Osterberg Cell (O-cell®) method of Static Pile Load Testing in Korea
오스터버그 셀(O-cell®)을 이용한 말뚝 정재하시험의 국내 적용

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SYNOPSIS : 그 동안 몇 차례 오스터버그 셀(O-cell®)을 이용한 양방향 말뚝 재하시험기법이 국내에 성공적으로 소개/적용된 바 있다. 이 방법은 상대적으로 새롭고 독특한 방법으로서 시험비용과 기존 재래적인 시험방법이 적용상 제한을 받는 경우나 대규모 시험에서 발생할 수 있는 문제점들을 극복할 수 있다. 국내에서는 설계목적을 위한 시험말뚝 뿐 아니라 설계하중이 큰 실제말뚝에 대한 시험이 증가하는 추세에 있다. 이 논문에서 소개하는 양방향 재하시험 방법을 적용하면 기존의 소규모 재하시험 방법에서 발생될 수 있는 주면 마찰력과 선단지지력의 분리측정이나 각각의 지지력에 대한 극한상태를 확인하지 못하는 한계를 극복할 수 있고 시험하중이 270MN을 초과하는 경우까지 적용할 수 있는 장점을 갖고 있다. 본 논문에서는 오스터버그 셀을 이용한 정적 재하시험 방법에 대하여 말뚝종류별로 상세히 기술하였으며 이 시험방법의 장점과 국내현장에 적용되었던 사례를 소개하였다.

Key words : O-cell®, Bi-directional test, Static load test, Osterberg cell

1. Introduction

With improvements to equipment and the materials used in the construction of deep foundations, it is now possible to construct very high capacity foundations. It is therefore even more important to have good quality assurance and quality control in the construction of large diameter, deep bored piles.

As a tool for determining pile capacity and pile performance the Osterberg cell (O-cell®) method, a relatively new and efficient method, overcomes the typical limitations associated with kentledge and anchor reaction systems used for conventional static load test methods. In Korea the typical load limitation for conventional static load test methods are 2-3,000 tons. As a consequence, conventional ("top-down testing") is often restricted to smaller scale 'model' piles or is completely overlooked in favour of more conservative design and rigid specifications. 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 conventional static load testing ('top-down loading'), this is not the case with bi-directional testing.

2. Bi-directional Testing

Dr. Osterberg's invention, the Osterberg Cell, or "O-cell®", has radically changed the way deep foundation load tests are designed, performed, and interpreted. In recognition or this achievement, he won the NOVA Award in 1994. The prestigious NOVA Award is given by the Construction Innovation Forum, an international non-profit organization (established in 1987), which recognizes innovations leading to improved efficiency and cost effectiveness in the construction industry. Nominations for this award are made from all segments of the construction industry and represent efforts of owners, contractors, architects, engineers, and others. The nominations represent proven cost savings and quality improvement on actual projects. The NOVA Award, which has been referred to as the "Nobel Prize" for construction, is awarded annually to noteworthy innovative solutions, processes, or products that improve the quality, efficiency, and cost effectiveness of construction.

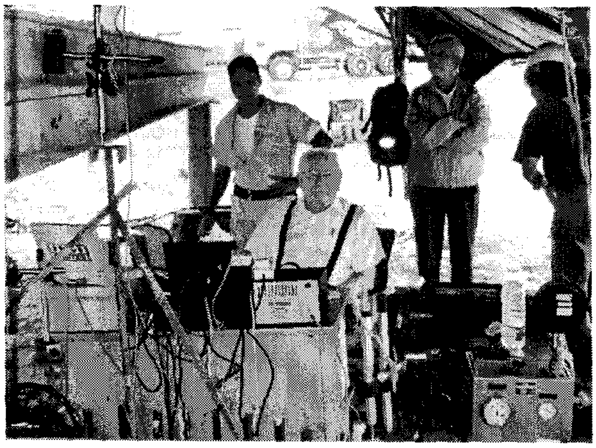

Figure 1. Dr. Osterberg, J.O. (seated) at a O-cell® pile load test for Hyundai construction, Singapore MRT-NEL 1999

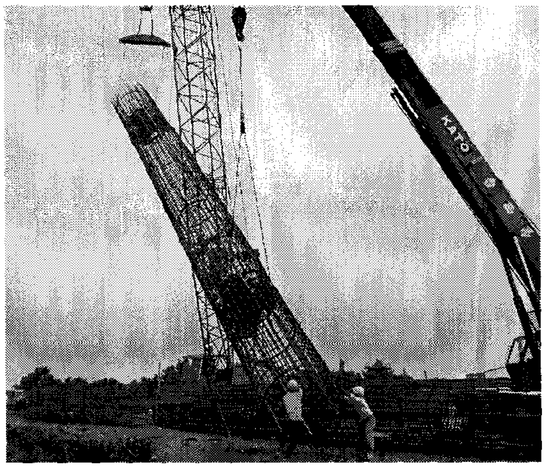

Figure 2. Multi-level bi-directional test installation for Taiwan High Speed Rail (HSR) Project October 2000.

The patented bi-directional O-cell® testing technique has been used extensively worldwide. The O-cell® method was for the first time used on a large scale in Asia for the Singapore MRT North-East Line in 1998-1999. Hyundai Construction realised substantial cost savings on this project by increasing the pile diameters (up to 2.4m diameters in old alluvium soils) but they required a method of testing loads in excess of 10,000 tons. LOADTEST Inc from America who is licensed by Dr. J. O. Osterberg to perform bi-directional testing could with the O-cell® method test these high capacity piles. Over a 2-year period 12 preliminary and 18 proof tests were successfully performed. Dr. Osterberg visited the test site in 1999 (see Figure 1).

The method is continuously breaking records for loads on large diameter bored piles and is performing tests in conditions that were previously thought impractical or impossible. The bi-directional pile testing method is now providing confidence in deep foundation design and construction in conditions which conventional static load testing cannot meet.

2.1 The O-cell®

The O-cell® is a hydraulically driven, calibrated, high-capacity sacrificial jacking device, with a unique design, which can allow for a tilt of up to 3-5 degrees across the O-cell®. Tilting can typically occur when the O-cell® is located near the pile base and the base provides uneven reaction. The loads are, even in these extreme conditions, applied without generating large internal jack friction commonly incurred with conventional jacks, even under ideal conditions. It is therefore possible to calculate loads by directly relating the measured applied hydraulic pressure, using the calibration report, which is not possible when using conventional hydraulic jacks (load cells are commonly used for the load measuring).

The O-cell® is installed within the pile shaft, with one portion of the foundation element 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 of the O-cell® or for measuring downward O-cell® movements. By also measuring the pile head movement and compression, the movement of each of the elements can be determined.

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. This eliminates the many problems associated with assembly, usage and safety of these conventional external reaction systems at ground level.

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 horizontal plane, the available test load can be increased to more than 270 MN. If O-cells are utilised on different planes, distinct elements within a shaft or pile can be isolated for testing (see Figure 2). There are no cast-in-place foundations that cannot be tested due to difficult location or access restrictions.

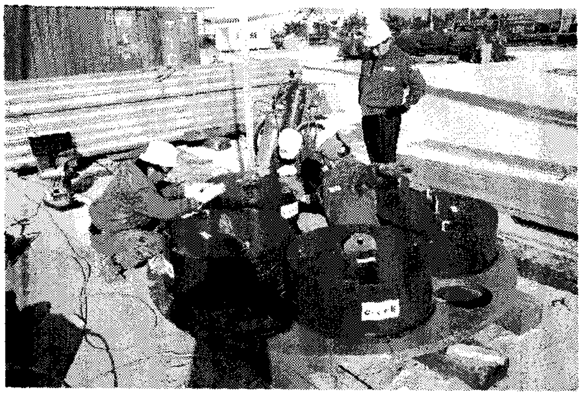

Figure 3. Multiple O-cell® assembly for a 3m diameter pile in Incheon 2nd Bridge link, Korea.

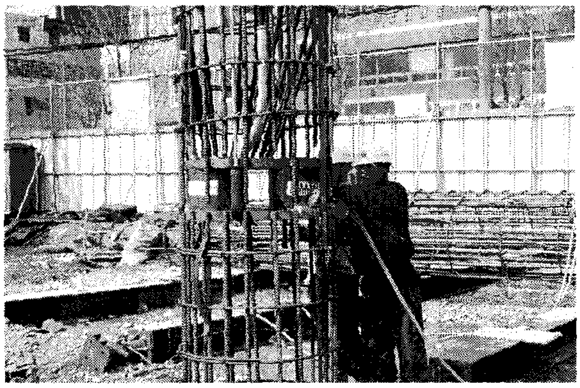

Figure 4. O-cell® Installation using 2 O-cells on same plane, Bando Bora sky view building, Busan Korea. May 2003

The World record 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 280MN 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. was 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 9.

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 metres below water level.

2.2 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.

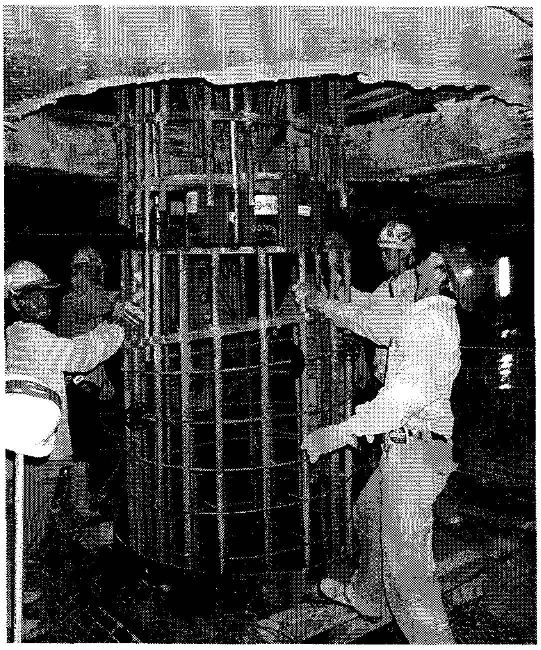

Figure 5. Installation of O-cell® instrumented pile cage inside existing building basement, New Supreme Court building, Singapore February 2002.

Figure 6. Bi-directional O-cell® test in progress, Bando Bora sky view building, Busan Korea. May 2003

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 placed with the tremie as per normal, up and around the O-cell® assembly, until cut-off level.

The required work area, both overhead and laterally, is greatly reduced when compared to any other static load testing system. Testing has been performed inside buildings (Figure 5), under overpasses, in highway central reservations and at offshore locations.

2.3 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 within the pile itself.

As illustrated in Figure 6, 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.

2.4 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.

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 7).

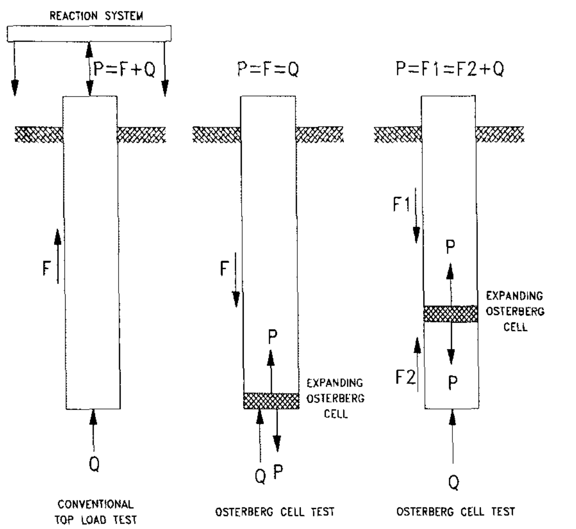

Figure 7. Test method comparison

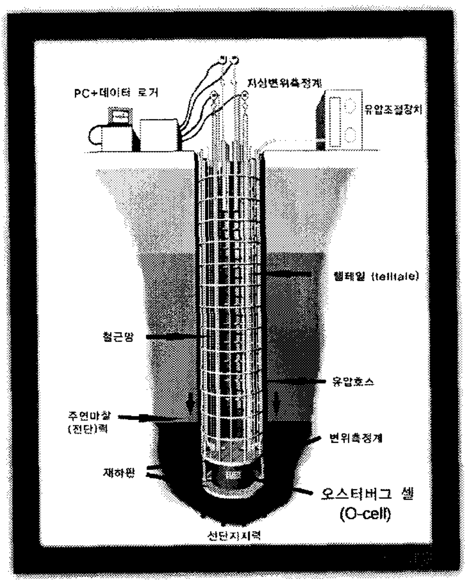

Figure 8. Bi-directional test schematic

By use of embedded strain gauges a detailed analysis of the soil capacity 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.

2.5 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 8) and the system can run under computer control.

When the O-cells are first pressurised, the load applied will break temporary welds. These welds prevent the O-cells from opening prematurely during assembly and are especially suited for this (as opposed to small steel members) since the breaking only requires minimal strains (less than 1-2mm) in order to 'break clean'. Once the welds break, the pressure (applied load) will drop and the pile is unloaded immediately before the actual testing is started. Any other method using steel members would incur larger strains, which would affect the measured load versus movement behaviour by reinforcing the separation plane. A horizontal separation across the pile at the O-cell® location is then successfully created and 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 conventional static load test procedures or by recommendation. However, it is highly recommended on instrumented bi-directional testing to perform one loading cycle (until full required load) and to apply loads in equal loading steps (minimum of 20 steps until full loading) and of equal time durations (about 15-20 minutes) for each increment. 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 9).

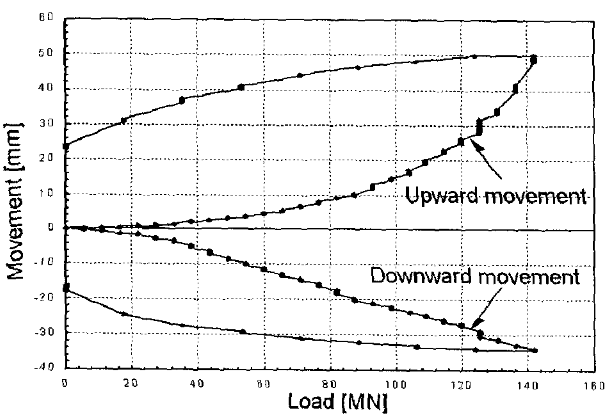

Figure 9. Load-Movement Curves Incheon Bridge, Korea

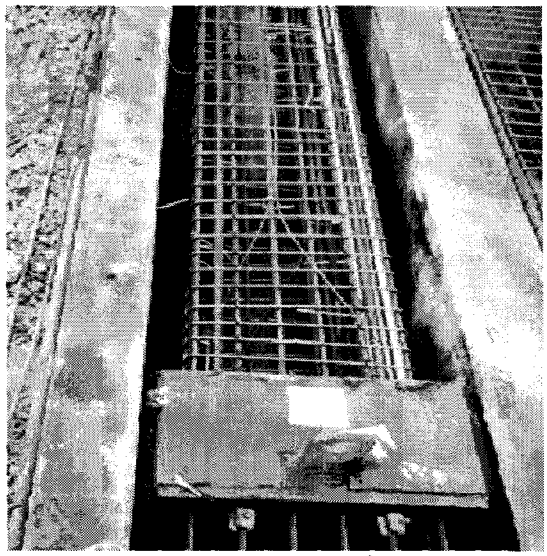

Figure 10. Placement of O-cell® in pre-cast pile at manufacture

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. In order to make a load-movement comparison between bi-directional testing and 'top down' testing it is necessary to analyse the measured compression and/or load distribution occurring in the bi-directional test. A calculation of the equivalent 'top down' displacements that would occur if the bi-directionally tested pile was loaded from the pile head can then be made by adding additional elastic shortening which would have incurred in a 'top down' loading. This approach is fairly straightforward and detailed studies have shown that even a simplified method treating the two pile segments as one element each, can be used without affecting the results.

3. 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.

3.1 Bored piles

The O-cell® method was initially envisioned to provide testing of rock capacities in bored insitu cast piles. The method is especially suited for this pile type since the test loads are applied directly to potentially deeply buried high capacity rock formations without the need for load shedding / transfer through the overburden soils. Conventional static load testing can only achieve this with expensive and sometimes challenging or impossible de-bonding of the upper pile section above the rock layer(s). The majority of the over 1000 O-cell® tests performed worldwide to date is on Bored Piles.

3.2 Continuous Flight Auger (CFA)

Pushing forward the boundaries of CFA piling, some of the deepest ever CFA (auger cast) piles are being constructed in Miami, USA. O-cells have been placed within these piles, plunging the reinforcing cage and test assemblies to depths of up to 50m. 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. Test loads for CFA piles have so far been up to 25MN.

3.3 Pre-cast driven piling

When reaction piles are used for conventional 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.

By casting the O-cell® arrangement within the pile at manufacture (Figure 10), these difficulties can easily be overcome. Only the test pile has to be installed at the test location since no anchor piles are required for reaction. Figure 11 shows a typical pre-cast pile under test. Tests have been performed on square precast piles of 300mm, 450mm 600mm and 750mm.

There is no fundamental restriction to the size and capacity of piles, which can be accommodated. Currently a research program is under development by LOADTEST (Korea) Co Ltd and Dong-A University to perform O-cell® testing on a PHC piles (segmental circular pre-stressed concrete driven pile) near Busan in Korea.

3.4 Barrettes

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

The inclusion of O-cells during the construction of barrettes/slurry walls (Figure 12) 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.

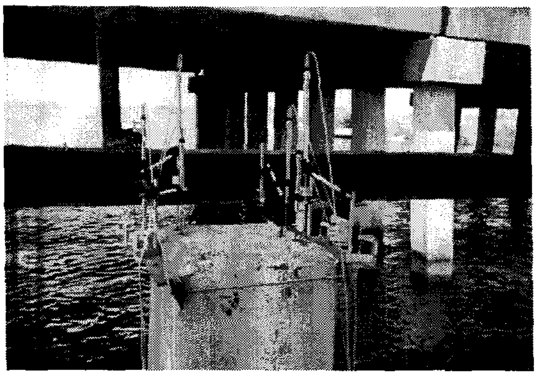

Figure 11. Testing of pre-cast pile over water.

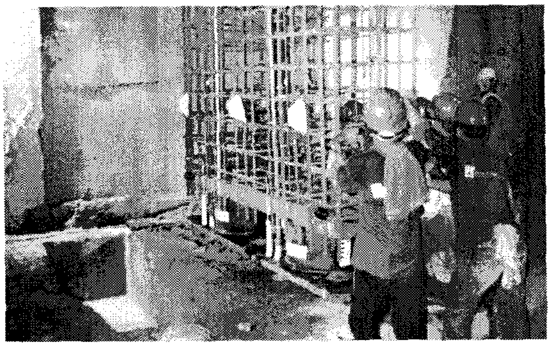

Figure 12. Installation of barrette instrumented with two O-cells for Alfaro's Peak, Manila, Phillipines, 1998

3.5 Dedicated Preliminary Piles

For preliminary test piles, dedicated for testing only, construction of a full-scale steel reinforcement 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 (Figure 13).

3.6 Proof tests on working Piles

The principle of the bi-directional test method is to separate one pile into two pile segments by loading them against each other. It is therefore necessary on production piles (working piles) to reconstruct a connection between the upper and lower pile sections for carrying compression working loads below the O-cell® level under working conditions in the finished structure.

It is possible to test production piles (working piles) by using the patented O-cell® fluid return system, which, besides allowing for de-airing the hydraulic fluid, also allows replacement of the hydraulic fluid with a solid. In practice, the O-cell® hydraulic fluid is replaced with a non-shrink grout by pumping through one end of the hydraulic line and thereby replacing the hydraulic fluid out through the other return line.

Once the grout is cured this confined solid will allow for load transfer through the O-cell(s) without relying on "locking" a fluid inside the hydraulic system (O-cell®) throughout the lifespan of the structure.

In addition to grouting the interior of the O-cell®, the void created around the O-cell® (with a height equal to the O-cell® expansion at zero load after completed testing) is also grouted. It is more of a cosmetic operation on which the load transfer between the two disconnected pile sections does not rely.

If the working piles are subjected to tension loads and bending moments, it is important to check that the available capacity of the upper pile section above the O-cell® level is sufficient for carrying these tension loads under working conditions.

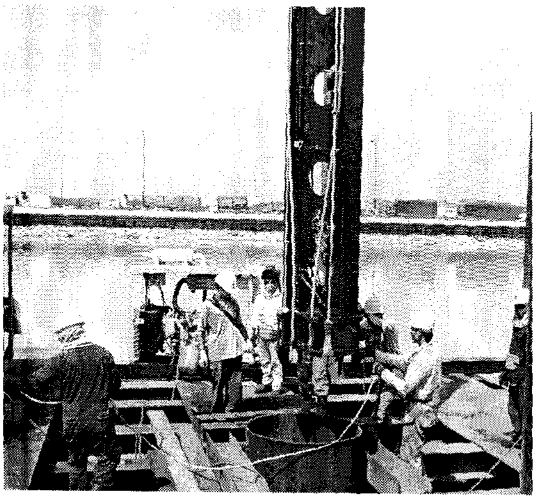

Figure 13. Carrying Frame with 2 O-cells Johor Bahru, Malaysia to Singapore new 2nd link causeway, August 2002.

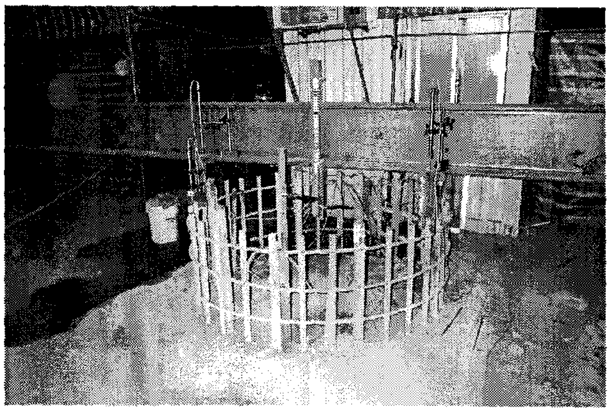

Figure 14. Advantage of improved safety: O-cell® Testing of bored pile for Taiwan HSR Project C260 in 2000. All energy is in the ground and not overhead.

Since the O-cell® level is typically located lower than 2/3 of the full pile length there is typically no tension loads from bending moments at the O-cell® location. And since 1/2 the applied test load is applied upward and the applied test load is typically minimum 150% of the compression loads, the O-cell® test would essentially provide information on the available 'tension' capacity equal to minimum 75% of the working compression loads.

In most compression piles the tension load requirements are much less than 75% of the compression load requirements and therefore the O-cell® tested pile, if passing the test requirements, is sufficient in carrying any bending moments and tension loads.

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

- Full scale testing: Use of bi-directional O-cell® testing technique enables collection of full-scale test data even under the most extreme and difficult conditions.
- Reduced work area: Required work area, both overhead and laterally, is greatly reduced with respect to any other static load testing systems.
- Improved safety: No reaction system is required at ground level and the test energy is safely buried well below ground. (Figure 14)
- Deep cut-off levels: O-cell® testing with deep cut-off levels below ground can be performed; eliminating pile extensions to ground level and pile head preparations.
- Piles with embedded steel columns: Testing of piles with plunged columns and other non-standard pile heads is possible.
- Friction / end bearing components: O-cell® tests are designed to separate test piles into 2 or more pile sections; thus automatically measuring the reaction of each of the components.
- Automation/static creep effects: The O-cell® test is a static maintained load test and uses automatic data acquisition techniques and load maintenance for accurate, efficient data processing and creep measurements.
- Working piles: Post-test grouting techniques allow for testing of production piles.

- Performance: The subsequent performance of O-cell® tested production piles will be similar to the non-tested working piles due to the lower amount of generated residual stresses in the pile, as compared to applying full test loads "top-down."
- Offshore: The O-cell® test method particularly excels in offshore testing environments.
- Rock sockets: High test loads can be applied directly on deeply buried rock or soil formations without load shedding in overlaying soils, which eliminates the need for de-bonding techniques.

The loading with bi-directional testing is only limited by the smaller of the two capacities of the foundation elements above and below the O-cell® location. This restriction can result in not achieving the desired testing loads, especially if the construction technique applied is not optimal and the tested shear and/or end-bearing capacities are much lower than the anticipated capacities. It is therefore recommended that the scope and process of the pile construction and test program is well understood and all aspects adequately considered (preferably with the help from experienced professionals who has extensive knowledge in the application of bi-directional load testing) before the pile construction and O-cell® installation is performed.

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