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Degradation of Axial Shaft Capacity of Piles in Soft Clay Due to Cyclic Loading

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DEGRADATION OF AXIAL SHAFT CAPACITY OF PILES IN SOFT CLAY DUE TO CYCLIC LOADING

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ABSTRACT

This paper presents details of the installation and axial compressive cyclic load tests performed on the UCD 76mm diameter highly instrumented steel pile at a soft clay test site in Belfast. Lateral stress measurements and pore pressures are obtained through pressure transducers mounted diametrically opposite each other in the pile wall at three levels. The pore pressures during installation are seen to drop off as pile-slip occurs for a given jacking stroke before rising to higher ultimate values, resulting in a brittle load response. Following an equalisation period two cyclic load tests were performed, where the loads were applied from zero up to a prespecified maximum and cycled about these values for a number of cycles, N, before ramping up the load and repeating the process. Cyclic loads at 33% and 66% of the installation resistance generate negligible displacements with the pore pressure and total stresses remaining relatively stable. High level loads at 150% of the installation resistance cause rapid displacement accumulation to occur. The pore pressure behaviour for a given cycle is comparable to that observed during installation as temporary reductions in pore pressure when cyclic loads are applied results in a dynamic capacity resisting cyclic loading which is greater than the static capacity. However positive pore pressure generation results in decreased effective stresses as the pile displaces under the higher loads. A comparison with normalised uncycled fully equalised radial effective stresses indicates degradation in excess of 50%, resulting from the high level cyclic displacements.

INTRODUCTION

Piles subjected to variable loads due to wind and wave action are generally designed by considering the ultimate static pile capacity and ensuring a prespecified margin of safety against expected extremes in environmental loads over the foundation lifetime. The influence of cyclic loading on the axial shaft capacity is rarely considered explicitly in design. As we move toward reliability based design approaches, which require quantifiable safety projections, all factors influencing the pile resistance will need to be considered to produce an acceptable probability of failure.

Estimation of the static capacity of piles has improved significantly with the introduction of effective stress design approaches that have been developed from the results of instrumented field tests (Jardine et al, 2005). However, there is a dearth of field data detailing the effect of cyclic loading on the effective stress regime around a pile. Lehane et al. (2003) report cyclic load tests performed on un-instrumented 6 m long, 250 mm diameter square concrete piles driven into soft clay at a geotechnical test bed site in Kinnegar, Ireland. The authors performed one way, high-level load cycling on both single piles and groups of five piles. They found that degradation of the shaft resistance of single piles commenced when the cyclic load level reached 90% of the ultimate shaft resistance for the single piles and 60% for the pile groups. The amount of degradation suffered depended on the number of load cycles (N) applied, with the single piles suffering a 14% reduction in shaft resistance and the group piles exhibiting an 18% reduction. These reductions were seen to be temporary with the piles demonstrating increased axial shaft resistance when static load tests were performed after periods of equalisation following the cyclic load tests.

A difficulty in analysing the results of cyclic load tests performed on un-instrumented piles lies in the quantification of capacity degradation. It is usual to compare the capacity of the pile (at some given displacement level) to the resistance developed during a static load test. However, Lehane et al. (2003) note that pre-testing either using static or cyclic loading regimes may alter the pile capacity and it is difficult to determine an appropriate reference capacity for a given pile.

Gavin et al. (2008) describe the installation of single model and full-scale piles at the Kinnegar test site and examine the effect of pile installation method on the radial total stress (σ_r) and porewater pressures (u) measured at a number of levels during installation and on the equalised radial effective stress, which control the long term pile capacity. All the model piles were installed by jacking, with varying stroke lengths from 100 mm, 200 mm and 400 mm and one pile was installed in one single push. The full-scale 250 mm square concrete pile was driven through an upper fill layer, and penetrated under self-weight through the soft clay to a depth of 6m below ground level (bgl).

The authors concluded that during installation both the σ_r and u values mobilised at a given location on the pile shaft, increased as the jacking stroke length increased. However, once dissipation of the excess porewater pressures generated during installation had taken place, the equalised radial effective stress (σ'_{rc}), which controls the long-term pile capacity, appeared to be independent of the installation technique and depended only on the soil state prior to pile installation and the pile geometry.

This paper describes cyclic load tests performed on a highly instrumented pile at the Kinnegar test site. The paper investigates the mechanisms controlling the degradation of the axial resistance of the pile through measurements of the effective stress response at the pile shaft, and to quantify the degree of degradation by comparing the effective stress profiles after cyclic loading with σ'_{rc} values measured on untested piles at the same test site.

SOIL PROPERTIES

The pile tests described in this paper were conducted at the Kinnegar geotechnical test bed site located just outside Belfast city in the North-East of Ireland. The geological properties of the underlying deposits, known locally as sleech, have been well documented by Bell (1977). The site is located on the shores of Belfast Lough and has been developed for geotechnical research through extensive laboratory and field tests (McCabe, 2002).

The site stratification, shown in figure 1(a), highlights four distinct soil layers. A one metre deep layer of fill material, mainly consisting of building rubble and gravel, overlies a sandy silt layer approximately 2m thick, which in turn overlies 6m of soft silty clay “sleech”. The soft estuarine deposits are underlain by a uniform fine to medium dense sand; however as the pile tests considered were founded completely in the sleech, little investigation of the sand layer has been conducted. Between 1m and 3m bgl. the proportion of sand and clay is 20% and 10% respectively, whilst below this level the proportions reverse as shown in figure 1(a). The water table for the site is tidal varying between 1 and 1.3m below ground level.

The mechanical properties of the sleech as determined in lab tests confirm:

(i) A natural water content in the range 60 ± 10%
(ii) A liquid limit and plasticity index of 65 ± 10% and 35 ± 5%, respectively
(iii) Permeability ranging from 1.5×10^{-10}m/sec to 5×10^{-10}m/sec.

The in situ soil strength is illustrated in figure 1(b) and (c), through CPT cone end resistance and undrained shear strength parameters. The q_c values measured in the upper sandy sleech are quite variable and are considerably higher than those measured in the underlying clayey sleech, which shows a uniform increase in q_{cnet} resistance from 175kPa at approximately 2.3m bgl to 240kPa at 6m bgl. Uncorrected undrained shear strength parameters as measured in in-situ vane tests show a similar slight linear increase with depth from 20kPa at 2.5m to approximately 25kPa at 8m depth. Further details pertaining to the soil properties can be found in McCabe (2002) and Gallagher (2006).

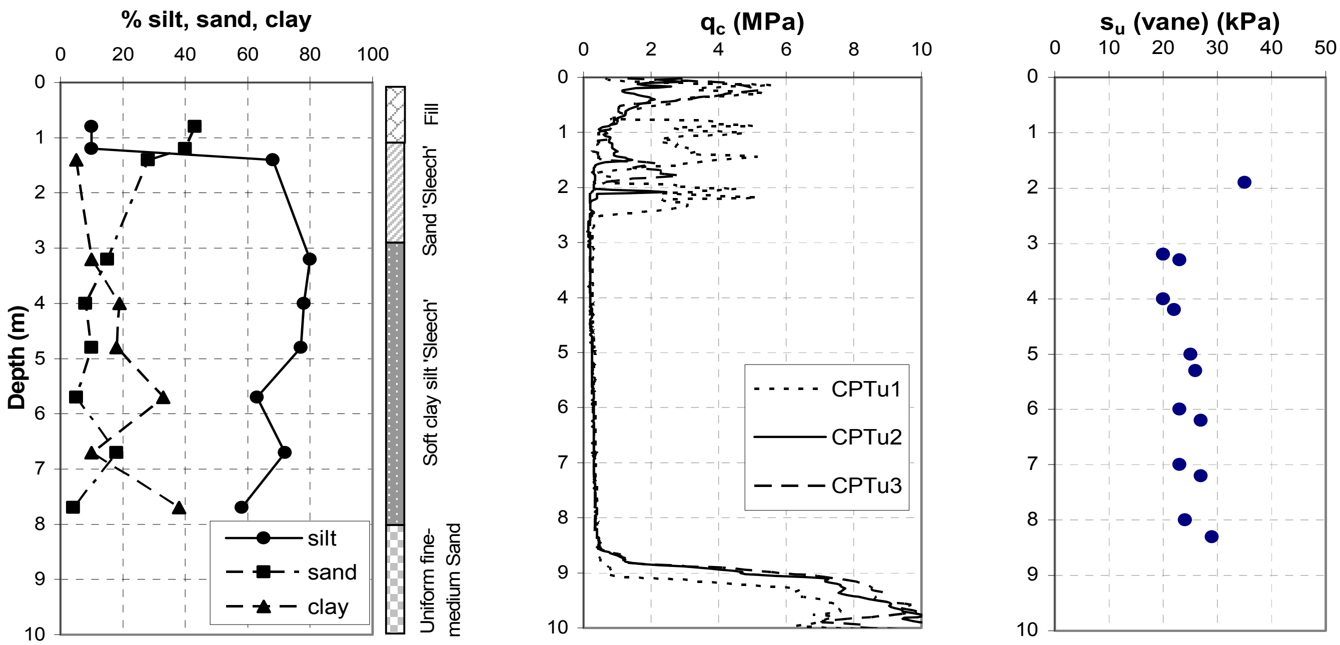

Figure 1(a) Particle Size Distribution (b) CPT trace (c) Undrained Shear strength at Belfast test site

A specific laboratory investigation, examining some of the cyclic soil properties, conducted by Lehane et al (2003) reveals:

(i) The undrained strength in triaxial compression increased by 15% per log cycle increase in axial strain rate.

(ii) Preshearing in a cyclic DSS tests slowed the accumulation of permanent displacements with respect to the number of cycles (N).

(iii) Stress controlled cyclic DSS tests, showed no increase in strain amplitude but a steady increase in the mean displacements which varied approximately with respect to the log of N.

TESTING PROGRAMME

The instrumented closed ended model pile used in the tests is shown schematically in figure 2. The pile is 73mm in external diameter and the section containing the pressure transducers is 2m long. Additional 1 m long extension pieces, which are instrumented with strain gauges, can be added to give a total pile length of 6 m. Lateral stress measurements and pore pressures are obtained through pressure transducers mounted diametrically opposite each other in the pile wall at three levels, each described in terms of their height above the base (h) normalized by the piles external diameter (D). The h/D values used are 1.5, 5.5 and 10.5 (figure 2). 120 Ohm uniaxial electrical resistance strain gauges were bonded to the inside of the pile wall at 4 levels to provide a distribution of the pile load along the length of the shaft. These gauges also allow separation of the shaft and base load.

Measurement of the radial total stress, porewater pressure and shaft shear stresses were made during installation, cyclic load tests and ultimate load tests to failure. A load cell mounted on the pile head recorded the applied load during testing, while displacement was monitored using LVDTs during the load tests.

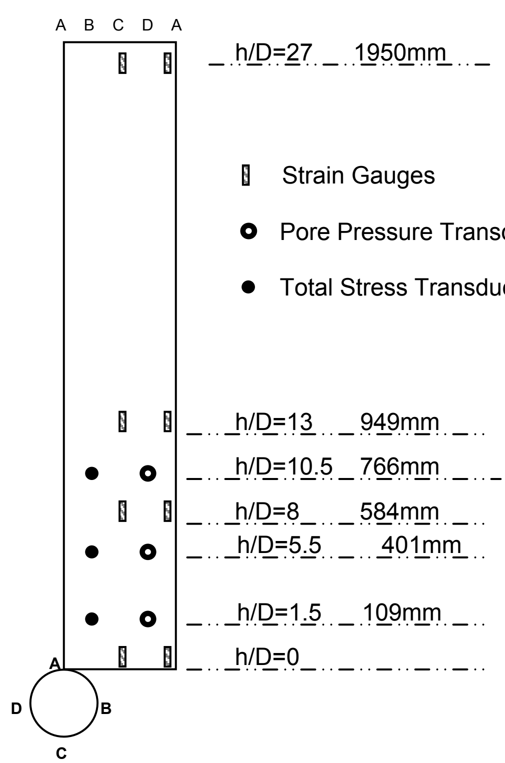

Figure 2: Schematic of pile instrumentation layout

EXPERIMENTAL RESULTS

Installation

The pile was installed from the base of a 1.45m deep starter hole to a final depth of 4.7m using a manually controlled hydraulic cylinder. Thirty-three jacking strokes of 100mm length were applied to install the pile. The installation rate during each jacking stroke was approximately 1.6 mm/sec. Because of pause periods required to add extension pies to the pile the total time taken to install the pile was 290 minutes, giving an average installation rate (including pause periods) of 11 mm/min. The base resistance during installation was on average 0.7 kN (≈ 180 kPa), which is similar to the CPT q_c resistance and agrees well with base pressure readings recorded by Gallagher (2006) at the same site. The axial resistance during installation shown in figure 3 is seen to increase steadily to a maximum value of 5.5 kN at the end of pile installation.

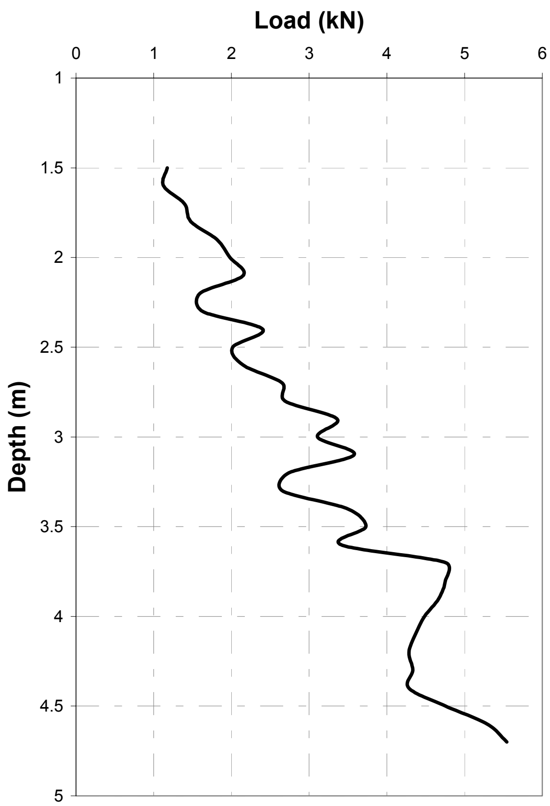

Figure 3: Load during installation

Lehane and Jardine (1994) have discussed the complex porewater response which develops at the pile-soil interface during installation of piles in clay. Careful field measurements have shown that during a jacking stroke, reductions in porewater pressure can occur as a result of shear induced stress changes in a thin shear zone which develops at the pile-soil interface. When the pile comes to a rest reconsolidation occurs and the porewater pressure at the interface rises to reflect values in the soil mass outside the shear zone, resulting from the increased mean stress caused by pile installation.

The effect of this porewater pressure response on the installation resistance of the pile during a typical jacking stroke is considered in Figure 4, which plots the porewater pressure (u) at all h/D values, and the load resistance for the 100 mm jacking stroke. The porewater pressure response can be considered in three phases:

(i) an initial phase where pile head settlement is low (<3mm) and the u values remain largely unchanged,

(ii) when pile-soil slip begins, the u values decrease rapidly, reaching minimum values when the pile head displacement is less than 10 mm, and

(iii) For displacement above 10 mm, the u values recover at all levels, and increase sharply when the pile head load is removed at the end of the jacking stroke.

Whilst the decrease in u values noted in phase (ii) is associated with a peak resistance being developed by the pile, the subsequent increase in u during phase (iii) is accompanied by a reduction in pile resistance, which is seen to cause the brittle load-displacement response evident in Figure 4.

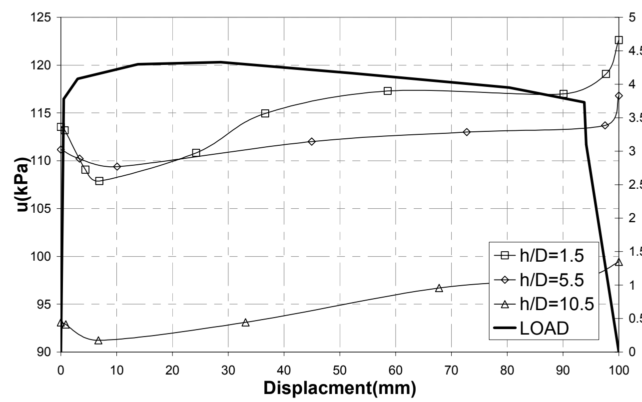

Figure 4: Typical Pore Pressure Response during a Jacking Stroke

Cyclic Load Tests

Two cyclic load tests were performed on the test piles following periods of porewater pressure equalisation. The first test (Cy#1) was conducted after a seven day equalisation period at which stage excess porewater pressure dissipation of 85-95% had occurred. The second test (Cy#2) was conducted after 30 days, when equalisation was complete. In both tests, one-way compression loading was applied to the pile in batches of 100 cycles. The load was varied from zero to the peak load during each cycle, and the peak load was incremented after each batch of 100 load cycles, such that the load represented 33%, 66%, 100% and ≈ 150% of the peak installation resistance. The first fifty load cycles of each batch were applied with a 30 second pause period (where the pile was fully unloaded) between each load cycle. This was followed by a batch of 50 rapid load cycles with the minimum pauses between each load cycle.

In test Cy#1 the loads were applied manually using a hydraulic hand pump. The desired loading level was achieved by monitoring the load cell output during cycling and releasing the pressure valve once a predetermined load was observed. An acceptable level of control was achieved using this method, although in at least one load cycle the pile was significantly overloaded, which affected the subsequent response. The second cyclic test was conducted using a custom built hydraulic unit that provided more accurate loading control, through electronically controlled pressure relief valves and timers.

Load-Displacement Response

The load-displacement response during both cyclic load tests Cy#1 and Cy#2 were similar. The load and displacement response with time measured during test Cy#2 is shown in Figure 5. The displacement is seen to be essentially elastic during the application of the first two load batches (1.9 KN and 3.8 kN, representing 33% and 66% of the installation resistance respectively). Accumulation of plastic displacement starts when the load level is increased to 100% of the installation resistance, and the rate of accumulation increase rapidly when the load level is increased to 150%. Additional features of note from the load-settlement response are:

a) The displacement amplitude experienced at a given load level was constant, whether the pile displacement response was elastic or the pile was experiencing settlement accumulation.

b) Changing the pause period between loading cycles did not appear to affect the load-displacement response.

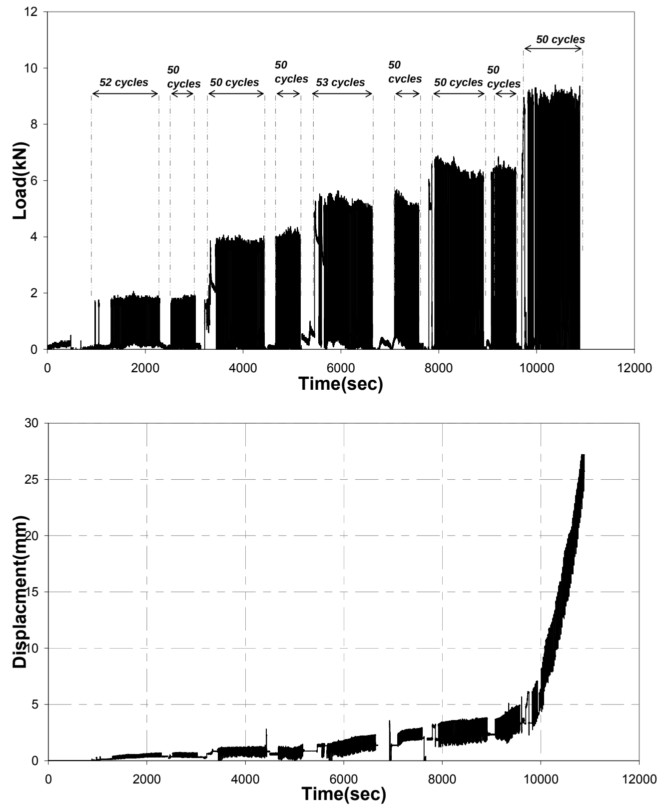

Figure 5: Raw Load & Displacement Data for Cy#2

Variation of in-situ stress during cyclic loading

The response of the total pressure and pore pressure sensors is considered in detail for test Cy#1 in Figure 6 (a-d) and for test Cy#2 in Figure 7 (a-d).

The load-displacement response of test Cy#1 is shown in Figure 6a. At cyclic load levels below the installation resistance, pile head displacement was low (< 1 mm), and the total stress measurement ($\Delta\sigma$) illustrated in Figure 6b, remained essentially unchanged. Small changes in porewater pressure (Δu) occurred during pile loading (See Figure 6c), with the value dropping when the pile was loaded (u_m) and increasing during pause periods (u_s). When an (accidental) extreme loading event was applied at cycle 300, large increases in porewater pressure occurred, which resulted in a significant decrease in effective stress ($\Delta\sigma'$), See Figure 6d, at the pile-soil interface.

The load-displacement and pressure sensor response measured during Cy#2 is shown in Figure 7. In this case the pressure sensors (Figure 7b) show reductions from early stages of the test. The pore pressure changes (Figure 7c) were small until cycle No. 300. At this load level, the pile head displacement exceeded 3 mm and reductions in porewater pressure became more significant, and positive pore pressures began to develop during pause periods. When the high level cyclic loading began, the displacement increased dramatically. The porewater pressure response initially shows a decrease followed by recovery to higher values once the pile head displacement exceeded 10 mm. These pore pressure changes are reflected in the effective stress changes (Figure 7d) which show the effective stress initially decreasing when the pile head movement begins, and then falling rapidly in response to the generation of positive porepressures at larger pile head displacement.

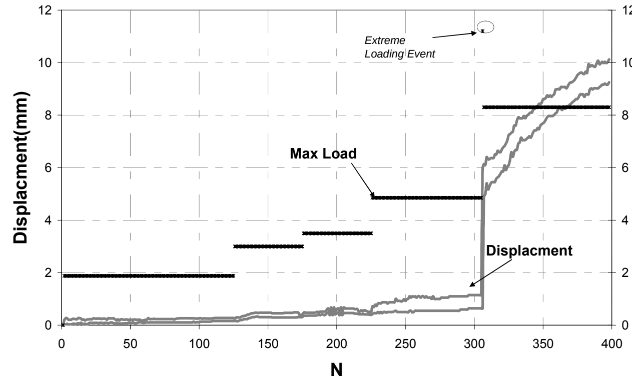

Figure 6a: Load Displacement response with respect to the number of cycles for Cy#1

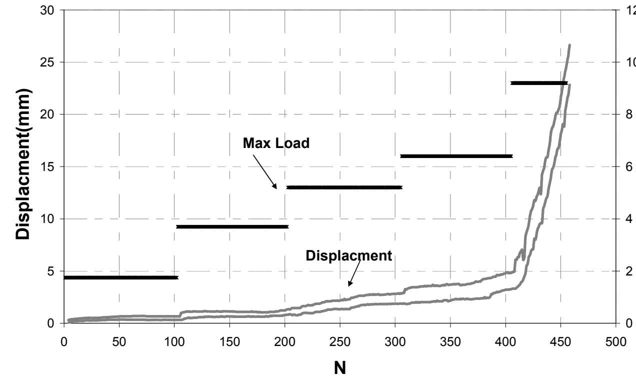

Figure 7a: Load Displacement response with respect to the number of cycles for Cy#2

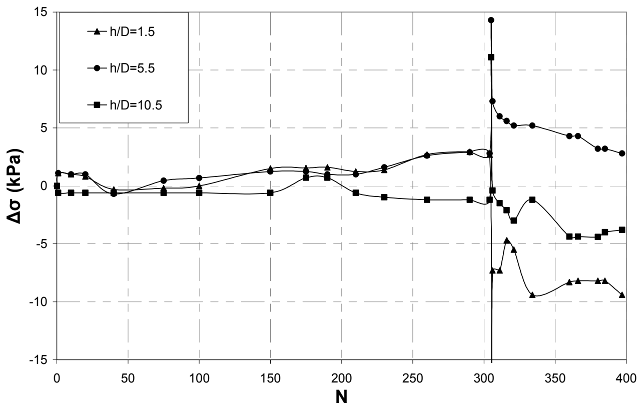

Figure 6b: Total Stress Change for Cy#1

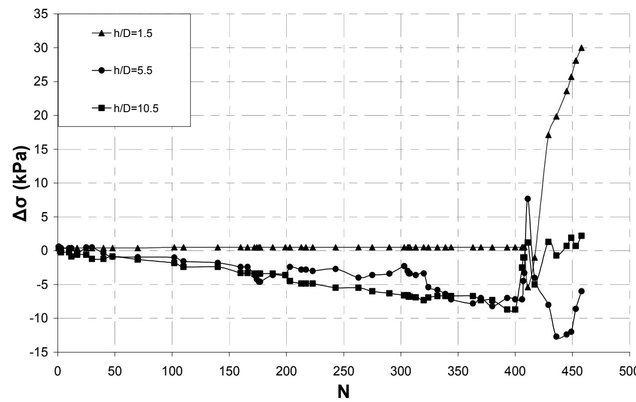

Figure 7b: Total Stress Change for Cy#2

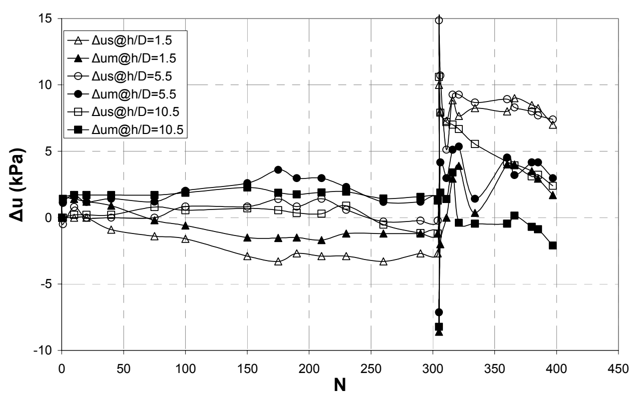

Figure 6c: Pore Pressure Change for Cy#1

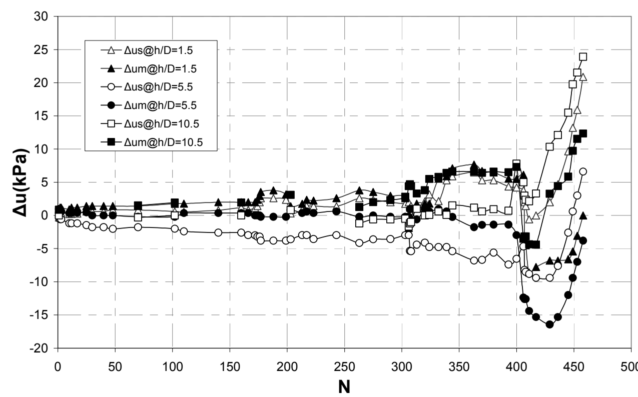

Figure 7c:Pore Pressure Change for Cy2#

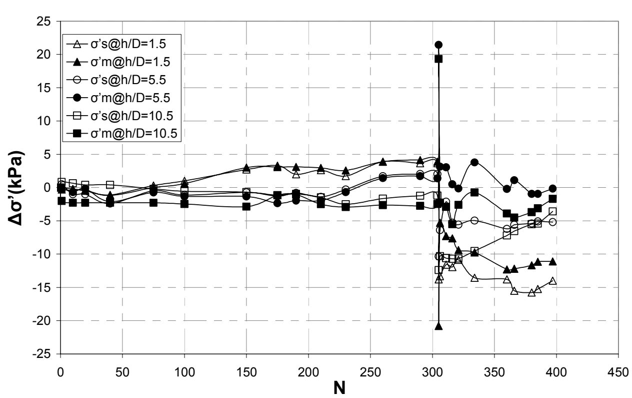

Figure 6d: Effective Stress Change for Cy#1

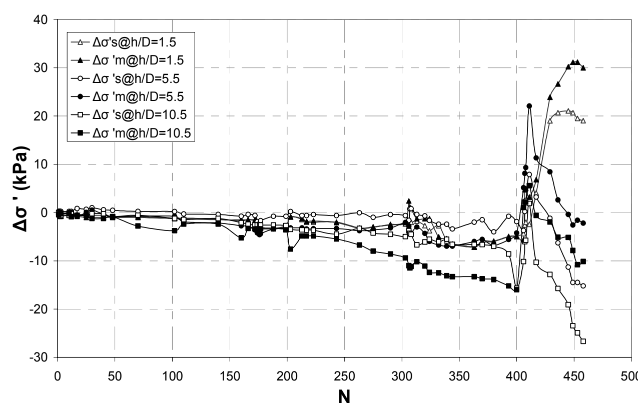

Figure 7d: Effective Stress Change for Cy#2

DISCUSSION

The brittle response observed for a given jacking stroke during installation, see figure 4, showed a temporary reduction in pore pressure that corresponded to the peak load for a particular push. Similar behaviour is observed in the cyclic tests where once the pile starts to suffer significant displacements with respect to the number of cycles the pore pressure was seen to drop off dramatically during the loading stage and recover to the higher stationary values once unloading occurred. This systematic drop off in pore pressure as the pile moves results in the dynamic capacity, which is governed by the moving stresses, being significantly higher than the static capacity which is controlled by the stationary stresses just prior to loading.

The pore pressure response and effective stresses were relatively stable at low cyclic loads indicating limited degradation, whereby loads amounting to 150% of the installation resistance caused rapid degradation to occur, resulting from large positive pore pressure changes. This degradation is illustrated in figure 8, which compares the normalised effective stresses at various stages of the cyclic load test to fully equalised radial stresses on untested piles (Gavin et al, 2007). The high level load cycles applied in Cy#2 amount to 92% of the estimated static pile capacity, and are shown to ultimately cause degradation of over 50% from the fully equalised radial effective stress values. This indicates that for piles cycled about their working loads the level of degradation will be minimal. However for high level cycles that result in significant displacements the degradation can be unstable with the effective stresses decreasing rapidly and continuously in response to the pore pressure build up. It is interesting to note that despite the 5mm accumulated displacement that occurs in Cy#1 under the loads at 82% of the estimated capacity, no net change in effective stress is observed. This contrasts to the previously discussed effective stress reductions for Cy#2 at similar displacement levels, indicating that the effective stresses are influenced by the load magnitude applied. A load threshold value between the loading magnitudes applied in these two tests may be responsible for the observed behaviour. However the extreme overloading cycle in Cy#1could also be an influencing factor on any subsequent behaviour for that test.

CONCLUSION

Details of the installation and cyclic load tests conducted on an instrumented driven steel pile were presented. The main focus of which was the changes in effective stresses at different loading levels with respect to the number of cycles.

The main observations are as follows:

- The displacements are relatively small up to a particular load level corresponding to 150% of the installation resistance, whereby rapid displacement accumulation started to occur.

- The cyclic nature of the pore pressure response indicates a higher dynamic capacity available to resist cyclic loads resulting from a temporary drop off in pore pressure as the pile moves.

- At loads in the working range of the pile limited stress changes are observed which indicates very low levels of degradation will occur within these loading levels.

- The pore pressure response and effective stresses were stable at low cyclic loads indicating limited degradation, whereby loads amounting to 92% of the static capacity caused extreme degradation to occur, resulting from large positive pore pressure changes. The effective stress changes that occur due to cycling seem to be a function of displacement, cycle number, and the load magnitude.

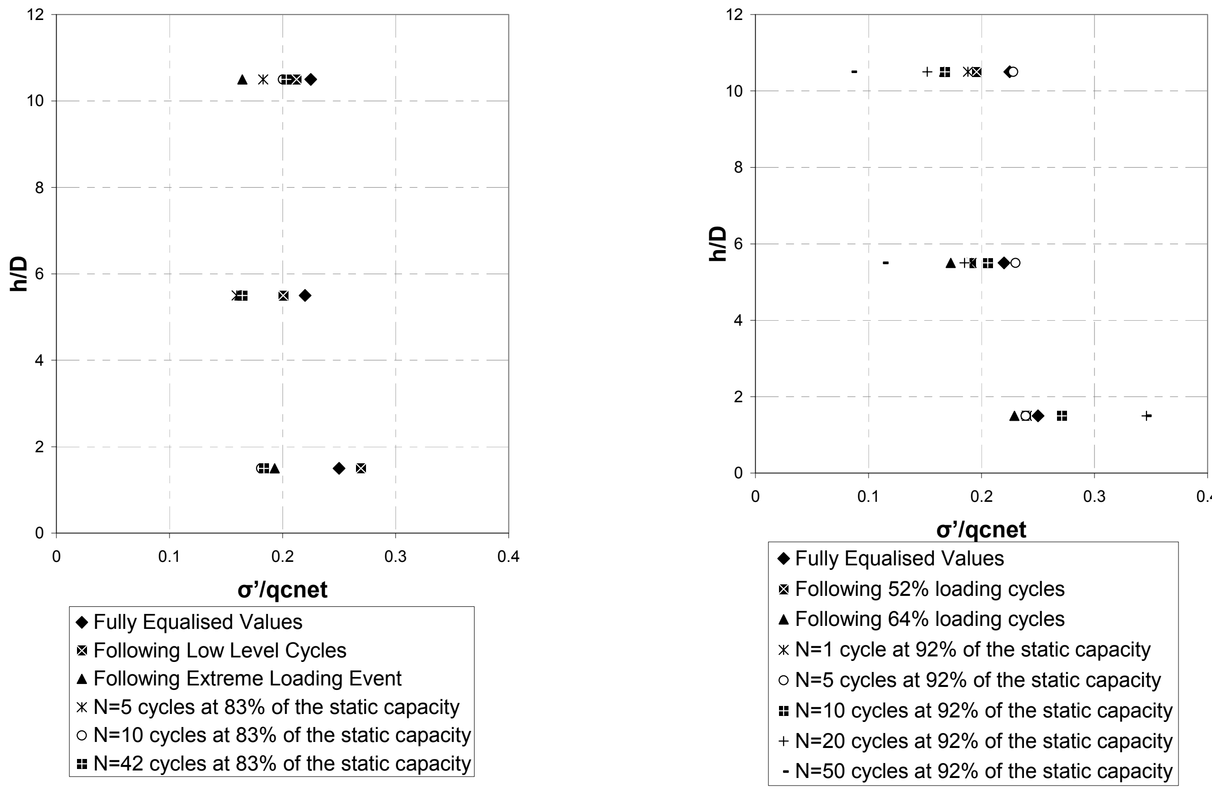

Figure 10: Normalized Effective Stresses During Cycling in Cy#1 and Cy#2

Additional cyclic tests are required to quantify the relationship between cyclic load magnitude, displacement and degradation of effective stresses. Also the difference between static and dynamic capacities resulting from the temporary drop in pore pressure warrants further investigation.

ACKNOWLEDGMENTS

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