# TOP-LOADED BI-DIRECTIONAL TEST AND THE CONVENTIONAL BI-DIRECTIONAL LOAD TEST, A DIRECT COMPARISON

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## ABSTRACT

The Top-Loaded Bi-Directional Test ("TLBT") and the conventional Bi-Directional Load Test ("BDLT") are full-scale load tests where loads are applied bi-directionally to the foundation element. The BDLT uses an embedded loading source consisting of a jack assembly with one or multiple hydraulic jacks located between two steel bearing plates. As the jack(s) within the jack assembly is/are pressurized, the plates receive the load from the jack(s) and transfer these loads to the foundation element. In the case of the TLBT, the loads are also applied bi-directionally to the foundation element. However, in the TLBT case, the loading source is located above the foundation head. With the TLBT's non-embedded and reusable load assembly, the loads are applied to the foundation using the steel shaft bearing and base bearing plates cast within the foundation.  These plates are connected to the load assembly at the foundation head via Grade 75 or Grade 150, threaded, steel bars.

This paper presents comparison results from a full-scale load test performed by both bi-directional load testing methods on adjacent test shafts. Details regarding subsurface conditions as well as test shaft construction and installation are included for the comparison tests. Test results and corresponding analyses are presented and discussed in detail.

**Key Words: bi-directional load test, top-loaded bi-directional test**

## Test Background

The methodology associated with a conventional bi-directional load test has been well documented by Osterberg (1995, 1998), Schmertman et. al., (1998), and numerous others. The test method requirements are further delineated in ASTM D8169/D8169M-18, Standard Test Methods for Deep Foundations Under Bi-Directional Static Axial Compressive Load. The main advantage of the conventional bi-directional test is the ability to test up to twice the jack assembly capacity since the embedded jack pushes in both directions from its embedded location. The main disadvantage of the test is that the jack assembly is embedded and is therefore not retrievable.

The top loaded bi-directional test, Moghaddam et. al. (2021a), embeds only the bearing plates and moves the jack assembly to the foundation head. In this test, the jack reacts against a reusable load assembly connected to the embedded bearing plates using threaded, shaft mobilizer and base mobilizer bars. A minimum of three or more bars of each type are used depending on foundation diameter and required test load. Test instrumentation for determining bearing plate movements and load transfer behavior is similar to a conventional bi-directional test. A generalized schematic of the two test arrangements is presented in Figures 1 and 2. Details on the top loaded bi-directional test can be found in Moghaddam et. al., (2021b).

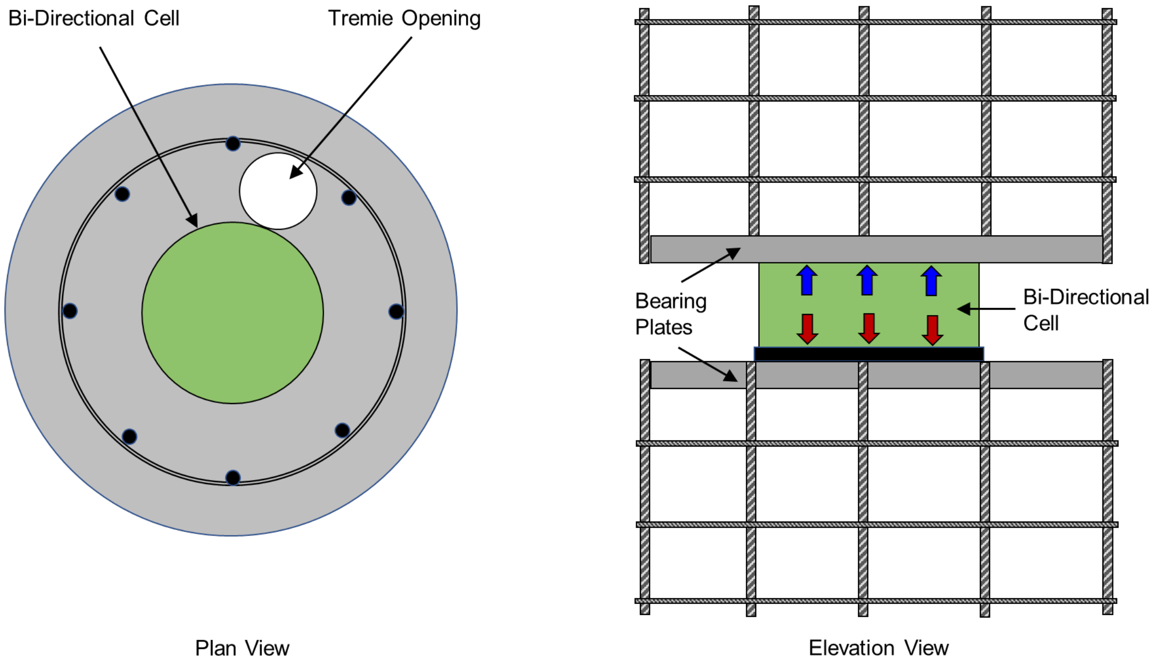


Fig. 1. General schematic of a Conventional Bi-Directional Load Test (BDLT)

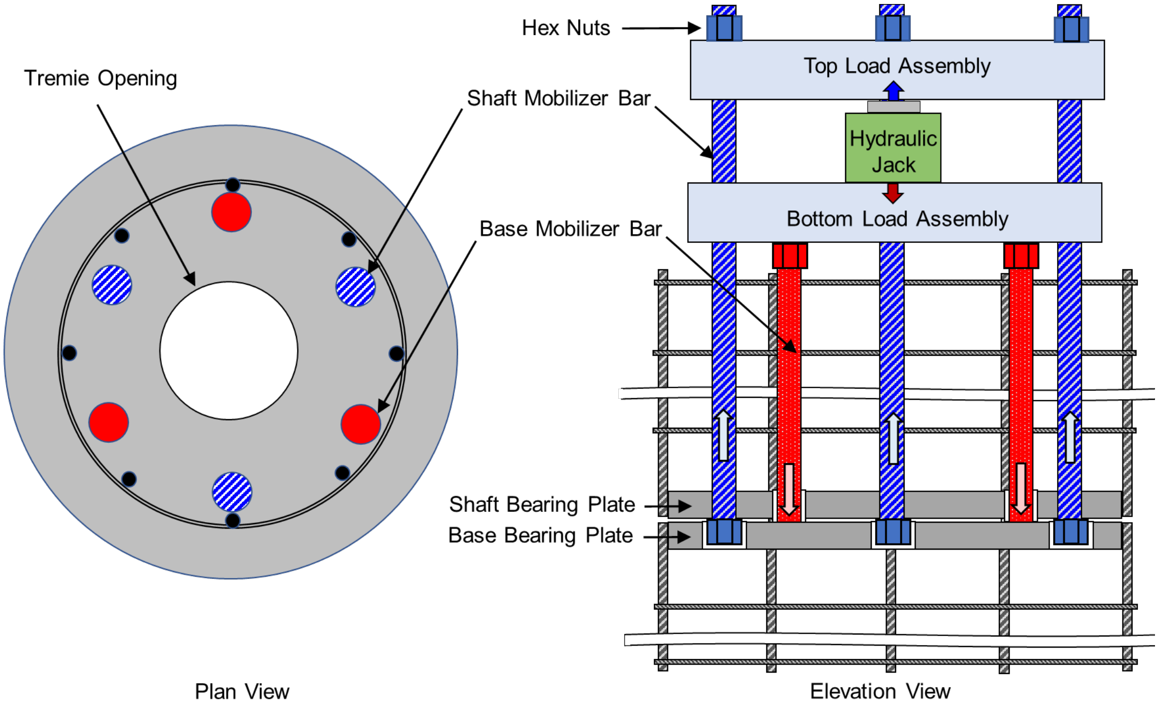


Fig. 2. General schematic of a Top-Loaded Bi-Directional Test (TLBT)

Both conventional and top loaded bi-directional tests were performed in close proximity to one another at a test site near San Antonio, Texas. Based on the closest soil boring to the two test shafts, the soil conditions from the ground surface at EL 656 to a depth of 43 feet below grade were reported to consist of very stiff fat clay. Below that depth, the clay was noted as becoming hard. Shale bedrock was encountered in the soil boring at a depth of 86 feet. Groundwater was not encountered during the soil boring but seepage into the borehole was noted at a depth of 50 feet.

## Test Shaft Construction Details

At the test site, two 48-inch diameter test shafts were installed 20 feet apart center-to-center. Both shafts were drilled without casing with the BDLT excavation remaining dry and the TLBT excavation accumulating groundwater seepage at the base over time. The conventional bi-directional load test shaft was drilled to a depth of 40 feet. Unexpectantly, a hard shale was encountered at the shaft base instead of the anticipated very stiff clay noted in the soil boring. The nearby top-loaded bi-directional test shaft was drilled to a depth of 39.7 feet and terminated in the very stiff clay. Following cage placement in the TLBT shaft excavation, an occasional thud was heard indicative of some side wall slough-in.

The reinforcing cages were constructed using 28 #8 vertical bars spaced evenly around the cage perimeter in a 14 double bar configuration with #5 spiral steel at 10-inch spacing. The reinforcing cages were identical for both shafts with the exception that one bundle of vertical bars was missing from the BDLT cage. Photographs of the instrumented reinforcing cages are presented in Figure 3a for the conventional bi-directional load test, and in Figure 3b for the top-loaded bi-directional test. The shaft and base mobilizer bars were kept isolated from the shaft concrete by the Schedule 40, 3-inch I.D. PVC pipe that encased the bars. This allows the shaft mobilizer bars and base mobilizer bars to be removed after the load test and reused.

**Fig. 3a. 500-ton BDLT jack assembly in cage.**

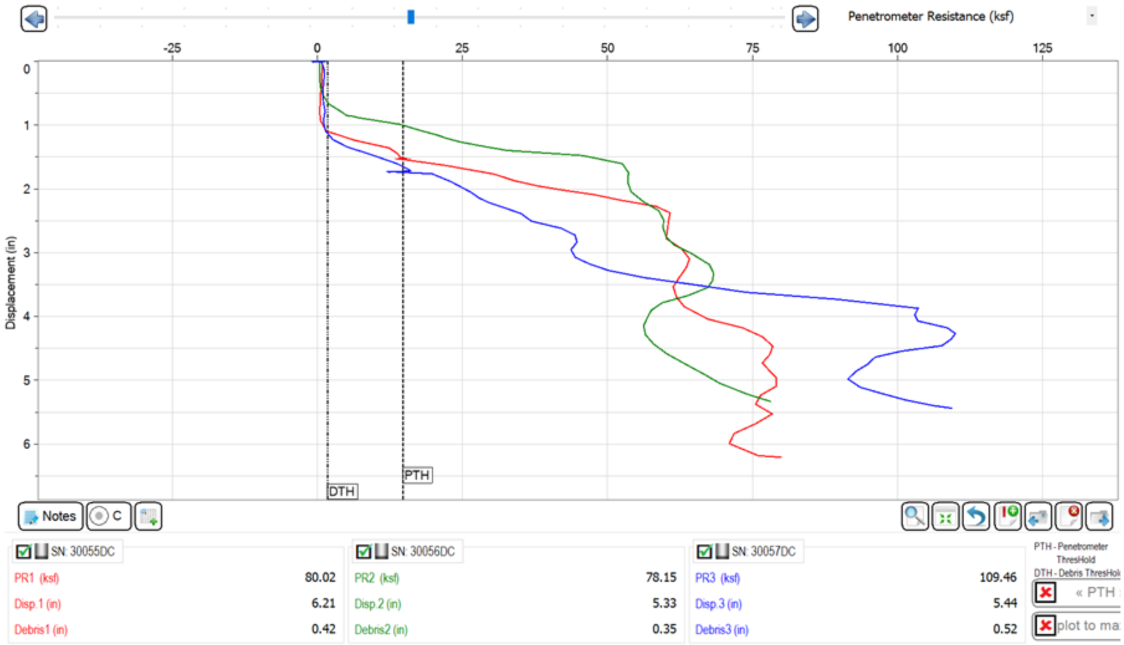
**Fig. 3b. TLBT bearing plates in cage.**

In the BDLT shaft, the top of the 500-ton jack assembly was located at EL 623.9, the break plane was located at EL 622.6, and the bottom of the jack assembly was located at EL 622.6. For the TLBT shaft, the top of the shaft bearing plate was located at EL 623.9, the break plane was located at EL 623.8, and the bottom of the base bearing plate was located at EL 623.6.

The two test shafts were instrumented with vibrating wire strain gages (VWSG) at similar elevations. The BDLT shaft had sister-bar mounted VWSGs centered at EL 643.7, 635.6, and 627.7 with a concrete embedment style VWSG at EL 619.2. The TLBT shaft had sister-bar mounted VWSGs centered at EL 647.1, 637.2, and 629.0 with a concrete embedment style VWSG at EL 620.7. Concrete embedment style VWSGs were used below the bearing plates due to the limited space available for sister-bar VWSGs.

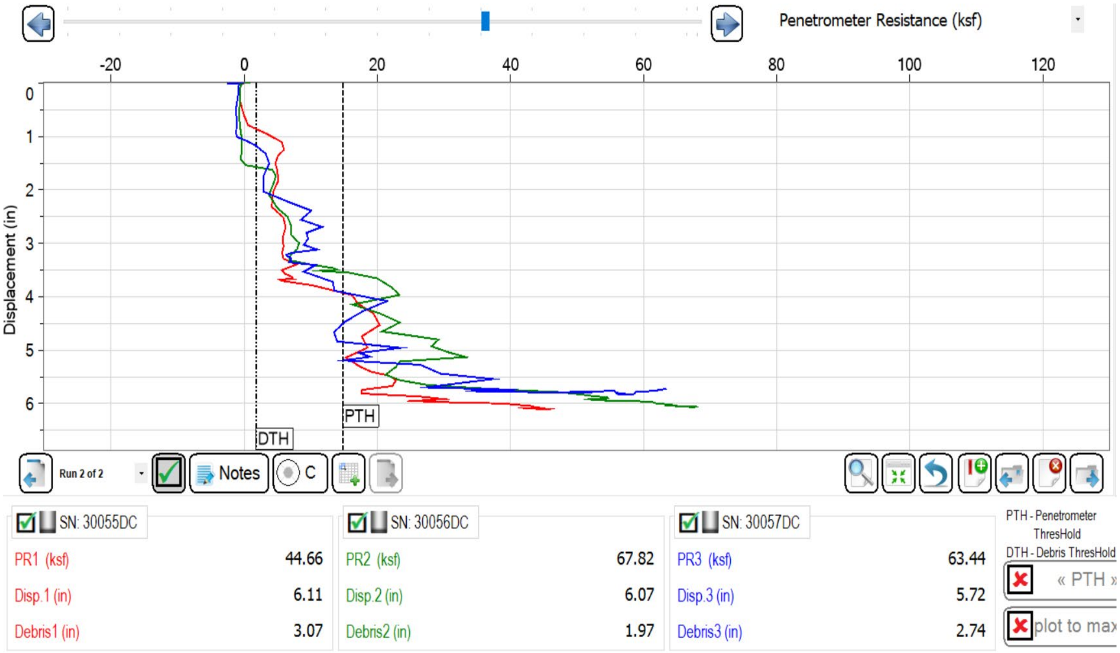
Both test shafts used telltale assemblies attached to the upper and lower bearing plates to determine bearing plate movements and in the case of the BDLT, jack assembly expansion. The telltale assemblies consisted of a ½-inch Schedule 40 steel pipe casing, and a ¼-inch unrestrained, stainless steel rod inside and resting on the bottom of the casing. Telltale assemblies were also installed to the shaft base to calculate base movement. For the BDLT shaft, two vibrating wire displacement transducers ("VWDT") were installed across the jack assembly to measure jack assembly expansion. For both test shafts, shaft head movements were determined using two Leica Model LS15 digital levels with each digital level independently monitoring an Invar target attached to the reinforcing cage above grade.

A Shaft Quantitative Inspection Device or SQUID was used to check the base condition prior to concrete placement. Base cleanliness test results are presented in Figure 4 for the BDLT shaft and in Figure 5 for the TLBT test shaft. The plots of penetrometer resistance versus displacement confirmed the shaft excavation observations and indicate the base materials of the two test shafts differed. The base material at the BDLT shaft location exhibits greater strength at less displacements. In the BDLT shaft, the debris thickness at the shaft base ranged from 0.35 to 0.52 inches with an average of inches 0.40 inches. For the TLBT shaft, the debris thickness ranged from 1.97 to 3.07 inches with an average of 2.59 inches. This debris thickness exceeded typical guidance such as GEC-10 (2018) for drilled shaft excavations drilled dry in soils where the maximum thickness of loose or disturbed material is limited to 1.5 inches prior to placing concrete. However, time constraints dictated that additional base cleaning efforts were not performed.



| ☑ SN: 30055DC | | ☑ SN: 30056DC | | ☑ SN: 30057DC | |
|---|---|---|---|---|---|
| PR1 (ksf) | 80.02 | PR2 (ksf) | 78.15 | PR3 (ksf) | 109.46 |
| Disp.1 (in) | 6.21 | Disp.2 (in) | 5.33 | Disp.3 (in) | 5.44 |
| Debris1 (in) | 0.42 | Debris2 (in) | 0.35 | Debris3 (in) | 0.52 |

Fig. 4. SQUID Results for BDLT Shaft.



| ☑ SN: 30055DC | | ☑ SN: 30056DC | | ☑ SN: 30057DC | |
|---|---|---|---|---|---|
| PR1 (ksf) | 44.66 | PR2 (ksf) | 67.82 | PR3 (ksf) | 63.44 |
| Disp.1 (in) | 6.11 | Disp.2 (in) | 6.07 | Disp.3 (in) | 5.72 |
| Debris1 (in) | 3.07 | Debris2 (in) | 1.97 | Debris3 (in) | 2.74 |

PTH - Penetrometer ThresHold
DTH - Debris ThresHold

**Fig. 5. SQUID Results for TLBT Shaft.**

A concrete mix with a 4,000 psi design strength was placed into both test shafts using a pump truck. The average concrete compressive strength was 5,575 psi at 12 days after placement for the BDLT shaft concrete and 4,865 psi at 13 days after placement for the TLBT shaft concrete. Concrete test reports indicated the BDLT shaft concrete had a slump of 7.5 inches and a concrete temperature of 110 degrees whereas the TLBT shaft concrete had a slump of 7.75 inches and a concrete temperature of 107 degrees when placed.

## Bi-Directional Test Results

The load test on the BDLT shaft was performed 13 days after shaft construction, and the load test on the TLBT shaft was performed 15 days after shaft construction. A 600-ton jack with a load cell and spherical bearing plate, located in the 41-inch distance between the top loading plate and the bottom loading plate, was used to apply the TLBT loads. The bottom loading plate was 43 inches above the top of shaft concrete to accommodate the displacement transducers atop the telltale assemblies. Figure 6 presents a photograph of the test site with the BDLT shaft in the foreground and the TLBT in the background with the jack resting on the bottom loading plate.

Plots of the upper and lower bearing plate movements versus applied load are presented in Figure 7 for the BDLT shaft and in Figure 8 for the TLBT shaft. The BDLT shaft failed in shaft resistance above the upper bearing plate at a jack assembly applied load approaching 900 kips. In comparison, the TLBT shaft has a much softer base response and a lower mobilized resistance below the lower bearing plate than the BDLT shaft. This was anticipated based on the visual observations during construction of the excavated base materials as well as the SQUID penetrometer resistance and base cleanliness results. It should be noted that the upward plate movement at 690 kips is very similar in both tests.

**Fig. 6. BDLT Shaft (foreground) and TLBT Shaft (background).**

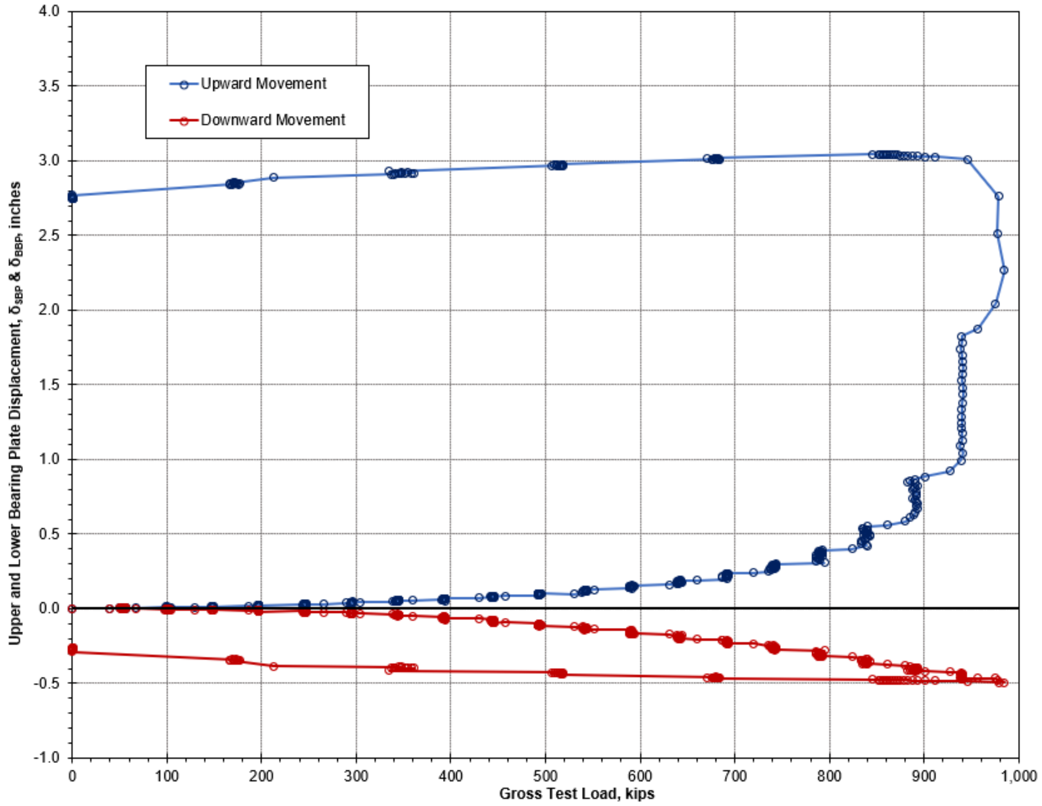


**Fig. 7. BDLT Results 13 Days after Installation.**

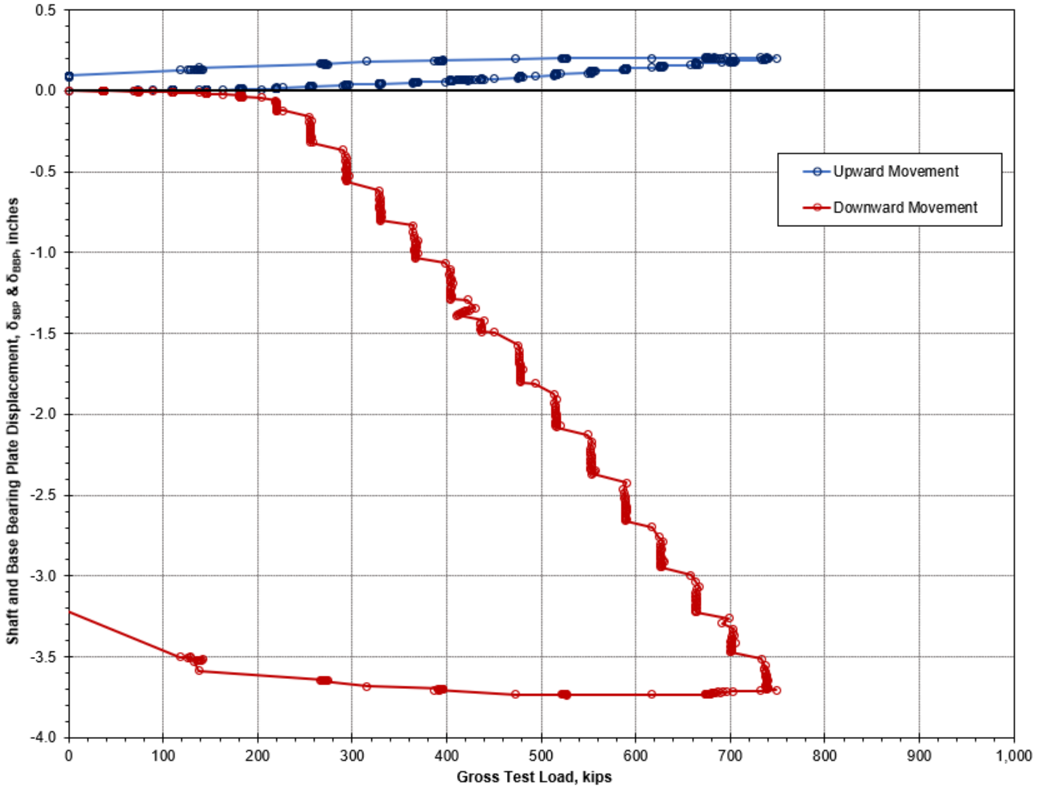


**Fig. 8. TLBT Results – Initial Test 15 Days after Installation.**

Unfortunately, above grade buckling of the base mobilizer bars in the TLBT prevented applying a greater load to the TLBT shaft during its initial loading test. Differing opinions exist as to the cause of the bar buckling. Possibilities include the bar size, the bar yield strength, the type of connection to the embedded base bearing plate, as well as the height of the bottom load assembly above the top of shaft. A large clear distance was required between the bottom load assembly and the top of the test shaft because of the solid load assembly frame design and the instrumentation type and length chosen to read the telltale rods.

The buckled bars were subsequently removed and replaced, and the load test was rerun 83 days after shaft construction. The plot of the upper and lower bearing plate movements versus applied load from the retest are presented in Figure 9. In the retest, the mobilized shaft resistance above the upper bearing plate exceeded 900 kips at 0.35 inches of movement. The lower plate movements reduced in the retest due to the previous loading cycle. In addition, a greater maximum load was applied in the retest following load application system improvements and new bars.

Another variation in the test results can be attributed to variations in shaft shape. Thermal Wire Cables were installed in both test shafts allowing an assessment of the as-constructed shaft shapes from the construction records of the placed concrete volume. The as-constructed shaft shapes from Thermal Integrity Profiling analysis are presented in Figure 10a and 10b for the BDLT shaft and TLBT shaft, respectively. The TLBT shaft has an apparent bulge from 13 to 19 ft below grade which may explain the slightly greater mobilized resistance above the upper bearing plate when comparing the BDLT and retest TLBT results. Both shafts appear to be slightly oversized beyond the 24-inch nominal radius in the upper portion of the shaft and slightly undersized below the BDLT jack assembly or TLBT bearing plates. In the case of the TLBT, the temperature reduction toward the base is also attributed to reduced quality concrete material potential due to slough in materials.

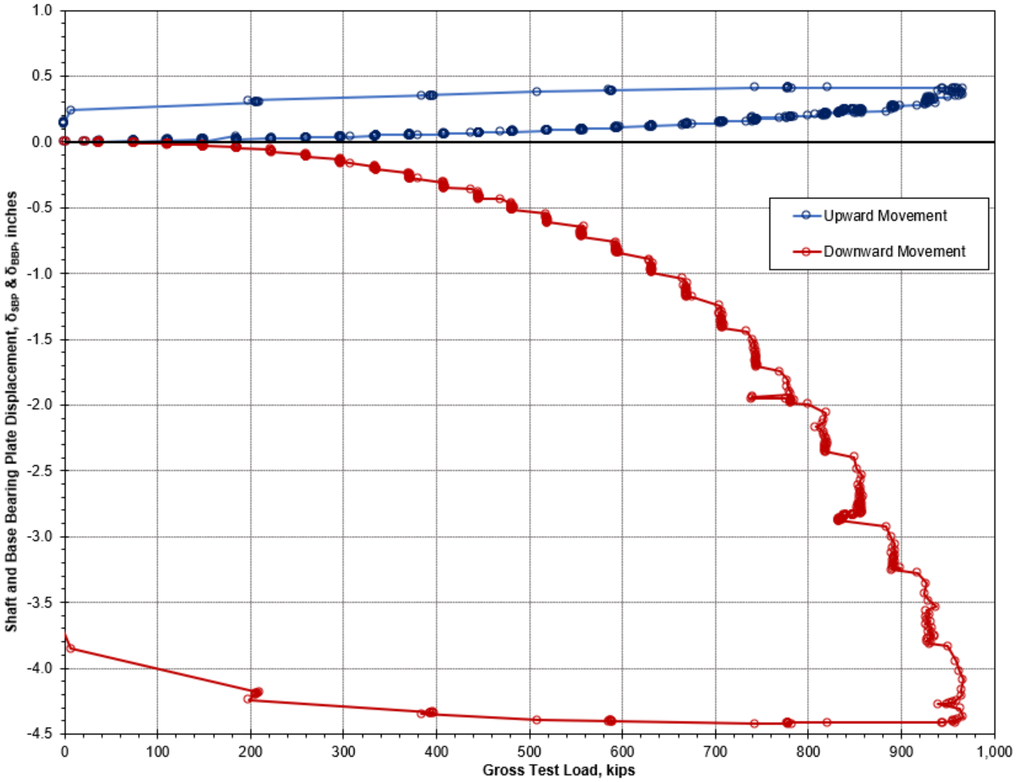


Fig. 9. TLBT Results – Retest 83 Days after Installation.

## Load Transfer Profiles

The measured strains were converted to calculated internal forces. The internal forces in the foundation at each strain gage level were calculated using the average strain, and the foundation axial rigidity at that level. Foundation axial rigidity is the product of composite-section elastic modulus times cross-sectional area (EA), and was determined using the American Concrete Institute (318-14) relationship between concrete elastic modulus and unconfined compressive strength as well as the nominal cross sectional area adjusted, if necessary, based on TIP data considerations. The resulting internal force profiles above the bearing plates are presented in Figures 11a and 11b for the BDLT shaft and the retest of the TLBT shaft, respectively. The internal force at a given elevation generally varies by less than 20% between the two methods with the TLBT value being greater. Considering the variations in shaft geometry, soil conditions, potential bending effects, and the test date after installation this variation appears reasonable.

The measured strains below the bearing plates using the concrete embedment style VWSG's appeared to be heavily influenced by the proximity to the bearing plates. Calculated internal forces were therefore not presented below the bearing plates. Another BDLT and TLBT comparison test will be completed shortly. This comparison test will use sister-bar mounted VWSG's throughout and hopefully will provide better insight into the calculated internal forces above and below the bearing plates.

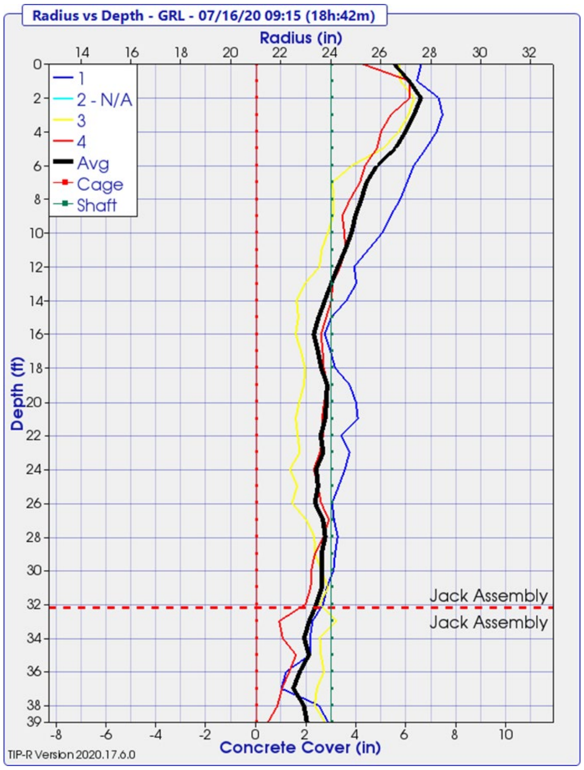


**Fig. 10a. BDLT Thermal Integrity Profile.**

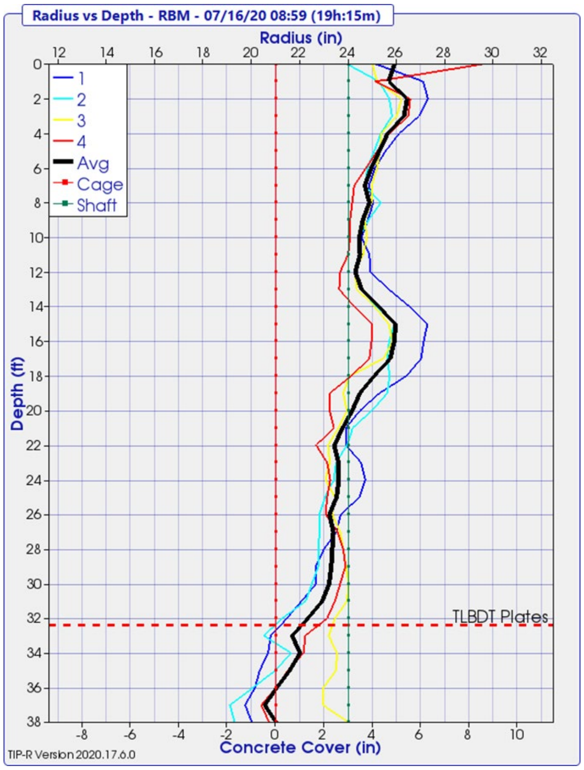


**Fig. 10b. TLBT Thermal Integrity Profile.**

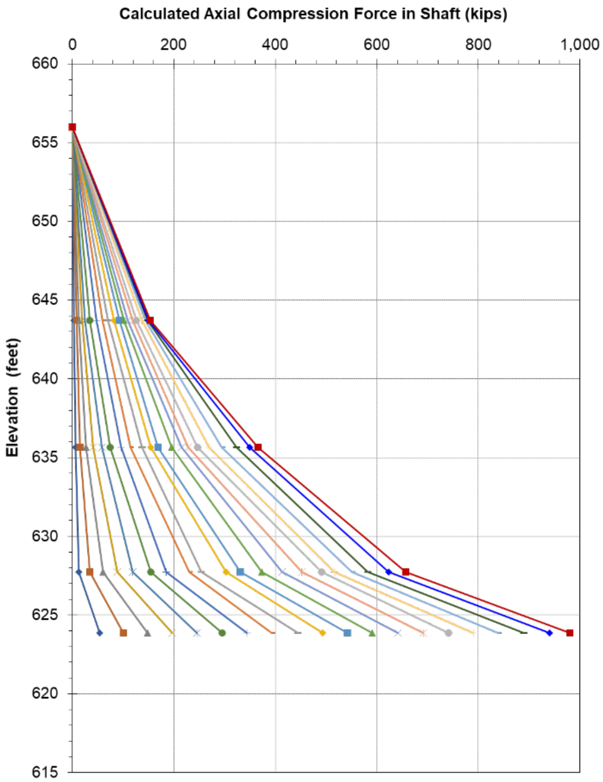


**Fig. 11a. BDLT Shaft Internal Force Profile.**

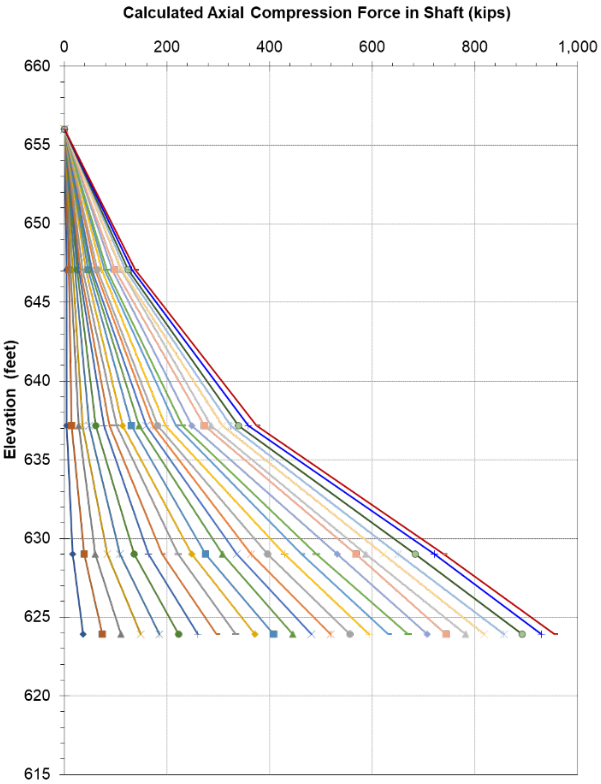


**Fig. 11b. TLBT Shaft Internal Force Profile.**

## Equivalent Top Loading Curves

Osterberg (1995) proposed that an equivalent top loading ("ETL") curve could be developed by adding the loads mobilized by the upward and downward bearing plates at equal plate movement. The elastic compression of the foundation was considered negligible in this procedure which is referred to as the original ETL method. An equivalent top loading curve can also be developed using the modified ETL method which includes the foundation deformation from elastic shortening under the applied load. According to Seo et. al. (2016), this modified method was never formally published, but it became the standard analysis procedure for generating ETL curves from bi-directional load test results during the summer of 2000.

Figure 12 presents the ETL curves generated using the modified method for the bi-directional load test shaft as well as for the initial test and retest of the top loaded bi-directional load test shaft. The differences in the maximum ETL loads are due to the bearing plate loads reached at a given displacement. When significant differences occur between bearing plate load-displacement behavior, the maximum ETL load relative to the maximum test load is reduced. The ETL curve for the retest has been plotted without consideration of any permanent set from the initial load test performed 2 months earlier. Compared to the conventional bi-directional load test ETL curve, the diverging response between the BDLT and TLBT ETL curves after 1200 kips supports the observation that a softer base condition was present in the TLBT shaft.

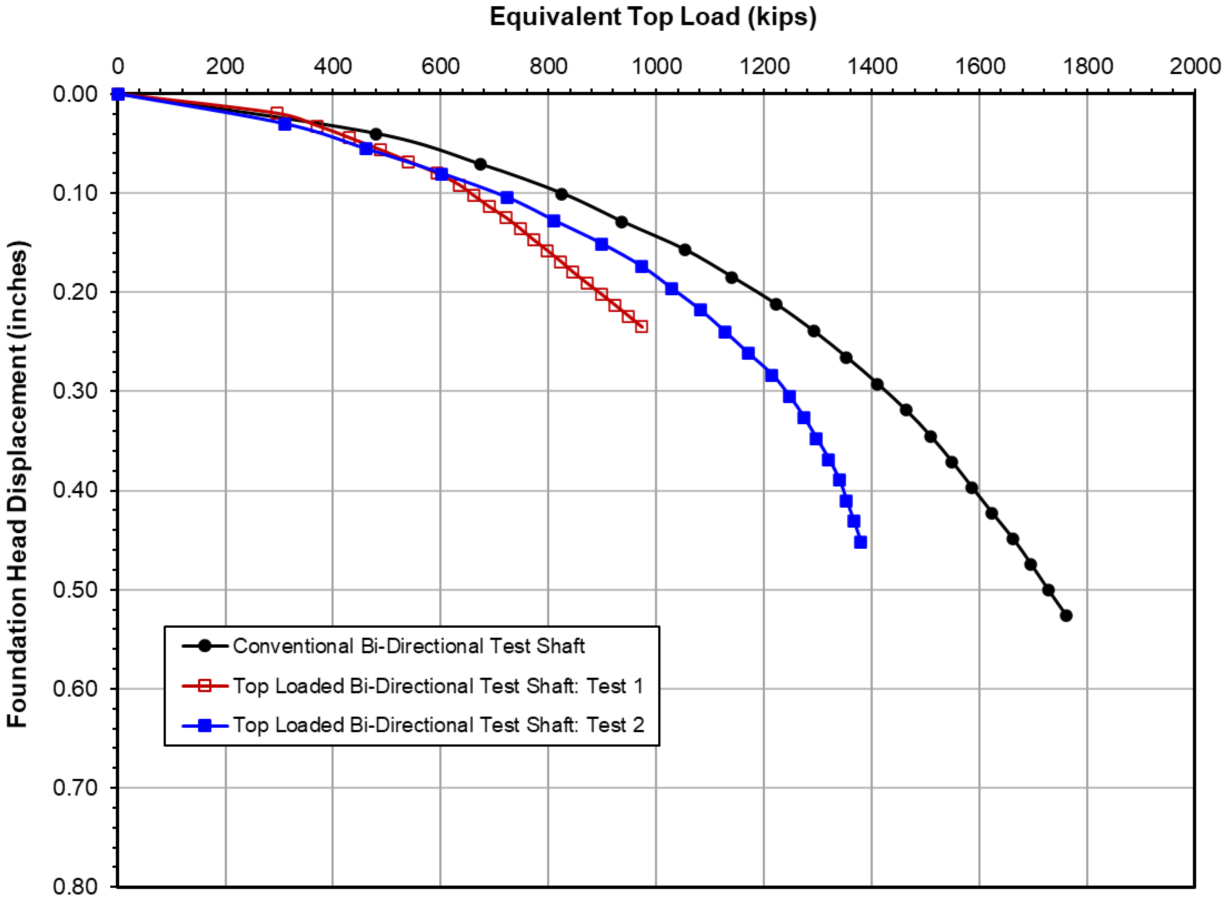


**Fig. 12. Equivalent Top Loading Curves Results Using Modified Method.**

## Load Frame Modifications

Load frame modifications have occurred since the initial comparison test reported herein. Figure 13a presents the original load frame used on the 4 foot diameter TLBT test shaft. Figure 13b shows a modified load frame design used on a 3 foot diameter test shaft. The modified load frame allows a lower loading frame height to accommodate instrumentation extending out from the foundation top as well as accommodate multiple diameter (generally 3 to 6 feet) and rebar cage sizes thereby broadening potential test application.

**Fig. 13a. Initial TLBT Load Frame**

**Fig. 13b Modified TLBT Load Frame**

## Conclusions

These initial comparison tests demonstrate that the reusable TLBT provides comparable bi-directional load test results to the conventional BDLT when shaft construction and site variability factors are considered. The TLBT is a viable load test solution that is ideal for lightly to moderately loaded drilled shafts, large diameter ACIP piles, large driven concrete piles, and large diameter concrete filled pipe piles.

Additional comparison tests with more extensive instrumentation are in progress to assess bar loads, plate stresses from the TLBT shaft and base mobilizer bars, as well as to further evaluate load-transfer behavior in companion BDLT and TLBT drilled shafts.

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