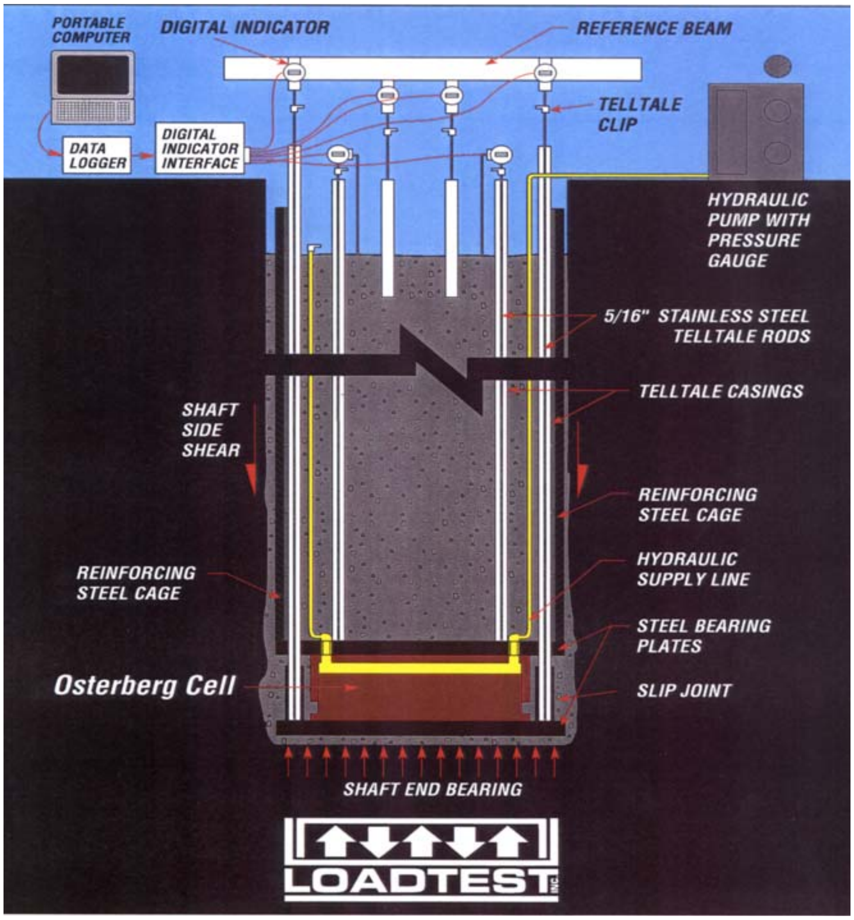
The O-Cell — A brief introduction to an innovative engineering tool

Bengt H. Fellenius, Dr.Tech., P.Eng.



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THE O-CELL
A Brief Introduction to an Innovative Engineering Tool

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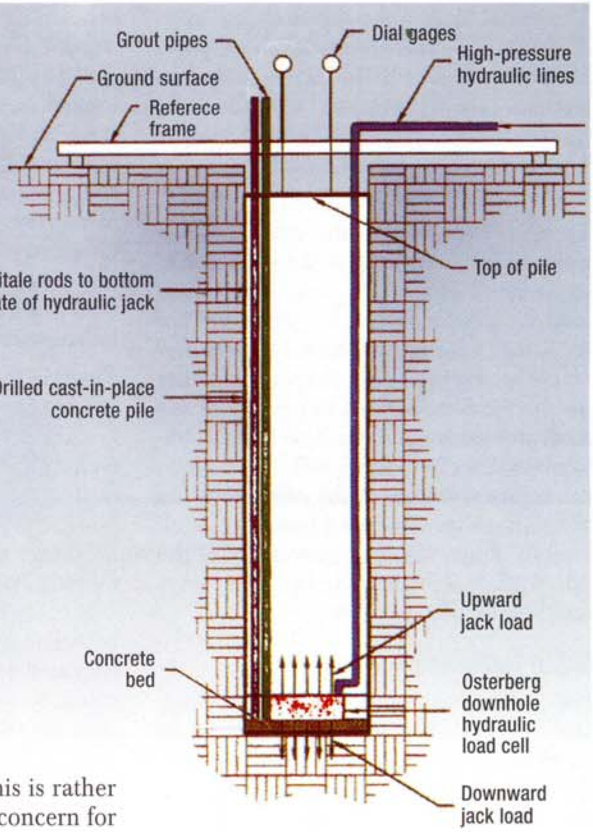

Fig 1. Schematics of the O-Cell Test (Meyer and Schade, 1995)

Introduction

The current state-of-the-art of foundation analysis and design is such that most foundations can be reliably designed without full-scale site verification, However, the design of pile foundations must frequently still incorporate a full-scale loading test to verify the performance. In case of driven piles, dynamic testing using the pile Driving Analyzer has become a ubiquitous feature and experienced geotechnical engineers will usually employ the PDA to test a few piles during initial driving and restrike for a pile foundation project. Static loading tests are normally only used where special concerns exist, and, then, in order to provide information in addition to dynamic testing.

Drilled shafts (called bored piles outside North America) are rarely subjected to dynamic tests (due to the somewhat irrational fear of the dynamic test being a destructive test when employed for this type of pile). However, because of the large loads applied to drilled shafts, the static test is often very costly. While the costs of a conventional static loading test up to a maximum test load of 3000 kN (twice a working load of about 150 tons, which pertains to the most driven piles) can range from $5000 to $10 000, bored piles often have working loads in excess of 5000 kN (about 500 tons) requiring a maximum test load of 10 000 kN (about 1000 tons). The costs of tests to such loads can easily amount to $50 000, often more, and they are also much more time-consuming and difficult to arrange and execute. The profession, therefore, takes a very conservative approach to the design of drilled shaft, assigning them smaller loads, i. e., larger factor of safety. This is rather illogical, because problems of concern for a drilled shaft usually relate to excessive settlement and construction difficulties that are unrelated to whether the pile is intended for a "conservative" working load of, say, 5 000 kN, or the more economical value of, say, 9 000 kN.

The results of a conventional static loading test are usually limited to showing the load-movement for the pile head. However, problems and questions arising from the site conditions and construction procedures require knowledge of the load-movement of the pile toe. The shaft and the toe load-movements can be separated by means of analysis of data from instrumented test piles. However, not many have the knowledge and experience of how to design, build, and perform a static loading test on an instrumented pile.

Slightly more than a decade ago, Dr. Jorj Osterberg[1] developed an innovative testing method, the Osterberg Cell, O-cell for short [5]. The O-cell test is a relatively low-cost method to test a pile.

It includes separate measurements of the shaft and toe load-movements, as well as other results important for assessing the adequacy of the pile, and its construction and long-term performance.

Principles of the O-Cell Test

The O-cell method incorporates a sacrificial hydraulic jack (Osterberg-Cell) placed at or near the toe (base) of the pile to be tested. When pressure is applied to the jack fluid, the O-cell expands, pushing the shaft upward and the base downward. The upward movement of the O-cell top is the movement of the shaft at the O-cell location and it is measured by means of telltales extending from the O-cell top to the pile head or to the ground surface. In addition, the expansion of the O-cell (i.e., increase of distance between the top and bottom) is simultaneously measured by displacement transducers inside the O-cell. The downward movement of the O-cell bottom is obtained as the difference between the upward movement of the O-cell top and the expansion of the cell. Fig. 1 gives the schematic of the O-Cell-test.

At the start of the test, the initial load in the pile at the location of the O-cell is carried structurally by the O-cell (fluid pressure in the O-cell is zero). The test consists of applying load increments to the pile by means of incrementally increasing the pressure in the O-cell and recording the resulting expansion of the O-cell (and the movement of the O-cell top). The O-cell assembly is constructed with an internal bond between the top and the base, a construction feature, which breaks at a low pressure level allowing the expansion to start. The next few pressure increments transfer the initial load in the pile to the O-cell fluid. The transfert is reached at minimal expansion.

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[1] Jorj Osterberg was born to Swedish immigrants to the USA. His many innovative contributions to geotechnical engineering through 60 years of practice have been widely recognized.

load developed during and after the construction of the pile. For slender and/or long piles, the residual load is normally larger than the buoyant weight of the pile.

The O-cell load versus the upward movement of the O-cell top is the load-movement curve of the pile shaft. The O-cell load versus the downward movement of the O-cell base is the load-movement curve of the pile toe. This direct information on the load-movement behaviors of the shaft and toe is not obtainable from a conventional static loading test. Of course, the buoyant weight of the pile above the O-cell must be subtracted from the O-cell load to obtain the load-movement of the pile shaft. It is included in the load-movement of the pile toe, however.

O-Cell Test Examples

Fig. 2 shows an example of the results of an O-cell test. The test was performed on a barrette with a 2.8 m by 0.8 m cross section installed to a depth of 30 m in a silty and clayey residual soil in Manila, Philippines (LOADTEST Inc,. personal communication). The O-Cell was placed about 2 m above the pile toe. The pile was unloaded once the upward movement showed that the ultimate shaft resistance had been reached. After completed unloading, the pile was reloaded until the shaft resistance again reached its ultimate value.

The example shown in Fig. 2 demonstrates more than just the measured movements. Several important aspects of general application are revealed in the simple graph, as follows:

The upward load-movement is governed by the shear resistance characteristics of the soil along the shaft. Ultimate shaft resistance develops at a very small movement. For the case shown in Fig. 2, the movement is smaller than about 10 mm. This movement is measured at the O-cell location and includes the accumulated shortening of the pile shaft for the load, about 8 mm. Thus, the test confirms the well-known and, yet, frequently overlooked fact that ultimate pile shaft resistance develops for a very small relative movement between the pile shaft and the soil, a millimetre or two, at any one point. Moreover, many similar tests on piles of different diameters have shown that the movement required to mobilize the ultimate shaft resistance is not just small, it is independent of the pile diameter.

The downward load-movement is governed by the compressibility of the soil below the pile toe. Note that Fig. 2 shows no indication of approaching failure despite that the downward movement of the pile toe is as large as 60 mm. More than any other testing method, the O-cell test method has demonstrated that the concept of toe bearing is flawed. As discussed by Fellenius (1999a), pile toe bearing capacity is indeed a delusion (neither does it exist for shallow foundations, such as ordinary footings).

The solid line added to the beginning of the toe movement in Fig. 2 indicates an eyeballed extension of the toe movement back to the initial load, i. e., the residual load at the toe. The intersection of the line with the ordinate identifies a lower-bound value of the initial load and its intersection with the abscissa can be taken as a reference to the amount of precompression of the soil at the pile toe. (The precompression can be a pre-test toe movement induced during the construction of the pile or be due to reconsolidation of the soil following construction; the soil hangs on the pile moving it downward until an equilibrium between the downward acting force and the upward acting toe resistance plus some shaft resistance).

For the example pile, the mentioned solid line indicates a residual toe load of about 2 500 KN and a pre-test toe movement (precompression of the soil at the toe) of about 10 mm. When adding this pre-test movement to the maximum toe movement, 65 mm, measured in the test, the total movement at the maximum load is about 75 mm, that is, about 10 % of the barrette width.

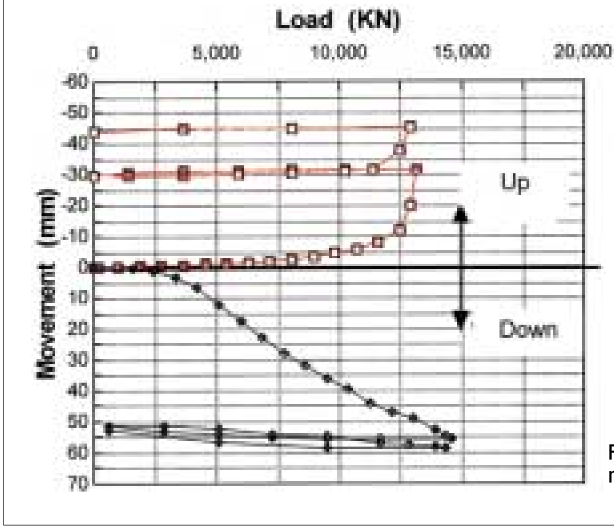


Fig 2. The basic upward and downward movements obtained in the O-cell test

A second example is given in Fig. 3, presenting the toe load-movement results of an O-cell test on a 2.5 m circular-shape, bored pile, constructed 85.5 m into a clayey silty soil in Vietnam (Urkkada Technology, 1998). The steep rise over the first 25 mm movement as opposed to the behavior thereafter appears to suggest that a failure value could be determined. For example, by the intersection of two lines assumed to represent the initial and final trend of the curves. However, the assumption would be erroneous, because also this pile (as are all piles, really) is prestressed by the surrounding soils to a significant residual load. This initial load can be larger or smaller than the buoyant weight of the pile. (In the latter case, a neutral plane exist somewhere up in the pile). Moreover, the load can exert a stress that is smaller than the preconsolidation stress in the soil at the pile toe.

As shown in the diagram, the initial load can be estimated by an approximate (eyeballed) extension of the curve, and the intersection of the extension curve with the ordinate suggests the lower-bound magnitude of the initial load (residual load). The value is about 10 KN, which is about equal to the buoyant weight of the pile. The intersection of the extension curve with the abscissa suggests that the build-up of residual load resulted in an about -30 mm pre-test toe movement, if the soil at the pile toe would be normally consolidated.

Compare the initial load-movement curve to that of the two reloading curves. The reloading curves show that the residual load increased for each such cycle. The maximum toe movement is 180 mm. The relative movement is 7 % (or 8 % if the precompression movement is included). The data show no evidence of approaching failure despite the large toe movement.

Fellenius (1999a;1999b) suggested that the measured toe load-movement or stress-settlement behavior of a footing or a pile toe, such as shown in Figs. 1 and 2, can be described by Eq. 1.

$$\sigma_1 = \sigma_{ref} \left(\frac{\delta_1}{\delta_{ref}}\right)^e$$

σ_1 = applied stress

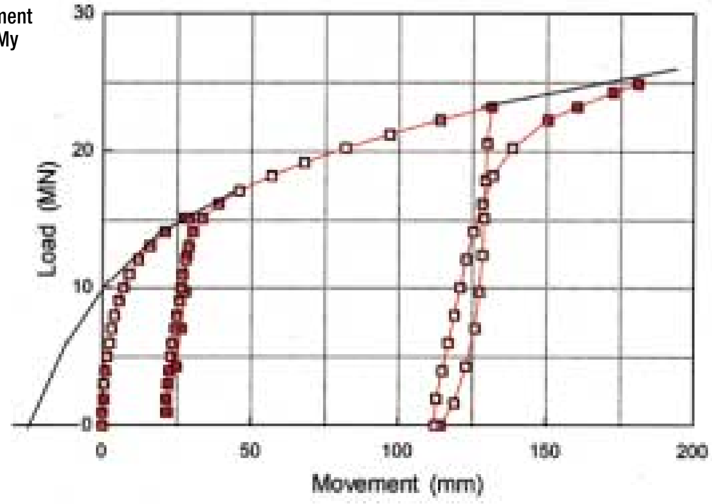
σ_{ref} = reference stress

δ_1 = observed settlement (or relative settlement)

δ_{ref} = observed settlement (or relative settlement) for the reference stress

e = an exponent

Fig 3. Toe Load-Movement from an O-Cell Test at My Thuan Bridge, Vietnam (Urkkada Technology, 1998)



The equation implies that a load-movement curve can be approximated to the test data by fitting an exponent to the load and movement values of only two points. Of course, the two points need to be judiciously selected. Note, the equation presumes that the fitted curve goes through the coordinate origin.

Fig. 4 shows the test same data after offsetting the load-movement curve by an assumed pre-test movement (offset) of 40 mm together with three curves fitted to the data: a thin line, a gray band, and a dashed line.

For the first of the three, Eq. 1 was used (before the 40 -mm offset) with the values measured just before the two unloading occasions, which determined the exponent, e, to the value of 0.26. The fitted curve is remarkably close to the measured values. It is even difficult to discern it from the measured curve.

For the second curve, different values of pre-test movement (offset values) were assumed and the calculations were repeated. The reference point was chosen to the data immediately before the second unloading. The visually best agreement to the overall appearance was obtained for a pre-test movement of 40 mm and an exponent of 0.40. The fitted curve is indicated as the gray band in Fig. 4.

The third curve is the dashed curve in Fig. 4 and it is the result of a curvi-linear regression of the last seven of the test data and plotting the resulting curve to its intersection with the abscissa.

The second and third fitted curves imply a residual load of about 12 MN. However, the implied values of pre-test movement are quite different–40 mm and 90 mm. One cannot state that one is more representative for the true residual load condition and pre-test movement than the other. Or, for that matter, that even one of the two indeed is representative. Curve fitting is an acceptable tool for interpolation between values. However, using the fitted results to extrapolate the test data does not necessarily imply truth. In this case, the exercise is limited to serve the purpose of determining that the pile is indeed subjected to a residual load of approximately 12 MN and pre-test compression of the soil at the pile toe of probably more than 30 mm, but less than about 100 mm.

Of the three fitted curves, the one of some usefulness to the designing engineer is the first one, the one approximating the test data. That curve, or its fitted curve, can be used to estimate what toe movement to expect for a particular load on the pile, and, together with other considerations, the settlement of the structure supported on the pile. A conventional head-down static test, cannot provide this measurement information so important for a settlement analysis.

Usually piles and drilled shafts are installed through less competent soils layer to bearing in competent soil. That is, the toe bearing is the most important aspect of a test. A conventional static loading test provides only the load-movement behavior of the pile shaft leaving the engineer to deduce or ”guesstimate” the toe loading characteristics of the unit. The O-cell test method provides the means to test the toe directly.

To satisfy the engineer used only to work with conventional tests, a ”head-down” load-movement curve can easily be produced from the O-cell test data by plotting the sum of shaft and toe loads for equal values of movement and then be analyzed by usual methods. For slender piles, the compression of the pile for the load must be calculated and added to the measured movement. As shown by Fellenius et al. (1999), the so constructed ”head-down” load-movement curve is equivalent to the curve actually measured in a conventional test. This approach has some merit because the so-produced curve can serve to improve on the assessment of conventional ”head-down” tests performed on adjacent piles. However, as to assessing the results of an O-cell test itself, it is akin to trying to see the details of a design drawing by stepping away from and squinting toward the drawing; a rather ineffective approach.

Residual toe load presupposes the existent of competent soil at the pile toe. While this will have developed for most driven piles (if driven into a competent soil), this may not be the case for a drilled shaft, where, sometimes, debris and soft soil will accumulate at the bottom of the hole during the construction. When the accumulated material cannot be compressed and/or displaced by the concrete pressure (in casting the pile), large toe movements will have to develop before the pile can resist the imposed load. In fact, the possibility of a soft base is one of the main reasons for some engineers not allowing for toe bearing, only shaft resistance in design. (That others do exactly the opposite is due to other reasoning not relevant to this article). As demonstrated by the case history shown in Fig. 5, the O-cell provides the means for assessing the conditions at the toe.

Fig. 5 shows O-cell data from a test in Albuquerque, New Mexico, on a 1.375 m diameter drilled shaft installed above the water table (”in the dry”) through gravel and silty sand to a depth of 16 m to inten-

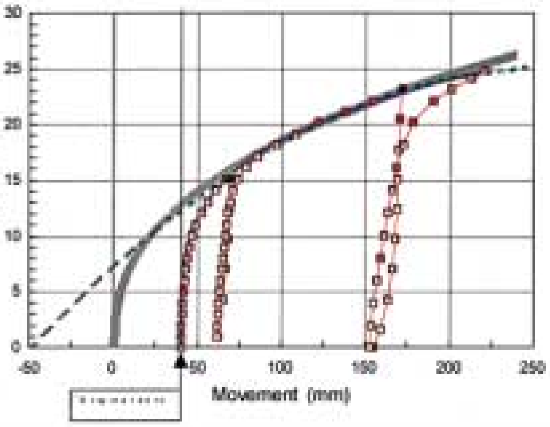


Fig 4. Curves fitted to the Data shown in Fig. 3

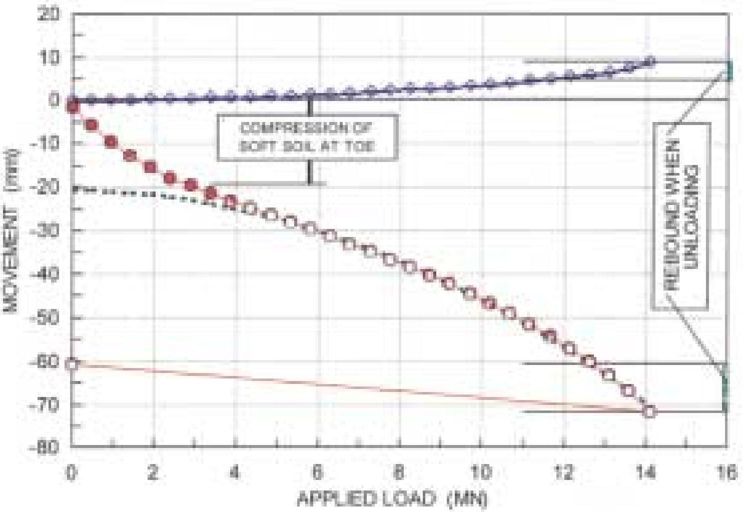


Fig 5. Toe load-movement for a pile with a soft toe (Data from Osterberg and Hayes, 1999)

ded bearing in very dense sand. It is likely that the bottom of the unit had been disturbed during the construction and/or that debris had fallen off the side of the shaft accumulating at the bottom. The fluid weight of the concrete was not enough to compress or displace the soft debris layer.

Initially, as is evident in Fig. 5, the pile toe moved appreciably downward for very little load, revealing the consequence of the deficient conditions at the pile toe. A 25 mm toe movement, achieved at a 4 MN load, was required before the indication of the soft toe conditions disappeared from the records. The stiff response in unloading indicates that the base had been compressed in the first cycle and that the pile toe had been restored to proper conditions.

The test data between toe movements of 25 mm and 70 mm were used in a curvilinear regression curve-fit to establish the dashed curve in Fig. 5. The curve-fit indicates that the pile experienced a 20 mm initial movement due to the undesirable conditions at the pile toe. If the pile had not been subjected to the test, it is conceivable that, in time, the pile would have experienced this movement regardless of the magnitude of the load 'supported' by the pile. Considering that the typical limit movement (allowable settlement) for foundations supported on drilled shafts lies in the range of 10 mm through 25 mm, the test results show that the serviceability of the pile has been impaired. That is, not really for the tested pile, where, as stated, the unloading shows that the O-cell test restored the stiffness of the pile toe, but for other, not tested piles at the site, which potentially have the same problem.

A solution to the problem is to provide all the piles with an O-cell and precompress all piles. Not only would this measure safeguard against a soft toe condition, it would also improve the stiffness of the pile toe and allow the use of both shorter and smaller diameter piles, which would be designed for settlement, as opposed to capacity (with the then necessary larger factor of safety). This is not a farfetched solution. It has several technical and economical advantages over conventional design and construction, and it has actually been used (Meyer and Schade, 1995).

Closing Comments

The three examples demonstrate the basic O-cell method. The full method includes strain gages placed at preselected locations along the pile for estimating the load at other locations in the pile. Moreover, the O-cell does not have to be placed at the pile toe. The cell, or additional O-cells, can be placed anywhere in the pile.

During development of the O-cell method, several lessons were learnt that are incorporated in the system. For example, when large pore water pressures exist at the O-cell location and the soil is not free-draining, the expansion of the O-cell creates a suction in the soil that will affect the measured loads. To counter this, it is necessary to install a stand-pipe down to the O-cell and keep the water in the pipe at a height corresponding to the phreatic height of the original pore pressure at the pile toe. Also, the pore pressure at the pile toe must be considered in the evaluation in similarity to how the static cone point stress is corrected for the pore pressure acting on the cone shoulder.

Moreover, the O-cell expansion creates a tension in the soil outside the cell location. The tension zone is about ±3 pile diameter in length. This is of minor consequence for an O-cell placed at or near the pile toe, but could have a larger effect for a cell placed up in a pile. For small diameter piles, the length of the affected zone is short in relation to the pile and, therefore, of little consequence. For large diameter piles, the influence of the tension zone must be addressed in the analysis of the test results.

The O-cell is truly not a new idea. Various case-specific similar methods have been used in the past; each time redesigning the wheel, as it were, without the benefit of prior experience. In contrast, Dr. Osterberg's innovation provides more than just the idea, it is a proven and an engineered system that is readily adaptable to the particular conditions at a site and the needs of the design engineers.

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