Common Pitfalls in Bi-Directional Static Load Testing

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ABSTRACT

The bi-directional static load test (BDSLT) has become a widely accepted and popular test method for deep foundation elements, such as drilled shafts, ACIP piles, and barrettes. The assembly, installation, and testing of BDSLT foundation elements and interpretation of the resulting data are both an art and a science. Irretrievably installing a hydraulic loading apparatus and instrumentation deep into concrete in a manner that ensures that everything will work correctly takes planning and experience. Once successfully installed, the inverted nature of the test itself requires that the data be properly interpreted in order to be useful for the client, engineer, and ultimately the owner. This paper discusses some of the issues which can arise during the assembly, testing, and interpretation of BDSLTs to the detriment of the project. The various observations have been collected from the author's extensive experience in the BDSLT field as well as published results in the literature.

INTRODUCTION

Bi-directional testing was first conceived of by various researchers and practitioners perhaps as early as the 1960's (Amir, 1983). More widespread documented use first appeared in the 1980's in Brazil, Japan and the United States, as described by Fellenius (2015). Bi-directional static load testing (BDSLT) is now a common and widespread practice in deep foundation engineering and construction. As of 2018, it has its own ASTM standard (ASTM D8169/D8169-M - 18).

The basic premise of BDSLT is quite straightforward. By embedding the loading apparatus within the foundation element rather than applying load at the pile head, the need for an external reaction system is eliminated, and significantly higher loads can be generated safely. The tradeoffs to the traditional static load test method are primarily the loss of sacrificial equipment (hydraulics) and the additional assumptions and more complex analysis of the test data necessitated by the reversed loading of the upper foundation segment. On the other hand, BDSLT provides measurement of the load in the pile that is unaffected by residual force ensuring a greater reliability in the evaluation of the axial load distribution. In recognition of its advantages, BDSLT has grown in popularity worldwide and is accepted by many local, regional and national agencies responsible for overseeing foundations and the construction industry in general globally.

As with many specialized engineering and testing services, properly planning, designing, assembling, installing and successfully carrying out a BDSLT is as much an art as a science. Herein, some of the less-obvious pitfalls related to bi-directional load testing are discussed.

A BDSLT SHAFT IS NOT A METHOD SHAFT

A dedicated BDSLT foundation element will be constructed to the same standards as production elements, often with the same reinforcement and all of the same QA/QC requirements (including inspection and integrity instrumentation such as sonar calipering, cross-hole sonic

(CSL) tubing, thermal integrity profiling (TIP) wire or similar). In addition, it will have one or more bi-directional load assemblies installed in it, which inevitably will create a large blockage or discontinuity in the element. The element will also have significant additional instrumentation (strain gages and displacement transducers) and associated signal cables and hydraulic lines. All of this combined can lead to a very congested reinforcing cage, which makes placement of concrete more challenging.

To make matters worse, project specifications sometimes designate the test foundation element as the method or demonstration element, since it will not become part of the production foundations and is thus often seen as a waste of construction time, effort and materials.

Because of the additional equipment required for the bi-directional test, it makes for a poor demonstration element. For one thing, lifting, installation and concreting plans may be different, to account for the additional weight and physical configuration of the loading apparatus. Cage splices will inevitably take longer, as connections for hydraulics and instrumentation must be factored in. At the same time, there is no room for error due to the financial and scheduling impact of not installing the element and load apparatus correctly, with all the test equipment in good working order. A true, dedicated method element can be used to learn what not to do, and which issues to correct for during production. The BDSLT element has no such luxuries. It has to be done right the first time.

It is not uncommon to receive a phone call or email from the drilled shaft contractor after installing a BDSLT element and before testing it, with the news that a significant defect has been identified by the CSL, Gamma-Gamma or TIP inspection of the pile. The 'defect' most often turns out to be the loading apparatus itself. Consisting of high-pressure hydraulic jacks and surrounded by steel bearing plates, the load apparatus is in fact an anomaly in the element which significantly distorts QC results. Figure 1 presents two examples of foundation elements tested within the last few years by the author:

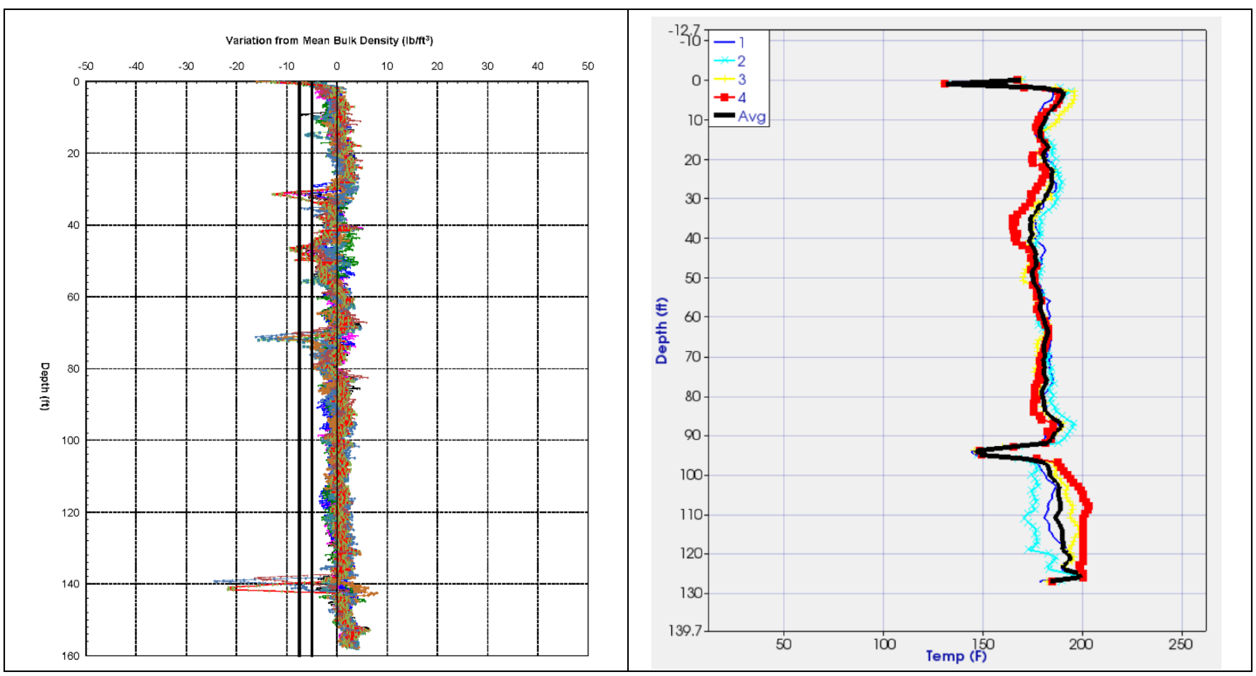

Figure 1 – Examples of QC Result Distortions Caused by BDSLT Load Devices

The significant anomaly seen at depth 140 ft. of the Gamma-Gamma report (Figure 1 left) and at depth 95 ft. of the TIP report (Figure 1 right) represent the location of the BDSLT apparatus in a drilled shaft and an augercast pile, respectively.

Apart from the 'defect' which is the bi-directional apparatus itself, the temptation to test a perfect foundation element persists. In the first example given in Figure 1 above, additional zones of concern were indicated in the upper half of the shaft by the Gamma-Gamma results. Initially, the client wanted to either reject the test shaft outright, or attempt to mitigate the suspected voids via coring and grouting. After additional inspections using CSL equipment and intense consultation, the client was persuaded to test the shaft without mitigation of any kind. Coring and grouting would have exposed the embedded BDSLT hydraulics and instrumentation to significant risk of damage. Strain gages were carefully observed during the test for any indication of crushing or uneven strain distribution during the test. In the end, this supposedly defective shaft carried a higher-than-anticipated load with no sign of any anomalies in the shaft concrete.

A TOLERANCE FOR ECCENTRICITY

Dr. Jorj Osterberg, who acquired the patent for bi-directional static load testing, also had a knack for marketing. His trademarked name for the sacrificial loading apparatus, the 'Osterberg Cell' or 'O-cell', became so ubiquitous that even now, in a globally competitive market, many engineers and specification documents still refer to the loading device as an 'O-cell' or its generic equivalent, 'load cell'. However, the proper definition of a *load cell* is a load-*sensing* device, not a load-*generating* one. And in the vast majority of its embodiments, the BDSLT 'cell' is simply a hydraulic jack which must possess two specific features: The first is a calibrated, linear and repeatable correlation between pressure and load. The second is a tolerance for minor tilting (i.e. the ability of the top and bottom halves of the jack to rotate relative to one another), without affecting the linear pressure-to-load correlation.

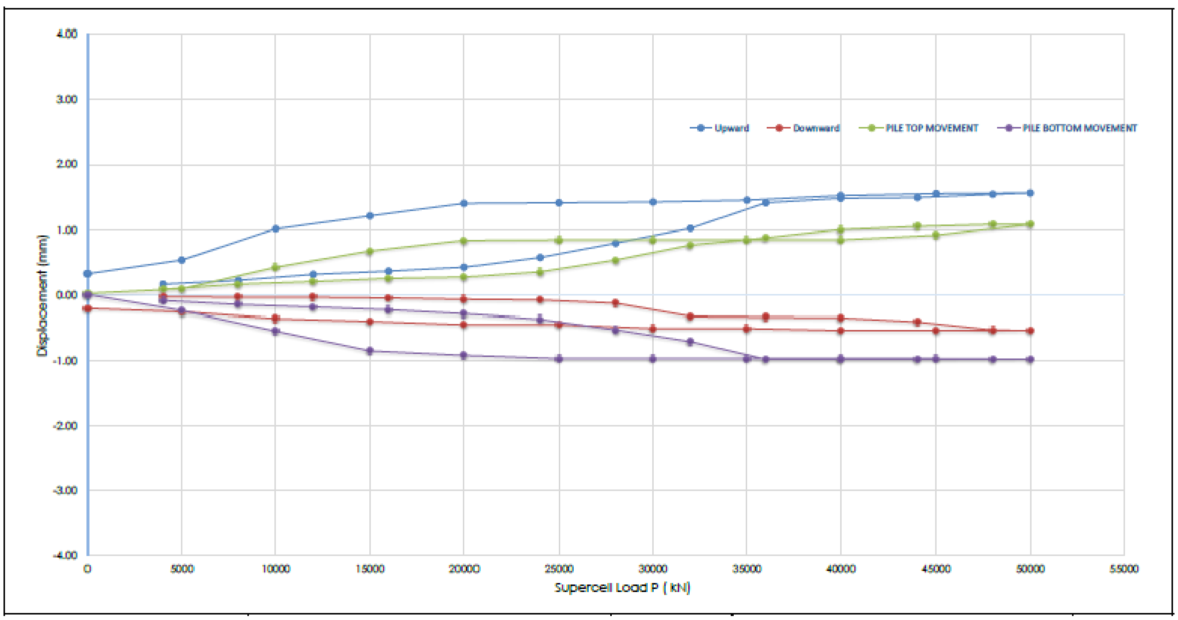

Figure 2 – (Sakhuja et. al. 2019 Figure 9 – Load Vs Displacement Curve for Bi-Directional Load Test)

Without this tolerance, the in-situ pressure to load relationship can change without the testing engineer being aware, up to and including the jack(s) seizing up completely and becoming static pressure vessels which do not generate any additional external load under increased pressure. A possible example of this can be seen in the load test described by Sakhuja et. al. (2019). Figure 9 from that publication, the load-displacement curves for the test, is reproduced below:

Note the flattening out of both the upward and downward displacement curves at the applied load of 35 MN. The load apparatus stops expanding, although the curves up to that point displayed the classic curvature characteristic of geomaterials' response to load. Unless the material both above and below the jacks simultaneously strain-hardened to a very high degree, the simplest explanation is that some additional force besides soil reaction restrained the jacks from opening further.

Although Sakhuja does not provide elevation details, a photo of the loading apparatus in the rebar cage indicates that it was positioned within one diameter of the shaft base:

Figure 3 – (Sakhuja et. al. 2019 Figure 8 – Positioning of Jacks in the Pile Cage)

It is quite common for end bearing reaction to be somewhat eccentric relative to the centerline of load application, thus imposing a bending moment on the loading device. Since the jacks had already expanded smoothly 2.5 mm at the 35 MN of applied load, some kind of internal binding seems to be a likely explanation for the load-displacement behavior above 35 MN applied load.

Multiple measurements of expansion around the perimeter of the loading apparatus are necessary to detect differential opening of individual jacks and to assess the degree of tilting. A critical inspection of the test results is also needed. Load-displacement curves that look too good to be true, often are.

STRAIN GAGES ARE NOT SILVER BULLETS

Strain gages are often employed in deep foundations element top-down static load tests (SLT) and rapid load tests (RLT). However, for BDSLT they are especially important. Assessing the force distribution within the element is critical to evaluating its likely top-down behavior.

Typically, two or more strain gages per level will be installed in a test element. This arrangement allows for an estimate of the strain at the centroid of the pile to be computed as an average of the individual strain measurements. This is desirable to compensate for any bending in the pile due to eccentric loading or uneven soil resistance. Strain gages installed in the field into cast-in-place foundation elements have a relatively high probability of failure λ, due primarily to installation procedures for deep foundations. For drilled shafts and barrettes, heavy rebar cages must be picked by crane, tilted from horizontal to vertical and then inserted into the excavation. Concreting then takes place, either via the tremie method or by gravity pour, either of which is a dynamic process with plenty of opportunity to damage a gage. For ACIP piles, the rebar cage is lifted at the head to facilitate rapid insertion into the wet grout. This necessitates inducing a 90° bend into the cage in many cases, followed by rapid insertion of the cage into grout under self-weight. During a recent test program carried out by the author for example, from a total of 675 sisterbar vibrating wire strain gages installed in eleven test piles, thirteen failed to function during testing, for a λ of 2.5%.

Recognizing that individual gages have a relatively high failure rate, some project specifications call for three rather than two gages per level, in the hopes of increasing redundancy:

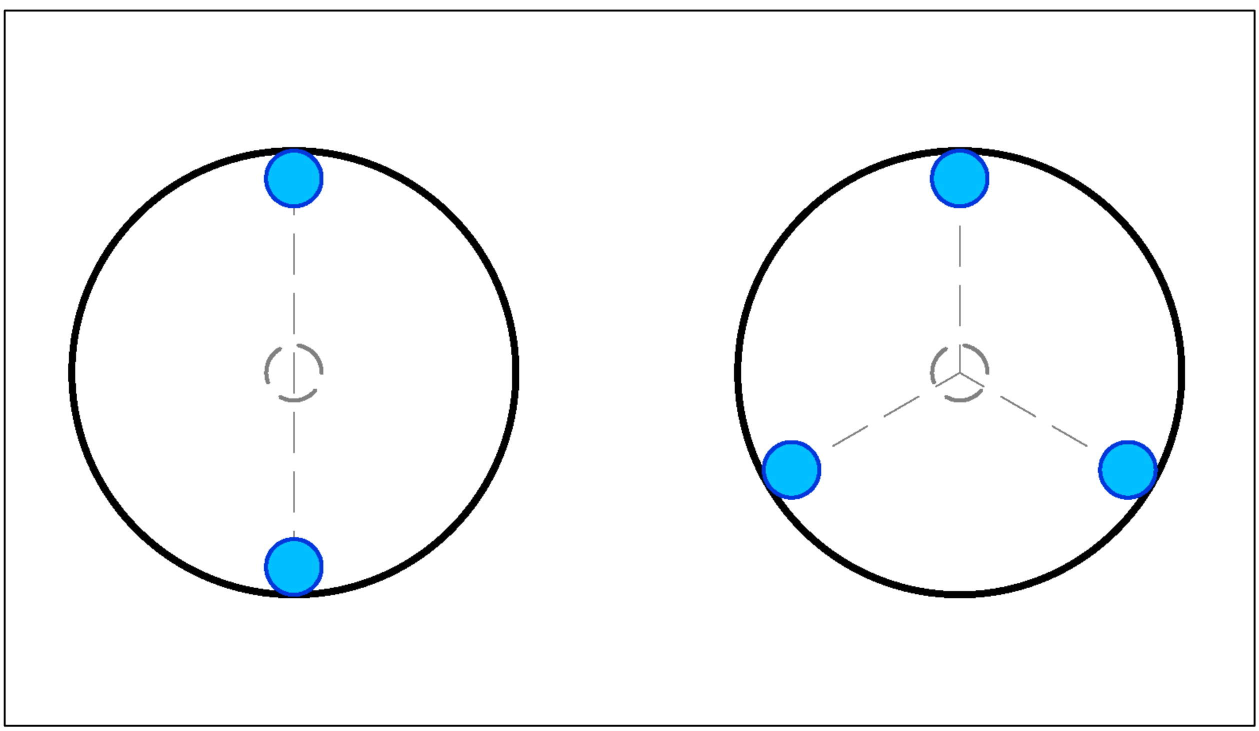

Figure 4 - Typical arrangement of opposed pair and triplet strain gages in pile cross section with computed average (dashed lines)

Counter-intuitively, this arrangement actually *decreases* the overall system reliability. In order to compute the average strain at the centroid of the pile cross-section, all the gages at a given level must function. Given n gages at a level, the probability of success S_n is computed as the simultaneous probability of survival of all the gages:

$$\boldsymbol{S_n = (1 - \lambda)^n} \qquad \textbf{Equation 1}$$

Although in practice if a single gage fails the remaining gage(s) are often still utilized to measure the strain, this is a suboptimal solution because the averaged strain is now off the pile centroid and thus is not likely to represent the true net axial strain. Using Equation 1 and an example value $\lambda = 3\%$, the probabilistic result is that installing three equally-spaced gages per level (presumably for increased redundancy) results in a lower probability of successfully obtaining the average strain at the pile centroid ($S_3 = 91.3\%$) than using two gages in an opposed pair ($S_2 = 94.1\%$). At the upper bound, if $\lambda = 10\%$, then $S_2 = 81.0\%$ and $S_3 = 72.9\%$. To truly increase the redundancy, four gages arranged as two independent opposed pairs should be installed at each level. The probability of success of this arrangement S_{2x2} is computed as the probability of at least one opposed pair functioning:

$$\boldsymbol{S_{2x2} = 1 - (1 - S_2)^2 = 1 - (1 - (1 - \lambda)^2)^2} \qquad \textbf{Equation 2}$$

Using the lower bound example gage failure rate of 3%, the probability that at least one opposed pair of gages functions, and thus strain at the pile centroid is correctly measured, is 99.7%. Even at an individual failure rate of 10%, $S_{2x2} = 96.4\%$.

Once the strain is accurately measured, it must be interpreted. This is quite straightforward in theory: strain times modulus equals stress, and stress times area equals force. Unfortunately, deep foundation elements are a composite of two materials (concrete and steel) whose stiffness properties are an order of magnitude apart. Second, concrete itself is a material with properties which are heterogeneous. It varies widely with mix designs and placement techniques and its stress-strain curve is non-linear under any significant applied load. Lastly, the cross-sectional area of drilled shafts, augercast piles and other cast-in-place bearing elements can vary, sometimes significantly, from nominal dimensions. All these factors combine to make estimating the pile stiffness (modulus times area) to the precision required to accurately interpret embedded strain gage data quite complex.

A top-down static load test usually overcomes many of these issues by embedding one set of strain gages near the head of the element, above ground elevation, i.e., at a point where there is no or insignificant shaft resistance between the hydraulic jack and the gage level. These gages are subject to the full force of the applied load in a free-standing column, and the element's stiffness is back-calculated as the applied load divided by the average strain in this top level of gages. This technique is known as the secant stiffness method (Fellenius 2020).

For bi-directional tests with an embedded load apparatus, the secant stiffness method is not an option. Strain gages have to be located at least two pile diameters away from the load assembly for uniform plane strain to develop. However, over this length load is shed via skin friction. In other words, even the closest strain gages to the load apparatus will not be subject to the full applied load, but rather a reduced load. How much load is shed is a function of the load computed from the strain gage, so that data cannot be used (directly) to compute the element stiffness because it becomes a circular calculation.

The tangent stiffness analysis method (Fellenius 2001) can often overcome this problem. The method allows for an indirect analysis of foundation element stiffness by plotting the change in strain divided the change in applied load vs. total load, then integrating the resulting linear regression fit. A further refinement in nonlinear stiffness analysis (Sinnreich 2012) was developed to address highly variable element stiffness, such as when concrete cracks under tensile strain. Moreover, if the soil is either strain-hardening or strain-softening, the evaluated pile axial stiffness will be quite different from the true axial stiffness of the pile (Fellenius 2020). While these papers explain the material in a straightforward manner, perusing them should convince most readers that interpreting strain gage data in deep foundation load testing is far from trivial. More often than not, judgement must be applied (for example which data points to exclude in the tangent stiffness regression fit), which opens the process of strain gage analysis up to subjective interpretation.

CREEPING TOWARDS A TEST RESULT

Bi-directional testing, as an ‘alternate’ method to a traditional top-down load test, has typically fallen under the specifications of standard compressive static testing. Until 2018, BDSLT did not have a dedicated published standard, and was typically performed in ‘general’ accordance to ASTM D1143/D1143 M - 2013, the top-down compressive static load test standard. This standard specifies several alternate step-and-hold procedures, wherein loading is maintained at various levels for various durations of time. One method, which is ideal for bi-directional testing, is the ‘quick’ test method whereby load is increased by equal amounts and each step is maintained for an equal duration of time. However, this is not the only possible method, and local building codes or practices also often impose additional requirements originally intended for top-down tests onto the bi-directional test. The result can be a loading schedule which includes holding some factor of the design load for a longer duration than the typical load step interval, maintaining intervals until the rate of displacement achieves a specified value, and/or testing in several cycles of increasing maximum load.

A bi-directional test is in many ways two simultaneous independent tests on two very dissimilar foundation elements. The segment above the load mechanism, resisting load in pure shear, often displays very different displacement and rate of displacement (velocity, often misnomered as ‘creep’) characteristics than the segment below, which typically includes both shear and bearing components of load resistance. These two independent load-displacement curves then have to be analytically stitched back together, since the working foundation element will be an intact unit with both segments moving together. In practical terms, this means it is not possible to define ahead of time at what point in the test any specified top-down load is achieved. The equivalent top load analysis (see next section) needs to examine the full load-displacement behavior of both segments before the top-down behavior can be computed. As such, interrupting the loading scheduled by maintaining the element’s ‘design load’ during a bi-directional test is educated guesswork at best.

Another factor to consider is the ‘creep’ (velocity) of the two elements. Since each segment is resisting the same load, and since the intact working element must move as one body, whichever rate of displacement is the smaller should dictate the velocity criterion, though this is typically not done in practice. Furthermore, in general each test segment is achieving its own *rate* of displacement at a different *total* displacement. The segment with the smaller velocity may have the greater displacement. Yet, the intact element must move with one velocity through one displacement curve. Trying to enforce simultaneous compatibility on all factors of the test (load, duration, displacement and velocity) is impossible. The best practice, as defined in ASTM D8169 (2018), the bi-directional testing standard, is to apply small (~5% of expected maximum), equal load increment steps, maintained for equal durations of time, in one cycle, increasing monotonically until some limitation of the test is achieved (rapid displacement of one or both of the test segments, maximum jack capacity, or similar). This ensures that the resulting unit capacity curves and equivalent top load curve are smooth, constructed from many data points, and represent an element loaded top-down in the same equal load steps of equal time duration as the actual bi-directional test.

Engineers specifying a load test, especially one with long periods of maintained load for creep rate analysis, must appreciate the realities of trying to achieve high-precision displacement measurements on a construction site. The typical practice of placing a reference beam across the test element implicitly assumes that this beam is an absolute, rigid benchmark. However, the list of environmental factors that can affect its stability to a noticeable degree is quite extensive. Thermal variation (sun/clouds, day/night cycle) will deform the beam itself, while its supports can be displaced by adjacent construction site activity (vibration), ground freezing/thawing, rain (erosion of supports), ground settlement or heave due to the test element and/or reaction pile displacement, and wave and current action for offshore tests. It has been the author's experience (Sinnreich and Simpson 2009) that maintaining an absolute reference can be quite challenging, all the more so the longer testing continues and especially when very fine accuracy for creep rate analysis is required.

Finally, cyclical loading generally serves no purpose to a BDSLT except in special circumstances. Compared to top-down testing, a bi-directional test is inherently safe, since the load energy is buried deep underground. Thus, testing can and sometimes does continue right up to complete failure of the test element and/or the load mechanism (hyperextension of the jack). Any safety benefit of cycling the loads (to test the response of an external reaction system) is unnecessary. Modern bi-directional tests are by necessity heavily instrumented with shaft elastic compression telltales and strain gages, to enable the test engineer to properly interpret test results. Thus, any benefit of cyclic loading in terms of building up information on plastic soil deformation and pile head 'set' is superfluous, as this information can be extracted from the embedded instruments directly. Cyclic loading adds nothing to a typical bi-directional test except hysteresis loops in the unit capacity curves, and complicates the analysis of the test results (Fellenius and Nguyen 2019, Fellenius 2020). The only practical exceptions to this known to the author are the common practice of re-loading production test elements to demonstrate that testing did not damage skin friction capacity of the element, and a single test program where long-period wind loading on a structure was simulated by a large number of rapid, repeated load-unload cycles to the same maximum and minimum load to test the fatigue capacity of the test element.

EQUIVALENT TOP LOAD CURVES – WHO NEEDS THEM?

The equivalent top-load curve is derived from bi-directional static load test data. It is an add-on to a test method that doesn't actually produce a single load curve. The results of the BDSLT are best presented as separate unit capacity end bearing (q-z) and side friction (t-z) curves based on the analysis of embedded strain gages, to a greater or lesser degree of accuracy as discussed above. However, engineers were used to seeing the traditional static top load test (SLT) curve, and demanded the same from the bi-directional test. Fellenius et. al. (1999) first discussed a simple analysis method for deriving the equivalent top load (ETL) curve from the BDSLT data. Essentially, it's a first order simplification of the 1-D finite-element soil-spring t-z analysis used in many foundation design and analysis programs. Fellenius (2013) gives a more detailed explanation, and Seo et. al. (2016) present a good overview of the method.

The ETL analysis has many sources of uncertainty, some of which are obvious and some which may be more subtle. Significant assumptions have to be made to construct the curve, including that the soil has the same shear resistance loaded upward as opposed to downward and that the BDSLT upward load distribution curve can simply be inverted to compute the additional elastic compression of a top-down load. On the other hand, a load-displacement curve from a traditional load test will by necessity include the effects of the reaction piles, anchors or reaction mass supports, while an ETL curve is constructed from a truly isolated foundation element. The few direct comparison studies between top-down SLT and bi-directional ETL curves seem to show fair agreement if not an exact duplicate (Kwon et. al. 2005, Lee et. al. 2008). The best that can be said of the ETL curve is that it has utility as a visual aid and to benchmark against other tests.

The optimal use of a BDSLT test is as a source of q-z and t-z curves, which can be used to validate or improve design assumptions or computer models such as FB-MultiPier or UniPile. Note that this is best accomplished by correlating the unit capacity curves to an on-center soil boring at the test element location, which is another requirement that should be specified in every test program. Using the ETL curve as a primary criterion for judging if a foundation element 'passed' the test is not recommended due to all the uncertainties enumerated above.

CONCLUSIONS

Bi-directional static load testing is a useful tool for deep foundation design and construction validation. However, like all test methods it has limitations. Using the test shaft as a method shaft may save some money but also increases risk. The loading apparatus is crucial and must be installed correctly and monitored carefully to ensure the presumed load based on applied pressure is actually delivered to the foundation segments. Strain gages embedded in concrete are not the straightforward load-sensing devices that they are sometimes assumed to be. The so-called 'quick' test method of small load steps of equal duration is ideal for the analysis of test results, while other testing schedules or criteria usually only complicate the analysis with little benefit. The ETL curve is a good approximation of the true top-down behavior, but is not a measured value and should not be used to apply a pass/fail assessment of the test foundation element.

Seemingly small details in the installation, test execution or test data analysis can result in significantly different results, or equally critical, significant differences in the *interpretation* of results. An engineer who specifies bi-directional static load testing for a project should be aware of both the advantages and the limitations of the method and its resultant data interpretation. The test results are best-utilized in validating and improving the t-z and q-z inputs for foundation design procedures or codes. Test data reports should be carefully examined alongside all available shaft QA/QC data, to assess if the load-displacement and load distribution results make sense.

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