct Displacement Based Design method of Priestley et al (2007).

The best-fit curve in Figure 9a can be used to predict foundation moment-rotation curves for other values of the vertical load on the foundation (the vertical load controls the moment capacity of the foundation and hence the asymptote at the end of the curve). The slope of the curve at small rotations is controlled by the elastic rotational stiffness of the foundation which is calculated using standard formulae, Gazetas (1991), but uses an operational modulus for the soil less than the small strain modulus obtained from site investigation measurements. The conclusion from this is that the curve in Figure 9c depends on the static factor of safety of the foundation.

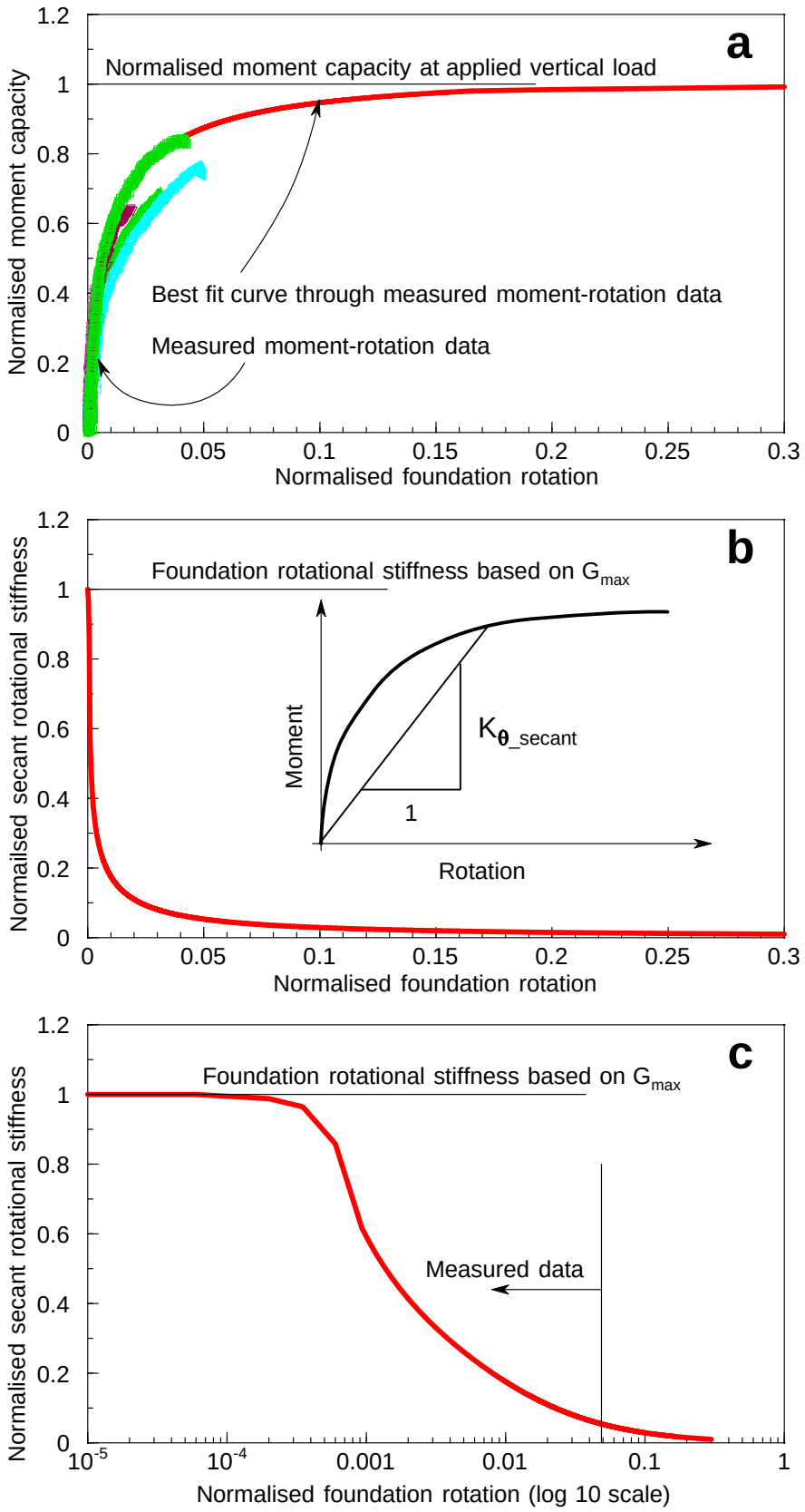

Figure 9: Curve-fitted moment-rotation relations matched to the recorded data for the first three pull-backs of Test 7 and Test 9. (a) moment-rotation data, (b) and (c) secant modulus against foundation rotation.

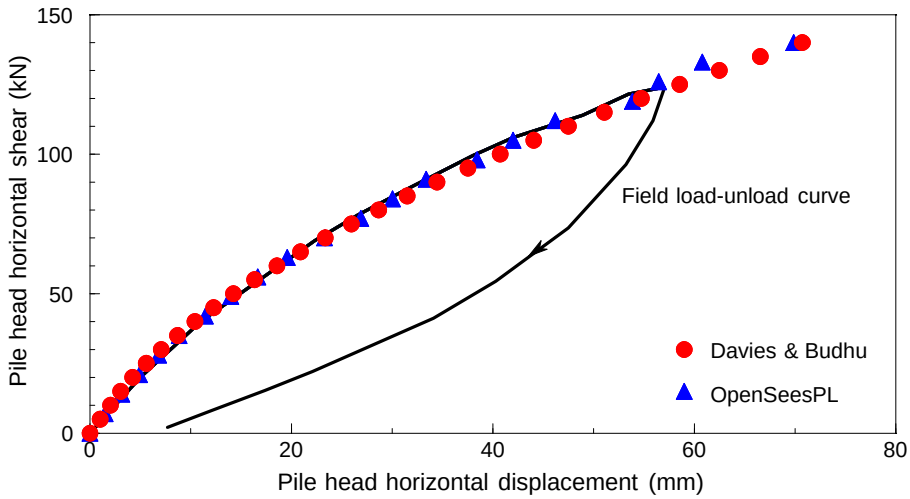

Figure 10: Comparison between the OpenSeesPL and Davies and Budhu predictions of the loading part of static load-deformation behaviour of the pile.

Finally, in Figure 10 pull-back data for the piles is compared with calculations using the OpenSeesPL 3D nonlinear finite element software, Lu et al (2010). Figure 10 also shows modelling of the lateral load behaviour of one of the piles using the Davies and Budhu (1986) pile head macro-element equations which is a simple method for evaluation of the nonlinear lateral response of long piles. It can be seen from the figure that this matches the measured and computed response of the pile very closely. This verification shows that the Davies and Budhu equations provide a convenient method for performing push-over analysis of pile foundations.

The data obtained from the pull-back and snap-back tests can also provide input to macro-element modelling of shallow foundations response to earthquake time histories, Pender et al (2009), Toh and Pender (2010) and Toh et al (2011).

6 CONCLUSIONS

We reached the following conclusions based on our experience of using snap-back testing on shallow and pile foundations:

- The snap-back test method is relatively simple to perform, can be repeated easily, and provides a good information return in relation to the investment of time and resources.
- The snap-back results show that the load-deformation of both shallow and pile foundations is highly nonlinear.
- As well as nonlinear soil behaviour, nonlinearity is also induced by uplift over part of the shallow foundations and the opening of gaps between pile shafts and the surrounding soil.
- Generally the damping observed during the oscillations after snap-back release of the shallow foundations was found to be larger than that for the pile foundations.
- The response of shallow foundations has two forms of nonlinearity; geometric nonlinearity and nonlinear soil behaviour. It was shown that both should be considered in seismic shallow foundation analysis.
- The Davies and Budhu macro element, in that it produces results comparable to those obtained from OpenSeesPL and also models the measured pull-back response of the pile, provides a useful tool for preliminary design and also a simple means of assessing output from sophisticated computer modelling.

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