RECENT EXPERIENCES WITH BI-DIRECTIONAL STATIC LOAD TESTING

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Static load testing, where loads are applied vertically to the top of the pile and often referred to as 'top down testing', has been used for many years and has become a 'standard' test for the world of foundation engineering.

The method, although well developed, cannot be used under certain circumstances, magnitude of load being a particular issue. There is a finite limit to the load capacity that can be applied with either kentledge, the use of reaction piles or anchors, and as the loads increase, the costs escalate dramatically.

A novel test method seeks to overcome all the associated problems of large scale and restrictive area "top down testing", utilising static load testing techniques. The method requires the foundation element to be divided into two or more sections and these can be loaded axially as required using a portion of the foundation element as a reaction.

This paper presents some recent applications and developments in the use and application of the bi-directional testing technique using the Osterberg Cell or O-cell® and outlines some of the many advantages of the system.

Recent bi-directional test loads applied to bored piles have mobilised capacities of 279 MN and with flight auger piles up to 25 MN.

Introduction

The improvements to equipment and the materials used in the construction of deep foundations, have made it possible to construct much higher capacity foundations than were thus far thought possible.

Quality assurance and quality control in the construction of large diameter, deep bored piles used in the construction of major structures is of paramount importance on-shore as well as off-shore.

In many parts of the world the maximum load that may be applied "top-down" using anchor piles or kentledge is limited in comparison to service loads demanded.

As a consequence, top-down testing is often restricted to smaller scale 'model' piles or is completely overlooked in favour of more conservative design and rigid specifications.

High quality testing programs and the acquisition of high quality data are a prerequisite for any major piling construction works.

There have been many papers written relating to the influence of side wall roughness on friction capacity of piles. Work undertaken by Seidel and Collingwood (2001), and comments by M.W. O'Neill (1998) have indicated that the influence of side wall roughness may have a significant inverse relationship between the unit skin friction and pile diameter, especially in rock sockets.

The difference in unit skin friction between piles of different diameter, even where the construction process may be the same in every other aspect, can be large. In general, the cause may not be attributable to surface roughness alone.

In practice, the use of piles of different diameter for modelling purposes should be used with caution. Hayes (2005), points out some of the initial findings of full scale tests in shale, where a remarkable decrease of unit friction with increasing diameter is deduced.

These difficulties are of great importance when the designer considers testing piles of a reduced diameter instead of full size pile testing. Adopting this approach may lead to an unsafe extrapolation of the measured unit skin friction from smaller 'model' test piles to larger diameter piles used in production. Although the usual reasons for this approach are related to cost when the required loads are high for top-down loading, this is not the case with bi-directional testing.

Bi-directional Testing

Since inception, the Osterberg or O-cell®, has radically changed the way some foundation load tests are designed, performed and interpreted.

The patented bi-directional O-cell® testing technique has now been used extensively world-wide. Loads mobilised have exceeded national records for loads on auger bored and flight auger piles.

Scaling errors can be totally eliminated by testing the full size production piles using this method. Ground conditions, not the test method, now determine the magnitude of load that may be applied.

The subsequent performance of an O-cell® tested working pile will be similar to the non-tested production piles due to the lower amount of generated residual stresses in the pile, as compared to applying full test loads "top-down", so integration into the structure, after post-test grouting, is advantageous.

By the use of a hydraulically driven, calibrated, sacrificial jacking device, (the O-cell®) installed within the pile shaft, one portion of the foundation element is tested against the other. In effect, two static load tests are performed simultaneously, working in two directions, upwards, against skin friction and down-wards, against skin friction and end-bearing.

Each O-cell® assembly is specially instrumented to allow for direct measurement of the expansion. By also measuring the pile head movement and compression, the movement of each of the elements can be determined.

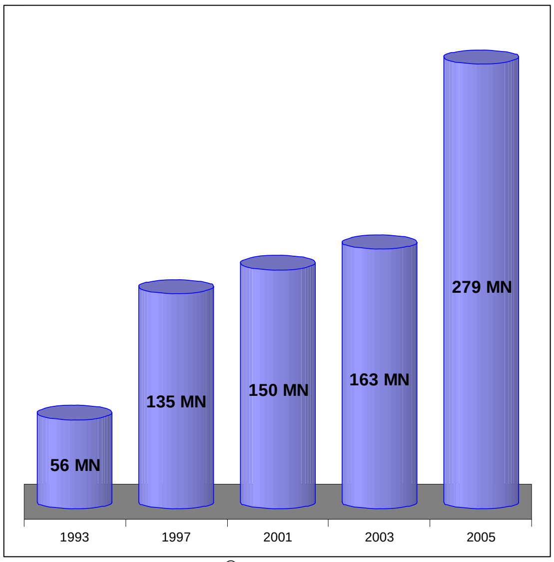

Figure 1. O-cell® history of maximum test loads applied

Installing the testing apparatus within the pile shaft means the bi-directional test is not restricted by the limits of overhead structural beams, kentledge weight or reaction piles. The many associated problems of assembly, use and safety of external reaction systems at ground level are eliminated.

This advantage proved very cost effective on one major bridge construction contract in Tunisia, where the ground conditions consisted of very soft alluvial clays to depths of up to 400 metres.

A top down test was considered which would require either several anchor piles to lengths equal to or in excess of the test pile or heavy kentledge that may be unstable on the soft ground.

A bi-directional test using one O-cell® assembly in a 1500 mm diameter pile was installed at 21m above the pile toe in a 60 m deep bored pile. To accommodate predicted large movements, an extended stroke O-cell® with up to 225 mm travel was used.

The load test was carried out using the whole of the 225 mm stroke available mobilizing an effective total capacity of 16 MN (8 MN in each direction).

Where steel columns have been cast in the top of the pile, these often interfere with top-down testing techniques, and the O-cell® testing method is likely to be the only cost effective way of performing a full scale static load test on these piles.

A range of different size O-cells now exist, with capacities from 0.7 MN to 27 MN. By using multiple O-cells on a single plane, the available test load can be increased to more than 235 MN. If O-cells are utilised on different planes, distinct elements within a shaft or pile can be isolated for testing (see Figure 2).

Figure 2 Multi-level bi-directional test over water.

Recent tests undertaken at Incheon Bridge, Korea illustrate this point. The testing was undertaken on full-sized large diameter piles to loads believed to be impossible to achieve by other techniques. By installing multiple cells on one level (Figure 3), combined upward and downward loads of over 280 MN have been achieved.

The test programme at the Incheon Bridge is a tribute to the foresight and execution of the work by Samsung Corporation for the concessionaire, KODA Development Co., (with 51% AMEC and 49% Incheon City ownership). Daewang E&C Co. were the foundation contractor for the four preliminary test piles (European Foundations Autumn 2005). The load-movement curves for the largest of these tests are shown later in Figure 8.

The bi-directional testing technique also allows the testing of piles with deep cut-off levels. At the tests at Incheon Bridge, the concrete was brought up to the seabed level, 14 m below the average water level.

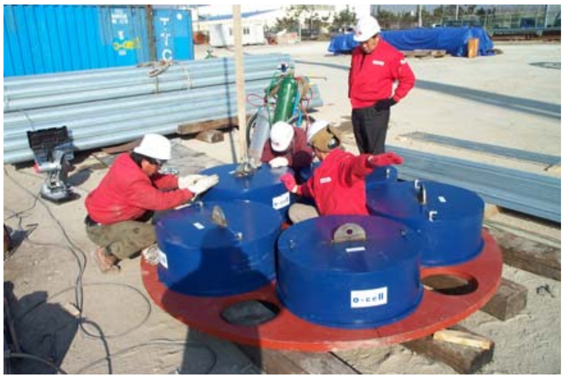

Figure 3 Multiple O-cell assembly for a 3m diameter pile in Korea.

A testing programme in the heart of Frankfurt, city centre, on the main shopping street, "Zeil", (this street is amongst those of the highest pedestrian traffic in Germany), required an evaluation of a 10 m rock socket in the Limestone 45 m below existing ground level.

Using to advantage a feature unique to bi-directional tests, only the section of pile in the rock socket was concreted and the remainder of the bore (35 m) backfilled with granular material for stabilisation. Subsequently the pile was base grouted and a 5 m test section shaft grouted (It is typical practice to shaft and base grout piles in the Frankfurt limestone).

The test element was separated into two sections of 5 m mobilising in excess of 78 MN.

These and similar techniques can be used where high capacity is required in deeply buried rock or soil formations. The load can be applied directly without load shedding in overlaying soils, eliminating the need for de-bonding techniques.

In Moscow City, a design for the foundations of several impressive projects required piled raft foundation solutions. One of the key questions regarding the design was the ultimate end bearing capacity in the Suvorov Limestone. A top down test was considered which would require complex sleeving through the caprock and a 19 to 20m thick Voskrensky clay layer. As an alternative, bi-directional testing was used with the O-cell® assembly cast close to the pile toe to load the Suvoroy Limestone layer directly.

Testing was performed on 900 mm and 1200 mm diameter piles, located on three separate plots. The maximum mobilized capacity was in excess of 60 MN.

Installation

The O-cell® assembly is installed into the pile cage or carrying frame, either at or close to the pile toe, or along the shaft at a level where approximately equal capacity will be available above and below.

Figure 4. Cage showing O-cell® assembly attached for a 0.9m pile – State of Qatar

The pile is constructed as normal and the cage is placed in the pile bore with the O-cell® assembly attached. Electrical and hydraulic connections are made and cables and hoses are brought to the pile head. A guide arrangement is constructed to aid insertion of the tremie into position where appropriate. Concrete is then pumped as normal into the pile shaft and around the O-cell® assembly.

The required work area, both overhead and laterally, is greatly reduced vs. any other static load testing system. Testing has been performed inside buildings, under overpasses, in highway central reservations and at offshore locations.

Figure 5. Bi-directional test in progress (at 163 MN) West Virginia, USA

Safety

The safety considerations with 'top-down' testing are sometimes challenging, especially at high loads as very tall kentledge assemblies need to be constructed or reaction beams need to be assembled high off the ground. In contrast, bi-directional testing has all reactions generated from within the pile itself.

As illustrated in Figure 5, apart from a horizontal beam used purely for reference, all that is visible at ground level is the pile head and the top of pile instrumentation. The size of the test area is little more than the perimeter of the pile shaft.

Method of operation

When load is applied with top-down testing at the pile head via a reaction system, an equal force, P, is applied downward to the pile and upward to the reaction system. All of the load measured at the pile head is applied to the pile, mobilising skin friction and the end bearing, P=F+Q.

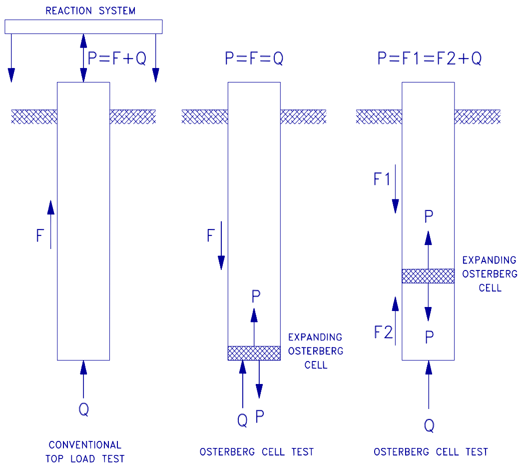

Figure 6. Test method comparison

With an O-cell® placed at the toe of the pile, the load is applied directly to the end bearing. 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, P=F=Q.

Where the skin friction (F1+F2) is expected to be higher than the base resistance, the O-cell® can be placed at some balance point along the pile shaft where P=F1=F2+Q. The pile element above the O-cell® uses the friction and end bearing below as a reaction (Figure 6).

By use of embedded strain gauges or other devices, detailed analysis of the soil properties along the pile shaft can be made.

Using the O-cell®, the application of deep foundation load testing has been elevated, from expensive, time consuming, small scale field tests, to state-of-the-art, cost effective full scale static load testing of dedicated preliminary or working piles.

Testing Procedure

Once the O-cell® system has been installed within the pile shaft and the placed concrete has reached sufficient strength, the test can commence.

Gauges are connected to a data logger (Figure 7) and the system can be run under computer control.

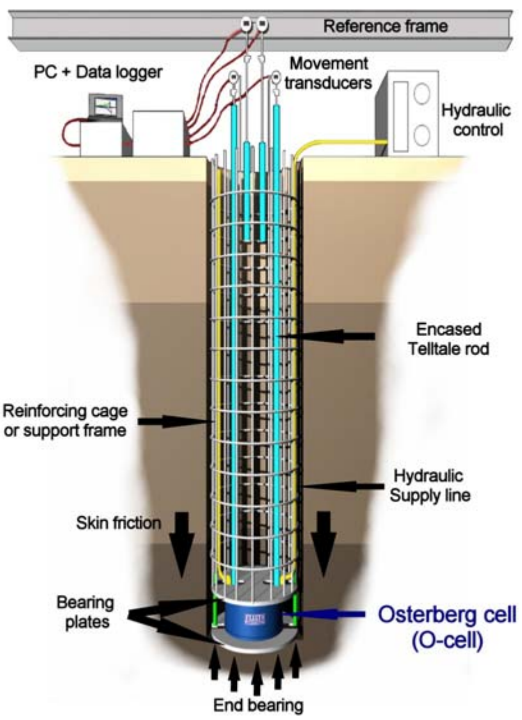

Figure 7. Bi-directional test schematic

When the O-cells are first pressurised, the load applied will break temporary welds (to prevent the O-cells from opening prematurely during assembly) and form a horizontal separation across the pile at the O-cell® location.

Once this is done, the test can be performed much the same as a top-down test, by applying the load in stages and measuring movements of each of the components. Testing schedules can be adopted from standard procedures or by recommendation. References are also taken at the pile head by precision digital level.

The readings can be displayed graphically as the test progresses. Thus, load/displacement data recorded above and below the O-cell® level is available for immediate assessment (as that illustrated in Figure 8).

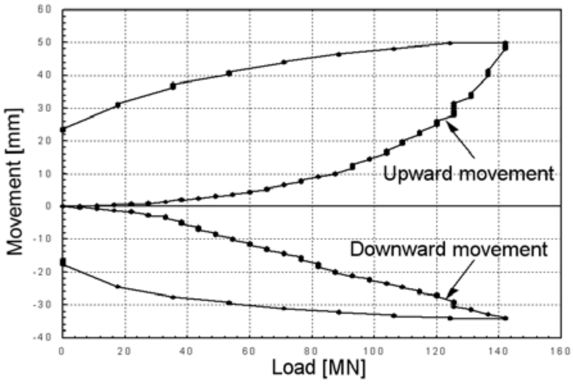

Figure 8. Load-Movement Curves Incheon Bridge - Korea

Since the load applied is in two opposite directions simultaneously, the total load mobilised in the pile is twice that applied by the O-cell® system, allowance can be made for the buoyant weight of the pile. The stresses within the concrete are, therefore, half that required by an equivalent top-down load test.

Comparisons of static loading results between “top-down” loading and bi-directional testing have provided excellent correlation.

Importance of High Quality Data

Good quality static load testing is recognised to be important. However, the significance of maintaining the load truly constant and the potential for analysis of the displacement–time behaviour with methods such as Timeset®, England (1992) to facilitate the long term load-settlement analysis of the pile behaviour is not always obvious.

Further, in some recent tests, the displacement-time analysis has been applied to the evaluation of skin friction under cyclic loading

There is a perceived danger (in particular cases real) of some soils exhibiting some form of structural collapse upon disturbance. These have been recognised as typical of specific calcareous deposits and a consequence that is relatively easy to detect is degradation of skin friction with axial cyclic loading.

In order to correctly interpret that degradation of skin friction may occur in a given set of conditions, it is imperative that the load applied is restored to the same values with a high degree of accuracy (<1% variation). Some of the merits of constancy of load holding are described by England (2002).

Further, since there is likely to be creep taking place, i.e. movement of the pile with time, one needs a means of interpreting the expected creep behaviour from the data measured, in a manner that allows assessment of any additional displacement recorded being due to cyclic loading may be indicative of degradation of skin friction.

If cyclic loading is performed without means of comparison to anything else, or without due attention to the creep which will be present in the data; one would expect larger displacements to be recorded for every cycle of loading. As a consequence, one could erroneously interpret some form of degradation of skin friction as a result in all cases.

A method devised for appraisal of this has been to apply a truly constant load (<0.2% variation) for sufficient time (say 3-6 hours) to ensure a unique Timeset® (displacement-time model) analysis can be derived for this reference load. The load cycling can then be to a lesser load (say 75% or 50% or the reference load – often significantly higher than the expected "live load") and returning to the reference load in 10 to 100 cycles.

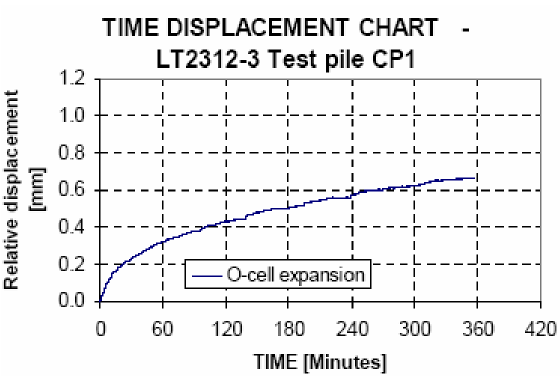

Figure 9 –Displacement Time Chart for 6 hour hold of constant load

The interpretation can be by comparison of the displacements recorded upon return to this reference load for each cycle with the projected displacement that would have occurred if the reference load had been held for a longer duration.

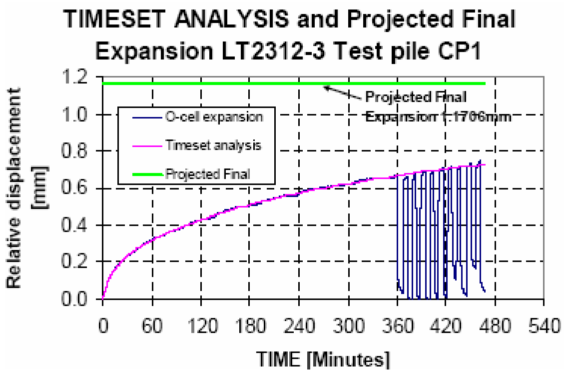

Figure 10 –Displacement Time Chart showing cyclic loading and additional displacement

The displacement-time data measured for the O-cell® expansion, shown by way of example in Figure 9, from a testing programme on a 1.5m diameter pile in Doha, Qatar, where a constant load of 8.30 MN was applied. Figure 10 illustrates this same data, matched with the double hyperbolic model and extended to cover the time when 10 cycles of unload to approximately 50% and reload were applied.

As illustrated in detail in Figure 11, there appeared to be some additional displacement recorded on each cycle, which, when compared to the projection (or expected creep behaviour for that load) suggested that the additional movements for each cycle were expected and not a result of degradation of skin friction.

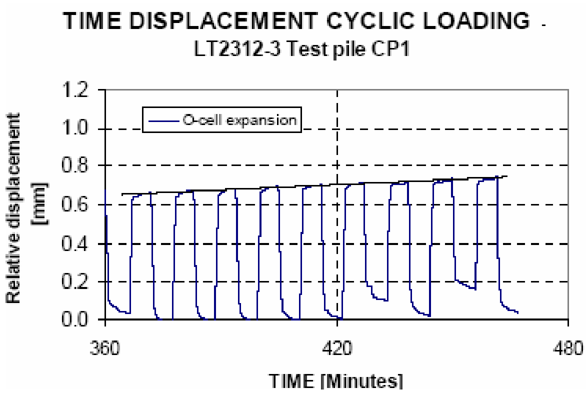

Figure 11 –Displacement Time Chart for 100 minute cyclic loading

In the limited number of cases in sand and in chalk where this form of analysis has been performed on axial pile behaviour in this manner, it has not been possible to conclude that any reduction in skin friction resistance was induced by cyclic loading.

TYPES OF PILES TESTED

As well as increasing the limits of testing capacity, the limits of the system capabilities are also expanding. In addition to conventional bored piling, the test method has been developed to encompass other piling techniques.

Continuous Flight Auger (CFA)

Some of the deepest CFA (auger cast) piles are being constructed in Miami. Employing grout in some of these piles, depths beyond 50 m have been constructed.

O-cells have been placed within these piles, plunging the reinforcing cage and test assemblies to depths of up to 50 m. Utilising a modified O-cell assembly design to facilitate plunging the entire cage into the wet grout/concrete, O-cells of significant cross sectional area with respect to the pile diameter, have been used. Table 1 illustrates limits of the geometries employed so far.

CFA piles using grout with pea shingle (<10mm) have also been tested, plunging the O-cell® in to the wet cementitious mix to depths of up to 30 m and pile diameters of 610 mm and 760 mm (Figure 12).

Test loads for CFA piles have been up to 25MN so far.

Figure 12 CFA pile installation in Miami

Table 1 Examples of the biggest and deepest CFA piles tested to date

Pile diameter [mm]	O-cell® diameter [mm]	Pile Depth [m]	Test Load [MN]
610	330	31	12
760	405	38	18
760	405	51	12
760	540	37	25

Pre-cast driven piling

When reaction piles are used for top-down static load testing of pre-cast driven piles, their installation may lead to increased capacity due to densification of the ground or lifting of the test pile due to heave during driving of the test pile or the anchors.

These difficulties have been overcome by casting the O-cell arrangement within the pile at manufacture (Figure 13).

Figure 13 Placement of O-cell® in pre-cast pile at manufacture

Only the test pile has to be installed at the test location since no anchor piles are required for reaction. Figure 14 shows a typical pre-cast pile under test.

Figure 14 Testing of pre-cast pile over water.

Tests have been performed on square precast piles of 300mm, 450mm 600mm and 750mm.

There is no fundamental restriction to the size and capacity pile which can be accommodated.

Barrettes

O-cell® technology is not restricted to piled shafts/bored piles.

The inclusion of O-cells during the construction of barrettes (Figure 15) has allowed full scale testing of these elements. They have the added advantage, when using multiple O-cells, of evenly distributing the load along the length of the element. The required test loads for barrettes normally exceed the testing capability of top-down loading methods.

Figure 15 Placement of O-cells in a barrette cage, test capacity 88 MN – Dubai, UAE

Dedicated Preliminary Piles

Where the pile to be tested is to be used solely for the purpose of testing, i.e. for a preliminary pile test, construction of a full-scale steel pile cage is not essential. A specially constructed carrying frame can be used to place the O-cell® assembly or assemblies at the exact depths required and to facilitate construction and integration of the instrumentation (Figures 16 & 17).

Figure 16 Carrying Frame used at Weida Bridge, Germany for a multi-level bi-directional test.

Figure 17 Dedicated carrying frame and O-cell assembly ready for installation

Summary of bi-directional testing experiences using O-cell® technology.

- Some of the largest loads on bored piles and CFA piles have been applied.
- Use of bi-directional O-cell® testing technique enables collection of full-scale data even under the most extreme and difficult conditions.
- No reaction system is required at ground level and the test energy is safely buried well below ground.
- The bi-directional test is a static maintained load test and has benefited by the use of automatic data acquisition techniques and load maintenance for accurate, efficient data processing and analysis.
- The O-cell® test method particularly excels in offshore testing environments and the top of the foundation element does not need to be cast above water.

Ground conditions together with the capacity of the foundation element and not the test method determine the limit to the magnitude of load applied.

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