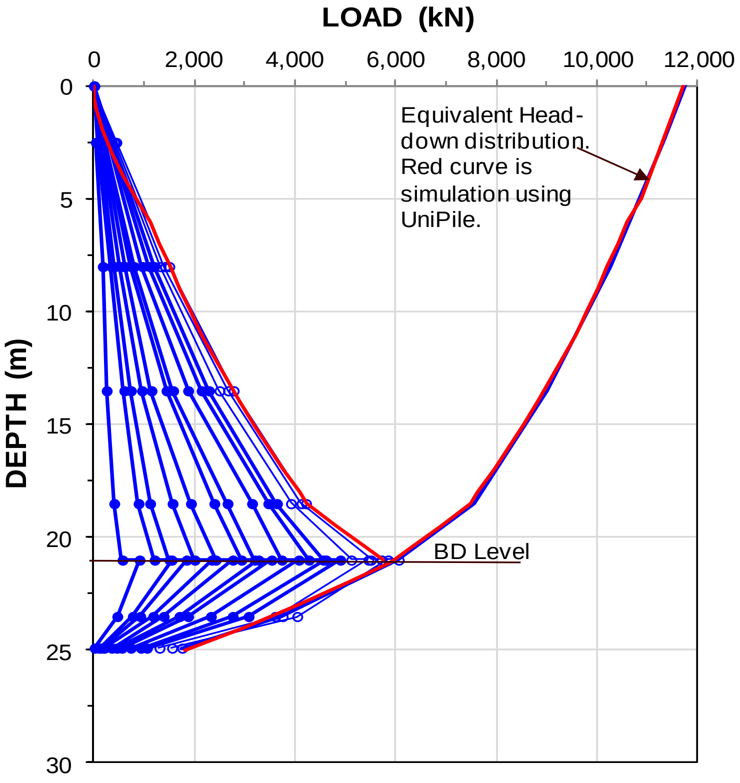

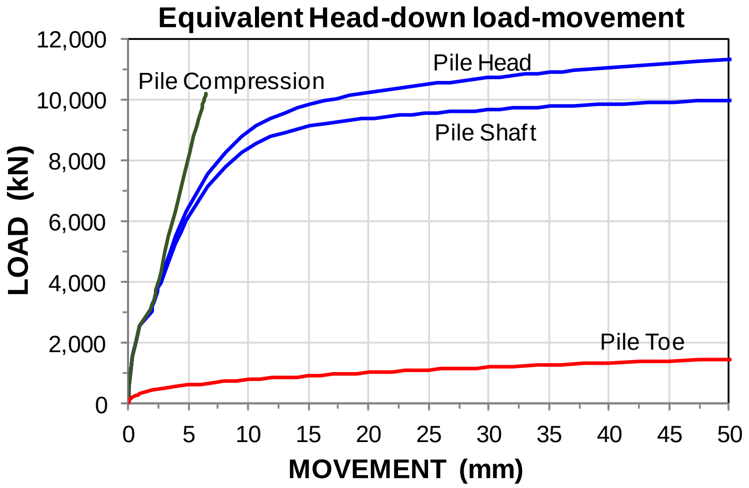

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Bidirectional pile testing: what to expect

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ABSTRACT Bidirectional (BD) testing of foundation piles was first introduced by Pedro Elísio (Brazil) in 1981 and Jorj Osterberg (USA) in 1987. It is still, however, not fully embraced by the industry despite its substantial technical and economic advantage over the conventional head-down test. This article provides a brief description of the state-of-the-art in bidirectional testing of foundation piles, advantages, difficulties, and recommendations. Case histories from the authors' experience illustrate some issues that can be encountered in BD testing. One issue being the effect of uneven shaft resistance distribution on strain gage. Also discussed is the location of strain gages, and whether strain-gage instrumentation is warranted in short piles. This is intended to raise awareness and confidence in specifying bidirectional testing as an effective tool for optimizing a piled foundation design. The authors recognize the importance of sharing experience in a field where trial and error can come at high cost and better planning can lead to more rewarding tests..

RÉSUMÉ Le test bidirectionnel (BD) des pieux de fondation a été introduit pour la première fois en 1981 par Pedro Elísio (Brazil) et Jorj Osterberg (USA) en 1987. Cependant, ce type d'essai n'est pas encore adopté complètement par l'industrie. Cet article fournit une brève description de l'état de l'art dans les essais bidirectionnels des pieux de fondation, avantages, difficultés, et recommandations. Des exemples de cas provenant de l'expérience des auteurs illustrent certains des enjeux rencontrés. L'un des enjeux étant la distribution asymétrique de résistance de fût. On discute également de l'emplacement des jauges de contrainte. Cet article est destiné à accroître les connaissances et la confiance pour spécifier des tests bidirectionnels pour l'optimisation d'une conception de fondations en pieux. Les auteurs reconnaissent l'importance de partager l'expérience dans un tel domaine où les erreurs peuvent venir à un coût élevé et une meilleure planification produira des tests plus efficaces

1 INTRODUCTION

It is difficult to determine the magnitude of the portion of the applied test load that reaches the pile toe. Even when a strain-gage pair is placed at the pile toe and a telltale is used to measure the pile toe movement, interpretation of the data from a conventional "head-down" test is complex. While the portion of the applied load reaching the pile toe can be known, the actual toe response is often not known due to the presence of a residual force at the pile toe already before the start of the static loading test.

The difficulty associated with wanting to know the pile-toe load-movement response, but only knowing the pile-head load-movement response, is overcome in the bidirectional (BD) test, which incorporates one or more sacrificial hydraulic jack-like device(s) placed at or near the toe (base) of the pile to be tested (be it a driven pile, augercast pile, drilled-shaft pile, precast pile, pipe pile, full-displacement pile, H-pile, or barrette). By jacking the upper and lower portions of the pile against each-other, and measuring the movement of the pile at pile toe, pile head, and upper and lower plates of the BD Cell), the shaft and toe of the pile are mobilized simultaneously andwithout the need for extensive, and sometimes hazardous reaction system at the surface.

In contemporary BD tests, some of the conventional telltales are replaced with electronic transducers to measure displacement (opening of the jacks) and strain (axial compression of the pile) at various locations as judged suitable considering the soil profile.

Like any advanced procedure, planning and execution details can make a difference in the outcome, and earning from past experience is essential for a successful test and obtaining reliable results. In this paper, a brief description of the test elements, principles, execution, and interpretation is provided, with illustrations and contributions based on test cases from south of Calgary, Alberta. Case 1 comprises a 1,200-mm diameter and 30.3 m long pile with a bidirectional (BD) cell installed at 27 m below the pile head (top of concrete, TOC). The pile head was about 1 m below grade). Case 2 comprises a 900-mm diameter, 9 m long pile with a BD cell installed at 7.5 m below TOC.

2 HISTORY

Early bidirectional testing was performed by Gibson and Devein (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 production offered commercially by Arcos Engenharia, Brazil, to the piling industry. In the late 1980s, Dr. Jorj Osterberg independently saw the need for and use of a test employing a hydraulic jack arrangement placed at or near the pile toe and established a US corporation called Loadtest Inc. to pursue the bidirectional technique now often referred to it as the "Osterberg Cell test" or the "O-cell test". Today, several companies around the world provide advanced bidirectional testing, including Arcos Engenharia (Brazil), AATech Scientific (Canada), Applied Foundation Testing (USA), GRL Inc. (USA), Strainstall (UK), and others.

Further information can be found in Fellenius (2017).

3 TEST DESCRIPTION

As stated earlier, the BD test consists of jacking two sections of the pile against each-other as opposed to the traditional head-down test where the pile is pushed down against a counterweight or a reaction frame. The jacking cylinders are sandwiched between two bearing plates, thus, forming the BD Cell and positioning at a strategic location within the pile shaft where the available pile resistance above and below the cell are expected to be comparable. Typical instrumentation includes the following:

1. Two pairs of telltales, one pair anchored on each of the two bearing plates. Alternatively, the telltales on the lower bearing plate can be replaced by one or more pairs of linear displacement sensors linking the two plates to measure the opening of the cell during the test. An alternative method to determine the opening of the BD Cell (a valuable back-up option) is to measure the volume of the fluid used to expand the BD Cell.
2. At least one pair of telltales should be anchored near the pile toe, unless the BD cell is placed at the pile toe, in which case the instruments in Point 1 are sufficient.
3. Pairs of strain gages may be installed for longer test piles, ideally at levels near the interfaces of distinct soil layers. Strain gages closest to the BD Cell (above and below) are most critical for assessing the pile modulus. The recommended distance between the plates and the strain gages is a minimum of one pile diameter to ensure even stress distribution across the pile section.
4. Other instrumentation may be incorporated in the pile, such as Crosshole Sonic Logging (CSL) access tubes, Thermal Integrity (TIP) sensors, etc.

The cell and instruments can be mounted on a specially designed frame in the case of sacrificial test piles, as shown in Figure 1, or on the actual reinforcing cage in a production pile. In the latter case, however, the reinforcing cage must be separated into a lower and upper part if the cell is not placed at the pile toe level. Minimal connecting members securing the BD Cell plates are broken before the start of the test, splitting the pile horizontally at the lower plate level by pressurizing the Cell.

3.1 Principles and construction

Usually the test arrangement aims to place the BD Cell so that the shaft and toe resistances below the lower BD Cell plate, are roughly equal to the shaft resistance above the lower cell plate. It is important to note, however, that, when in doubt, the design engineer should err on the side of caution and favour a BD Cell placement that will ensure full mobilization of the soil shear along the upper length. The reason being that, in such case, a simple and inexpensive solution to complete the test, if desired, would be to apply a relatively small counterweight to the pile head after failing the upper shaft. The test can then be continued to move the lower portion of the pile as required. The solution in case of a premature failure of the lower portion of the pile is not as elegant, but planning for and installing tension members in the upper shaft can allow for upward jacking against a bearing frame at the pile head to assist in testing the upper portion of the pile. Alternatively, a head-down test engaging just the upper length can be performed.

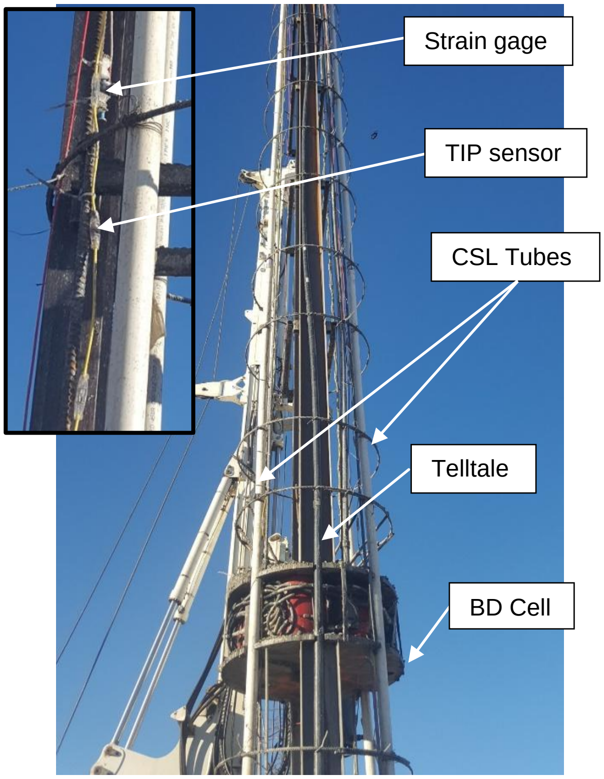

Figure 1. Instrumented BD Test pile frame. The "TIP sensor is a Thermal Integrity sensor. (Photo courtesy AATech Scientific Inc.).

Once the BD Cell is located and installed along with the desired instrumentation, concrete is carefully poured using a tremie tube through a special opening into the BD Cell plates, then all the way to the pile head. A tremie guide cone is necessary around the opening above the upper plate. The guide is usually built-up of steel reinforcing bars secured to the plate in a funnel-shaped arrangement.

3.2 Performing the Test

Before starting the actual test, the hydraulic pressure in the BD Cell is gradually increased until a sudden small release of pressure is observed indicating that the connections between the upper and lower plates are severed and the concrete section is split at the lower plate level. The pressure is then reduced to zero and the test is started by applying the load increments in accordance with the test specifications.

It is imperative that a robust monitoring system is used such that all instruments are read at practically the same time and the records kept in a common data collector referenced to a common time stamp. To adequately capture the test, a readout frequency no longer than 20 s is recommended. Figure 2 shows an instrumentation and readout setup at the pile head.

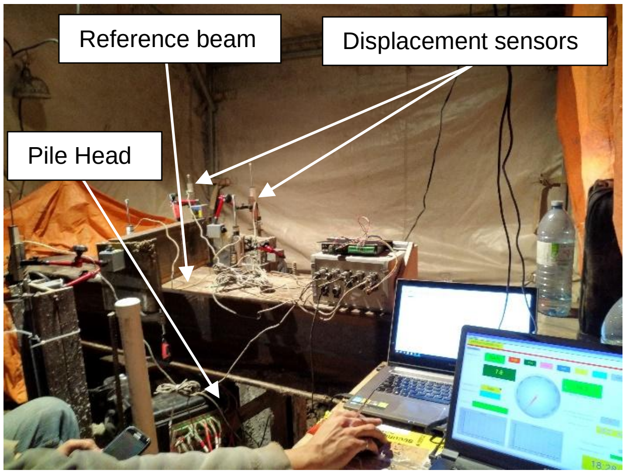

Figure 2. Instrumentation and monitoring setup at pile head (Photo courtesy AATech Scientific).

By pressurizing the BD Cell, equal force is applied simultaneously to the upper and lower lengths of the pile, while the instruments relay the opening and movement of the BD Cell plates, the displacement of the pile toe and pile head, and the strain in the pile at each gage level. Figure 3 shows the test results as load versus upward and downward movements measured at the BD Cell upper and lower plates, respectively (Case 1 performed by AATech Scientific Inc.). It should be noted that the records shown in Figure 3 are the result of a successful placing of the BD cell as the upper and lower lengths of the pile (above and below the BD Cell) both moved appreciably for the applied BD load.

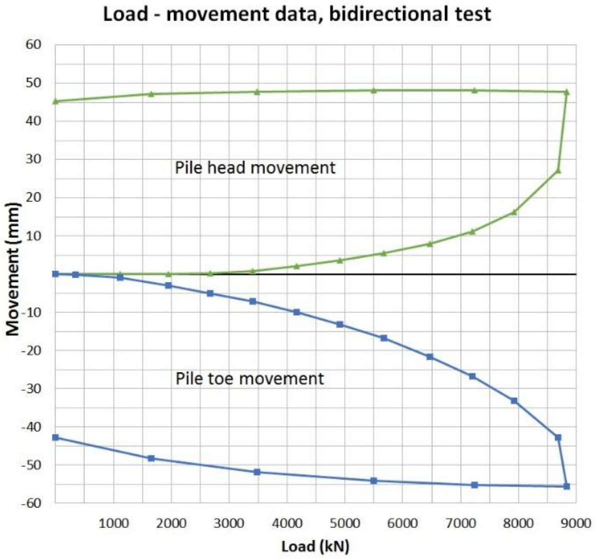

Figure 3. Load vs. displacement measured in Case 1.

3.3 Interpreting Test Records

It is worth mentioning that there are several advantages to using a BD Cell with multiple hydraulic cylinders evenly distributed across the section rather than one large cylinder at the centre. One main advantage is that strain gages can then be placed at relatively close proximity to the Cell, especially if redundant gages are installed with at least two pairs across the section. Specific minimum distance depends on the number of cylinders and their distribution pattern, the pile diameter, etc.

The first step in interpreting a BD test is to determine the stiffness (EA) of the pile cross section to convert the measured strain to force

$$\sigma = \frac{F}{A} = E\,\varepsilon \;=>\; F = E\,A\,\varepsilon \qquad (1)$$

Where:
σ = stress in the pile section
F = force in the pile section
A = cross-section area of the pile
E = Young's (elastic) modulus of pile material
ε = measured strain

The force at a strain gage level is equal to the load applied by the BD Cell minus the shaft resistance engaged between the BD Cell and the strain gage level. Once the relative movement between the pile shaft and the adjacent soil is sufficient to fully mobilize the shaft between the BD Cell and the strain gage level (and assuming the continued shaft shear is plastic), the additional load applied is transferred in its entirety to the section where the strain gages are. Therefore, beyond this load, the continued load-strain is linear, as expressed in Equation 2.

$$\Delta F = EA\,\Delta\varepsilon \qquad (2)$$

Using the records from Case 1, Figure 4 shows the incremental stiffness ($\Delta F/\Delta\varepsilon$) against the strain ($\varepsilon$) as an approximately straight line with an ordinate intercept equal to the pile stiffness, EA, for low strain. A horizontal line indicates a constant pile stiffness, whereas a sloping line indicates a pile modulus reducing with increasing strain. A slight slope is indicated, that is, diminishing stiffness with increasing strain, but the range of imposed strain is not large enough to ensure this assessment. The procedure is known as the "Tangent Modulus or "Incremental Stiffness method" (Fellenius 1989; 2017).

Note that in Figure 4, only the strain gage levels closest to the point of loading (BD Cell) were used in the determining the stiffness. The differentiations involved in the process are sensitive to the precision of the measured strains and applied loads in relation to the actual value of strain resulting from the applied increment of load. It is therefore highly recommended to size the test pile such that the anticipated strain level induced in the pile during the test exceeds 300 $\mu\varepsilon$ for better data quality (Fellenius 2017).

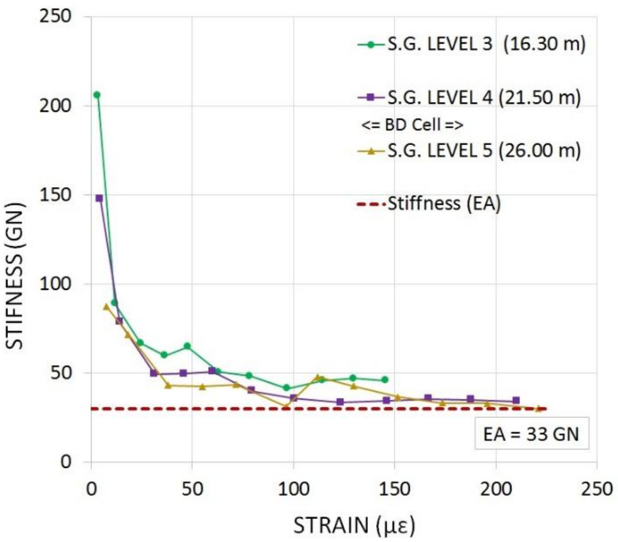

Figure 4. Tangent modulus plot, Case 1

The Case 1 strain gages were installed at 30.0, 26.0, 21.5, 16.0, 10.0, and 7.5 m depths (gage levels). One pair of diametrically opposite gages is installed per level.

Figure 5 shows the resistance distribution determined from the Case 1 gage records. The resistance computed directly from the strain gage data is plotted in lines with square markers going from the BD Cell load to the pile head (where the load is zero). The records can be "flipped over" (mirrored) to produce an Equivalent Head-down distribution shown in marker-free lines.

The loads evaluated from the strain records show a slight incongruity with regard to the estimated distribution for the maximum applied load. A resistance distribution for the maximum applied load is shown as a thick (bold) line in the plot. The line is adjusted to smooth the trend of the gage measurements as opposed to drawn from record to record.

In Case 2 (test performed by AATech Scientific Inc.), pile gage pairs placed at 3.0, 5.2, 6.9, and 9.5 m depths. At each level, two pairs of diametrically opposite gages are installed, and labelled Gages A and C, and B and D, respectively. The B and D gage pair was installed at 90 degrees from the A and B gage pair.

Figures 6 through 8 show the strains measured in the Case 2 pile gage pairs, plotted as applied load versus strain. It is obvious from the strain measurements in Figure 6 (Depth 3.0 m) that a bending in the pile section was initiated in the pile when the applied load at the BD Cell exceeded about 1,350 kN.

The bending was more pronounced in the direction of Gage Pair B and D, where Gage B even showed a slight tension strain during the last applied load increment. Despite the bending between the gage sides, the average strains from individual pairs and throughout the pile section were consistent.

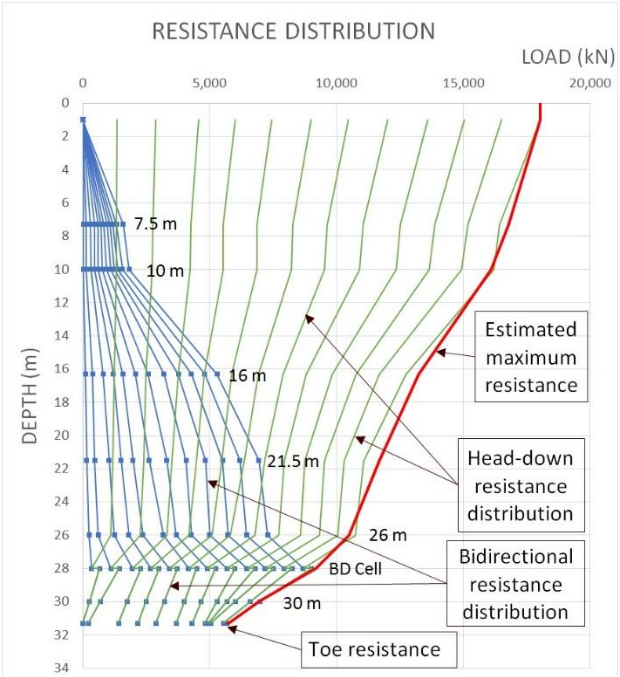

Figure 5. Interpreted resistance distribution, Case 1

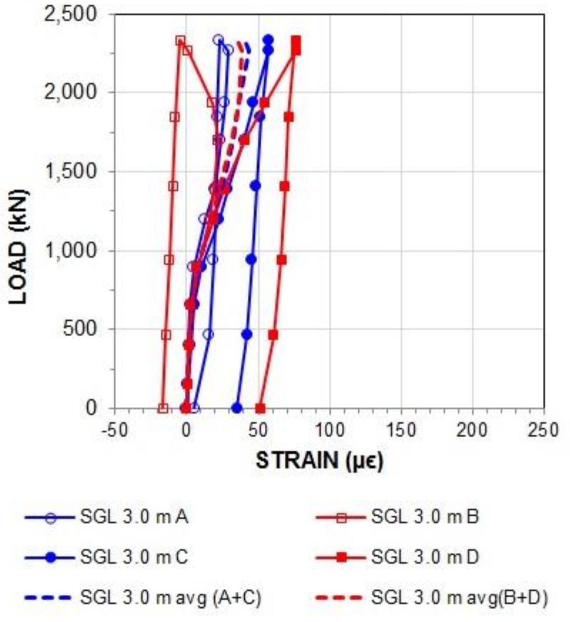

Figure 6. Strain measuremeYnts at 3.0 m depth,

Looking at one level below (Depth 5.0 m; Figure 7), similar bending response is noted. The bending between Gages B and D is severe while Gages A and C show a more uniform compression, which indicates absence of bending due to rotation perpendicularly to the line between the gages. Bending at this section started earlier in the loading sequence at an applied load of about 1,200 kN. This is to be expected as the 5.2-m gage level is closer to the point of loading, the BD Cell, and, therefore, is be engaged earlier on in the test. Again, the average strain for the two pairs is similar and consistent. Moreover, a higher tension strain is indicated by Gage B near the end of the loading sequence. The tensile strain is sustained throughout the unloading sequence and remains after full unloading, which suggests possible plastic deformations or cracking due to stress concentration at the gage location. A similar response is shown by Gage D, in compression. Some remaining strains after full unloading may also be explained by residual stresses (locked-in loads) in the pile.

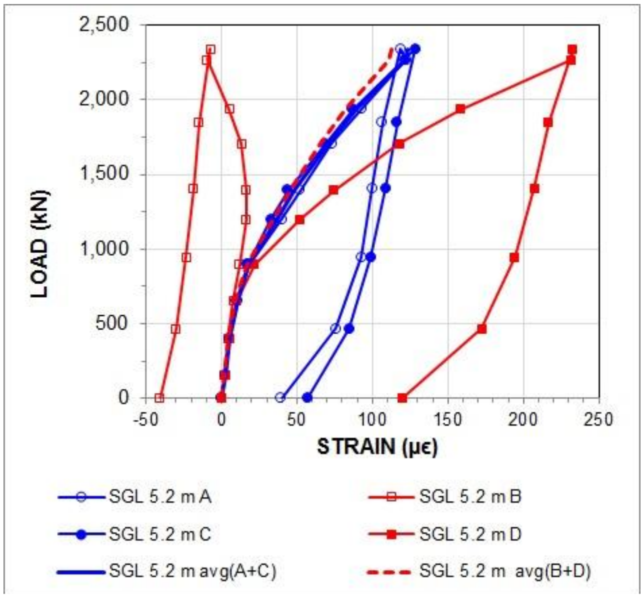

Figure 7. Strain measurements, at 5.2 m depth.

In contrast, the strain gage measurements at 6.9 m depth (Figure 8) show a more regular response with constantly increasing compressive strains in all four gages throughout the loading sequence. The deviation between the individual gage readings is to be expected due to the proximity to the point of loading and the skewed reaction from the upper pile section. The strain averages between pairs and across the sections are also in sync at this level.

Even though the strains at the 5.2 m gage level averaged out to seemingly consistent values throughout the test (see Figure 7), there is evidence that at higher load increments, where bending became increasingly severe, that the measured strains are not representative of the actual force in the pile transferred through the section. This became evident when the resistance distribution was computed from strain readings for each load increment as shown in Figure 9. Note the apparent excessive load reported by 3.0-m gage level as the load in the BD Cell increased. This caused the interpreted head-down distribution to deviate from the general trend established for the site and confirmed by the early load increments and other gage levels.

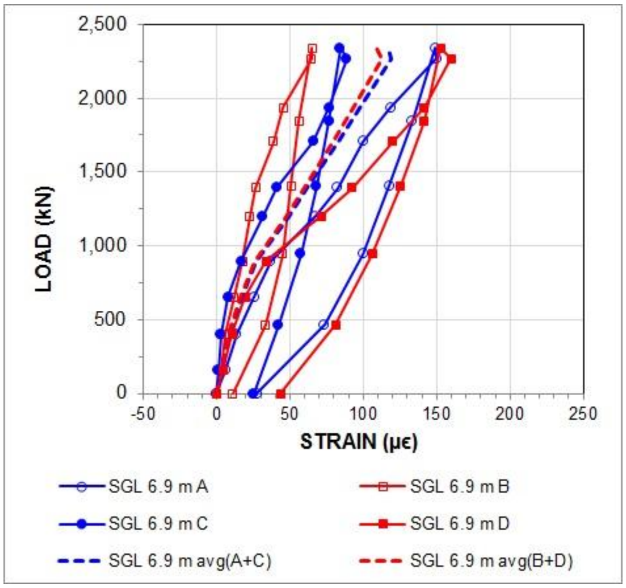

Figure 8. Strain measurements at 6.9 m depth

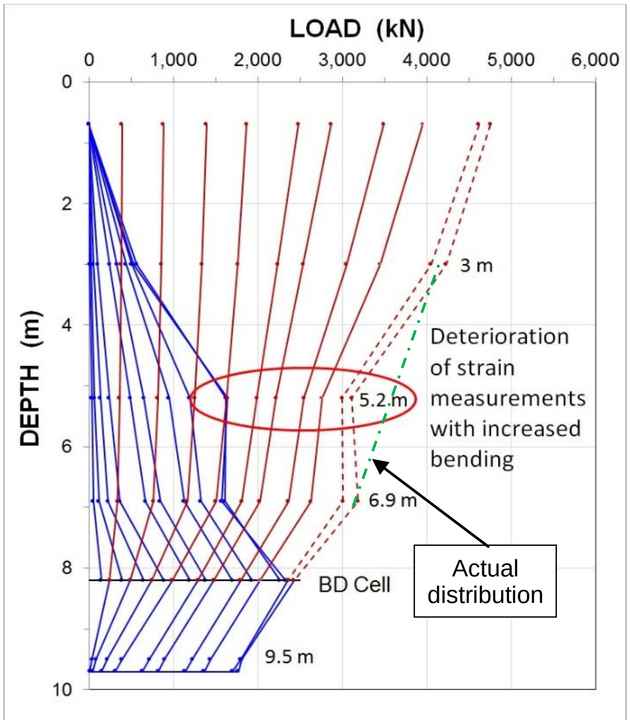

Figure 9. Resistance distribution, Case 2

It is important to note that without Gage Pair B and D, there would have been no indication of bending or any other anomaly in the gage readings from the 5.2-m gage level. Furthermore, the deterioration of apparent force in the pile at the 3.0-m gage level might have been erroneously attributed to an arbitrary cause such as severe strain softening in the response of the soil strata between the depths of 5,2 m and 6.9 m.

As demonstrated in Figure 9, strain gage readings from levels above and below the problem gage level can help recovering from distortions in the calculated resistance distribution caused by these gages as the resistance distribution can be established by interpolation, bypassing the damaged gage level. Therefore, adding intermediate gage levels is a viable alternative to increasing the number of gages per level for redundancy purposes. It is imperative, however, that the instrumented diameter at the redundancy levels be rotated 90º with respect to the instrumented diameter at the original (planned) levels. The advantage of this alternative is that in the absence of gage malfunction, a more accurate resistance distribution profile can be obtained.

4 ADVANTAGES OF BIDIRECTIONAL TESTING

In comparison to traditional head-down pile loading tests, the most obvious advantage of bidirectional testing, especially for high-capacity tests, is eliminating the need for massive reaction systems which require the construction of additional piles, anchors, or dead load platforms, in addition to the high-capacity reaction beams to be fabricated and transported. This could translate into significant savings in cost and time. The advantage becomes more critical in tests with space restrictions and cannot accommodate the large footprint of a reaction system. It is important to add that only half the test load needs to be applied to perform the BD test, which can be an important advantage at higher load levels where loading devices become specialized equipment and more difficult and costly to procure. Another related issue worth mentioning is the environmental cost of unnecessarily manufacturing and constructing reaction piles and anchors that will not be used to support any structures or have any use beyond the performance of the test.

The second most obvious advantage, which often gets overlooked, is safety. There is an inherent risk when using small devices to apply loads in hundreds, or thousands of tons to a reaction system when people must be close by to observe. The literature contains many cases of dead-load platforms collapsing, loading systems turning into projectiles at high loading, welds snapping, etc., with sometimes, sadly, a high human cost. Bidirectional testing, while delivering a superior test in terms of results and benefits, eliminates all these safety risks by applying the loads safely deep below ground.

On the technical side of comparing the BD test and the head-down test, the issue of residual load is worth discussing. Residual load is caused by the difference in stiffness between the embedded pile and the host soil, which causes the soil to apply a downward (negative direction) friction on the pile shaft. The pile resists the negative skin friction by engaging upward soil resistance along a lower portion of the shaft and part of the toe resistance. The shift from negative to positive direction shear occurs at a depth called the “neutral plane”, which is where the maximum compression stress in the pile can be found. Residual load encompasses all these forces.

Moreover, the strain gages placed in the pile are subjected to the strains induced by construction, concrete shrinkage and swelling, in addition to the residual load.

At the time of the static loading test, strain gage readings are set to zero before the start of load application, and the stress history in the pile is ignored, Monitoring the gages continuously after construction does not solve this problem as it is not possible to accurately separate residual load effects from localized hydration-induced stresses. In contrast to loads applied to the pile head in a head-down test, the load applied by the BD cell implicitly includes the residual load and is the true load in the pile at the BD Cell location. Moreover, a careful study of the bidirectional test records will actually show the residual load, if any, present in the pile at the BD cell level. That is, in contrast to a head-down test, the bidirectional test will establish the true load in the pile.

Not often realized is that using anchor piles or a loaded platform for reaction to a head-down test can result in a stiffening of the response of the test pile, falsely indicating a stiffer pile than that of the pile the test is supposed to represent.

5 DISCUSSION AND CONCLUSION

This document is by no means a comprehensive manual on bidirectional testing, however, it highlights aspects of the test that are very helpful to owners, engineers, and contractors for deciding on, and planning successful bidirectional tests.

Some of the many advantages of the BD test, financial, environmental, safety, and technical, are discussed in Section 4 of this paper, and put in perspective the importance of the test.

In addition to the test description and advantages, practical tips on improving the quality and efficiency of a BD test, based on experience and lessons learned are provided. Some of the highlighted issues include comments on planning contingency measures in case of uneven resistance above and below the BD Cell to help ensure a successful test.

The paper also emphasized the importance of redundancy in the instrumentation by showing practical examples.

Also highlighted herein is the advantage of using multiple cylinders in the BD cell to distribute the load over the pile section which allows for strain gages to be placed closer to the cell elevation.

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