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Recent experiences of full scale static pile load testing in chalk

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ABSTRACT Historically, in London, piled foundations were designed not to penetrate the chalk layers due to concerns relating to possible contamination of the aquifer and consequences to water extraction. There is, therefore, a lack of good quality in-situ full scale pile test results available to compare with design values. With the advent of projects such as Thameslink and Crossrail and with the need to span existing underground tunnels and other sub-surface obstructions, foundation designs have required fewer piles, which have become larger and deeper to accommodate the desired design loads. The use of the O-cell bi-directional static load testing method has made it possible, not only to load to capacities unachievable by conventional means, but to quantify and separate the shaft friction and end bearing capacities of chalk at depth. Previous to this technique, designers were left guessing, because top down techniques could not mobilise the load in the chalk directly without first loading the strata above. The top down load required was often too large to be applied safely so designers resorted to scaled down pile tests and extrapolation of the results as a best estimate for larger diameter piles. Without the physical data to back up these scaling techniques, design values needed to be conservative.

Several recent test piles have been undertaken where the piles are founded in chalk. The O-cell method has allowed the point of loading to be placed within the chalk deposits directly. These tests have provided results of skin friction and end bearing parameters of the chalk which can be compared to the design values. Recent preliminary pile load tests have exceeded 100 MN, a record for the highest load mobilized in the UK (in chalk).

1 INTRODUCTION

Since there are a limited number of full scale in-situ tests which have been undertaken in chalk in the past, design values tend to be conservative and on the side of caution with limits placed on the estimation of both skin friction and end bearing capacities. Correlation between in-situ sampling and laboratory testing results are also somewhat limited and the accurate design prediction of foundation capacities is not straightforward.

The introduction of the bi-directional load test method has assisted greatly in this respect providing actual foundation behaviour results, specifically for the high loads in a safer and more cost effective manner than with traditional top down loading tests. The designer can now specify full scale static load testing to test loads previously unattainable, placing the load directly at the point of interest in order to determine the skin friction and end bearing parameters and to verify and optimise their designs. This bi-directional method of testing is compatible with deep concrete cut-offs which are now a requirement for many projects to avoid the infrastructure below the planned building or to allow ‘top-down’ construction techniques. In London, the requirement is often for larger but fewer bearing piles that may straddle underground tunnels, other sub-surface structures or even existing old piles. With the increase in load requirement placed on fewer piles, the required toe depths are deeper, penetrating the chalk.

The use of bi-directional static load testing on bored shafts with their bases within the chalk stratum has become more widespread allowing designers to add quality data to their designs values and the evaluation of piling techniques not commonly undertaken in chalk.

2 THE OSTERBERG CELL®

The O-cell® is a hydraulically driven, calibrated, sacrificial jacking device installed within the pile shaft. Working in two directions, upwards against skin friction and down-wards against skin friction and end-bearing, the O-cell automatically separates the resistance data as, in effect, two static load tests are performed simultaneously. By installing the testing apparatus within the pile shaft, the O-cell test is not restricted by the limits of overhead structural beams, kentledge or reaction beams and piles.

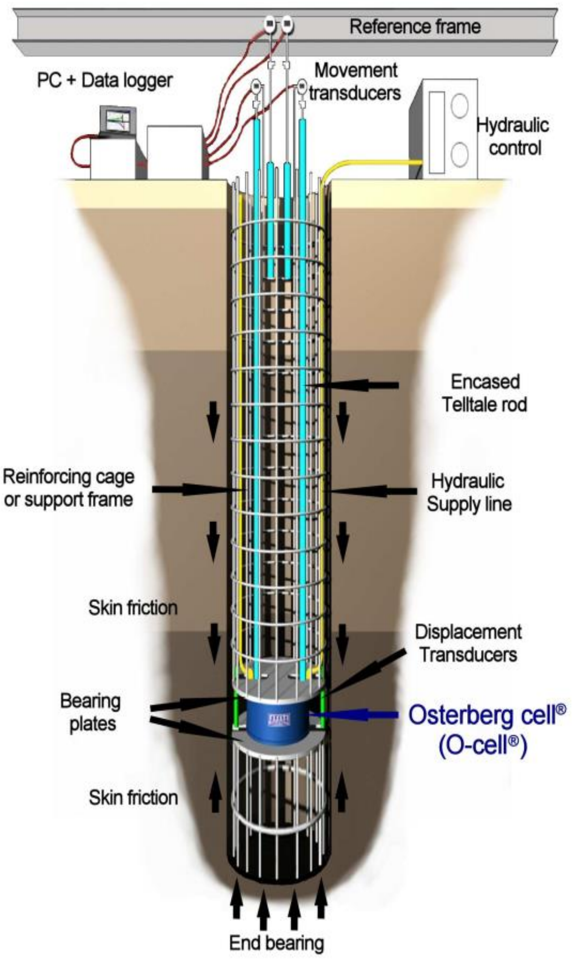

Figure 1. Bi-directional Test: General Schematic.

Each Osterberg Cell assembly is specially instrumented to allow for direct measurement of the O-cell's expansion. By also measuring the pile head movement and compression, the downward movement is determined.

Individual units range in capacities from 0.7 MN to 27 MN and can be used in multiples at the same elevation or in multiple planes, the available test capacity can be increased to more than 300 MN. If O-cells are utilised on different planes, distinct elements within a shaft or pile can be isolated for testing. The O-cells are placed between bearing plates forming an O-cell loading assembly which is welded into the reinforcement cage or carrying frame. Once the test begins, the welds holding the O-cells closed for installation are broken and the pile becomes two pile sections, one loaded statically upwards using the upper skin friction as reaction and the other downwards using the lower skin friction and end bearing as reaction.

Static load testing with the O-cell can follow any specification requirement and can continue increasing incrementally until one of two things occurs, either the ultimate capacity upwards or downwards is mobilised or the maximum O-cell capacity is reached.

2.1 How the o-cell works

In a traditional top-down static load test, the load is applied at the pile head via a reaction system. An equal force 2P is applied downward to the pile and upward to the reaction system. The load measured at the pile head is the reaction from the pile in skin friction acting upwards (F) and the end bearing mobilised (Q), 2P = F + Q.

With an O-cell placed at the toe of the pile, the load is applied at the toe. The skin friction is used to mobilise the base resistance and vice versa. Therefore, the skin friction and the base resistance mobilised are equal until one or the other reaches ultimate capacity or the O-cell system exceeds its capacity, O = F = Q. If the O-cell is placed at an elevation where equal maximum reaction can be achieved upwards and downwards, for a given displacement, the friction and end bearing mobilised downwards are in the same direction as with a traditional load test and the friction above the O-cell is mobilised resisting upward movement.

By use of embedded strain gauges, extensometers or other devices, detailed analysis of the effect of the soil along the pile shaft can be made allowing the load distribution to be calculated.

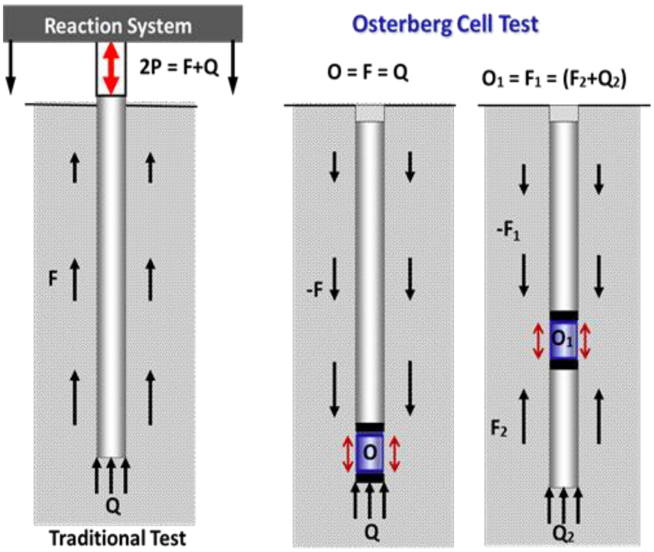

Figure 2. O-cell reactions vs top down loading.

It should be noted that because the load is applied in each direction the maximum stresses in the pile cross section are half those required in a traditional top-down loading to mobilise the same reaction.

3 CASE STUDIES

Several case studies from various locations across London have illustrated that the design values taken for chalk have been conservative and sometimes quite different to the actual chalk parameters derived from the O-cell test pile result analysis.

3.1 Case study 1: FARRINGDON STATION

The first use of the Osterberg static load testing technique within the London chalk strata was undertaken at the Farringdon Station site for the Thameslink program. Expanded Piling installed the 46.7 m long, 1500 mm diameter pile from 105.6 mAOD to 58.9 mAOD. The sub-strata, common in the London basin, consisted of London Clay Formation overlying the Lambeth Group with Thanet Sand Formation below with Chalk Group underlying the Thanet Sand Formation at 69.9 mAOD, giving a pile shaft penetration of approximately 11 m into the chalk which was described as weak, high density, unstained (Grade B3).

The pile was instrumented with strain gauges to determine the load distribution and to evaluate the skin friction along the pile shaft. Two 610 mm O-cells were installed within the pile reinforcement at an elevation of 62.0 mAOD, approximately 3 m from the pile toe. Although the bi-directional testing method does not require the concrete to reach ground level and can be left at a lower level negating the requirement for friction reducing sleeves, the requirement for this pile was to bring the concrete to ground level in a sleeved casing within the top section of the pile to a depth of 89.8 mAOD. Telltale extensometers were installed down to this level to measure the efficacy of the sleeving technique by measuring the resulting compression under load of this section. The sleeving sought to remove the skin friction of the London Clay Formation and a substantial portion of the Lambeth Group from the test.

The design working load for the pile was 15.15 MN and the test designed to load the preliminary pile to beyond design ultimate capacity estimated to be 22.7 MN of skin friction and 17.67 MN of end bearing. Since this was considered to be conservative by design, the loading steps were arranged to reach the maximum rated capacity of the embedded O-cells at approximately 52.5 MN in 12 equal steps following recommended standard procedure for load testing bi-directionally.

Once loading started it soon became apparent that the capacity of the pile would be substantially higher than that predicted by design. There is some overcapacity built into the system which allows an additional 50% load to be applied, although the hydraulic integrity cannot be guaranteed at these pressures. The scheduled steps were completed and loading continued above the rated capacity of the O-cells for a further 6 steps to the maximum possible load giving a gross sustained loading of 40.8 MN in each direction or 81.6 MN total gross load, a new UK static load testing record set back in 2010 and more than double the estimated design capacity.

At this loading, the movements of the pile were approximately 22.8 mm upwards and 53.8 mm downwards, indicating the pile had even more capacity than the maximum load applied. A mobilised skin friction value for the chalk below the O-cell was calculated to be in excess of 1,700 kPa with a mobilised end bearing pressure in excess of 9,100 kPa. Cemset® analysis (Fleming 1992, England 2006, 2008) suggests that an ultimate capacity for the skin friction would be in excess of 50 MN with 75 MN end bearing.

Given the total estimated 125 MN ultimate pile capacity, the working load of just over 15 MN would seem very conservative. The estimated skin friction from the design for the chalk had been taken as 400 kPa, which is less than 25% of the actual value calculated by analysis from the test results.

Figure 3. Cage and O-cell assembly installation at Farringdon station.

3.2 *Case study 2: NEWFOUNDLAND PROJECT, CANARY WHARF*

The initial phase of the project in 2012 involved testing a highly instrumented pile of 1200 mm diameter installed by Expanded Piling during the preliminary design phase of the Newfoundland Project to the South of Canary Wharf.

At this location, the upper London Clay Formation was not present, with ground conditions entering the Lambeth Group close to the surface, again underlain by the Thanet Sand Formation layers which cover the Chalk Group deposits.

The test specification supplied by Arup as consultant to Canary Wharf Contractors, required a bi-directional loading of 60 MN, 30 MN in each direction, with the loading assembly positioned 3 m from the pile toe, within the 5.76 m long chalk rock socket. Four strain gauges were positioned at five levels within the pile with additional mechanical extensometers at 4 levels above the O-cell position.

In order to meet the loading requirements it was necessary to install five 405 mm diameter O-cells at the required elevation. Although a tight fit, consideration was given to the arrangement to allow the concrete to flow around and past the O-cell elevation using a tremie pipe.

The design positioning of the O-cell had assumed an estimated 530 kPa as the unit skin friction for the chalk and given Fugro's previous experiences at Farringdon Station, it was expected that higher values might be obtained during testing.

During testing, the upper section of the pile proved to be the limiting factor on load applied with only 16.4 MN being mobilised in each direction. However, the estimated 530 kPa for the chalk skin friction was exceeded with a mobilised skin friction value of 647 kPa being assessed from the strain gauge analysis under the O-cell elevation. The total skin friction above the O-cell elevation was lower than anticipated resulting in the pile being fully mobilised upwards. However, the pile section below the O-cell was seen to be stiffening with increasing load and the ultimate skin friction below the O-cell, together with the end bearing capacity, would be considerably higher than the mobilised values obtained. The upper section of the pile above the chalk was subjected to micro-fracturing during concrete curing, observed from the strain gauge readings which were monitored during the curing period. Due to this micro-fracturing, analysis of the load distribution proved challenging.

Figure 4. Reference beam over the O-cell test in progress at Canary Wharf.

The movements were sufficient for the Cemsolve® model to provide a unique solution on the pile behaviour despite only 32 MN gross load having being applied. Cemset provided a modelled analysis assessing ultimate capacity in skin friction as 16 MN with 52 MN of end bearing capacity.

In 2014, a second phase design of the foundation for the tower required the piles to be placed in close proximity to the underground tunnel directly below the building footprint. A complicated design of large diameter piles cantilevered across the tunnel was required and a further test to verify the capacity of these larger diameter piles was requested.

A preliminary pile test was designed by Arup for a 1500 mm diameter, 51.3 m long bored pile with a penetration into the chalk of 12.97 m, which was installed by Balfour Beatty Ground Engineering.

With the increase in pile diameter, it was possible to install 2 x 670 mm O-cells, giving a nominal available maximum test load of 64 MN. Strain gauges and mechanical extensometers were required to determine load distribution within the pile shaft and estimate mobilised skin friction. In addition, fibre optic sensors were also installed by Cambridge University. Three levels of six strain gauges were installed below and above the O-cell assembly within and just above the chalk with a further three levels of four strain gauges within the Thanet Sand Formation and the Lambeth Group strata.

Figure 5. Assembly of the O-cell reinforcement cage inside the steel manufacturer's workshop.

A total of 18 load steps were applied to mobilise a load of 30.94 MN in each direction, where the maximum expansion of the O-cells was approached and the test concluded. The pile section below the O-cell was not fully mobilised but sufficient movement was obtained to provide the full geotechnical behaviour for design purposes.

Analysis of the strain gauge data indicated that the mobilised skin friction in the chalk was 594 kPa above the O-cell assembly and a mobilised skin friction value of 420 kPa was obtained below the O-cell level, in line with the estimated 530 kPa from the original design values, confirmed by interpretation of the extensometer results and later by the analysis of the fibre optic results.

The Cemset analysis provided an excellent model for the ultimate pile capacities with a total of 41.4 MN for the pile skin friction and 65 MN end bearing capacity.

3.3 *Case Study 3: SPIRE LONDON*

Bachy Soletanche required two test piles at their Spire London site on 2100 mm diameter piles, 57.5 m long and socketed 15.6 m into the chalk. With a SWL of 36 MN, the preliminary load test requirements were to provide an O-cell arrangement capable of exceeding 90 MN, as per the design by Robert Bird Group. To achieve this, three 690 mm O-cells were installed at approximately 12 m from the base.

The soils encountered were very similar to those at the Newfoundland Project, with River Terrace Deposits overlying the Lambeth Group (consisting of mainly stiff clay at this location) with the Thanet Sand Formation in turn overlying the Chalk, Group described as Medium Dense Granular Chalk.

Five levels of sister bar strain gauges were installed, two levels below the O-cell elevation and three levels above.

For the pile design the shaft friction in the chalk was limited to 300 kPa and an ultimate pile capacity of less than 80 MN was predicted although it was hoped that the capacity would exceed the existing UK static load test record held since the Farringdon Station project.

The test results did not disappoint, as the first test pile far exceeded the existing record with a bi-directional gross load of 53.97 MN in each direction being applied in 22 steps setting the UK static test load record at a total gross applied load of almost 108 MN. (Hard et al 2018).

The second test pile confirmed the results of the first test at a slightly lower gross load of 104 MN.

The mobilised skin friction within the chalk was substantially higher than the predicted 300 kPa with average values of 600 kPa being assessed, very similar to those values calculated at Newfoundland. However, considerable capacity below the O-cell level was not mobilised during the testing, ultimate skin friction values within the chalk below the O-cell may be considerably higher.

Figure 6. Lifting the O-cell cage to vertical ready for installation in the pile bore (Canary Wharf).

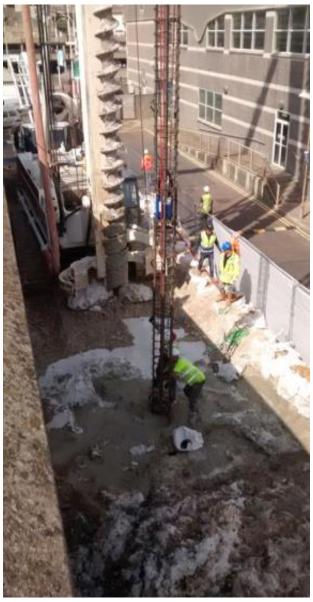

Figure 7. Installation of the 20 m long reinforcement cage with O-cell assembly into the CFA pile (Brighton).

3.4 Case Study 4: BRIGHTON MARINA

Approximately 50 miles south of London, Miller Piling required a CFA test pile in a very small footprint to evaluate the strength of the chalk for the second phase of the Brighton Marina development.

Ultimate capacity for the 600 mm diameter, 20.1 m long CFA pile was estimated to be around 5 MN. A single 320 mm O-cell was installed within the pile reinforcement so that it would sit 4.1 metres above the pile toe. The pile was constructed using grout to allow easier installation of the O-cell when plunging into the wet pile. The installation of the reinforcing cage proved to be very simple.

Testing of the pile proved that the chalk had excellent skin friction properties with the O-cell only opening 3.4 mm at a gross load of 7.88 MN with the O-cell being overloaded to well above the rated capacity. The upward and downward movements were still predominantly elastic compression with the ultimate capacity of the pile being out of reach of the load the O-cell could apply. The strain gauge assessment put the mobilised skin friction at 520 kPa although the ultimate skin friction would be much higher.

4 CONCLUSIONS

A limited set of results presented from full scale load testing with O-cell bi-directional loading have provided actual results of the in-situ behaviour of some large diameter piles installed in the chalk.

In general, it would appear to suggest our current designs could be quite conservative. It is also noted, that the unit skin friction in the chalk not only can be seen to be exceeding the design guidelines but appears to vary considerably with some areas of London, for example, having significantly larger skin friction values.

Foundation design optimisation in chalk can provide significant savings if preliminary testing full scale load testing is carried out.

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