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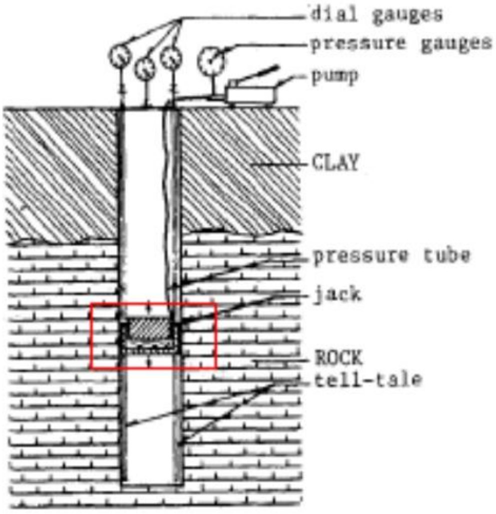

Illustration by Amir (1983)

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Analysis of results of an instrumented bidirectional-cell test

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ABSTRACT: The bidirectional-cell test has been around since the early 1970s. The first commercial development came about in the early 1980s in Brazil and about a decade later in the USA. The use of strain-gage instrumented tests was pioneered by the US supplier of the test method. The results of a bidirectional-cell test on a strain-gage instrumented 1.2 m diameter, 40 m long, bored pile were analyzed to establish the load distribution in the test pile, the distributions of beta-coefficient along the test pile, and the unit shaft shear resistance versus movement relative to the soil. The response to the applied load was modeled in an effective stress analysis to determine the t-z and q-z functions, as fitted to the measured upward and downward curves. The equivalent pile head-down load-distribution was modeled from the functions, including the separate modeling of the pile response for the pile head, pile shaft, and pile toe. The calculated pile head load-movement curve was compared to a load-movement curve manually calculated directly from the test data.

KEYWORDS: Bidirectional-cell loading test, effective stress analysis, t-z and q-z functions, equivalent head-down load-movement; equivalent head-down load-distribution.

INTRODUCTION

Most engineering practices employ the pile-head load-movement curve as the primary means for interpreting the results of a static loading test. However, this curve provides the least information on the soil response to the load applied to the pile. To take full advantage of a static loading test requires instrumenting the pile for measuring the load distribution. Over the last thirty years, the static loading test has advanced into the bidirectional method of testing, which does provide this information. A bidirectional test is a test method where a hydraulic jack, or an assembly of jacks, is placed inside the pile, usually at or near the pile toe, to generate an upward and downward directed force and movements at the cell level. A conventional head-down test in its simplest form—no instrumentation in the pile—only provides the load and movements measured at the pile head. In contrast, a bidirectional test provides, as a minimum, the load and movement in two places, at the pile head and at the cell level. Although the load at the pile head is zero, it is a known load and a key information along with the pile head movement. The movement at the cell level is an important part of the bidirectional test. It is measured by using a telltale to record the pile shortening for the applied cell load and obtained as an addition to the movement of the pile head measured conventionally.

Early bidirectional testing was performed by Gibson and Devenny (1973), Amir (1983), and Horvath et al. (1983). About the same time, an independent development took place in Brazil (Elisio 1983; 1986), which led to an industrial method offered commercially to the piling industry in Brazil. In the mid-1980s, Dr. Jorj Osterberg also saw the need for and use of a test employing a hydraulic jack arrangement placed at or near the pile toe (Osterberg 1998) and established a US corporation to pursue the bidirectional technique. On Dr. Osterberg's in 1988 learning about the existence and availability of the Brazilian device, initially, the US and Brazilian companies collaborated. Outside Brazil, the bidirectional test is now called the "Osterberg Cell test" or the "O-cell test". During the about 30 years of commercial application, Loadtest Inc. has pioneered a practice of strain-gage instrumentation in conjunction with the bidirectional test, which has vastly contributed to the knowledge and state-of-the-art of pile response to load.

Figure 1 shows an example of the basic results of a bidirectional test (Elisio 1983). The pile was a 13 m long, 520 mm diameter, bored pile constructed through 7 m of sandy silty clay and 6 m of sandy clay silt. The groundwater table was at a depth of 11.8 m. The bidirectional cell was placed 2.0 m above the pile toe. One of the many benefits of the bidirectional-cell test is that the records will indicate a presence of residual load in the pile at the cell depth, and, as indicated, the figure shows the presence of a small residual load in the pile at the cell level in addition to the weight of the pile above the cell level.

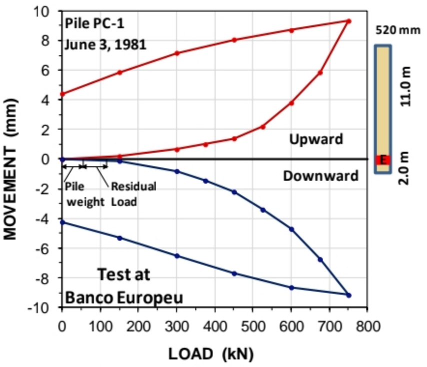


Fig. 1 Upward and downward load-movement measured in the bidirectional-cell test (Elisio 1983)

EXAMPLE OF A BIDIRECTIONAL TEST

The following presents the results of a bidirectional test and illustrates how they can be applied in an analysis to display the response of the pile thus establishing a result base for further use in the subsequent design of the piled foundations. A bidirectional-cell test was performed on a strain-gage instrumented, 1,200 mm diameter, 40 m long bored pile (Loadtest 2002) for a bridge foundation. The soil profile consisted of about 10 m of clayey silt, on about 15 m of sandy silt deposited at about 25 m depth on dense to very dense sand with gravel. The depth to the groundwater table was 4.0 m. A 540-mm diameter bidirectional cell was placed at 35 m depth, 5 m above the pile toe. The test was terminated at a maximum cell load of just about 8,000 kN, when the upward response of the shaft was in an ultimate resistance mode. The maximum upward and downward movements were 100 mm and 60 mm, respectively. The test procedure was a quick test in

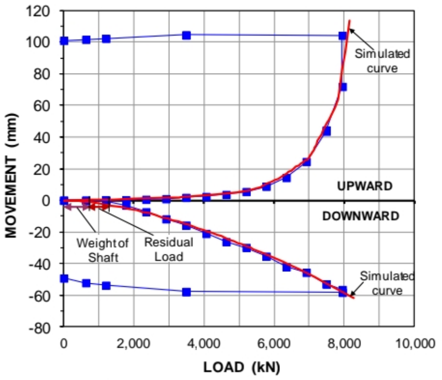


Fig. 2 Measured load-movement curves

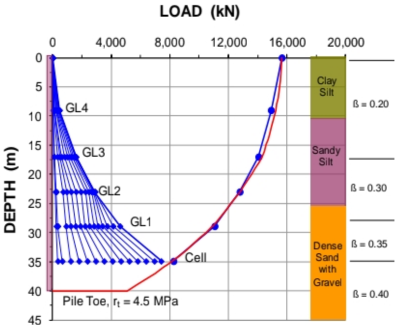


Fig. 3 Measured load distributions and the equivalent head-down load-distributions for the last increment of load (r_t = toe resistance)

fourteen increments, each held for 10 minutes. No unloading plus reloading cycles that would have disturbed the test were included. Figure 2 shows the measured upward and downward curves for the applied bidirectional-cell loads, including a simulation of the curves as discussed in this paper.

The loads shown in Figure 2 are the directly measured cell loads: the upward load curve does not include the weight of the pile above the cell level and the downward curve does not include the effect of water force. For the upward curve, as the pore pressure will provide an uplift force on the pile (developing once the cell opens causing a crack in the pile). To establish the shaft resistance along the upper pile length, the measured load has to be adjusted for the buoyant weight of the shaft above the cell level, which was 550 kN for the test pile. As the cell load is determined from the fluid pressure measured by a pressure gage located at the pile head, the actual pressure in the cell includes the pressure from the height of the hydraulic fluid—water—between the cell and the pressure gage. Thus, the water force is equal to the pore pressure acting on the entire pile cross section at the cell level. This is in analogous to the pore pressure adjustment of the cone stress for the piezocone.

The strain-gage instrumentation was at four levels: 9 m, 17 m, 23 m, and 29 m depths. The strain records were used to determine the pile stiffness relation, EA, and the load distribution in the pile at the gage levels. The results of the evaluations are shown as load distributions in Figure 3 for the applied cell loads and the loads evaluated from the strain-gage records. The curve to the right is the equivalent pile-head load-distribution for the final test distribution obtained by "flipping over"—mirroring—the distribution of the final set of measured loads, thus providing the distribution of an equivalent head-down test encountering the same maximum shaft shear and toe responses as the cell test.

An effective stress calculation of the load distribution was fitted to the equivalent head-down distribution and the fit indicated the beta-coefficients shown to the right. The effective-stress back-calculation of the load distribution applied the UniPile software (Goudreault and Fellenius 2013). An adjustment to the small residual load was made; it did not affect the second decimal of the beta-coefficients. The cell loads and the head-down distribution are adjusted for the pile buoyant weight and the downward water pressure.

The difference in loads measured at the gage levels was divided by the pile circumference and the distance between gage levels to produce the average unit shear resistance between the gage levels (GL), as plotted in Figure 4. The curves show that the shaft resistance is elasto-plastic to GL2 at 23 m depth. Between GL2 and GL1 and GL1 and the cell, the response appears to be increasing with increasing strain—strain-hardening. However, this is mainly indicated by the data from one gage level (GL2) and could be misleading. The upward load-movement of the cell plate does show continuous increase of movement for the maximum load, which suggests that the shaft resistance response is not strain-hardening.

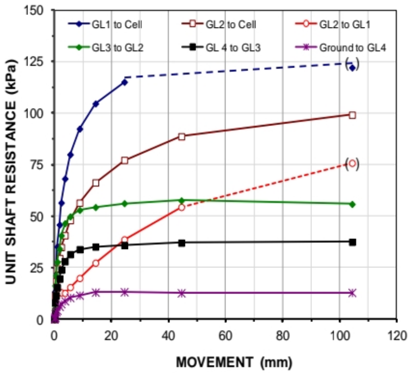


Fig. 4 Unit shaft resistances versus movement

The unit shaft resistance curves were modeled as t-z curves—also using the UniPile software. It was found that the curves could be closely modeled by the ratio method, which assumes that the ratio of any two loads is equal to the ratio of the corresponding movements raised to an exponent (Fellenius 2014). A fit to the upward curve was found for assigning a pile element t-z response to the ratio function with an exponent of 0.15 and setting the movement for the maximum load to 70 mm (a strain-hardening response). The ratio function was also used for the shaft resistance below the cell level and the toe resistance. Here, the ratio exponents were 0.8 and 0.9, respectively, and the movement at the maximum load was set to 60 mm. The beta-coefficients obtained from the fitting of the calculated load distribution to the measured were used to simulate of the upward and downward load-movement curves. Figure 2 shows the results of fitting the measured load-movement curves to calculated using the t-z and q-z functions.

The engineering practice is to combined the measured upward and downward load-movement curves to produce an equivalent pile-head load-movement curve. The principle for producing this curve is first, Step 1, to add the upward and downward loads for equal movements. However, while the measured downward load provides the movement response directly, in a head-down test, the toe load has to be conveyed through the pile, which causes additional pile 'elastic' shortening equal to the shortening of a free-standing column load by that same load. Thus, Step 2 involves calculating and the pile shortenings for each load and adding the values to the movements determined in Step 1. The principle for adding this component is described by Loadtest (2002). Other direct approaches have been presented, e.g., Kim and Mission (2011).

The direct approach disregards that the fact that the upward movement starts by mobilizing the stiffer shaft resistance at the depth of the cell, whereas the head-down test starts by mobilizing the less stiff load-movement response near the pile head. This problem can be avoided by first back-calculating the resistance in an effective stress analysis and fitting separately the measured upward and downward curves to curves obtained in a modeling of the pile, soil, and cell load-movements using t-z and q-z functions as demonstrated in Figure 2. This done, calculations of the head-down load-movement curves engaging of the upper soil layers first are easily carried out using the UniPile software with the parameters resulting from the fit to the measured load-movements. Figure 5 shows the resulting distributions for the pile head, the piles shaft, and the pile toe. The dashed portions of the curves identify the extrapolation beyond the measured values.

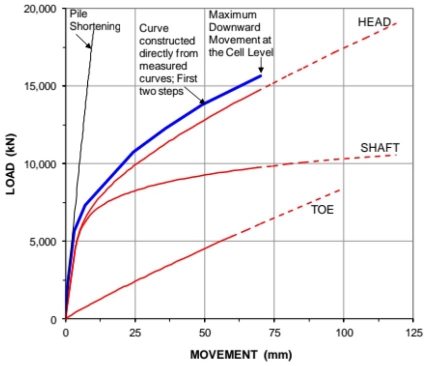


Fig. 5 Equivalent head-down load-movement curves constructed from the bidirectional-cell data and by simulation from fitted soil parameters

The figure also shows the equivalent pile-head load-movement curve according to Steps 1 and 2 produced manually from the upward and downward measured curves. The curve does include the effect of the larger pile compression occurring in the head-down test. However, it does not include the effect of the larger stiffness response of the upward load-movement of the bidirectional test, as opposed to the softer initial response of the head-down test, the curve marked "Head". The difference between the two curves represents the effect of the larger stiffness at the beginning of the bidirectional test as opposed to the smaller stiffness at the beginning of the head-down test.

The difference between load-movement curves determined from pushing-up from below and pushing down from the pile head is further demonstrated in Figure 6 which presents the measured upward load-movement curve for the length of pile above the cell and the head-down curve calculated using the fitted parameters.

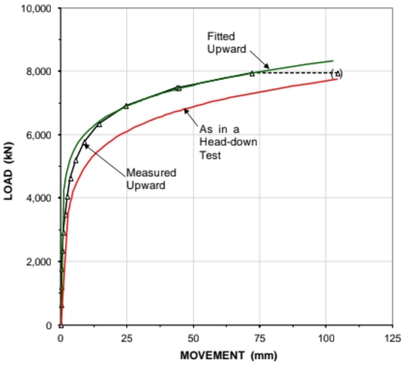


Fig. 6 Load-movement curves for the length of pile above the bidirectional-cell comparing the measured cell upward curve to the equivalent head-down curve for the section above the cell level

The pile-head load-movement curve is what the profession usually employs to determine the working load to be placed on a pile. Because of this, it is important to establish this curve. There is little other reason for this, however, as there is not much of value of the head-down curve for the design of piled foundations. The main value of a static loading test is the results shown in Figure 3, because those results can be combined with intended or desirable working load for the long-term conditions and be decisive for determining the settlement of the piled foundations (Fellenius 2014). In short, determining that a working load has an adequate factor of safety (or resistance factor) on some capacity value determined from the pile-head load-movement curve does not at all ensure that the long-term settlement of the piled foundations will be within an acceptable limit. In contrast, when a piled foundation has been designed to be within the acceptable settlement limits, it will always have an adequate capacity.

Most bidirectional-cell tests on long piles include a strain-gage instrumentation. However, even a cell test without instrumentation will provide the load in the pile at two points: at the pile head and at the cell level. Although such a test would be rather crude for long piles, the equivalent head-down load distribution, such as it would be, would still provide some information on the distribution of resistance with depth and be helpful for the design of the piled foundations.

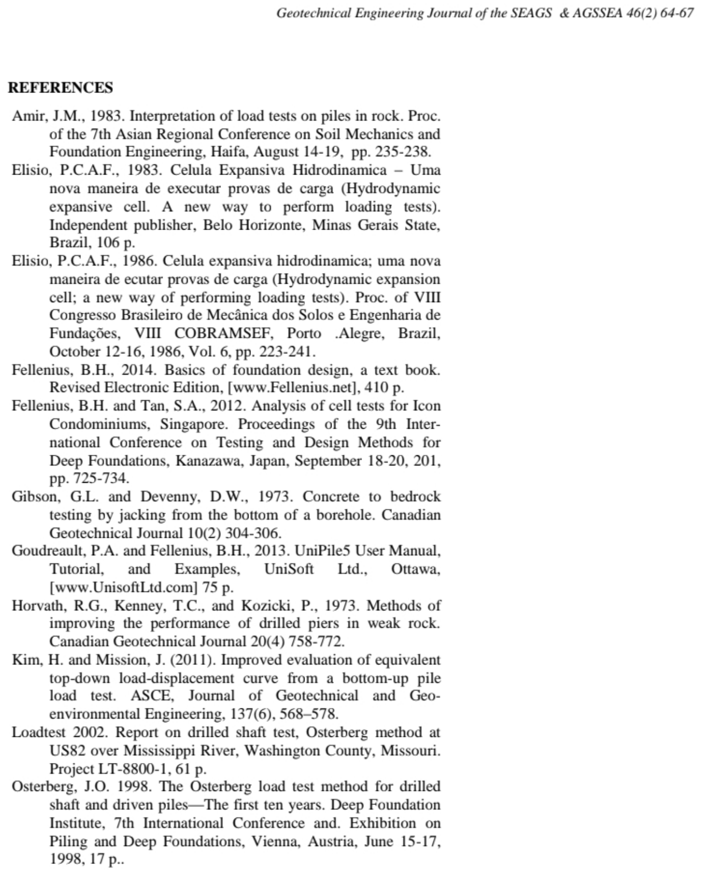
CONCLUSIONS

The subject case is a quite simple routine bidirectional-cell test on a pile with four gage levels. The data were used to establish the load distribution for the pile, which enabled determining the distribution of the effective-stress beta-coefficients for the pile response.

The differentiation of loads between the gage levels established the unit shaft resistance versus movement, that is, the t-z and q-z functions of the pile response.

The t-z and q-z functions were used to fit the soil parameters to simulation of the measured upward and downward load-movement curves and, then, to calculate the equivalent pile-head load-movement curve, as well as that for the pile shaft and the pile toe.

The equivalent pile-head load-movement curve produced manually from the measured load-movements appeared stiffer than the simulated curve (and an actual pile-head load-movement curve) because of the fact that the bidirectional-cell test activates the deeper down soils first, which have a stiffer response than the soil at shallow depth.



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REFERENCES

Amir, J.M., 1983. Interpretation of load tests on piles in rock. Proc. of the 7th Asian Regional Conference on Soil Mechanics and Foundation Engineering, Haifa, August 14-19, pp. 235-238.

Elisio, P.C.A.F., 1983. Celula Expansiva Hidrodinamica – Uma nova maneira de executar provas de carga (Hydrodynamic expansive cell. A new way to perform loading tests). Independent publisher, Belo Horizonte, Minas Gerais State, Brazil, 106 p.

Elisio, P.C.A.F., 1986. Celula expansiva hidrodinamica; uma nova maneira de ecutar provas de carga (Hydrodynamic expansion cell; a new way of performing loading tests). Proc. of VIII Congresso Brasileiro de Mecânica dos Solos e Engenharia de Fundações, VIII COBRAMSEF, Porto .Alegre, Brazil, October 12-16, 1986, Vol. 6, pp. 223-241.

Fellenius, B.H., 2014. Basics of foundation design, a text book. Revised Electronic Edition, [www.Fellenius.net], 410 p.

Fellenius, B.H. and Tan, S.A., 2012. Analysis of cell tests for Icon Condominiums, Singapore. Proceedings of the 9th International Conference on Testing and Design Methods for Deep Foundations, Kanazawa, Japan, September 18-20, 201, pp. 725-734.

Gibson, G.L. and Devenny, D.W., 1973. Concrete to bedrock testing by jacking from the bottom of a borehole. Canadian Geotechnical Journal 10(2) 304-306.

Goudreault, P.A. and Fellenius, B.H., 2013. UniPile5 User Manual, Tutorial, and Examples, UniSoft Ltd., Ottawa, [www.UnisoftLtd.com] 75 p.

Horvath, R.G., Kenney, T.C., and Kozicki, P., 1973. Methods of improving the performance of drilled piers in weak rock. Canadian Geotechnical Journal 20(4) 758-772.

Kim, H. and Mission, J. (2011). Improved evaluation of equivalent top-down load-displacement curve from a bottom-up pile load test. ASCE, Journal of Geotechnical and Geoenvironmental Engineering, 137(6), 568–578.

Loadtest 2002. Report on drilled shaft test, Osterberg method at US82 over Mississippi River, Washington County, Missouri. Project LT-8800-1, 61 p.

Osterberg, J.O. 1998. The Osterberg load test method for drilled shaft and driven piles—The first ten years. Deep Foundation Institute, 7th International Conference and. Exhibition on Piling and Deep Foundations, Vienna, Austria, June 15-17, 1998, 17 p..