Bi-directional load testing as a design tool to assess the bearing capacity and long-term behaviour of energy piles

M. England, BSc., MSc., PhD., DIC
Fugro Loadtest Limited, Sunbury, UK

Dipl.-Ing. C.M. Fischer
Scanrock GmbH, Celle, Germany

Abstract

Energy piles are increasingly used to heat and cool buildings, mainly skyscrapers with deep foundations carrying high loads. These projects are often located in heavily built up downtown areas. Adjacent or near by structures are generally sensitive to settlement and it is not uncommon that loads need to be transferred into complex ground formations. Energy piles are moreover subject to cyclical cooling and heating, which might affect their long-term bearing capacity. To design a safe and cost effective foundation subjected to these effects and limitations would require a precise knowledge of the interaction between foundation and ground.

In these cases the Osterberg Cell (O-cell) method for bi-directional static load testing of bored piles would be the preferred method for assessing the characteristics of this interaction. The article presents three projects where one or more of these aspects had to be considered. Two case histories describe how high test loads can be applied on bored piles even in downtown urban areas where very little space on the ground surface is available for testing. The third example deals with a research project that shows how the O-cell method was used to investigate long-term effects by retesting several piles many times, a procedure that would be required to determine the effect of cyclic temperature changes on the bearing capacity of energy piles over the long term.

1 Introduction

The O-cell method applies the test load within the pile itself, in contrast to the traditional top-down pile load test. Thus, the method needs no reaction structures at the surface, as the O-cell derives all reaction from the soil and/or rock system.

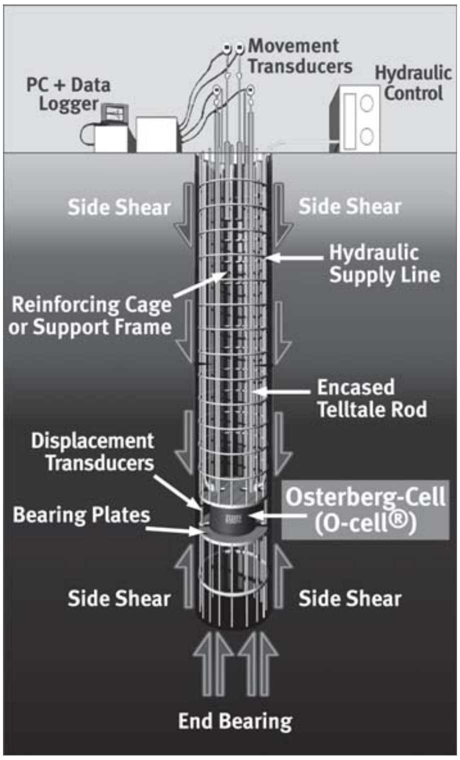


Fig. 1 Static pile load test set-up using the Osterberg Cell method

The O-cell is a calibrated hydraulic jack that is usually welded between two bearing plates attached to the reinforcement cage and concreted within the pile. The O-cell works in two directions, upward against side-shear and downward mainly against end bearing (Osterberg 1989). The main elements of a test set-up are shown on Fig. 1.

One or more O-cells can be arranged per level and multiple levels can be arranged per pile. The largest O-Cell has a capacity of 27 MN in each direction. With several large capacity O-cells assembled per level, testing capacities in excess of 220 MN can be achieved with a multi-level assembly (England 2006).

These advantages, i.e. that no reaction system is needed at the surface and thus only little space on the ground is required to carry out the test and that high loads can be applied along well defined pile sections determined that the Osterberg Cell method was chosen to test the bored piles at the two following projects.

2 Project FrankfurtHochVier

This mixed-use project located in the centre of Frankfurt consists of a 135-metre office tower, a 96-metre hotel tower, a shopping centre and an underground car park with 1.390 spaces. Integrated in the complex is a reconstruction of the historical Turn und Taxis Palais, which was originally built between 1729 and 1739 (Vogler and Katzenbach 2004). The complex was opened to public in February 2009. A model is shown on Fig. 2.

The site is located in the heart of the Frankfurt city centre in the pedestrian area called Zeil. The pile test was carried out in a narrow court adjacent to a building of the Deutsche Telekom, which was demolished later to permit the construction of the new structures.

The piles are founded in the Frankfurt limestone located at a depth of 40 m. Layers of clay, sand and gravel cover the limestone banks. Bored piles grounded in the Frankfurt limestone are usually shaft and base grouted. To evaluate the effect of this grouting procedure the test pile was subdivided into two 5 m long sections; the lower one was grouted.

The O-cell test was performed on a bored pile of 1.69 m diameter and 12.9 m length, located at 44.4 m depth. Thanks to a feature unique to bi-directional testing to be able to only load a defined pile section between specific levels in the bore, it was not required to fill the remaining section of the bore with concrete. The remaining bore length was simply backfilled with granular material for stabilization.

Fig. 2 Artists rendering

The test was arranged as a multi-level test. The lower level was located at 2.5 m above the pile toe and the upper level 5m above the lower level. Three O-cells of 9 MN nominal capacity each were installed on each level. This resulted in a total test capacity of 81 MN. The cage assembly with O-cells was manufactured at the cage factory in sections and assembled over the bore during installation.

The arrangement of two O-cell levels subdivided the pile in three sections. The longitudinal cross section on Fig. 3 shows the location of the O-cell levels and the instrumentation used to determine the pile movement and deformation.

During testing the pile compression of the upper section was monitored with a pair of rod extensometers, also called embedded compression telltales (ECT). The same applies for the pile middle section. The movement of the pile head was monitored with a pair of telltales extending to the ground level.

Rebar strain meters (also called “sister bars”) arranged in pairs at 180 degrees attached to the reinforcement cage were installed in three levels per pile section, as shown on Fig. 4.

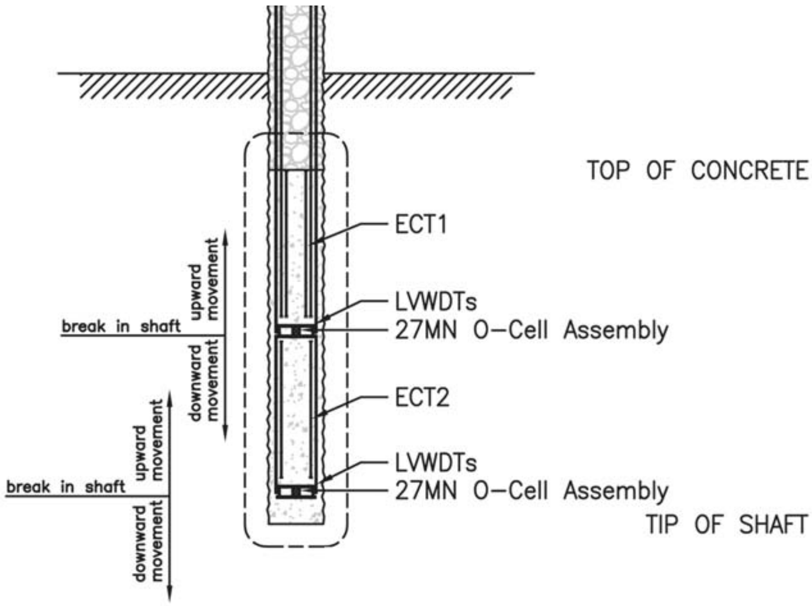


Fig. 3 Location of multiple O-cell levels

A multilevel O-cell test is usually carried out in several stages. In this case the upper 5 m section was loaded first. The load was applied in increasing steps until the maximum of 24 MN was reached. Fig. 5 shows the pile movement achieved as a result of increasing the pressure applied to the upper O-cell assembly.

Subsequently the hydraulic system of the upper O-cell level was left open for the hydraulic fluid to drain freely and thus to assure that no loads would be transferred to the upper section while the lower section was tested during the second stage. As the O-cells of the lower level were pressurized the lower 5 m section was loaded against the bottom 2.5 m of pile. With both stages the ultimate capacity in each of the sections of the rock socket could be mobilized. The effective capacity mobilised was 78 MN.

The results of the strain gauges were used to determine the distribution of shear resistance at specific elevations along the shaft under the axial test load. Loading the upper section lead to the interpreted load distribution curves shown on Fig. 6.

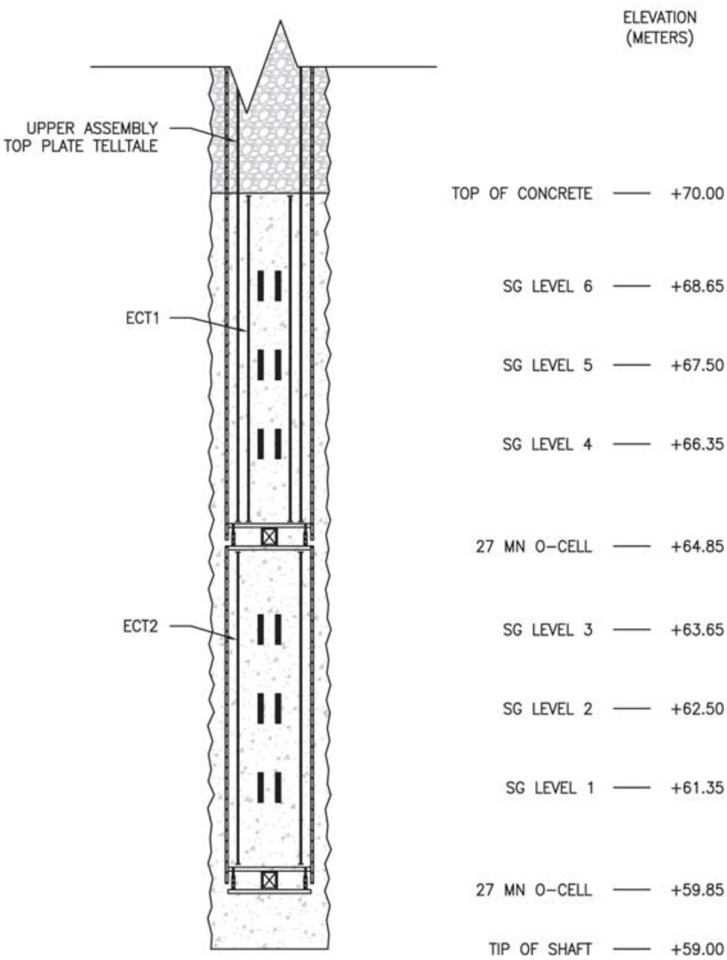


Fig. 4 Instrumentation to determine shaft strain distribution

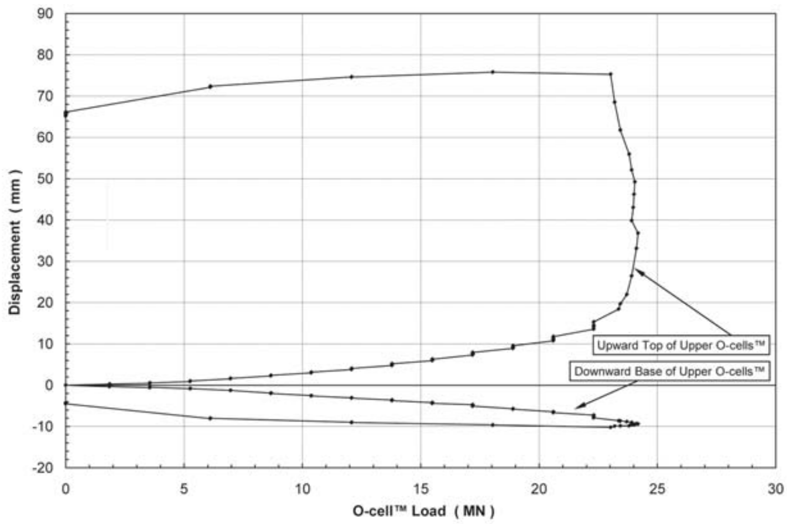


Fig. 5 Load-movement curves – Stage 1

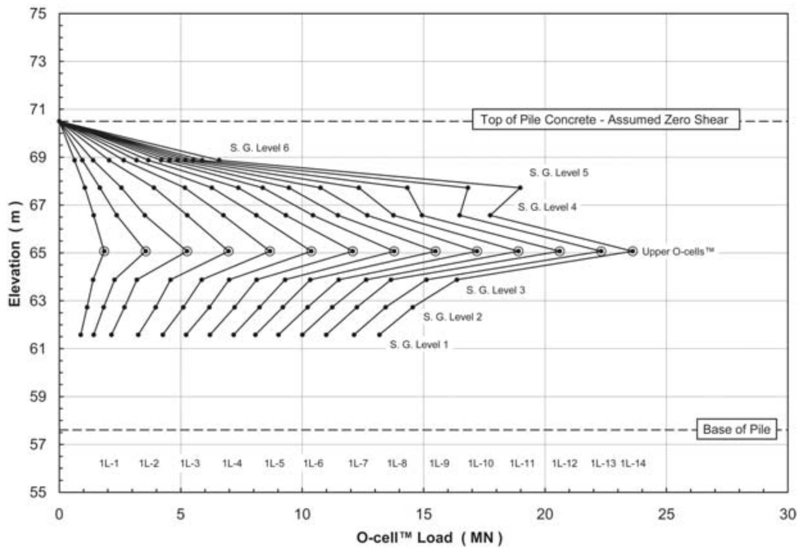


Fig. 6 Load-distribution curves – Stage 1

3 Project Medienhaus SWR Stuttgart

The SWR, short for Südwestrundfunk, is one of the nine members of Germany's public radio and television network ARD, which is a public-service broadcaster subdivided in regional organizations. The regional organizations are associated to conform the consortium of public-law broadcasting institutions of the Federal Republic of Germany. The SWR services the areas of the States of Baden-Württemberg and Rhineland-Palatinate.

Several offices, TV and radio studios located at the headquarters of SWR in Stuttgart are currently located in facilities distributed all over the city. It was decided to construct a new building to replace the existing central building, to concentrate the activities of those locations spread over the city and to create a multimedia centre that will be equipped with the most modern digital radio, TV and internet technologies. The new building will be ready to broadcast in 2011. A model is shown on Fig. 7.

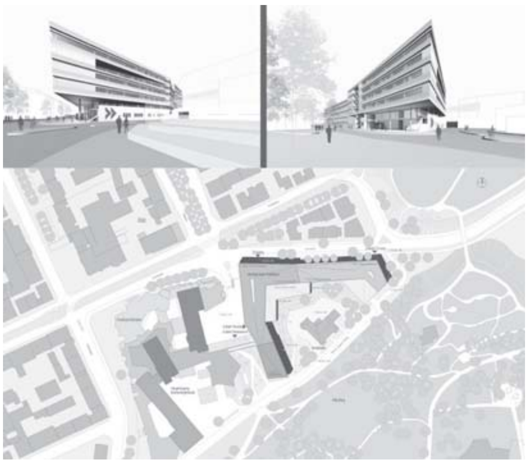


Fig. 7 Artists rendering 1

The geotechnical consultants had envisaged carrying out static pile load tests to optimize the design of the foundation for the new building. Several aspects had to be considered when it came to design the pile tests: its location in a heavily built up area, a complex soil profile and a nearby mineral water source; no construction activity would be allowed that would affect the aquifer.

Two test piles were envisaged for this project. Test pile 1 was conceived as a multilevel test to determine separately the resistance of a clay and sand layer and the resistance of a rock socket. For test pile 2 a single level test arrangement was sufficient, since the soil formation at this location was much more uniform. Both O-cell tests were performed on auger-bored piles of 873 mm diameter.

The O-cell levels at test pile 1, final depth of bore 25 m, were located at 2 m and 8 m above the pile toe. The concrete cut-off level was located at approximately 6.5 m below ground level. The O-cell level at test pile 2, final depth of bore 23.25 m, was located at 5.34 m above the pile toe. The concrete cut-off level was located at approximately 5.0 m below ground level.

At test pile 1 two O-cells of 3.6 MN nominal capacity each were installed on each level. This resulted in a total test capacity of 21.6 MN. The cage assemblies with O-cells were manufactured at the cage factory and transported to the site for installation.

Fig. 8 Carrying the pile cage to the bore on the pathway

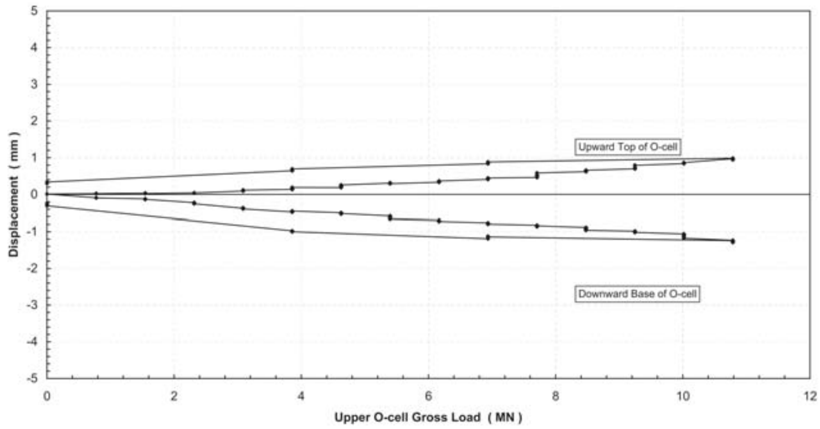
At the location of test pile 2 every activity related to drilling, installation and erection of test set-up had to be carried out on a pathway beside a narrow one-way street that was to be kept open to traffic. Special skilfulness was required from the driller to thread the drilling rig and the reinforcement cage through a network of overhead cables. The pile cage had to be carried to the bore along the pathway using a forklift, see Fig. 8.

Since the Osterberg method requires no reaction system on the ground it was possible to carry out the test on the narrow pathway. Fig. 9 shows the small marquis placed at the pile location, which had to suffice as a protection for the reference beam used to monitor the top of pile movement.

Fig. 9 Tent at the location of test pile 2

Safety considerations, as would have been necessary in case the test would have been carried out using the traditional top-down load test, were not necessary in this case, since the O-cell method applies the loads deep down in the ground. This allowed the adjacent street to remain open to traffic while the test was in progress.

Using a multilevel array at test pile 1 allowed to individually loading the two pile sections separately. The total mobilised resistance exceeded 30 MN. The test sequences were reversed, compared to the test procedure described for the previous project, i.e. the lower section was loaded first and the upper section second. The results of five levels of strain meters arranged in pairs were used to determine the distribution of shear resistance at specific elevations along the shaft under the axial test load. The values obtained largely exceeded the expectations. To achieve these high values the rated O-cell capacity had been exceeded by 40%. Fig. 10 shows the corresponding load-movement curves.



The single level array used at test pile 2 consisted of two O-cells of 3.6 MN nominal capacity each. This resulted in a total test capacity of 14,4 MN. The test mobilised a resistance of over 10 MN. The results of both tests allowed the pile design to be optimized. Permitting on one hand, advantage to be taken of the high bearing capacity of the limestone and on the other hand, that no damage would be caused to the highly valued mineral water sources.

4 Research project „Test piles driven in Florida“

For projects in urban areas where piles carrying high loads will be conceived as energy piles it might become necessary to not only verify their bearing capacity by executing static load tests but to also determine the effect of cyclic temperature changes on the bearing capacity of these piles over the long term (Bourne-Webb et al. 2009).

The case histories described previously have shown that the O-cell method fulfils the three criteria that characterize static pile tests to be carried out projects located in heavily built up areas: the need to apply high loads to complex underground strata with a small footprint available for testing. These are the boundary conditions that will most likely also characterize projects where energy piles will be envisaged as elements of deep foundations carrying high loads.

From the results of a research project involving a test pile program conducted by the University of Florida (Bullock et al. 2005) it could be inferred that the O-cell method can be used to also satisfy the requirement of determining the bearing capacity of energy piles over the long term.

To verify the often-reported observation that driven piles show an increase of side shear with time the research project studied five 457-mm square prestressed concrete piles that were driven at four different sites into a variety of soil types and stage-tested statically using Osterberg cells. Each test series included retesting each pile statically three to six times over time periods ranging from over two weeks to up to more than 4 years.

The special attraction of using the O-cell method for long-term static testing of energy piles resides in the fact that no reaction structure needs to be dismantled and re-erected each time a pile will be retested. To differentiate the effects of time on the behaviour of a conventional pile compared to a pile that has been configured as a heat exchanger pile both should be installed in the same soil formation and load tested in parallel.

Conclusion

The three projects described in the article are examples of the specific advantages of the Osterberg Cell method for statically load test piles: no need for reaction structures at the surface, a small footprint sufficient for testing, the ability to apply very high loads limited only by the structural integrity of the pile, to test individually well defined soil strata and the possibility to statically retest piles over long periods without the necessity to re-erect a reaction system.

Energy piles are often envisaged where the project conditions are characterized by lack of space and by deep foundations transferring loads into complex underground soil strata. Considering the previously mentioned advantages and capabilities of the Osterberg Cell method for static load testing and repeated retesting it seem sensible to suggest that this method be used to examine the effect of cyclic temperature changes on the bearing capacity of energy piles over the long term.

References

Bourne-Webb et al. (2009)
Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspects of pile response to heat cycles, Géotechnique 59, No. 3, pp. 237-248

Bullock et al. (2005)
Side Shear Setup I: Test Piles Driven in Florida, Journal of Geotechnical and Geoenvironmental Engineering, Volume 131, Issue 3, pp. 292-300

Bullock et al. (2005)
Side Shear Setup II: Results From Florida Test Piles, Journal of Geotechnical and Geoenvironmental Engineering, Volume 131, Issue 3, pp. 301-310

England, M. and Cheesman, P., (2006)
Recent experiences with bi-directional static load testing, 10th DFI Conference, Amsterdam

Osterberg, J.O., (1989)
New Device for Load Testing Driven Piles and Drilled Shafts Separates Friction and End Bearing, Proceedings of the International Conference on Piling and Deep Foundations, London, A.A. Balkema, p. 421

Vogler, M. and Katzenbach, R., (2004)
Ergebnisse einer Pfahlprobebelastung in den Frankfurter Kalken mit 78 MN Grenzlast, Messen in der Geotechnik 2004, Braunschweig, pp. 53-66