Fellenius, B. H., 2001. The O-Cell – An innovative enginering tool. Geotechnical News Magazine, Vol. 19, No. 2 pp 32- 33

# The O-Cell — An Innovative Engineering Tool

## Bengt H. Fellenius*⁾

### 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 test to verify the performance. In case of driven piles, dynamic testing using the Pile Driving Analyzer (PDA) 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. Bored piles 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, dynamic testing on bored piles (drilled-shafts, franki piles, compacto piles, etc.) is becoming more frequently used as the industry matures. Static loading tests are best used where special concerns exist, and, then, in order to provide information in addition to dynamic testing.

The results of a conventional static loading test are usually limited to showing the load-movement for the pile head. However, designs concerned with settlement of a pile foundation, or problems and questions arising from the site conditions and construction procedures, require knowledge of the resistance distribution along the pile, or at least the load-movement characteristics 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 developed an innovative, relatively low-cost testing method, the Osterberg Cell, O-cell for short (Osterberg, 1998). The O-cell test comprises a separation of the shaft and toe behavior, 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. The test consists of applying load increments to the pile by means of incrementally increasing the pressure in the jack, which causes the O-Cell to expand, pushing the pile shaft upward and the pile toe downward. The measurements recorded are the O-Cell pressure (the load), the upward and downward movements, and the expansion of the O-cell.

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 O-cell assembly is constructed with an internal bond between its top and 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 at the O-Cell location to pressure in the O-cell fluid. This transfer occurs at minimal expansion of the O-Cell.

The initial load in the pile is called “residual load” or “locked-in load”. Most piles, including bored

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*⁾ 1905 Alexander Street SE, Calgary, Alberta, T2G 4J3

piles, have a locked-in load developed during and after the construction of the pile. For slender and/or long piles, the 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

**Manila, Philippines**. An example of the results of an O-cell test is presented in Fig. 1 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. The O-Cell was placed about 2 m above the pile toe. The pile was unloaded when ultimate shaft resistance had been reached. After completed unloading, the pile was reloaded until the shaft resistance again reached its ultimate value.

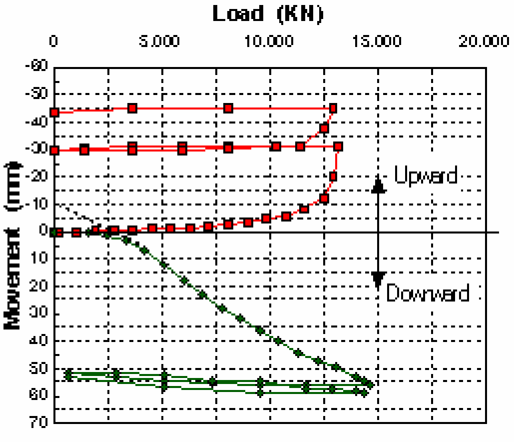

Fig. 1 Upward and downward movements obtained in O-Cell test, in Manila, Philippines

The example shown in Fig. 1 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. 1, 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. 1 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 capacity 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 dashed line added to the beginning of the toe movement in Fig. 1 is an eyeballed extension of the toe movement back to the movement axis. The intersection of the line with the load axis identifies the residual load; the load in the pile before the start of the test and its intersection with the movement axis 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. The residual load can be larger or smaller than the buoyant weight of the pile. (In the latter case, a neutral plane exists somewhere up in the pile).

The intersection of the dashed line with the load axis indicates a residual toe load of about 2,500 KN and its intersection with the movement axis indicates 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.

**My Thuan, Vietnam**. Usually piles and drilled shafts are installed through less competent soil layers to bearing in competent soil. That is, the toe load-movement relation is the most important aspect to determine in a test. A conventional static loading test, "head-down" test, provides only the load-movement behavior of the pile head leaving the engineer to deduce or 'guesstimate' the toe loading characteristics. The O-cell test method provides the means to test the toe directly. To illustrate this use of the test method, Fig. 2 presents an example of the toe load-movement results of an O-cell test on a 2.5 m diameter circular-shape, bored pile, constructed 85.5 m into a clayey silty soil in Vietnam (Urkkada Technology, 1998). Some may look for a specific "failure" point on the curve, which could be found by employing one or other of the several existing mathematical definitions of "failure". However, the approach would be erroneous. The shape of the load-movement curve is governed by the fact that the pile (as are all piles, really) is prestressed by the surrounding soils to a significant residual load.

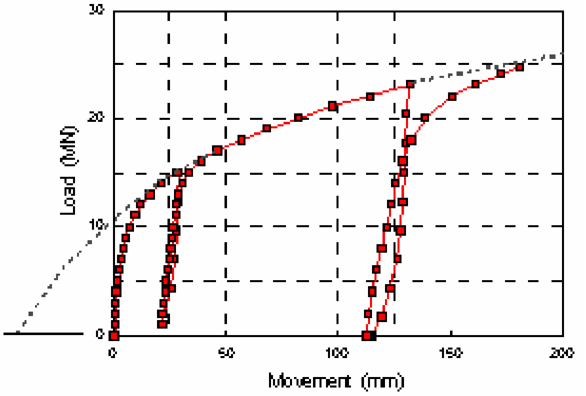

Fig. 2 Toe Load-Movement from an O-Cell Test at My Thuan Bridge, Vietnam (Urkkada Technology, 1998)

As before, 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 40 mm pre-test toe movement. That the shape of the initial curve is influenced by the residual load is clear when comparing it with the two reloading curves, which each is affected by the maximum load before the unloading—its residual load.

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.

**Estimating the shape of the toe load-movement curve**. Fellenius (1999a;1999b) suggested that the measured 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.

$$s_1 = s_{ref} \left(\frac{d_1}{d_{ref}}\right)^e \qquad (1)$$

where: $\sigma_1$ = applied stress (or load)
$\sigma_{ref}$ = reference stress (or load)
$\delta_1$ = observed settlement (or movement)
$\delta_{ref}$ = observed settlement (or movement) for the reference stress (or load)
e = an exponent

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. For a pile toe, where the residual load and its precompression distance has been considered, the exponent, e, lies in the range of 0.5 through 1.0.

**Head-down conventional test**. 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. For slender piles, the compression of the pile for the load must be calculated and added to the measured movement. The so-construed load-movement curve can be analyzed by usual methods. 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. However, converting the O-Cell test data to a conventional head-down load-movement curve has little merit. It is throwing away the benefit of having the results separated on the behavior of the pile shaft and pile toe.

**The pile toe response to load**. Residual toe load presupposes the existence of competent soil at the pile toe. While a residual load develops for most driven piles (if driven into a competent soil), it may not do this for a bored pile, 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 weight of the fluid concrete, large toe movements will have to develop before the pile toe can resist load. In fact, the possibility of a soft base is one of the main reasons for that some engineers exclude toe bearing and only allow to use 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. 3, the O-cell provides the means for assessing the conditions at the toe.

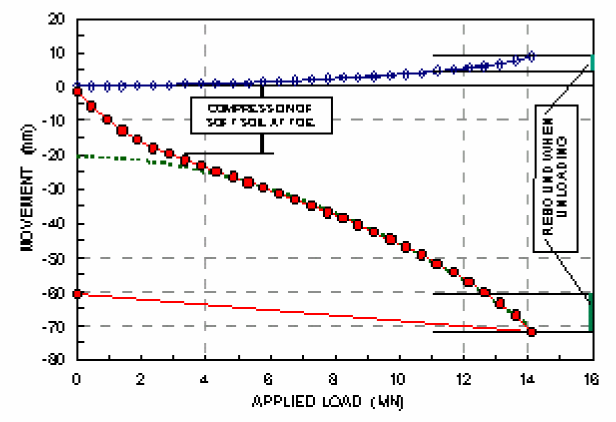

Fig. 3 Toe load-movement for a pile with a soft toe at Albuquerque, New Mexico (Data from Osterberg and Hayes, 1999)

The case history involves an O-Cell test in Albuquerque, New Mexico, on a 1.38 m diameter drilled shaft installed above the water table ("in the dry") through gravel and silty sand to a depth of 16 m to intended 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. 3, 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 curve-fit to establish the dashed curve in Fig. 3. 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 small—about a pile diameter in length. For short, large diameter piles, the influence of the tension zone should 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.

## References

Davisson, M. T., 1972. High capacity piles. Proceedings of Lecture Series on Innovations in Foundation Construction, American Society of Civil Engineers, ASCE, Illinois Section, Chicago, March 22, pp. 81 - 112.

Fellenius, B. H., Altaee, A., Kulesza, R, and Hayes, J, 1999. O-cell Testing and FE analysis of a 28 m Deep Barrette in Manila, Philippines. American Society of Civil Engineers, ASCE Journal of Geotechnical and Environmental Engineering, Vol. 125, No. 7, pp. 566 - 575.

Fellenius, B. H., 1999a. Bearing capacity — A Delusion? Proceedings of the DFI Annual Meeting, October 14 - 16, 1999, Dearborn, Michigan, 17 p.

Fellenius, B. H., 1999b. Basics of foundation design. BiTech Publishers, Richmond, BC, 2nd expanded edition 1999, 164 p.

Osterberg, J. O., 1998. The Osterberg load test method for bored and driven piles. The first ten years. Proceedings of the Seventh International Conference and Exhibition on Piling and Deep Foundations. Vienna, Austria, June 15 - 17, 1998, Deep Foundation Institute, Englewood Cliff, New Jersey, pp. 1.28.1 - 1.28.11.

Meyer, B. J. and Schade, P. R., 1995. Touchdown for O-cell test. American Society of Civil Engineers, ASCE, Civil Engineering Magazine, Vol. 65, No. 2, pp. 57 - 59.

Osterberg, J. O. and Hayes, J., 1999. Improving drilled shafts from tip to top. Foundation Drilling, Vol. 38, No. 8, November, pp. 26 - 34.

Urkkada Technology, 1998. Report to Loadtest Inc. on the analysis of O-cell test at the My Thuan Bridge Project, Vietnam.