TOP-LOADED BIDIRECTIONAL TEST, A NEW APPROACH TO DEEP FOUNDATIONS LOAD TESTING

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ABSTRACT

The Top-Loaded Bi-Directional Test ("TLBT") is a new method to apply bi-directional loads to a deep foundation element with the loading source located above the foundation head. In the TLBT reusable load assembly, loads are applied to the foundation using the R-System which consists of two stacked steel plates located at the geotechnical resistance balance point or at the foundation base connected to the load assembly via vertical elements. The top plate or the Shaft Bearing Plate ("SBP") will transfer loads to the foundation upper portion, and the bottom plate or the Base Bearing Plate ("BBP") will transfer loads to the foundation lower portion as well as the foundation base. At the surface, above the foundation head, a hydraulic jack is located between a Top Load Assembly ("TLA"), and the Bottom Load Assembly ("BLA"). The TLA and BLA are connected to vertical elements which are consequently connected to the R-system. As the jack is pressurized and expanded at the surface, the R-System plates are separated, and the foundation is bi-directionally loaded. This paper presents a brief description of the conventional Bi-Directional Load Test ("BDLT") including benefits and limitations followed by the TLBT method introduction including its benefits and advantages over other testing methods.

Like the conventional BDLT, the TLBT includes instrumentation to measure strains within the foundation element, upward movement of the SBP and downward movement of the BBP, and the jack pressure. From these measured values, loads and displacements are calculated. Due to the test method practical constructability, the TLBT provides a foundation testing system with reduced risk associated with foundation construction as well as load testing challenges.

Introduction

Full-scale load tests on deep foundations are often performed to verify whether the installed foundation(s) will indeed be able to support the load that they were designed to support. Typically, these tests are instrumented to measure parameters which are used in the engineering parameters calculations. Traditionally, full-scale static load tests can be classified as conventional top-down or top-loaded tests, and conventional Bi-Directional Load Tests (“BDLT”). This paper is primarily focused on the BDLT, and the novel Top-Loaded Bi-Directional Test (“TLBT”).

The conventional Bi-directional load testing (“BDLT”) has become ordinary to evaluate the geotechnical capacity of deep foundations, particularly bored and drilled foundations. The use of an embedded hydraulic jack assembly to apply loads upward and downward aids to better understand the foundation internal force distribution, as well as the shaft and base resistances activated and mobilized during the testing (Moghaddam and Komurka, 2019). In an instrumented BDLT, strain measurements are obtained using strain gages installed along the foundation element, and the measured values are used to calculate estimates of foundation internal forces.

The BDLTs are performed using a single or multiple expendable jack assembly embedded within the foundation element. Each jack assembly consists of a single or multiple hydraulic jack(s) located between upper and lower bearing plates. As hydraulic pressure is applied, the jack assembly can expand in both directions, and loads are applied to the foundation in an upward and downward direction. Depending on the design and purpose of the BDLT, the jack assembly may be located at the foundation base, or at some distance above the base where the foundation upper-portion shaft resistance is equal to the foundation lower-portion shaft resistance plus base resistance (Seo et al. 2016).

Although the conventional BDLT offers a variety of benefits, important challenges are present during the test foundation installation as well as the testing procedure. The presence of a jack assembly in the middle of the foundation element could present obstructions and difficulties for the construction and installation operations. Damage to the hydraulic lines extending from the jack assembly to the surface could create a hydraulic fluid leak during the test which impedes holding hydraulic pressures in the jack to complete the load testing. The presence of softer material or debris at the foundation base, could require jack strokes beyond the standard strokes offered by many embedded jacks which could also result in fully extended hydraulic jack without any resistance mobilization.

This paper introduces a new approach to the deep foundations bi-directional testing where the loading assembly is located at the foundation head. The arrangement allows the construction of the bored or drilled foundation to follow the standard practice without the need of special arrangements to by-pass the obstruction within the foundation element created by the jack assembly.

Throughout this paper, the conventional BDLT procedure is described, and related construction challenges are presented and discussed. Detail description of the new approach using the TLBT system including the test device, assembly, loading mechanism, and load transfer to the foundation is presented.

Conventional Bi-Directional Load Test

The conventional BDLT method development, applications, and analyses have been well documented by many researchers as well as practitioners such as Cernak (1984), Osterberg (1994), Schmertmann et. al., (1998), Fellenius (1999), Bullock (1999), Sinnereich and Simpson (2009), Boeckmann et al. (2014), Seo et al. (2016), Moghaddam and Komurka (2019), and numerous others. The BDLT requirements are further specified in the American Standard for Testing Materials ("ASTM") ASTM D8169/D8169M-18.

The conventional BDLT installation process starts with the jack assembly fabrication where the hydraulic jack(s) is (are) placed between one or more upper and lower bearing plates, Figure 1a. Once the jack assembly is fabricated, the foundation rebar cage is built around the jack assembly, Figure 1b. During this process, selected instrumentation such as strain gages and vibratory wire displacement transducers are also installed along the rebar cage. Once the rebar cage is finalized with the jack assembly and the instrumentation attached, the drilling process begins. In certain instances, the process could be completed simultaneously.

After the instrumented test foundation rebar cage with the BDLT assembly is inserted in the drilled excavation, concrete is placed following conventional drilled foundation construction procedures and/or the specialty contractor means and methods. In general, drilled shaft foundations concrete placement is completed using a center Tremie line which runs in the middle of the foundation rebar cage from the foundation base to the surface. When the BDLT assembly is in the center of the test foundation, typically a Slick line is used to by-pass the jack assembly and place concrete from the side of the rebar cage. This modification could be causing integrity issues or problems with the concrete at the foundation base, Figure 2.

(a) **(b)**

Figure 1. Hydraulic Jack a. Jack assembly and b. Jack Assembly installed within the cage

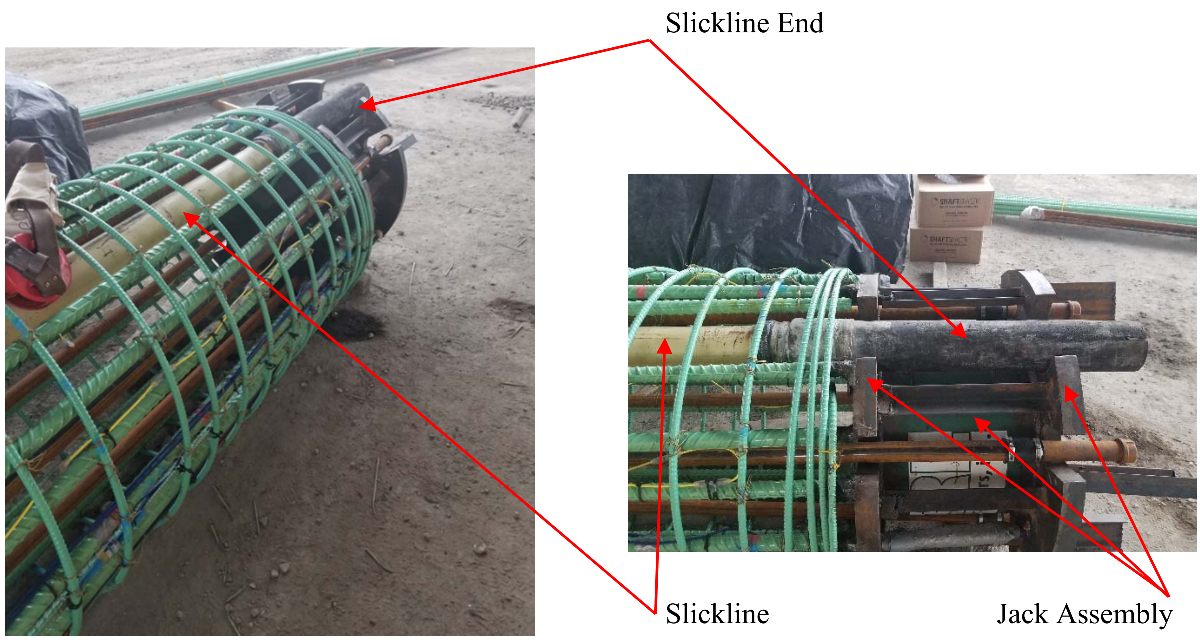


Figure 2. Conventional BDLT assembly and Slickline

During the BDLT, the hydraulic jack(s) is (are) pressurized to first break the tack welds holding the hydraulic jack together, and second to "crack" the foundation element into an upper and a lower portion. Next, the pressure is applied incrementally to bi-directionally load the foundation element. During the testing, the foundation upper portion provides reaction for the foundation bottom portion, and vice versa (Brown et al. 2018). A schematic diagram of a BDLT system is shown in Figure 3.

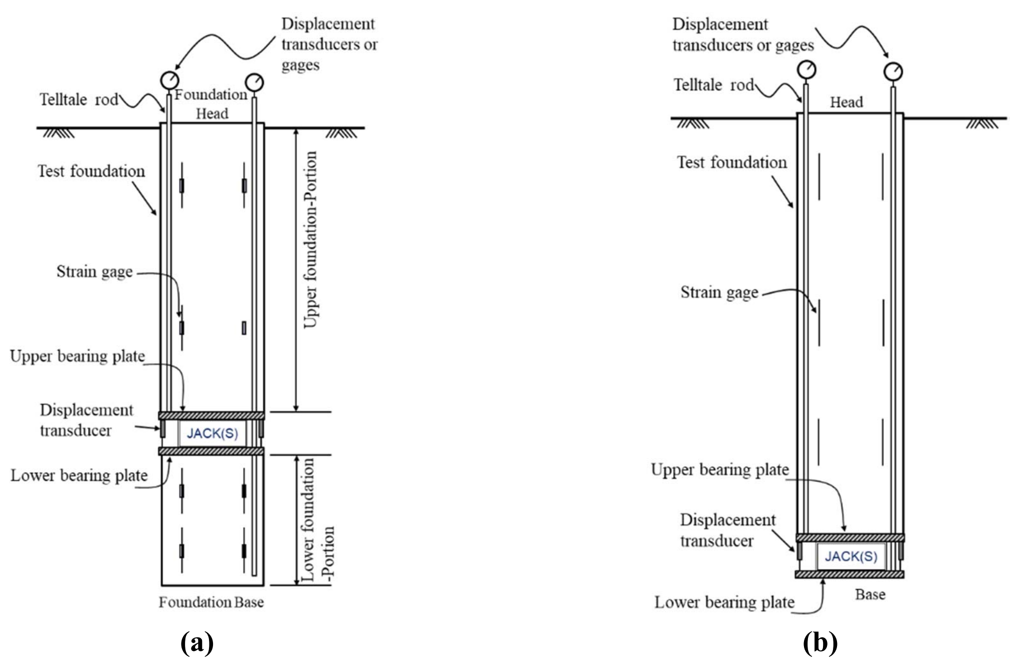
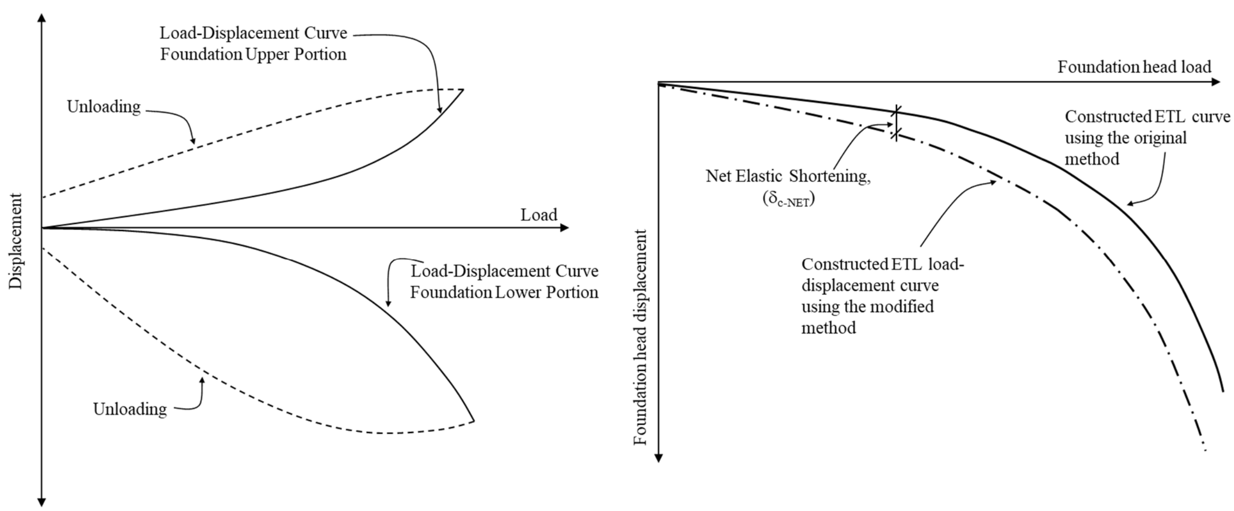


Figure 3. Conventional Bi-Directional Load Test arrangement **a)** Jack(s) at the geotechnical equilibrium point and **b)** Jack(s) at the foundation base

The BDLT initial results are typically reported in a butterfly-shaped plot presenting load-displacement behavior of the jack assembly's upper and lower bearing plates, Figure 4a. Upper bearing plate load-displacement behavior is governed by shaft resistance developed in the foundation upper portion; lower bearing plate load-displacement behavior is governed by shaft and base resistances developed in the foundation lower portion. One of the limitations of the BDLT is that the direction of the loading on the foundation upper portion is different from the actual loading direction from the superstructure, which is downward. Therefore, the foundation upper portion elastic compression will be smaller than the value had the top compression loading been applied. This limitation can be overcome by adding the elastic compression of the foundation measured displacement when constructing an equivalent top-loading curve ("ETL"), Figure 4b. According to Brown et al. (2018), there is little evidence that drilled shafts axial compression resistance in soil exhibit any significant difference in behavior associated with loading direction.



(a) **(b)**

Figure 4. Conventional BDSLT results, **a)** initial results, the "Butterfly-shaped" plot, **b)** Equivalent Top-Loading Curve, ETL

Top-Loaded Bi-Directional Test ("TLBT")

The Top-Loaded Bi-Directional Test ("TLBT") is a newly developed method to apply bi-directional loads to a deep foundation element with the loading source located above the foundation head. In the TLBT reusable load assembly, loads are applied to the foundation using the R-System which consists of two stacked steel plates located at the geotechnical resistance balance point or at the foundation base connected to the load assembly via vertical elements.

In the R-system, the top plate, or the Shaft Bearing Plate ("SBP") transfers loads to the foundation upper portion, and the bottom plate or the Base Bearing Plate ("BBP") transfers loads to the foundation lower portion and the foundation base. At the surface, above the foundation head, a hydraulic jack is located between the Top Load Assembly ("TLA") and the Bottom Load Assembly ("BLA"). The TLA and BLA are connected to sleeved vertical elements Shaft Mobilizer Bars ("SMB") and Base Mobilizer Bars ("BMB") which are consequently connected to the R-system. As the jack is pressurized and expanded at the surface, the R-System plates are separated, and the foundation is bi-directionally loaded. Figure 5 presents a schematic of the TLBT arrangement.

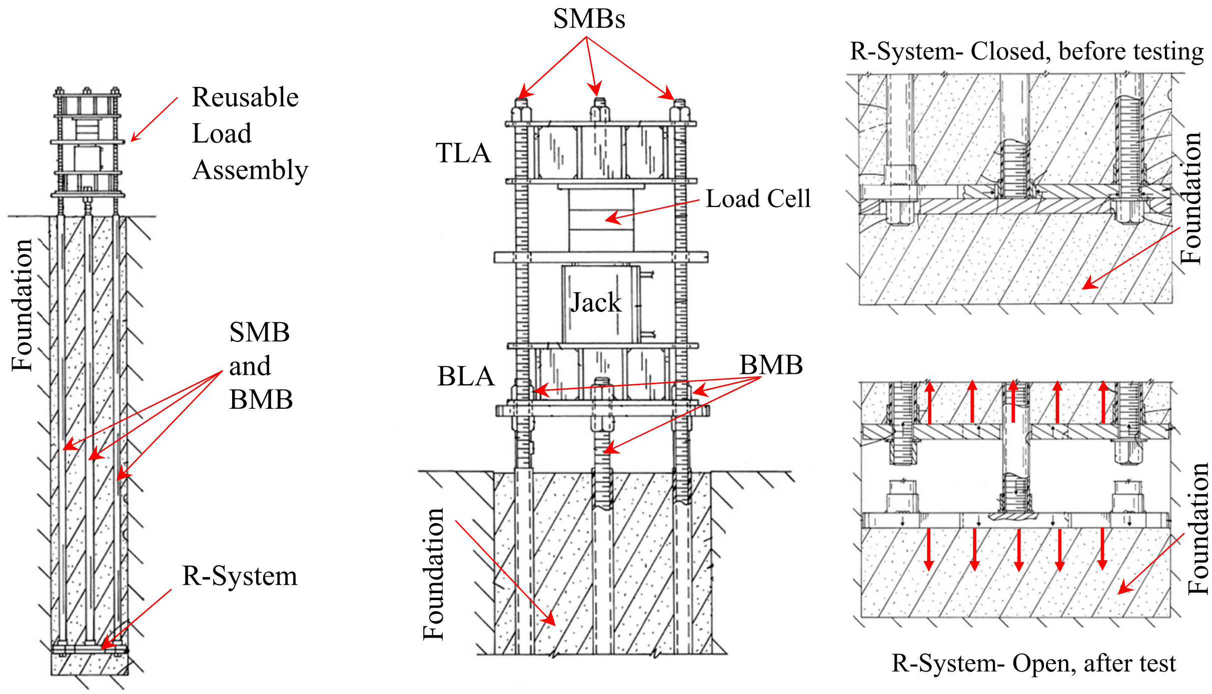


Figure 5. Top-Loaded Bi-Directional Test Arrangement

Considering the TLBT arrangement, some of the construction challenges faced during a conventional BDLT can be addressed. First, there are no embedded hydraulic lines needed in the TLBT system which reduces the risk of losing the test foundation due to a hydraulic fluid leak. Second, in the case of a mechanical failure on the jack assembly, the issue can be addressed at the surface which also contributes to lowering the risk of losing the test foundation due to a jack assembly failure. Third, the foundation total displacement is not limited to the hydraulic jack stroke. During the test, the jack can be re-set, and continue until failure or larger foundation displacements are achieved. and the Fourth, and to certain extent the most important constructability advantage, the R-System provides the center-hole spacing for a Tremie line to pass through which will not impact the concrete placement operations and lower the risk of creating soft-base conditions or concrete integrity problems at or near the foundation base. Figure 6 shows details regarding the R-System prior to installation in a rebar cage.

The vertical elements (SMBs and BMBs), size, strength, and quantity can be determined as a function of the test load. These elements are connected to the SBP and the BBP through hex nuts which creates a practical condition for the SMBs and the BMBs to be recovered at the end of the test. With the TLA and BLA being reusable, and the BMBs and SMBs recoverable, the only sacrificial element remaining in the TLBT arrangement is the R-System. Therefore, the TLBT might also represent a financial benefit to the user, but more importantly, with most of the test material being recoverable and reusable, more tests can be completed on a project site which could lead to optimized designs and higher resistance factors in case of projects designed under the Load and Resistance Factor Design ("LRFD") methodology.

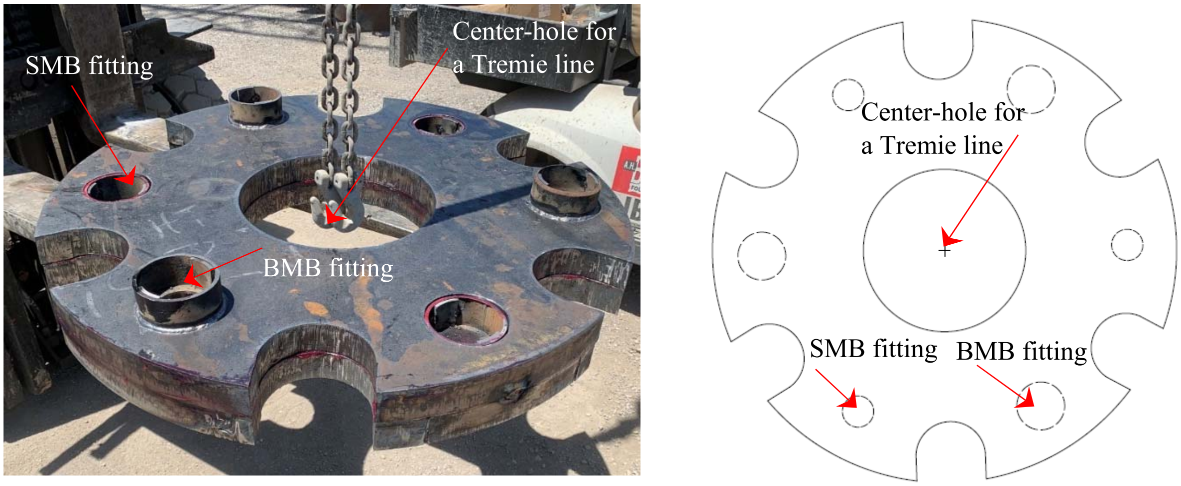


Figure 6. R-system prior to be installed in the rebar cage

The R-system is installed within the rebar cage like the BDLT jack assembly installation process. The main difference is that the hydraulic jack and related instrumentations are not within the R-system. Once the R-system is properly leveled, the rebar cage is welded to the side of the plates immediately above and below the concrete-break line which is approximately at the contact line of the two stacked steel plates, Figure 7.

Full-scale TLBT

As a proof of concept ("PoC") a TLBT full-scale arrangement was designed, planned, installed, and tested to observe a deep foundation behavior under loading conditions using the TLBT method. For the PoC purposes, a 48-inch diameter drilled shaft installed to a maximum depth of 40 feet measured form the surface was used. The foundation was instrumented using Vibratory Wires sister-bar Strain Gages ("VWSG") above the R-System and Telltale assemblies at the SBP, BBP, and the foundation base. Other non-destructive testing ("NDT") was performed which results are presented by Hannigan et al. (2021) but results are not directly relevant to this manuscript objective other than these test results did not show major integrity issues with the test foundation.

Based on the results of a 100-ft deep soil boring completed near the test foundation, the subsurface conditions can be described as a dark brown very stiff Fat Clay (CH) extending to a depth of 43 feet from the ground surface with an average 25% water content, average Plasticity Index of 43%, and an average undrained shear strength of 2 ksf. The upper CH layer was underlain by a very stiff to hard tan to gray Fat Clay (CH) was reported with an average 22% water content, average Plasticity Index of 46%, and an average Standard Penetration Test ("SPT") blowcounts of 61 blows per foot. Below 85 feet a hard gray

Shale was reported. According to the soil properties and strength values reported in the soil boring, the geotechnical resistance balance point was calculated to be approximately 5 feet above the foundation base, where the R-system was installed, Figure 7.

Figure 7. R-system installed within the rebar cage and at the geotechnical balance point

After finalizing the R-system installation, the SMBs and BMBs were installed within the PVC sleeves, and the foundation rebar cage was prepared for insertion into the drilled hole followed by concrete placement. The concrete was poured using a Tremie line inserted into the hole and passing through the middle of the R-system at approximately 1 foot above the foundation base. Once the concrete was fully poured and cured, the TLA, hydraulic jacks, Load Cells, and BLA were assembled at the foundation head, Figure 8.

One of the major and practical advantages of the TLBT over the BDLT became evident during the installation. in that the specialty contractor could not only assist, but to a certain extent, take over the installation of the TLBT system. This will reduce the presence of specialized test engineers during the preparation and installation of a test foundation in comparison with the very complex BDLT system installation.

The test was carried out following the ASTM D8169 guidelines with the R-system embedded instead of the conventional hydraulic jack-based assembly. The loading was completed in 21 cycles and the unloading was achieved in 5 unloading cycles. The maximum bi-directional load applied to the foundation was measured at 970 kips, and the initial results were plotted to create the butterfly-shaped plot, Figure 9.

From the butterfly-shaped plot and the foundation elastic compression calculations, the Equivalent Top-Loading Curve, ETL, was constructed to observe the foundation load-displacement relationship, Figure 10. Additionally, to visually observe the load-strain behavior when the TLBT method is implemented, the values of the load were plotted versus strain for each strain gage level, Figure 11. From the ETL and the load-strain plots the uniform loads transferred from the R-System to the upper and lower foundation portion was evident.

Based on the experience gathered during PoC process, and the test results, it can be concluded that the TLBT should be considered an additional deep foundation load testing tool providing equivalent results with simpler constructability, reusable equipment, and reduced risk of test component failure. Additionally, a direct comparison to conventional BDLT as well as Top-Loaded static load tests could strengthen the reliability of the TLBT. Hannigan et al. (2021) presents a direct comparison between BDLT and TLBT results which further emphasizes the similarities between the TLBT and BDLT results.

Figure 8. Finalized TLBT assembly immediately prior to testing

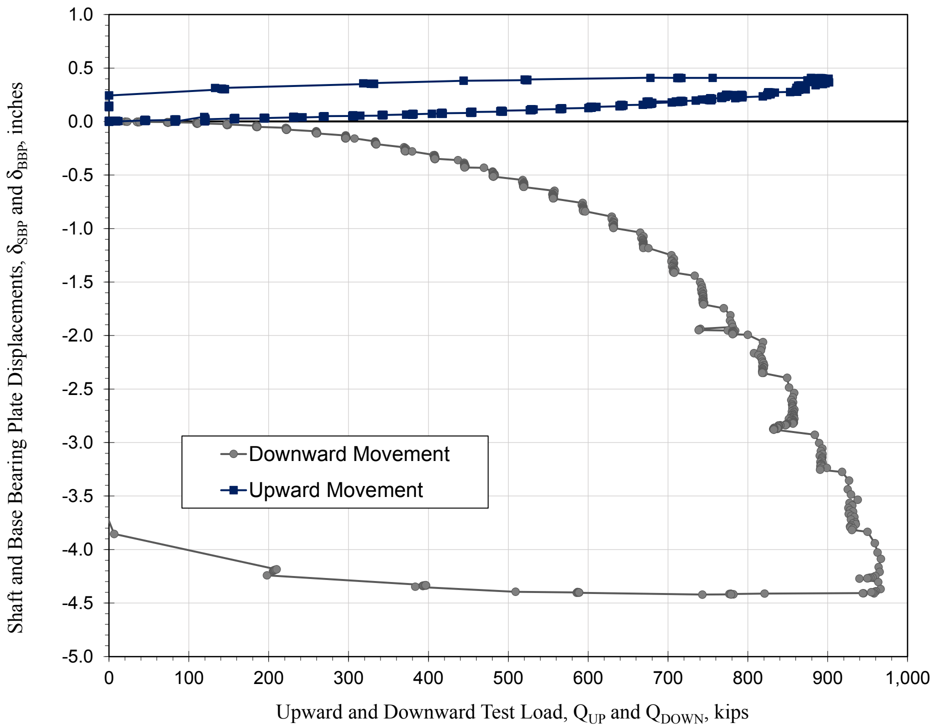


Figure 9. TLBT initial results represented as the butterfly-shaped plot

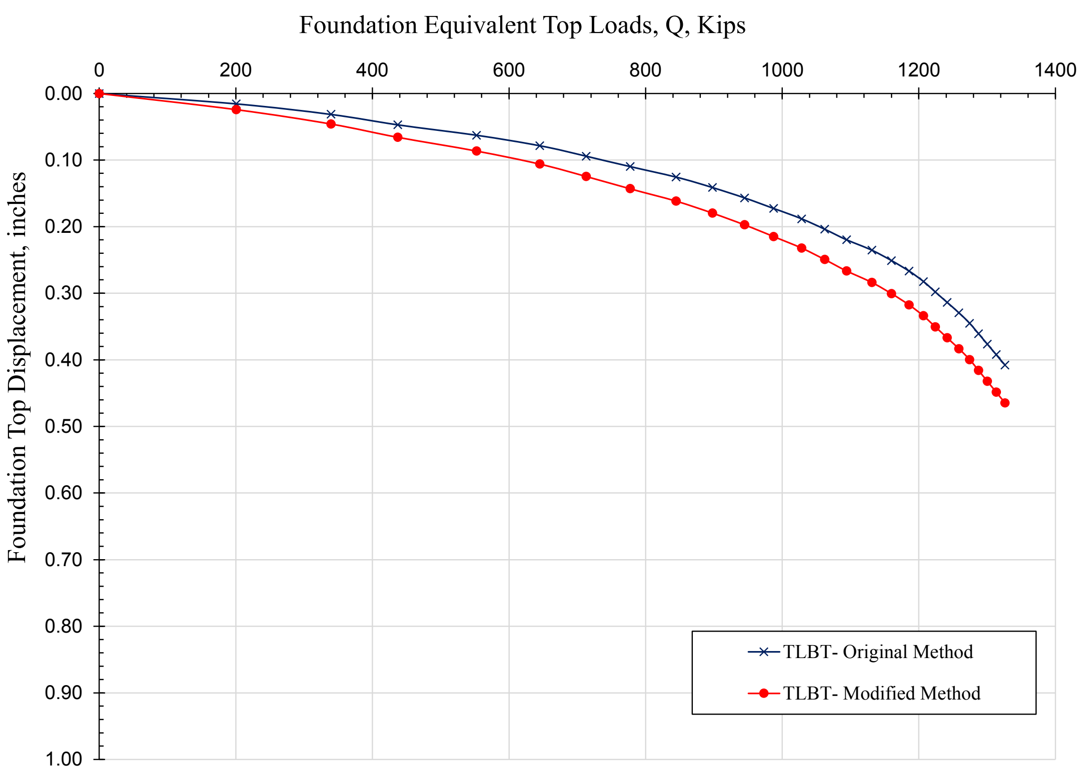


Figure 10. ETL curve constructed for the TLBT results

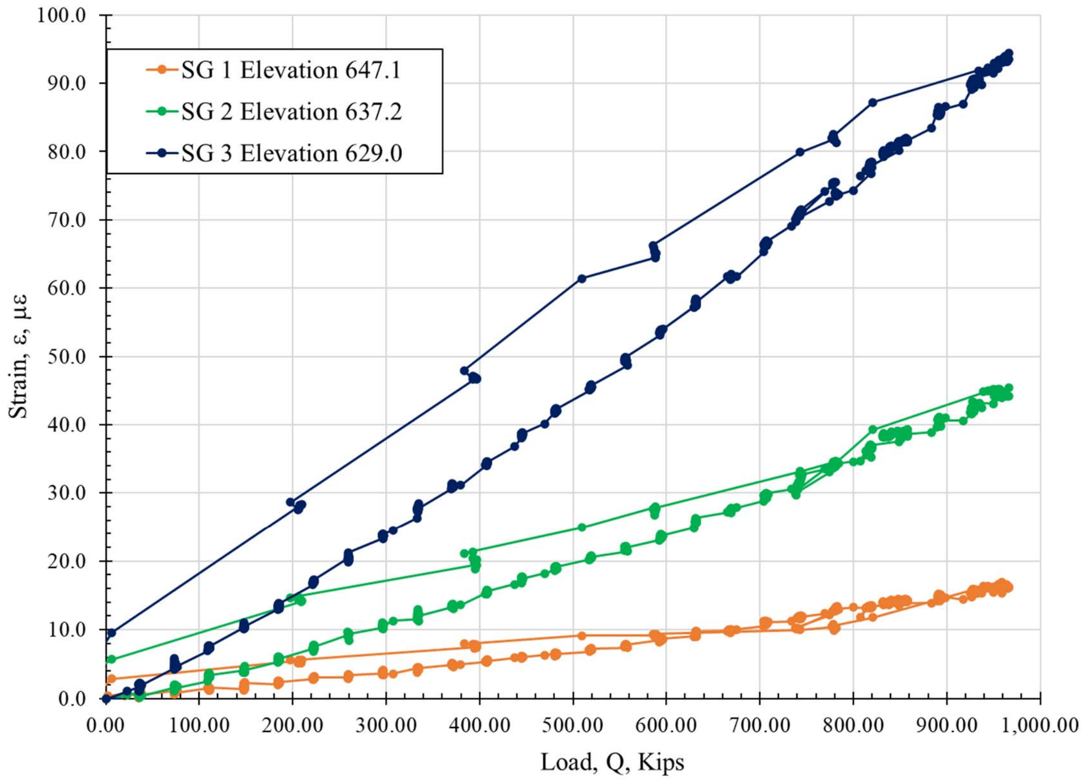


Figure 11. Strain-Load Relationship for three Strain Gage Levels for the TLBT

Summary and Conclusions

The Top Loaded Bi-Directional Test, TLBT, a newly developed approach to deep foundations load testing, has been introduced in this paper. In the TLBT method, all loads are applied by a reusable load assembly located at the foundation head. Additionally, the TLBT arrangement allows the construction of the bored or drilled foundation to follow the standard practice without the need of special arrangements to by-pass the obstruction within the foundation element created by the jack assembly.

Although, the conventional Bi-Directional Load Test, BDLT, has significant benefits over top-loaded load test, several challenges specifically regarding test foundation construction and installation should be considered. The existence of a jack assembly in the middle of the foundation element could create certain problems with concrete flowability resulting in major integrity issue. Additionally, any specific mechanical failure to the embedded hydraulic jack and/or the hydraulic lines could lead to test foundation abandonment which consequently results in higher financial and technical liabilities for the project. Insufficient jack stroke for situations with foundation soft base, would require abandonment of the test foundation element.

The TLBT's R-system allows for a center-line Tremie to pass through the middle of the foundation without modifications to the construction means and methods. Furthermore, any damage to the jack assembly can be repaired at the surface minimizing the need for abandoning the test foundation. Resetting the top loading assembly would theoretically allow for unlimited expansion between the R-system plates. Additionally, all test material is recoverable except the R-system which probably makes the test system financially competitive, and more importantly, allows for completing higher number of tests with the same equipment. With higher number of tests, optimized foundation design is achieved and in the case of Load and Resistance Factor Design, LRFD, the resistance factors can be improved.

As a proof of concept ("PoC") a fully instrumented TLBT arrangement was designed, planned, installed, and tested to observe a deep foundation element behavior under loading conditions using the TLBT method. A 48-inch diameter drilled shaft was installed at a maximum depth of 40 feet measured form the surface was used. From the measured parameters during the test, butterfly-shaped plots, Equivalent Top-Loading Curves, and the load-strain relationships were determined. Simplified constructability and equivalent results support the conclusion that the TLBT is expected to serve as another deep foundation testing method in the future.

One of the major and practical TLBT system advantages is that the specialty contractor could assist, and to certain extent, take over the construction of the TLBT system during the cage assembly phase. This will save time and resources during the cage fabrication since most of the TLBT system components inside the foundation cage are relatively simple structural steel elements, such as steel. Therefore, there is no major risk of damaging sensible jack(s) assemblies or hydraulic lines.

It is realized that like for any new development and technique, several challenges and limitations must be addressed. It is also realized that to address those limitations and overcome those challenges more tests need to be completed. However, the initial test results indicated that the TLBT method could be highly beneficial to the deep foundation community. The TLBT is beneficial to project Owners where more tests can be completed due to the test efficiency. It is further beneficial to specialty contractors since the TLBT system does not require the specialty contractor changing the means and methods of the drilled foundation installation. Additionally, the specialty contractor can procure and fabricate the rebar cage with the TLBT system already installed within the cage. So, there is no additional assembly arrangements prior to testing. Finally, it is extremely beneficial to the foundation engineering community, since the test practicability and not stroke limitations, allows for higher resistance source, i.e., unit shaft and base resistance, mobilization.

References

American Society of Testing and Materials (2018). ASTM D8169/D8169M-18, Standard Test Methods for Deep Foundations Under Bi-Directional Static Axial Compressive Load.

Boeckmann, A., Myers, S., Uong, M., & Loehr, J. E. (2014). Load and resistance factor design of drilled shafts in shale for lateral loading (No. cmr 14-011). Missouri. Dept. of Transportation. Research, Development and Technology Division.

Brown, D. A., Turner, J. P., Castelli, R. J., & Americas, P. B. (2018). Drilled shafts: Construction procedures and LRFD design methods (No. FHWA-NHI-10-016). United States. Federal Highway Administration.

Bullock, P. J. (1999). Pile friction freeze: A field and laboratory study. University of Florida

Cernak, B., A. Dvorak, J, Hlavacek, K. Klein, and J. Petrasek (1984), New approaches to problems of bearing capacity and settlement of piles. Proceedings of the Eight International Conference on SMFE, Vol. 2.1 Moscow pp 67-74

Fellenius, B. H., Altaee, A., Kulesza, R., & Hayes, J. (1999). O-cell testing and FE analysis of 28-m-deep barrette in Manila, Philippines. *Journal of Geotechnical and Geoenvironmental Engineering*, *125*(7), 566-575

Moghaddam, R. B., & Komurka, V. E. (2019). Modulus of Elasticity Impact on Equivalent Top-Loading Curves from Bi-Directional Static Load Tests. In Geo-Congress 2019: Foundations (pp. 178-188). Reston, VA: American Society of Civil Engineers

Moghaddam, R., Rausche, F., and Hannigan, P. (2021a). Top Loaded Bi-Directional Testing System and Method of Using the Same. United States Patent Application Publication No. US2021/0102863

Schmertmann J.H., Hayes, J.A., Molnit, T., and 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, Missouri

Seo, H., Moghaddam, R. B., & 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., & Simpson, R. C. (2009). Evolution of top of pile measurement techniques in deep foundation static load testing. DFI Journal-The Journal of the Deep Foundations Institute, 3(2), 65-69