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Cyclic and rapid axial load tests on displacement piles in soft clay

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ABSTRACT

Offshore piles are subjected to complex loading regimes, which include both rapidly applied static and cyclic loads. This note describes an experimental investigation conducted in order to assess the factors influencing the response of offshore piles to these loading conditions. The tests were performed using instrumented model piles installed in soft clay. During cyclic loading, the piles demonstrated a transition from stable to unstable behaviour when the applied loads reached a specific load threshold. Stable behaviour was defined when increments of plastic displacement decreased as the number of load cycles increased. During stable behaviour, radial effective stresses at the pile-soil interface remained constant. During unstable behaviour, pore pressures at the pile-soil interface rose as the number of cycles increased. This resulted in reduced radial effective stresses and progressively increasing displacement rates. Due to the presence of these excess pore pressures, the shaft resistance recorded during static load tests, performed after a period of unstable cyclic loading, were lower than those measured on piles where the pore pressure was fully equalised. However, the axial resistance was seen to be rate dependent. Fast loading of the pile resulted in reductions of pore water pressure at the soil-pile interface and enhanced shaft resistance which could overcome the negative effect caused by cyclic loading.

Subject Headings: Foundations, piles, pile load tests, cyclic loading, offshore piles

NOTATION LIST

API	American Petroleum Institute
CE	Closed Ended
CRP	Constant rate of penetration
D	Pile diameter
h	Distance from the pile tip
OE	Open Ended
N	Number of cycles
N_f	Number of cycles to failure
q_b	Base stress
q_c	Cone tip resistance
Q_{av}	Average applied load
Q_c	Applied cyclic amplitude
Q_{ult}	Ultimate static pile capacity
u	pore pressure
w	displacement
w_p	permanent plastic displacement
w_{cy}	cyclic displacements
Δu	Change in pore pressure
γ	Shear strain
τ	Shear stress
τ_{cy}	Cyclic shear stress
τ_{av}	Average shear stress
τ_{max}	Maximum shear stress

INTRODUCTION

Offshore piles are typically designed using empirical static total stress approaches such as the American Petroleum Institute (API) method. These approaches have largely been developed and calibrated using database studies of piles subjected to maintained load tests. Whilst there have been notable developments in modelling pile response to axial cyclic loading through the use of numerical approaches like RAZ (Randolph 2003), there is a limited amount of field data with which to calibrate these models. In order to address this, the results of an experimental study which considered the response of piles installed in soft clay to high magnitude, one-way cyclic loading are presented in this paper.

SITE DESCRIPTION

The pile tests described in this paper were conducted at a soft clay research site located near Belfast in Northern Ireland. The general soil conditions of the area have been described in detail by Gregory and Bell (1991) with the local site specific properties described more recently by Doherty et al (2010). The piles were installed into soft estuarine silty clay, locally termed “sleech” which extends from approximately 2 m depth to 8.5 m below ground level. The material has an undrained shear strength measured in triaxial compression, which increased with depth from approximately 17 kPa at 2.5m depth to 24 kPa at 7 m depth.

EXPERIMENTAL PROCEDURES

The test programme involved three installations of instrumented model piles, including two tests using the University College Dublin (UCD) Open-Ended (OE) model pile and one test with the UCD Closed-Ended (CE) pile. The main details of these installations are included in Table 1 and are described by Igoe et al (2010). Both piles were capable of measuring radial stresses and pore pressures at three locations along the pile shaft, at

normalised distances h/D of 1.5, 5.5 and 10.5, where h is the distance from the pile tip and D is the pile diameter.

The piles were installed by jacking from the base of starter holes to final depths of between 4.1 and 6.1 m below ground level (bgl). Maintained load and Constant Rate of Penetration (CRP) static load tests performed to provide reference (uncycled) static pile capacities with which to quantify the effects of cyclic loading are described in Gavin et al. (2010) and Doherty et al. (2010) for the closed and open-ended piles respectively.

After pile installation, cyclic load tests and CRP type static tests were performed. The cyclic tests were conducted using load control with the load increased from zero to a pre-specified maximum load, Q_{max} , with a period, T , between 8 s and 60 s. The loads were applied in batches of load cycles (typically 100-300) starting at the lowest load level with the magnitude of the peak applied load increasing for each batch of applied loads. The first test performed on each pile was a cyclic load test (Cy1), See Table 1. Thereafter, two piles, UCDCE4 and UCDOE3 were re-tested in a second cyclic test (Cy2) conducted after an equalisation period of approximately one week. Post-cyclic CRP tests were conducted directly after completion of cyclic tests. In most cases a number of CRP tests were performed on each pile and these are labelled CRP1-3, in chronological order. So for example, OE3-Cy1 refers to the first cyclic load test conducted on pile OE3, whereas OE3CRP2 refers to the second CRP test performed on the same pile.

EXPERIMENTAL RESULTS

The time history measured during a typical cyclic load test (OE3-Cy1) is shown in Figure 1, which depicts the pile head displacement w , measured during the application of over 720 load cycles. The reference static capacity determined from uncycled static load tests (Q_{static}) was 27.5 kN and the initial applied load of 10.3 kN was chosen to represent an applied load level (Q_{app}/Q_{static}) of 0.37 which is typical of that used in design practice. A total of 279 load cycles were applied which resulted in a net accumulated plastic displacement of 0.3 mm, which was generated within the first 15 load cycles. The applied

load was then increased to first 13.1 kN and then 16.1 kN (which represented Q_{app}/Q_{static} ratios of 0.48 and 0.59 respectively) and 200 load cycles were applied at each load level. An increase in accumulated displacement from 0.49 mm to 0.64 mm, which represents a total movement of less than 0.4% of the pile diameter was measured at the end of these load cycles. Significantly, at all three of the load levels considered, the rate of accumulation of plastic displacement decreased as the number of load cycles increased, indicating that the pile response was stable. By contrast, when the applied load was increased to 22.4 kN ($Q_{app}/Q_{static} = 0.81$) the response was markedly different, with the net displacement increasing as the number of cycles increased. As a consequence large movement of the pile head occurred with the total settlement exceeding 20 mm after the application of only a small number of load cycles. The difference between stable and unstable behaviour can be simply expressed by the inequalities in Eq. 1.

$$\text{Stable: } \frac{d^2w}{dN^2} < 0 \quad [1a]$$

$$\text{Unstable: } \frac{d^2w}{dN^2} > 0 \quad [1b]$$

An interesting feature of the response to cyclic loading was that the displacement amplitude (at a given load level) remained constant during both stable and unstable behaviour. Closer inspection of the response during discrete load cycles ($N = 1, 5, 10, 20$ and 39) at the highest applied load level shown in Figure 2 revealed the following:

1. Limited accumulation of plastic displacement occurred during the first 10 load cycles. However, the following 10 load cycles generated a net displacement of 3.5 mm, with the rate of displacement accelerating as the number of cycles increased.
2. Despite the rapid accumulation of plastic displacement, the stiffness response did not change appreciably from $N = 1$ to $N = 39$.
3. Although the loading period was constant throughout the test, the amount of creep recorded during a given load cycle increased significantly once displacement accumulation was initiated.

The average shaft stress (τ_{av}) mobilised during the application of load at the final two (highest) load levels for pile OE3Cy1 is shown in Figure 3. During cyclic loading of pile OE3 under a peak load of 16.1 kN, the mobilised shaft resistance was 6.5 kPa (62% of the ultimate resistance) and the pile response was stable. When the load increased to 22.4 kN, the mobilised shaft resistance increased to 8.7 kPa (83% of the ultimate resistance). As noted during the first 10 of these higher load cycles, the pile response was relatively stable as the rate of accumulation of displacement was low. However, when the pile head displacement exceeded 2.5 mm, the mobilised shaft resistance started to reduce and the displacement rate increased. The final τ_{av} value mobilised of 7.4 kPa represented a 15 % reduction from the value mobilised at the start of the cyclic load test and a 30 % reduction on the ultimate shaft resistance mobilised in the reference static load test.

Since the load applied during the cyclic load test was constant, any reduction in shaft resistance necessitated the mobilisation of higher base resistance as load transferred to the pile tip. This response is evident in Figure 4, which shows the mobilisation of base resistance during cyclic loading at 16.1 kN. As the cyclic load test progressed the mobilised base stress (q_b) increased from zero to 0.95 q_c . Once the pile head displacement exceeded 2 mm, residual base stress was seen to mobilise. As the mobilised base stress approached its ultimate resistance ($q_b = q_c$) creep effects became significant. In addition, unloading caused tensile shear stresses along the pile shaft (evident in Figure 3). Although the development of these tensile shaft stresses induced two-way cyclic shear stresses along the pile shaft, the relatively low base load meant that the shaft resistance mobilised in tension was small (≈ 1.2 kPa).

The creep response evident in Figure 2, suggested that the cyclic period would be a controlling factor in determining the number of cycles required to cause pile failure by excessive settlement. The effect of varying the loading period was investigated during cyclic load tests performed on pile OE2Cy1 (see Figure 5). The first 50 cycles were applied with a period of 60 sec and the next 50 had a period of 20 sec. It is clear that when the pile response was stable, the period had no appreciable effect on the

displacement response. However, when the pile response was unstable the period had a significant effect on the rate of displacement accumulation. At the highest load level, the initial 30 load cycles were applied with a period of 60 sec. When the period was reduced to 20 sec for the next 25 load cycles, the rate of displacement accumulation decreased. The final 50 load cycles were applied with a period of 8 sec and the rate of displacement accumulation again reduced.

DISCUSSION

The effect of cyclic loading on pile behaviour

Analysis of all tests indicates that a load threshold exists which separates stable and unstable cyclic behaviour. For piles in Belfast sleech this threshold occurred when the cyclic load reached 72 % ($Q_{av}/Q_{ult} = 0.36$) of the model piles static capacity, The mechanisms controlling the degradation of shaft resistance during cyclic loading are considered by examining the pore pressure response measured on pile CE4 during the application of 470 load cycles. For loads below the threshold load value the pore pressures remained close to hydrostatic levels . When the load was increased to 9.2 kN, the pore pressure response changed. During each load cycle the pore pressure dropped when the load was applied and recovered when the load was removed. During the first few load-cycles ($N < 10$), the pore pressures remained close to hydrostatic values. After a small number of additional load-cycles, the pore pressure started to increase. Given that total stress changes during cyclic loading were small, the radial effective stresses reduced, leading to a reduction in shaft resistance.

The pore pressure data is illustrated in Figure 6 which shows the pore pressure changes Δu which occurred under the peak cyclic load against pile head movement. During the initial stages of the test, when the measured total displacement was below 6 mm, shear induced pore pressure reductions caused increased radial effective stresses, which meant that the pile could initially support a small number of load cycles at a load-level above

the threshold value. Similar meta-stable response during initial loading at the peak cyclic-load level was evident in the cyclic load tests performed on the open-ended pile, e.g. OE3cy1, where the initial 10 cycles of high-level loading caused minimal plastic displacement accumulation. As the pile head movement increased in Figure 6, the porewater pressure measured between load cycles increased steadily. The variation in porewater pressure measured during a static load test on a pile at Belfast (pile CE2 – See Gavin et al. 2010) is compared to the cyclic load test in Figure 6. Both tests suggest similar pore pressure behaviour, with the faster rate of mobilisation seen in the static load test being the result of the higher load level applied in this test.

Post-cyclic loading rapid load tests

A wide range of capacities from 8 to 17 kPa was developed in CRP tests performed after cyclic loading tests. This was caused by two phenomenon namely; degradation of shaft resistance and positive rate effects. The maximum τ_{av} value mobilised in CRP tests, which experienced cyclic loading, were compared to tests where no cyclic loading had been applied. The maximum τ_{av} values were observed to increase for loading rates above 0.4 mm/sec. A 16-24% increase in normalised shaft resistance occurred for each log cycle increase in loading rate. So even though, cyclic loading produced an $\approx 20\%$ reduction in shaft resistance in slow tests, the data suggests that during rapid loading, loading rate effects can compensate for any degradation of shaft resistance caused by cyclic loading.

CONCLUSIONS

Field tests which examined the effect of cyclic loading on the axial shaft resistance developed on piles installed in soft clay were presented. The following observations were made:

1. A load threshold existed which separated stable from unstable load-displacement response, which is $\approx 72-85\%$ of the slow static capacity.

2. Stable behaviour exhibited constant pore pressures at the pile-soil interface throughout cyclic loading. During unstable loading, porewater pressures increased as the number of load cycles increased.
3. During unstable loading creep effects are significant, causing the rate of displacement accumulation to increase for slow tests or low frequency cyclic tests.
4. Rapid load tests yielded higher pile capacities although a loading rate threshold existed below which no benefit occurred.

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FIGURES

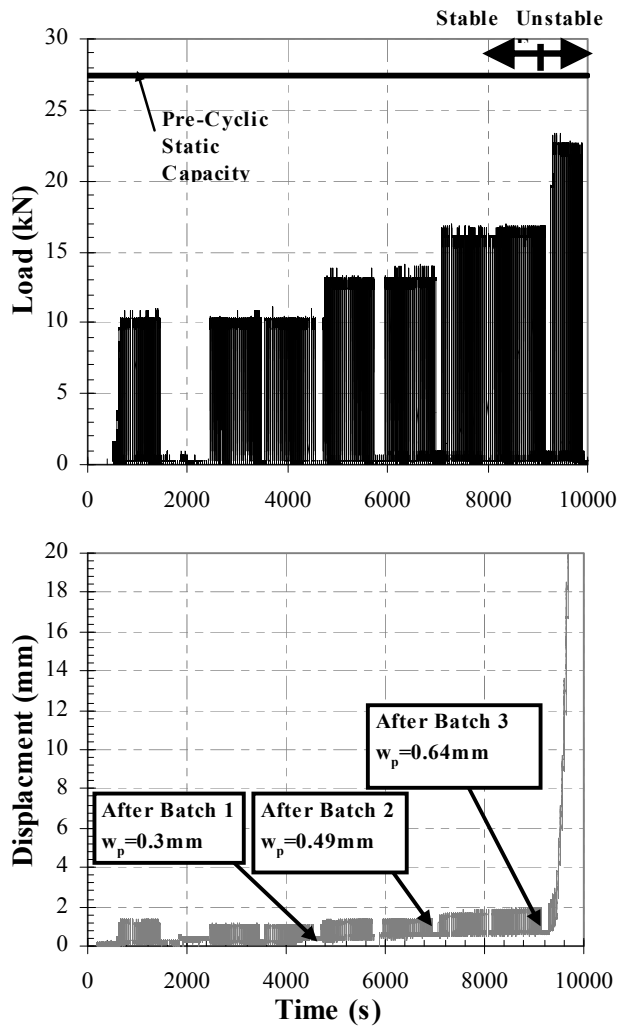


Figure 1: Transition from stable to unstable behaviour for UCDOE3-Cy1

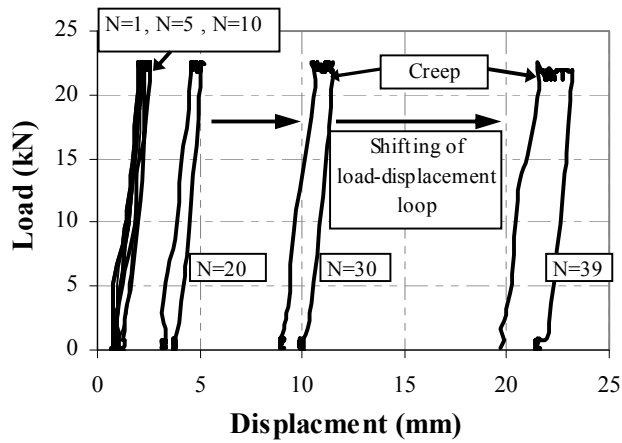


Figure 2: Discrete Load-Displacement response for individual cyclic loops during UCD-OE3Cy1

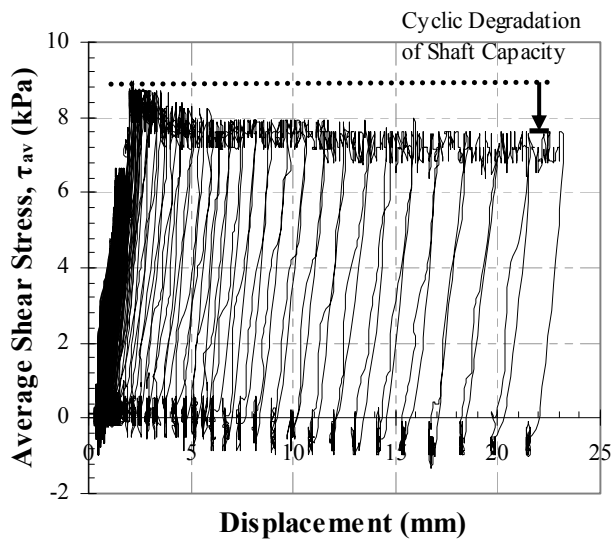


Figure 3: Average Shaft Shear stress mobilised during UCDOE3-Cy1

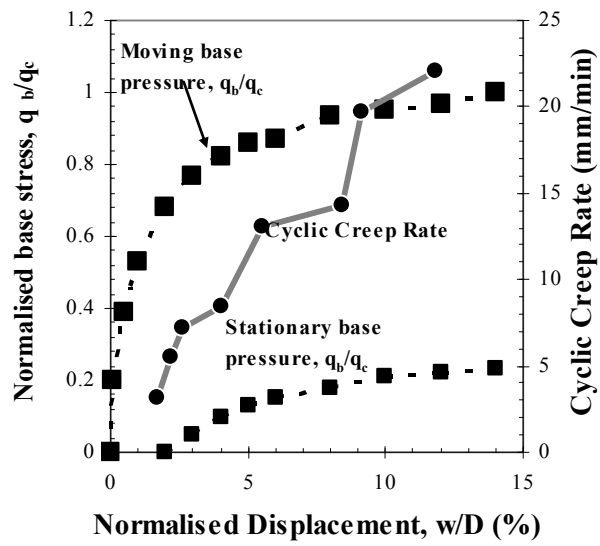


Figure 4: Base stress mobilised during UCDOE3-Cy1

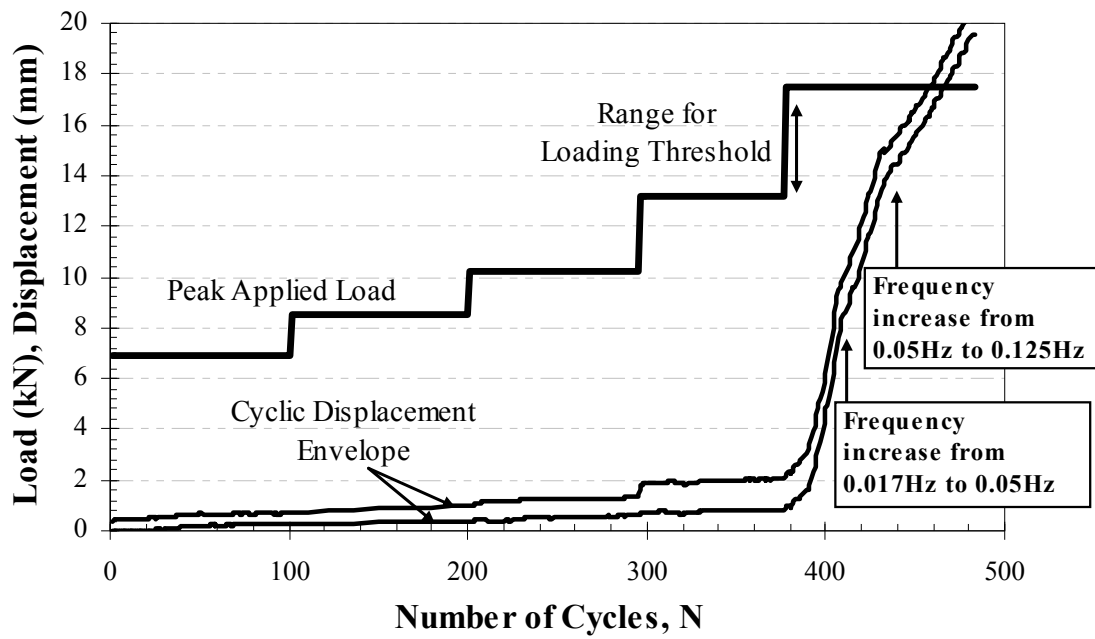


Figure 5: Dependence on Cyclic Frequency for UCD-OE2-Cy1

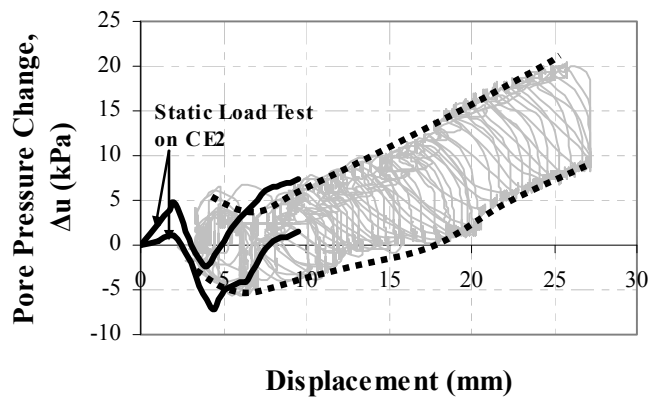


Figure 6: Pore Pressure- displacement behaviour during Cyclic testing UCD-CE4-Cy2

Table 1: Details of Model Piles

PILE	TEST	DATE	COMMENT
CE4 (D=73 mm)	Installation	02/07/2007	Jacked from a 1.45m borehole to a tip depth of 4.15m in 33 100mm strokes
	Cy1	01/08/2007	396 cycles applied at loads ranging from 1.88kN to 11.2kN
	Cy2	24/08/2007	467 cycles applied at loads ranging from 1.75kN to 9.2kN
	CRP1	24/08/2007	Rapid CRP in compression at 13 mm/s
	CRP2	24/08/2007	CRP in compression at 1.22 mm/s
OE2 (D=168 mm)	Installation	02/08/2007	Jacked from a 1.83m bore hole to a tip depth of 5.14m in 34 100mm strokes
	Cy1	23/08/2007	490 cycles applied at loads ranging from 6.9kN to 17.5kN
	CRP1	23/08/2007	CRP in compression at 1.5mm/s
	CRP2	23/08/2007	CRP in compression at 1.5mm/s
	CRP3	23/08/2007	CRP in tension at 0.72mm/s
OE3 (D=168 mm)	Installation	18/06/2008	Jacked from a 1.83m bore hole to a tip depth of 6.1m in 17 250mm strokes
	Cy1	02/07/2008	720 cycles applied at loads ranging from 10.3kN to 22.4kN
	Cy2	07/07/2008	2983 cycles applied at loads ranging from 7.95kN to 24.6kN
	CRP1	08/07/2008	Rapid CRP in compression at 1.37 mm/s
	CRP2	08/07/2008	CRP in compression at 0.068 mm/s
	CRP3	08/07/2008	CRP in tension at 0.02 mm/s