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Snap-back response of driven steel tube and screw piles in stiff clay

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ABSTRACT: We present data obtained from field testing of vertical steel tube piles, some installed by driving and others as screw piles. The 8 m long piles were 220 mm in diameter with a wall thickness of 8 mm. The soil profile, a stiff cohesive material, had CPT q_c values of about 2 MPa and a shear wave velocity of about 180 m/sec. A total of 12 piles were installed, 6 driven and 6 screw piles. The piles were arranged in 4 rows with 3 piles in line. Using the outer piles as reaction the central pile was pulled in alternate directions and the dynamic response recorded after sudden load release. This loading–snap release pattern was repeated under gradually increasing pullback forces for two piles; for another two piles the first phase of loading was at a large pullback force followed by series of tests at gradually increasing loads from an initial value of 5 kN. The results show that the driven piles had greater lateral stiffness than the screw piles. The cycle by cycle damping during the snap-back response depends on the amplitude of the vibration. Immediately after release the equivalent viscous damping ratio was 10 to 30 %. With each cycle the vibration amplitude decreased as did the damping ratio. It is suggested that the large damping value immediately after snap release is appropriate for design calculations, rather than the smaller values observed when the amplitude of the motion has decreased to 1% or less than the pile shaft diameter. After each snap-back response the vibration of the pile under hammer blow excitation was recorded, from which the elastic response of the system was observed and the natural frequency obtained. It was noted that the natural frequency decreases as the pullback load increases. This is interpreted as a consequence of gap formation between the pile shaft and the surrounding soil. From the decrease in natural frequency the depth of the gap, up to about 2 pile diameters, was inferred.

1 INTRODUCTION

The use of pile foundations in seismically active regions requires an understanding of the non-linear stiffness and damping provided by the foundation in order to assess the seismic demands on the supported structure. Although there have been thorough field testing investigations of the small displacement dynamic response (for example Blaney and O'Neill 1986), there has been comparatively little work to quantify the damping provided from pile foundations when the lateral deformations are sufficient to generate significant nonlinear pile-soil interaction.

We outline in this paper the results of a testing program that investigated the response of closed end, driven steel tube and screw piles. Three piles arranged in line were subjected to static monotonic, pseudo-static cyclic loading, and dynamic snap-back testing to quantify the free vibration response. The dynamic pile response from gradually increasing horizontal pull-back loads was assessed as well as the response when the first pullback force was from a large value followed by loadings starting as small values of the pullback then gradually increasing to the initial large value. A total of 12 piles was installed at the site; 6 screw piles and 6 closed-end driven piles. In this paper we present the results obtained from two-way loading of two of the driven piles and two of the screw piles.

The test site, located approximately 30 km north of Auckland, New Zealand, is noted on the relevant geological map as part of the Northland Allochthon (Edbrooke, 2001). The surface and near surface soils at the site are stiff clays, LL 60% and PL 31% with natural water content towards the plastic limit. The soil conditions at the site were determined prior to pile installation with CPT soundings at the location of each pile and two boreholes. Both CPT and borehole depths extended to a depth of 8 m, which was the approximate depth at the base of the piles. Borehole cores and CPT interpretations using soil behavior type index, Robertson and Cabal (2010), characterized the site as consisting of stiff silty clays overlaying very weak mudstone.

As the soil conditions at the site are fairly consistent the CPT results for each pile are similar, with an average tip resistance of 2 MPa for the top three metres and an average friction ratio of 6-7% over the same depth. Based upon interpretations from Robertson and Cabal (2010) the average Young's modulus of the soil for the top 3 m was approximated as 40 MPa. Further site investigation data is given by Hogan et al. (2017) and Pender et al. (2018).

2 TEST SETUP AND LOADING SYSTEM

The test piles were 220 mm diameter steel pipe (8 mm wall thickness) with bottom ends closed. The piles, both driven and screw, were installed to a depth of 7.75 m to achieve long pile behavior in which pile deformation and rotation was restricted to an active length near the ground surface. The piles were installed in rows of three, Figure 1, with the outer piles providing reaction for the pullback force applied to the centre pile. The free head pile shafts extended 1.25 m above ground. A 4.0 m spacing between the piles minimized pile-to-pile interaction. Stacked pieces steel billet, 150 mm square and 950 mm long, were attached to a platform on top of each pile, Figure 2, to bring the dynamic response of the piles within the frequency range of interest for many structures: 2-4 Hz. One of the end piles had approximately 1.8 tonnes attached to the head, the other two had approximately 3.5 tonnes each.

Soil was excavated around the pile shaft to a depth of approximately 100 mm and filled with water to help maintain consistent water content between different pile test set-ups. The water was removed the day of testing.

Piles were pulled laterally using a hydraulic jack connected between two piles. The two piles were pulled towards each other and deformations were measured from an independent reference frame with anchor points 2 m from the pile center line. Horizontal displacement was measured at ground level, load height, and the height of the centre of mass. The data logging system used a 16 bit A/D converter and during the dynamic snap-back response the channels were logged at 1000 Hz.

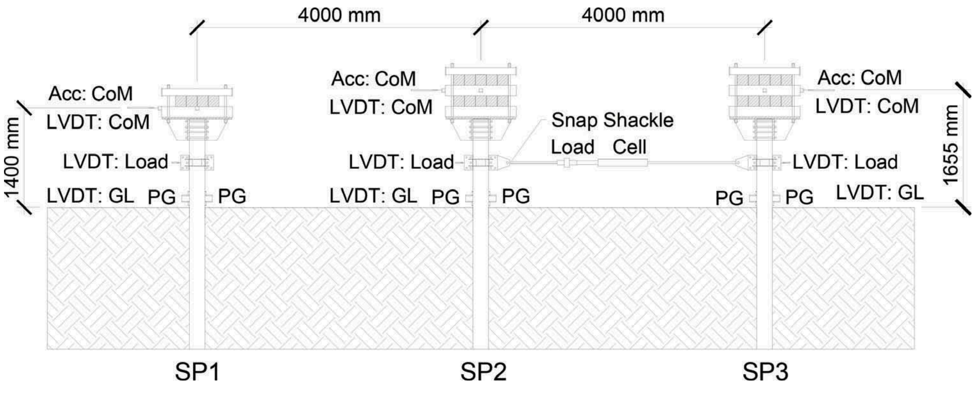

Figure 1. Pile test set-up.

Figure 2. Pile shaft with head mass, instrumentation, and lateral load attachment point.

Lateral pile testing occurred in three phases. The first phase consisted of a force-controlled monotonic pullback in which two piles were pulled towards each other to characterize their nonlinear static lateral stiffnesses. Once the desired pullback force had been reached, the load was released using a quick-release shackle. During this snapback phase, the two piles were allowed to undergo free vibration to quantify the dynamic response of both piles. The centre pile was then pulled in the opposite direction to the same load level repeating both pullback and snapback phases. Consequently, the exterior piles were displaced in only one direction while the centre pile was pulled in both forward and reverse directions. After each load step the elastic dynamic response of the pile and the surrounding soil was determined using hammer blows to excite the pile and mass (a soft head sledge hammer was used to avoid high frequency contamination of the response).

3 DYNAMIC TEST RESULTS

Figure 3 gives the natural frequency of the piles P5 and SP2 determined from hammer blow excitation before any lateral load is applied and then after each snap-back test. P5 is a driven pile and SP2 is a screw pile. The first conclusion from these plots is that the driven piles have greater lateral stiffness than the screw piles, as the initial frequency before any pullback is applied is 3.65 Hz for pile P5 and 3 Hz for pile SP2 (we are uncertain why the frequency for the third point for pile SP2 is slightly larger than 3 Hz). The method of estimating these frequencies is explained by Hogan et al. (2017), which also shows that the elastic damping of the system is about 3%.

The loading sequence for the two piles in Figure 3 is different. For pile SP2 the initial pullback force was 5 kN and then increased in a number of steps to 60 kN during which there is a steady decrease in the hammer blow natural frequency from about 3 Hz down to 2.1 Hz. This decrease is thought to be a consequence of: (i) the formation of a gap between the pile shaft and surrounding soil, and (ii) the large number of loading cycles the soil around the pile shaft had been subject to when the 60 kN pullback was reached. At a frequency of 2.1 Hz, we estimate that the gap depth is about 2 pile shaft diameters. For pile P5 the loading sequence

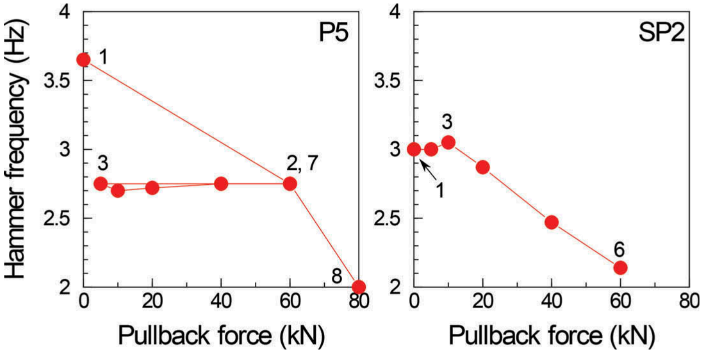

Figure 3. Results of hammer natural frequency tests (P5 – a driven pile, SP2 – a screw pile).

started with an initial pullback of 60 kN, after which the hammer frequency was 2.8 Hz. The next pullback was from 5 kN and those following worked back up to 60 kN and then a final pullback force of 80 kN. It is of interest that the hammer frequency for pullbacks 2 to 7 is nearly constant, but the frequency drops to 2 Hz after the final pullback of 80 kN.

Figure 4 shows the pile lateral displacement, normalized with respect to pile diameter, just prior to snap release. Piles P2 and SP2 were loaded gradually in a series of steps to the maximum pullback force, the well-known nonlinear pile lateral load – lateral deformation behaviour is evident. For piles P5 and SP5 the initial pullback was to a large force and was followed by a sequence of increasing pullbacks starting from 5 kN. For these two piles the plots show an approximately linear force-displacement relation under increasing pullback force as long as the pullback force is less than the previous maximum.

When it comes to estimating the equivalent viscous damping ratio during the dynamic pile response a question arises as to what value of the lateral stiffness should be used. The final stages of the pullback enable a secant value for pile lateral stiffness to be determined. However, this is not the stiffness to be used in modelling the snap-back response of the piles. Figure 5 shows how there is full pile-soil contact on the side of the pile from which the pullback occurs, but a gap forms on the other side between the pile shaft and the surrounding soil near the ground surface. When the snap-back release occurs the lateral stiffness of the pile is less than that at the final stages of the pullback as the initial motion is towards the gap.

Figure 6 shows the dynamic response of pile P2 when released from a 40 kN pullback force; it is apparent that there is considerable damping in the system during the free vibration decay. The results of two damping calculations are shown in the figure. First, in 6a, the observed response is overlain with that calculated for sudden release from pullback of an elastic single degree of freedom system equation 1 (Inman (2014):

$$x = \frac{F_o}{k} - \frac{F_o e^{-\xi\omega_n t}}{k\sqrt{1-\xi^2}}\cos(\omega_d t - \theta) \text{ with } \omega_d = \omega_n\sqrt{1-\xi^2} \text{ and } \theta = \tan^{-1}\left(\frac{\xi}{\sqrt{1-\xi^2}}\right) \qquad (1)$$

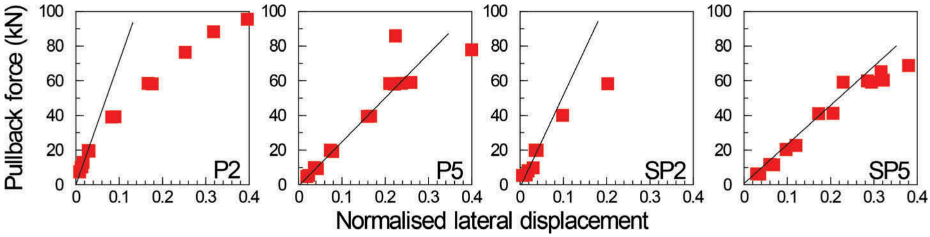

Figure 4. Relation between pullback force and displacement at snap-release.

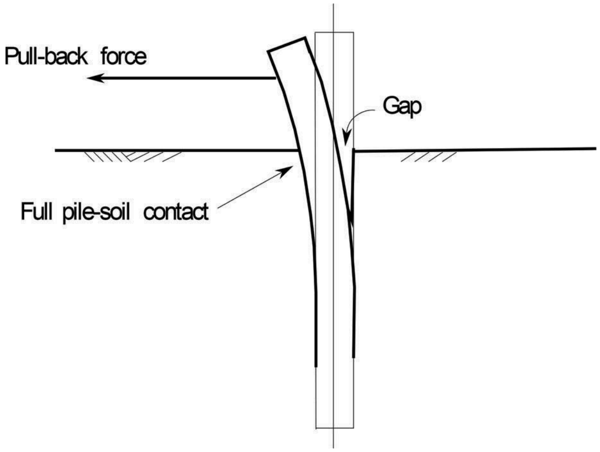

Figure 5. Explanation for the differing pile lateral stiffnesses during pullback and at snap release.

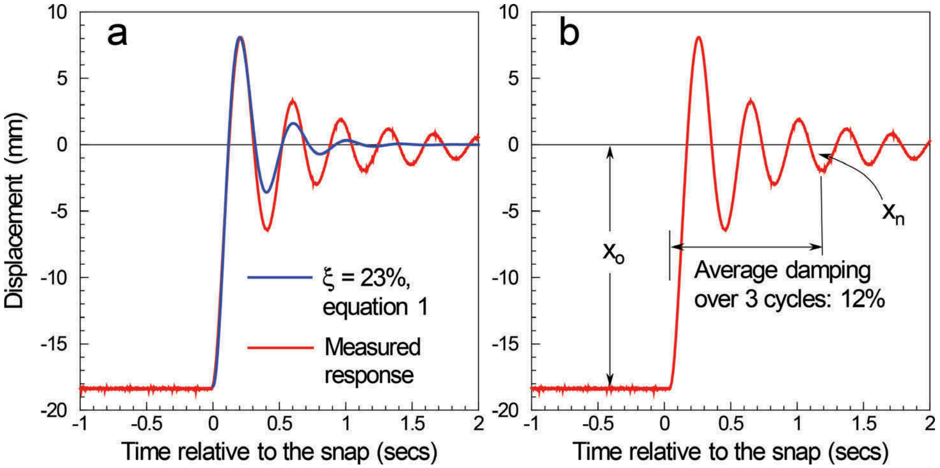

Figure 6. Snap-back response of pile P2 from a pullback force of 40 kN and associated damping values.

where: x is the displacement of the mass, ζ is the value for the equivalent viscous damping ratio, F_o the pullback force, k the lateral stiffness of the system, and ω_n the natural frequency of the system $(k/mass)^{0.5}$. The matching of the curves in Figure 6a was achieved using a trial and error process. We had not only to try different values of ζ but also of k,

as the stiffness at snap release is not the same as that at the end of the pullback because of the gap in front of the pile shaft at release, as shown in Figure 5.

Another damping approach, Figure 6b, is to use the logarithmic decrement method to obtain the average damping over a number of cycles:

$$\xi = \left(1 + \frac{4\pi^2}{\delta^2}\right)^{-0.5} \quad \text{with} \quad \delta = \frac{1}{n}\ln\left(\frac{x_0}{x_n}\right) \tag{2}$$

where: n is the number of cycles being considered since the snap release, x_o is the displacement at pullback, and x_n is the displacement amplitude at the nth cycle.

Damping values interpreted from the test results for the four piles are plotted in Figure 7. The values for the response immediately after the snap release are plotted in red; these have been estimated using equation (1) with trial and error adjustment of the damping value and stiffness until a satisfactory fit is obtained as shown in Figure 6a. The aim was to get a good fit over most of the first cycle of the response. The stiffness values used were typically half that of the stiffness at the end of pullback. For test P5 and SP5 the sequence of loading stages is indicated with the numerals near the plotted points for the damping immediately after snap release.

Also shown in Figure 7 are damping values obtained using equation (2). These are the average values to the point when the displacement amplitude had decreased to 1% and 0.2% of the pile shaft diameter. This involved counting the number of cycles until the displacement amplitude reached 2.2 mm and 0.44 mm respectively and substituting these values into equation (2). The plots in Figure 7 show that the response of the piles loaded initially to a large pullback force is different from that for the piles where the pullback sequence starts from a small force and increases gradually from there. Piles P5 and SP5, with the large initial pullback forces, show little difference between the 1% and 0.2% damping values and also little variation as the pullback forces are increased up to the previous maximum value. However, it is of interest to note that the

damping value immediately after snap release is not much affected by the prior loading history of the pile. Thus, for piles P5 and SP5 (initial large pullback force) and piles P2 and SP2 (gradual increase in pullback loads from a small initial value) the damping values immediately after snap release are similar.

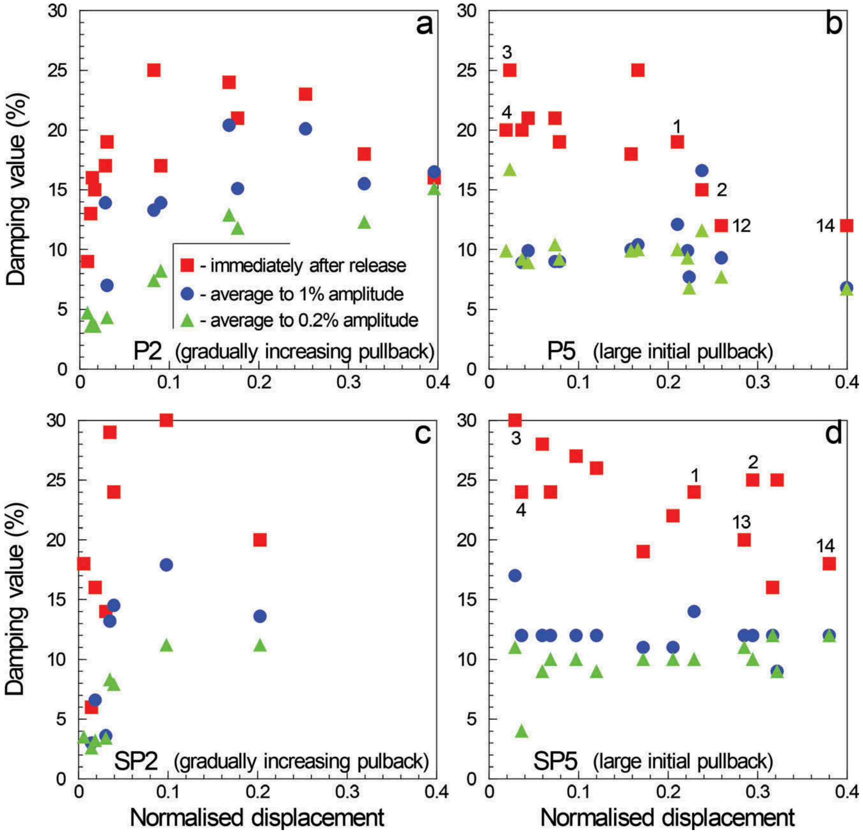

Figure 7. Various measures of damping from the snap-back tests.

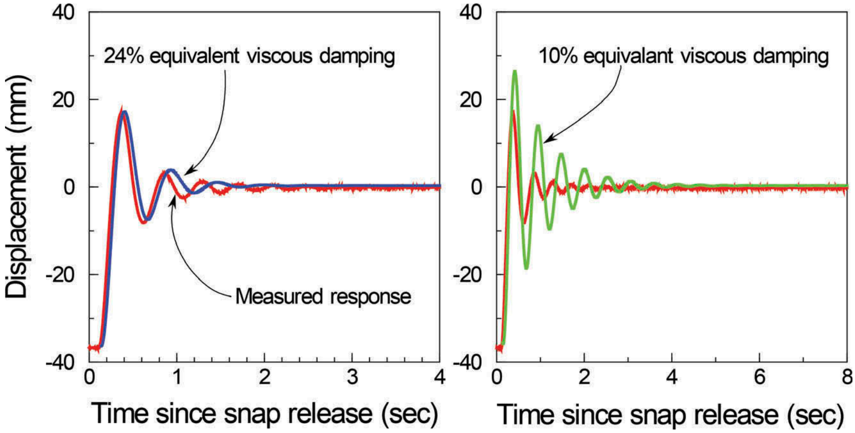

Figure 8. Damping comparison for one of the snap back responses for pile P2 (pullback force 58 kN).

4 DISCUSSION

Figure 7 shows that no single damping value describes the lateral vibration response of a free head pile embedded in stiff clay. The damping immediately after snap release is a function of the pre-snap pullback displacement. However, following many snap releases the damping values immediately after reduce, this is probably a consequence of the many cycles of loading degrading the soil stiffness, particularly near the ground surface. In Figure 7 there are also average damping values when the displacement amplitude is reduced to about 1% of the pile shaft diameter and others when the vibration amplitude is reduced to about 0.2% of the pile shaft diameter. As explained above, these values depend on the initial load step, starting with a large pullback value and then reverting to a sequence starting from 5 kN (Figures 7b and 7d) is different from starting at a small pullback value and increasing gradually to the largest value (Figures 7a and 7c).

What damping value should be used for pile design? From Figure 7 one could decide that a suitably conservative approach would be to use a value of about 8% to 10% for the equivalent viscous damping ratio. Reference to Figure 8 suggests that this might be overly conservative. On the left-hand side of Figure 8 the free vibration response of the pile is modelled with a damping value of 24%; it is clear that this fits well the first cycle of the response and does reasonably well for the remainder of the cycles. On the right-hand side of the figure the response is modelled with a damping value 10%. It is clear that this models the response poorly. From this we conclude that the initial cycle of the free-vibration response is very important as this dissipates much of the vibrational energy; it is the response during this first cycle which determines the remainder of the response. Thus, we suggest that the damping values required to model the first cycle of the free vibration response are relevant to design.

5 CONCLUSIONS

The following conclusions are reached:

- No single damping value describes the snap-back response of a single pile in stiff clay; the value obtained depends on the estimation process (Figure 7).
- The initial elastic stiffness of the driven piles is greater than that of the screw piles (Figure 3).
- The pullback load – lateral displacement curve for the piles with pullback starting from small loads is nonlinear; but for the piles first loaded at a large pullback force then followed

by gradually increasing values from small loads, the curves are approximately linear (Figure 4).

- The post-snapback hammer tests show a reduction in elastic natural frequency of the pile - mass system as the pullback force prior to the snapback increases (Figure 3); we think this is a consequence of increasing depth of soil gapping adjacent to the pile shaft and softening of the adjacent soil because of the number of loading cycles.
- Figure 8 shows that the snap-back response of the system is controlled by the damping value required to match the first half to one cycle of the response; this means the immediate damping values (red dots in Figure 7) are relevant to foundation design and not the values at displacement amplitudes of 1% or 0.2% of the pile diameter also plotted in Figure 7.
- The damping values discussed above are equivalent viscous damping ratios, however the actual mechanism of damping is hysteretic (with possible additional contributions from impact effects).

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