# Bi-Directional Static Load Tests: Criteria and Methods of Analysis in Practice

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Michael Diez de Aux, M.A.Sc., P.Eng. & Jason J Crowder, Ph.D., P.Eng.
*Grounded Engineering Inc., Toronto, Ontario, Canada*

ABSTRACT
Bi-Directional Static Load Testing (BDSLT) is becoming conventional practice in the Greater Toronto Area (GTA) when designing high-capacity cast in-place concrete piles (“caissons”) founded in either soil or bedrock. Methods of BDSLT engineering analysis, on the other hand, vary widely. This paper provides an overview and comparison of some analysis methods used in the GTA standard of practice. The numerical modelling approach, although computationally intensive, is the most appropriate and defensible method for designing highly loaded caissons using BDSLT data. The authors present a list of criteria for robust BDSLT analysis for consideration. The paper concludes with some lessons learned through experience.

RÉSUMÉ
Les tests de charge statique bidirectionnelle (BDSLT) utilisés pour la conception de caissons à haute capacité fondés sur le sol ou le substrat rocheux, sont désormais une pratique courante dans la région du Grand Toronto. Cependant, les méthodes d'analyse des données BDSLT sont diverses. Cet article fournit un aperçu de différentes approches d'analyse communément utilisées en Ontario. Cette étude nous permet de conclure que l'approche de modélisation numérique est, bien que nécessitant beaucoup de calculs, la méthode la plus appropriée et valide pour la conception de caissons fortement chargés à l'aide de données BDSLT. Les auteurs présentent une liste de critères à prendre en considération pour une analyse BDSLT robuste. Quelques retours d’expériences font partie de la conclusion de cet article.

## 1 INTRODUCTION

In the GTA, high-rise towers have traditionally been located where bedrock is available to support their very high loads. Downtown Toronto and Mississauga are notable areas where high-rise development has flourished because of the relatively shallow elevation of the bedrock for the support of tall structures. However, taller towers exceeding 45-50 stories are now economically desirable for developers in areas where bedrock is too deep to be financially viable to support foundation loads.

In cases where raft foundations are infeasible, typically due to ground conditions or excessive load-settlement characteristics, caissons designed with the support of a full-scale load test are becoming a conventional consideration, despite the large capital cost.

The Bi-Directional Static Load Test (BDSLT, also known as the Osterberg Cell or O-Cell Load Test) is the preferred method for testing the capacity of a full-scale caisson. The method and its benefits are widely reported internationally (Osterberg 1995, Schmertmann et al. 1998) and in Canada (Amini et al. 2008, Diez de Aux et al. 2023, Skinner et al. 2008).

The load cell consists of a bi-directional sacrificial hydraulic jack mounted between two bearing plates and cast into the caisson at a depth specified by the geotechnical engineer. The depth of the load cell is designed to balance side shear resistance with end-bearing resistance. The BDSLT concurrently tests downward capacity (end bearing plus side shear), which is resisted by upward side shear (see Figure 1). This balancing allows the load test to be completed without the need for expensive, large, and dangerous reaction frames resisted by additional sacrificial caissons.

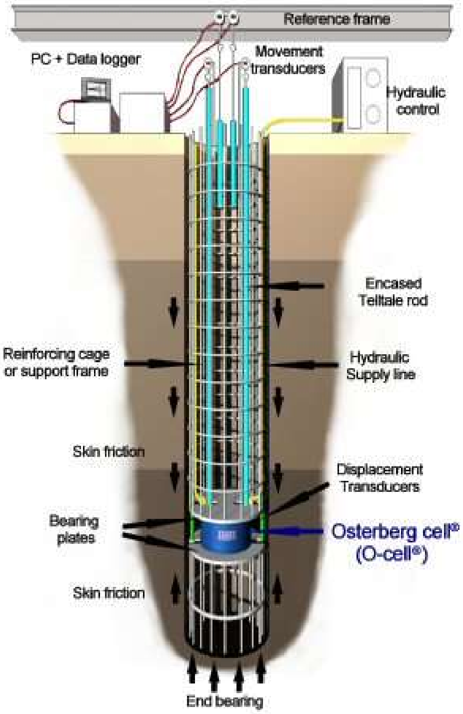

Figure 1. Typical Bi-Directional Static Load Test setup (from www.loadtest.com).

## 2 APPLICATIONS

There are several cases in which it is now local practice to design high-capacity caissons with BDSLT data.

**Soil caissons:** Piling drill rigs can install caissons to about 60± m below grade, depending on Kelly Bar length, ground conditions, diameters, and available equipment. Where bedrock is over 70± m below grade, high-capacity caissons supported entirely in soil are now a consideration for resisting high loads. The preferred method for these caissons is to make them deep and slender, which reduces concrete volume, drilling time, and risk of caving. They are designed to minimize the number of caissons, typically targeting one caisson per column. This paper discusses soil caisson BDSLT analysis.

**Rock Sockets**: Tall towers and other highly loaded structures (e.g. bridges) may be supported by caissons made to bear in bedrock. This approach is typically preferred over high-capacity soil caissons where bedrock is up to about 30-40 m below grade. Although BDSLT analysis methods for bedrock are outside the scope of this paper, they are briefly discussed here.

The basic approach when providing bedrock capacities is to provide conventional and widely used “rule of thumb” bearing capacities. Many consultants do not have access to the original data that proves these capacities (prior full-scale top-down load testing at Toronto’s Pearson Airport); as a result, bedrock capacities in the GTA have become somewhat apocryphal. They have also become noisy – “typical” capacities provided recently have deviated by ±50% from the average. Where additional capacity is needed, BDSLTs have been performed to test bedrock capacities at a handful of private development and public sites in the Greater Toronto and Hamilton areas. BDSLTs in the local bedrock have also been recently completed by the Ontario Ministry of Transportation (MTO) for new infrastructure (Hanson et al. 2023). Where they have been conducted, recent BDSLT data confirms that the conventional “desktop” bedrock capacities are conservative, and that additional capacity is available from the bedrock if supported by BDSLT data.

**Pile-Augmented Rafts:** There are also cases in which a raft foundation is marginally feasible, but settlements are excessive and outside of tolerable limits. A pile-augmented raft may be considered where ground conditions render a raft alone infeasible. To control settlement, the raft is stiffened by a few strategically placed caissons, and structural loads are shared between the caissons and the raft. To supplement design, pile stiffnesses and capacities are required, which in turn requires a static axial pile test (Poulos 2001, Katzenbach et al. 2001). BDSLT testing provides an economical method for understanding real pile stiffness and ground response. The BDSLT modelling method described in this paper also applies to pile-augmented raft design.

## 3 METHODS OF BDSLT ANALYSIS

Per standard test practice (ASTM D8169), a BDSLT caisson is instrumented with strain gauges (see Figure 2) to infer load carrying capacity along the length of the caisson, as well as Linear Variable Differential Transformers (LVDTs) and tell-tales for measuring displacements. The amount of instrumentation is substantial as it provides geotechnical information and BDSLT data, as well as redundancy.

Figure 2. Typical strain gauge rebar setup on the load frame in preparation for a BDSLT.

Figure 3. Load cell showing top and bottom plates, LVDTs and other instrumentation.

Analyzing BDSLT data is not as straightforward as a conventional top-down load test. For a “classic” top-down load test, the geotechnical engineer can simply review a top-down load curve to determine (often visually) the ULS and SLS capacities of the test caisson. A BDSLT, on the other hand, places the load cell near the pile tip, and load reaction curves reflect upward and downward movement at the level of load cell. Where the load cell is not at the bottom of the pile, the downward load is a combination of end bearing resistance and side shear resistance below the load cell, whereas the upward resistance is only side shear.

However, it is still the top-down load-deflection behaviour at the top of a production pile (not a test pile) that is of primary interest for structural design. As a result, methods are needed to convert the up-down load reaction curves into a top-down load curve, often referred to as the Equivalent Top-Down Load (“ETL”) curve.

A robust BDSLT analysis should be able to achieve the following four criteria:

1. It should simultaneously consider the three loading mechanisms that govern soil-pile deflection,

namely side-shear resistance, end-bearing resistance, and pile stiffness.

2. It should be able to consider caissons of different diameters and different pile tip depths.
3. It should be able to account for reductions in vertical effective stress, which is required if bulk excavation (e.g. basement excavation) is to occur after the BDSLT and before production pile installation.
4. It should be able to account for bulges in caisson geometry, which could occur if a boulder is removed or if there is a local sidewall sloughing during test pile installation. Bulges will tend to increase side shear resistance and cannot be reliably reproduced in production caissons.

## 3.1 Basic Method

The most basic method of BDSLT analysis employed locally is not rigorous and can be dubbed the “confirm initial parameters and improve resistance factor” method. The BDSLT is designed using initial side shear and end bearing parameters which are akin to the “rule of thumb” capacities described above. Once the BDSLT shows that the measured side shear and end bearing resistances are greater than or equal to originally contemplated, the designer concludes that their initial design parameters are appropriate.

As a static load test has now been conducted, a higher geotechnical resistance factor of 0.6 can be used for deep foundations in compression (CFEM 5th Ed.), whereas static analysis only (no load test) requires a resistance factor of 0.4. Thus, the load test can improve the factored geotechnical resistance at ULS capacity by 50% based on resistance factors alone. The factors above assume a “typical” degree of understanding, which is new to the CFEM 5th Ed. and is related to the amount of borehole information available.

The CFEM 5th Ed. also requires that settlements are now also factored, and those factors can also be improved if a load test is performed. Considering “typical” factors again, a higher geotechnical resistance factor of 0.9 can be used for deep foundations in compression supported by a load test (CFEM 5th Ed.), whereas static analysis only requires a resistance factor of 0.8. Therefore, a static load test allows the geotechnical reaction at SLS capacity to be improved by 12.5% without any further data analysis.

While the basic method of BDSLT analysis can work due to its over-conservatism and ease of use (no analysis or modelling required), there are several critical drawbacks. It does not actually use the BDSLT data to design the caisson, leaving a significant amount of available capacity unused. Nor does it address any of the four criteria for robust analysis laid out above. These deficiencies are mitigated somewhat by the basic method’s conservatism.

## 3.2 Analytical Equivalent Top Load (ETL) Method

The next evolution in BDSLT analysis is to use the upward and downward load-displacement data by converting it using analytical methods (i.e. hand calculation) into an Equivalent Top-Down Load (ETL) curve. The analytical ETL method was reported by Osterberg (1995), with modifications contributed by many others and summarized by Loadtest (2000) and Seo et al (2016). The increase to resistance factors outlined in Section 3.1 also still applies.

The various analytical ETL methods follow the same basic procedure: the upward and downward loads are added together at each increment of movement, which is then provided as an estimate of “top-down load” for each increment of displacement. For example, if at the load cell an upward load of 5 MN caused 25 mm of deflection, and a downward load of 15 MN caused 25 mm of deflection, then the Equivalent Top-Down Load of 20 MN creates 25 mm of estimated deflection. The buoyant weight and elastic compression of the pile can also be added into this analysis in a variety of ways. Loadtest (2000) describes the procedure as well as their own modifications, and an analysis of accuracy when compared to top-down load test data. They conclude that the analytical ETL method has “practical validity”. It is convenient that an analytical ETL curve directly calculated from the BDSLT data is also provided in a BDSLT data report.

The analytical ETL method allows for the results of the BDSLT to be used to estimate the factored ULS and SLS capacities directly, where deflections also consider the compressibility of the pile itself. As such, it satisfies the first criterion for robust analysis. However, analytical ETL analysis does not account for reductions in effective vertical stress due to future excavations (which is fundamental to soil caisson behaviour, as described below). Another significant drawback is the difficulty in extrapolating ETL results to caissons with different diameters. Nor can this method adequately compensate for defects in the test caisson. Thus, the analytical ETL method only satisfies one of the four criteria for robust analysis.

## 3.3 Modelling Method

The most computationally intensive BDSLT analysis methods involve numerical modelling by finite element analysis (“FEA”). These methods have also been widely reported. England (2008) provides a discussion of different FEA methods used for BDSLT analysis, as does Loadtest (2000). Unfortunately for the published literature, FEA methods change rapidly as new software is developed and computation power increases.

The authors use RSPile for BDSLT modelling. RSPile is a modern software package from Rocscience for general pile analysis. For axial analysis, it assumes three loading mechanisms that describe stress-strain relationships of axially loaded caissons: axial deformation of the pile, soil skin friction (or “side shear” resistance) along the shaft, and soil end-bearing resistance (see Figure 3). Finite element analysis of the discretized pile is used to solve the governing differential equation using the “t-z curve method”, which allows for non-linear stress-strain behaviour in soil by employing t-z (side shear resistance) and Q-z (end bearing resistance) curves. This is useful as BDSLT results are reported in terms of t-z and Q-z curves which can be utilized directly.

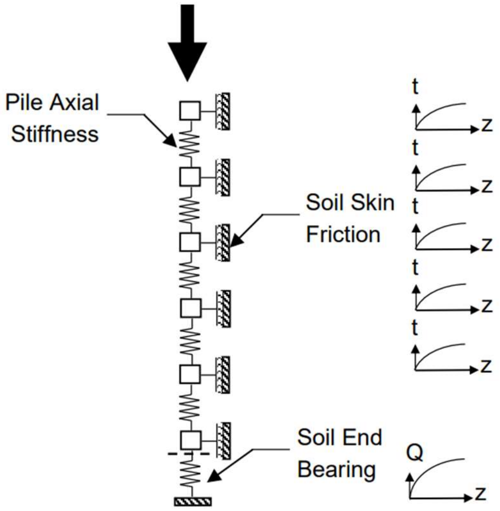

Figure 4. The three loading mechanisms that describe stress-strain relationships of axially loaded caissons in RSPile (from Rocscience).

### 3.3.1 Model Calibration

The first step in the Modelling Method is to simulate the BDSLT test, to validate ground parameters (t-z and Q-z curves). Figure 4 shows a typical BDSLT model calibration.

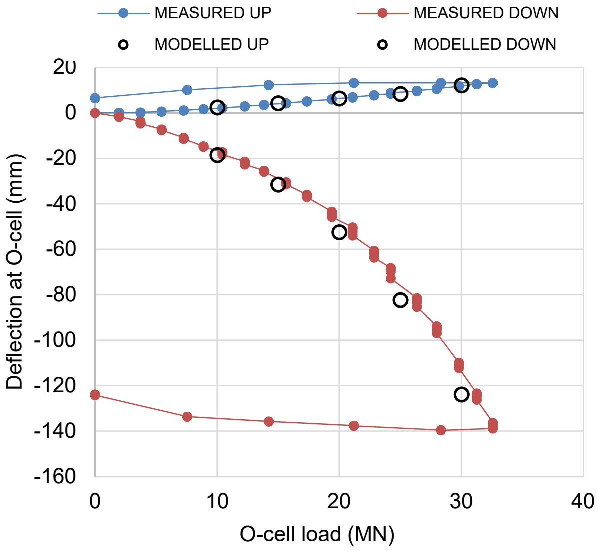

Figure 5. A typical BDSLT simulation result, comparing measured data with the simulation model output.

Often, the raw t-z and Q-z curves do not simulate the test adequately in the first round of modelling. This is often due to deformations in the borehole during caisson installation; RSPile considers a cylindrical caisson, whereas the real test caisson can have bulges and tapers. To observe any deviations in the caisson profile, it is standard conventional practice to use Sonic Caliper or similar technology to measure the borehole diameter, perimeter, area, and the centreline inclination and offset, for the full depth of the borehole, prior to core beam installation and concrete pour.

In cases where defects occur due to local sidewall sloughing or boulder removal, it is possible to correct the t-z data by neglecting high strain measurements in the strain gauges around a defect, averaging the t-z data across it. Any additional side shear stiffness from bulges must be discarded as unconservative. As the modelling method can do this adequately, it satisfies Criteria #4 for robust analysis.

### 3.3.2 Equivalent Top Load Confirmation

Once modelling parameters have been corrected such that they can simulate the BDSLT data adequately, the next step is to model the same caisson and ground parameters, but with the load now applied to the top. This produces a modelled ETL curve that can be directly compared to the analytical ETL curve estimated using basic techniques (as described above) and, conveniently, provided in a typical BDSLT data report.

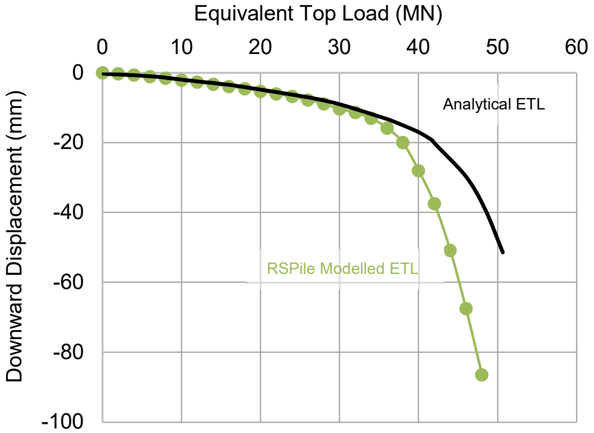

Figure 6. Comparing a conventionally estimated ETL with a numerically modelled ETL.

The typical ETL comparison plot (Figure 6) shows that an RSPile-modelled ETL is more conservative in the larger ranges of movement (i.e. there is more displacement per load step) than the simpler hand-calculated analytical ETL. The modelled ETL accounts for the three loading mechanisms that govern soil caisson deflection as well as pile buoyancy and, importantly, the development of plastic side shear response along the length of the pile from a top-down load. The modelling method thereby satisfies Criteria #1 for robust analysis.

It is noteworthy that both the Modelled and Analytical ETLs generally agree with each other within the range of typical serviceability displacements (i.e. up to 25 mm of top-down displacement). This result has been confirmed by the authors on many projects.

### 3.3.3 Modelling Production Caissons

Once the ground modelling parameters are confirmed and validated, production caissons can be modelled. To convert test caisson data into a production caisson model, the following adjustments are needed:

- a side shear multiplier to account for change in vertical effective stress due to **excavation,** and
- side shear and end-bearing multipliers for caissons of different **diameters**.

In considering the effect of vertical stress along the length of the pile, the CFEM 5th Ed. provides the following conventional equation for estimating the unit shaft friction ($q_s$) and in cohesionless soils:

$$q_s = \beta \sigma'_v \qquad [1]$$

where β is the combined shaft resistance factor (dimensionless) and $\sigma'_v$ is the effective vertical stress adjacent to the pile at depth z (kPa). β is a function of the lateral earth pressure at depth z, and the angle of friction between the soil and the caisson. The CFEM recommends using effective stress analysis (β method) for pile analysis in cohesionless soils, or cohesive soils with an undrained shear strength of over 100 kPa.

The ultimate end bearing resistance ($q_t$) of a pile is similarly governed by effective vertical stress at the elevation of the pile tip, per the conventional equation provided in the CFEM:

$$q_t = N_t \sigma'_t \qquad [2]$$

where $N_t$ is the bearing capacity factor (dimensionless) and $\sigma'_t$ is the effective vertical stress acting on the pile tip (kPa).

As such, the geotechnical axial capacity of a caisson is a function of effective vertical stress along the length of the pile. To control this effect, NAVFAC (1986) recommends that effective vertical stress be held constant below a depth of 20B (where B is caisson diameter). The authors have also observed (Diez de Aux et al. 2023) that the CFEM ranges for $N_t$ may be unconservative (high) for long slender caissons. This topic warrants further study. It is possible that $N_t$ should depend not just for founding stratum, but also on caisson depth.

BDSLTs are usually conducted from original grade, prior to any bulk excavation. Although inconvenient for analysis, this is usually necessary for foundation design to be completed and construction tendered well before the excavation is complete. As a high-rise tower will usually include underground parking levels, production caissons are loaded from the base of excavation, not from ground surface. Bulk excavation results in a net reduction in effective vertical stress, which results in reduced side shear and end bearing capacities.

BDSLT data (t-z and Q-z curves) can be corrected to account for the reduction in effective vertical stress induced by bulk excavation, when modelling production caissons. Per the RSPile documentation, t-z and Q-z multipliers are typically used to match empirical test data when there are test conditions, such as energy loss, that the data do not consider. A t-z reduction multiplier can be used to reduce side shear to account for excavation as follows:

$$\text{Side Shear (t) Multiplier} = \sigma'_{v2} / \sigma'_{v1} \leq 1 \qquad [3]$$

where $\sigma'_{v1}$ is the effective vertical stress calculated from the ground surface of the BDSLT, and $\sigma'_{v2}$ is the effective vertical stress calculated assuming bulk excavation has occurred. The side shear (t-z) multiplier is assessed at discrete intervals along the entire length of the production caisson. The resulting t-z multiplier profile can be imported directly into RSPile. This achieves Criteria #3 for robust design, as it accounts for reduced capacity due to bulk excavation. As the analytical ETL method cannot accommodate a profile of side shear multipliers, it becomes apparent that the numerical modelling method provides an improved method for estimating production caisson capacities.

Caissons of varying diameters can be modelled with RSPile using BDSLT data. To apply BDSLT data from the test diameter to other production caisson diameters, effects on both side shear and end bearing must be considered.

The relationship between caisson diameter and side shear capacity has been well documented; a review of data and the methods of analysis is provided by Sinnreich (2011). The data show that side shear resistance (taken at a constant deflection) decreases with increasing pile diameter. It is therefore conservative to use BDSLT data to model production caissons that are smaller in diameter to that of the test caisson. However, caution should be used when scaling up to larger diameters.

The relationship between caisson diameter and end-bearing capacity is based on elastic theory. The Loadtest recommended procedure for scaling end bearing deflection is to use the theory of elasticity of the settlement of a rigid disk subjected to uniform pressure on an elastic medium with a consistent Young's Modulus and Poisson Ratio, as follows:

$$\text{End Bearing (z) Multiplier, } S_f = S_t\,[D_f/D_t] = S_t\,[z] \qquad [4]$$

where $S_f$ is the predicted deflection of the caisson base, $S_t$ is the measured deflection from the load test, $D_f$ is the diameter of the proposed caisson, and $D_t$ is the diameter of the BDSLT caisson. This calculated Q-z multiplier (z) can also be entered directly into the software.

It is now possible for the model to consider production caissons with different base or tip depths. If a slight amount of additional capacity is needed, the base can be lowered in the model to provide additional side shear. So long as the bearing stratum remains consistent, this approach is conservative because the Q-z curve is assumed to remain constant, whereas in reality it should become stiffer due to the increased effective vertical stress. It is also possible to conservatively raise the base of the caisson to economize the design of any underloaded elements. In this case, the Q-z reaction curve may be discarded altogether, and the caisson is now assumed to act entirely in side shear.

With bulk excavation and different caisson diameters accounted for (achieving Criteria #2 for robust analysis), ETL curves can be modelled for different production caisson diameters. Data from a typical analysis are shown in Figure 7 below.

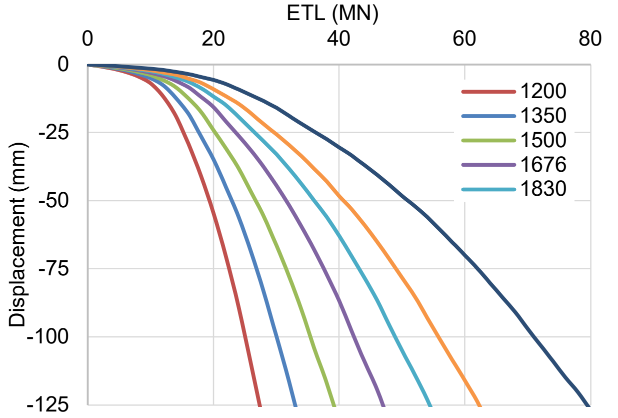

Figure 7. RSPile Equivalent Top Load (ETL) curves for production caissons of different diameters (mm).

Determining factored ULS and SLS capacities from a modelled ETL curve is straightforward. Ultimate limit state pile capacity is assessed from each ETL using a variety of conventional methods summarized by Fellenius (2001) and the CFEM 5th Ed.: the Davisson Offset Limit Load (original 1972, and modified 1993), the De Beer Yield Load, the Brinch-Hansen Criterion, the Butler and Hoy (1976) method, and many others. Full descriptions of these methods are widely reported, and beyond the scope of this paper. Several of these methods will typically converge on a visually obvious ultimate capacity (see Figure 8); Davisson and De Beer are usually too conservative and probably don't apply to caissons of these diameters and lengths. The ultimate capacity ($Q_{ULT}$) is factored by 0.6 per the CFEM to determine the factored geotechnical axial capacity of each pile at ULS ($Q_{ULS}$). It is noteworthy that ULS loads rarely govern the design of high-capacity deep soil caissons, if the analysis is conducted properly.

SLS capacities are evaluated simply, as we can take the load at 20 or 25 mm deflection as the SLS top-down load. This is elegant in its simplicity, as the SLS capacity now simultaneously considers side shear, end-bearing, plasticity, and the elastic compressibility of the caisson itself. The load at serviceability limit state (typically 25 mm) is then factored per the CFEM 5th Edition, by 0.7 to 0.9 depending on the "degree of understanding". It is justifiable to use a factor of 0.9 when BDSLT data is available, and a robust numerical modelling procedure has been employed.

BDSLT data reports also evaluate the creep limit, which is the load at which the BDSLT caisson experiences significant creep behaviour. Creep limits are evaluated at the load cell elevation and provided in both the up and down directions. A top-loaded shaft will not begin to creep until all resistance components exceed the displacement required to reach their respective creep limits (i.e. they behave plastically). It is expected that some of the side shear zones will behave plastically under SLS conditions, especially in the upper zones of the caisson; therefore, it is the downward creep limit that is critical to design. The downward creep limit should be checked for each production caisson at SLS loading at the appropriate elevation, to ensure that the creep limit is not exceeded.

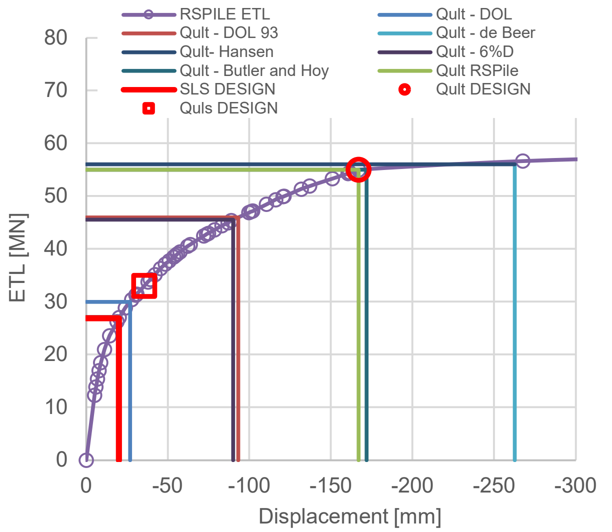

Figure 8. Comparison of different ultimate limit state pile capacity methods.

## 3.4 Comparison of Methods

The methods described above are by no means an exhaustive analysis of the analysis methods available.

The advantages and drawbacks of the three methods of BDSLT analysis summarized in this paper are provided in the following table:

Table 1. Comparison of presented BDSLT analysis methods.

| Method | Advantages | Disadvantages |
|---|---|---|
| Basic Method | Ease of use; no special training or calculations required. | Overconservative; ULS and SLS criteria for different caisson diameters not possible to evaluate; effects of bulk excavation are ignored.<br>Does not satisfy any of the criteria for robust BDSLT design. |
| Analytical ETL Method | ETL curve provided by load test consultant; considers all 3 modes of pile deformation; ULS and SLS criteria can be estimated reasonably well for the test caisson diameter. | No straightforward way to calculate ETLs for different caisson diameters; effects of bulk excavation are ignored.<br>Does not satisfy 3 of the 4 criteria for robust BDSLT design. |
| Modelling Method | Satisfies all 4 of the criteria for robust BDSLT design. | Most rigorous and computationally intensive method; most input parameters. |

## 4 LESSONS LEARNED

The authors have acquired some knowledge through experience of working on many such BDSLT projects, where high-capacity caisson design parameters were assessed through the modelling method.

1. **Two BDSLTs for a site are sometimes better than one**. This can be financially advantageous in certain circumstances in spite of the large additional cost. Sites with variable ground conditions or trapped methane gas are primary candidates, as geotechnical uncertainty usually means increased cost. If new construction methods are proposed (Diez de Aux et al. (2023) report on an investigation into the effectiveness of post-grouted caisson bases, for example), a two BDSLT approach is warranted for comparing and allowing both two options. Testing two diameters may be required if the proposed production caissons will vary widely in diameter (for example, if there are multiple buildings with different column loads), to address the issue of correcting side shear resistance for caisson diameter. With additional data, caisson design parameters improve, resulting in a more efficient design and cheaper construction costs.
2. **Four strain gauges are better than two.** Although the ASTM only requires four strain gauges per level on caissons exceeding a certain diameter, strain gauges can fail easily and are relatively cheap when compared to the full cost of the test. For this reason, four strain gauges per level should be considered for any BDSLT caisson regardless of diameter.
3. **Side shear rules.** When long slender caissons are designed to their maximal capacities, the outcome of the analysis is typically that load is shed primarily in side shear, then through concrete compression. By the time loads are transmitted to the base, only a small fraction remains. For this reason, tests should usually be designed to maximize side shear results as practically possible, while potentially not maximizing end bearing resistance.
4. **It is possible to push the envelope.** BDSLT data and rational engineering analysis as discussed in this paper show that soil and rock can safely support big loads. Van Hampton (2008), in his article on the legendary Clyde N. Baker Jr., lays out a brief history of caisson design in Chicago where BDSLT became conventional some time ago. Over a career of O-cell testing, Baker pushed the capacities of local soil caissons by 400%, and by 50% for rock-socketed caissons.

## 5 CONCLUSIONS

Complex models are not always ideal, and additional variables do not always improve analyses. Simple models have great utility; for example, it is hugely beneficial that the bearing capacity of a spread footing can be calculated easily by hand, even if the result may be conservative.

A complex model is only preferable over a simple model if the benefits outweigh the drawbacks associated with more parameters, more time, more specialist knowledge, a more opaque review process, and a higher risk than something will be done incorrectly. In the case of BDSLT analysis, we argue that the modelling method is highly advantageous in spite of its apparent complexity and should be employed when assessing BDSLT data for high-capacity soil caisson design parameters.

It is worth noting that not all BDSLT sites may benefit from the modelling described here. If caissons of only one diameter are proposed, and if there is no bulk excavation creating a reduction in effective vertical stress it may be advantageous to employ the simpler Analytical ETL method, which also entails an easier review process.

Ultimately through our practice, we are realizing that geotechnical engineers tend to underestimate deep foundation capacity using traditional investigation and design methodologies. Bi-Directional Static Load Tests reduce design uncertainty and ultimately foundation costs, but it is up to us as practitioners to elevate our profession and push our clients to spend money on high quality testing and analysis to reduce overall project costs. High-quality in situ testing, load tests, & numerical modelling are the future (and present) of geotechnical engineering in Canada.

## 6 REFERENCES

Amini, A., Fellenius, B. H., Sabbagh, M., Naesgaard, E. and Buehler, M. 2008. Pile loading tests at Golden Ears Bridge, *61st Canadian Geotechnical Conference*, Edmonton, AB, Canada, September 21-24, 2008.

ASTM Standard D8169. 2018. Standard test methods for Deep Foundations Under Bi-Directional Static Axial Compressive Load. American Society for Testing and Materials, West Coshohocken, PA, USA.

Butler, H.D., and Hoy, H. E. 1976. The Texas Quick-Load Method for Foundation Load Testing – Users Manual. Federal Highway Administration, Publication No. FHWA-IP-77-8.

Canadian Geotechnical Society. 2023. *Canadian Foundation Engineering Manual 5th Ed,* Canadian Geotechnical Society.

Diez de Aux, M., Crowder, J., and Westland, J. 2023. RSPile Analysis of Two Osterberg Cell Load Tests on Post-Grouted and Conventionally Installed Caissons in Vaughan, Ontario. *Proceedings of the Rocscience International Conference (RIC 2023),* Atlantis Press, Toronto, ON, Canada: 575–592.

England, M. 2008. Review of Methods of Analysis of Test Results from Bi-Directional Static Load Tests, *Deep Foundations on Bored and Auger Piles,* Van Impe & Van Impe: 235-239.

Fellenius, B.H., 2001. What capacity value to choose from the results a static loading test. Deep Foundations Institute, Fulcrum, May 2001, 4 p.

Hansen, D., Carvalho, J., and Dittrich, P. 2023. Evaluation of Full-Scale Pile Load Testing Using Osterberg Cell ® in Till and Georgian Bay Shale in Southern Toronto. *Proceedings of the Rocscience International Conference (RIC 2023),* Atlantis Press, Toronto, ON, Canada: 450-463.

Katzenbach, R., and Moormann, C. 2001. Recommendations for the Design and Construction of Piled Rafts. *15th International Conference on Soil Mechanics and Foundation Engineering,* ISSMGE, Istanbul, Turkey: 927-930.

Loadtest. 2000. Construction of The Equivalent Top-Loaded Load-Settlement Curve from The Results of an O-Cell Test. *Internal Publication.*

Naval Facilities Engineering Command (NAVFAC) Foundations & Earth Structures, Design Manual 7.02. 1986.

Osterberg, J. O. 1995. The Osterberg CELL for Load Testing Drilled Shafts and Driven Piles. Federal Highway Administration, Publication No. FHWA-SA-94-035.

Poulos, H.G. 2001. Piled Raft Foundations: Design and Applications, *Géotechnique*, 51(2): 95-113.

Schmertmann, J. H., Hayes, J. A., Molnit, T. & Osterberg, J. O. 1998. O-cell Testing Case Histories Demonstrate the Importance of Bored Pile (Drilled Shaft) Construction Technique. *Proceedings: Fourth International Conference on Case Histories in Geotechnical Engineering*, St. Louis, MO, USA: 1103 - 1115.

Seo, H., Moghaddam, R. B., and Lawson, W. D. 2016. Assessment of methods for construction of an equivalent top loading curve from O-cell test data. *Soils and Foundations*, 56(5): 889-903.

Sinnreich, J. 2011. The scaling effect of bored pile radius on unit shear capacity. *International Journal of Geotechnical Engineering* 5: 463-467.

Skinner, G. D., Becker, D. E., and Appleton, B. J. A. 2008. Full-scale pile load testing of cast-in-place caissons using Osterberg load-cell method – Anthony Henday Drive Southeast Ring Road case study, *61st Canadian Geotechnical Conference*, Edmonton, AB, Canada, September 21-24, 2008.

Van Hampton, T. 2008. Award of Excellence: Clyde N. Baker Jr. *Engineering News Record,* April 7, 2008: 2-12.