ADJACENT TOP-LOADED BI-DIRECTIONAL TEST AND CONVENTIONAL BI-DIRECTIONAL LOAD TEST RESULTS – SITE II

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ABSTRACT

The Top-Loaded Bi-Directional Test ("TLBT") and the conventional Bi-Directional Load Test ("BDLT") are full-scale static load test methods. In both methods, the test loads are applied bi-directionally to the deep foundation. The advantages of the conventional BDLT have been well established for cost efficient static load testing of deep foundations, particularly for large diameter, high-capacity drilled foundations. A conventional BDLT applies the bi-directional test loads using an embedded jack and bearing plates. The TLBT method also applies the bi-directional test load to embedded bearing plates but does so using reusable high-strength threaded bars attached to an above-grade hydraulic jack and load transfer assembly. The new TLBT method is well suited for load testing shafts of a moderate diameter, length, and nominal resistance or ultimate load. TLBT advantages include economic considerations resulting from the method's reusable load application components and constructability considerations as it readily accommodates a center concrete tremie pipe or pump line location.

This paper presents comparison results from full-scale load tests performed using both bi-directional load testing methods. Adjacent 3-foot diameter by 30-foot long BDLT and TLBT shafts were tested. Details regarding subsurface conditions and test shaft construction are included for the comparison of the TLBT and BDLT results. Corresponding test data and analyses for both test shafts are presented and discussed in detail. The BDLT shaft had a maximum uni-directional load of 240 kips at upper and lower bearing plate displacements of 0.5 and -3.8 inches, respectively. The TLBT had a maximum uni-directional load of 300 kips at upper and lower bearing plate displacements of 1.0 and -5.9 inches, respectively. These results as well as the load-transfer behavior and equivalent top loading curve results from the adjacent BDLT and TLBT drilled shafts are discussed. The paper also discusses the strain gage instrumentation on the TLBT load application bars and on the embedded bearing plates.

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

Introduction

The conventional bi-directional load test ("BDLT") has been well documented by Osterberg (1998), Schmertmann et. al., (1998), and numerous others. The test method requirements are further delineated in ASTM D8169/D8169M-18. Details on the top-loaded bi-directional test ("TLBT") method have been presented in Moghaddam, et. al., (2021a, 2021b). Similar to a BDLT, the TLBT method also applies the bi-directional test load to embedded bearing plates but does so using reusable high-strength threaded bars attached to an above-grade hydraulic jack and load transfer assembly. An initial comparison of conventional bi-directional load test and top-loaded bi-directional load test results from Site I was presented in Hannigan, et. al., (2021). At Site I in Converse TX, 4-foot diameter drilled shafts were installed 20 feet apart center-to-center. The current paper presents results from Site II in Solon OH where a conventional bi-directional load test and a top-loaded bi-directional load test were performed on 3-foot diameter test shafts located 30 feet apart center-to-center. The conventional bi-directional load test shaft at Site II had been installed in 2017. The top-loaded bi-directional load test shaft was installed in 2021 for an additional result comparison. For research and development purposes, the TLBT shaft at Site II had strain gage instrumentation added to the TLBT load application bars and to the embedded bearing plates.

A soil boring near the test shafts indicated the subsurface conditions consist of approximately 18 feet of stiff to very stiff lean clay overlying a 5-foot thick layer of loose sand. The sand layer was in turn underlain by 10 feet of stiff clay. Glacial till deposits were encountered below 33 feet with a 10-foot layer of stiff sandy clay followed by an 18.5-foot thick layer of very stiff to hard clay that extended to the end of the boring at 61.5 feet. Two cone penetration tests were also performed in the vicinity of the test shafts. Neither CPT test encountered the loose sand layer noted in the boring. Unfortunately, neither CPT could be advanced to the test shaft base level 30 feet below grade with one CPT encountering a cobble at 14.5 feet and the other refusing on a cobble at 22.0 feet.

Test Shaft Construction Details

At the Solon OH test site, two 3-foot diameter, 30-foot-long test shafts were installed 30 feet apart center-to-center. Both shafts were drilled in the dry without casing. The BDLT shaft containing a conventional 600-kip bi-directional cell with a 6-inch stroke was installed in September 2017. A second test shaft, containing the top-loaded bi-directional assembly, was installed in May 2021. In both test shafts, the top of the lower bearing plate was located at the same elevation approximately 7 feet above the shaft base. After excavation, both shafts were filled with concrete having a 28-day compressive strength of 4000 psi.

The TLBT shaft was constructed to accommodate six 2.5-inch O.D., 150 ksi threaded steel bars; three base mobilizer bars and three shaft mobilizer bars. Each shaft mobilizer bar was encased in a 3.0-inch I.D. schedule 80 PVC pipe to isolate it from the shaft concrete. Similarly, each base mobilizer bar was isolated from the shaft concrete with a 3.5-inch I.D. schedule 40 steel pipe. A larger diameter pipe around the base mobilizer bars was used to accommodate data transmission cables from instrumentation added to the mobilizer bars.

Fig 1. Drill rig and 300-ton bi-directional cell in cage for 2017 conventional BDLT

Fig 2. Drill rig and bearing plate assembly in cage for 2021 TLBT

Comparison of Conventional and Top-Loaded Bi-Directional Test Results

The conventional bi-directional load test and the top loaded bi-directional load test were performed 20 and 32 days after shaft installation, respectively. The tests followed the procedures outlined in ASTM D8169/D8169M-18, even though the conventional bi-directional load test was performed prior the standard being officially adopted. A 400-kip jack with a load cell and spherical bearing plate was used to apply the TLBT loads. Plots of the upper and lower bearing plate movements versus applied load are presented in Figure 3 for the conventional BDLT shaft and Figure 4 for the TLBT shaft. The conventional bi-directional load test was terminated at an applied load of 240 kips when the combined shaft and base resistances below the lower bearing plate failed geotechnically. In the TLBT, similar load-movement responses occurred up to 240 kips of applied load. However, the shaft base materials appeared to be stiffer at the TLBT shaft location. This, along with the jack having a 13-inch stroke, allowed the TLBT to be taken to greater upper and lower bearing plate movements and thereby mobilized a greater soil resistance.

Figure 5 presents a photograph of the top-loaded bi-directional test in progress including the loading frame, hydraulic jack, load cell, shaft and base mobilizer bars, and associated instrumentation. This design accommodates multiple shaft diameters (generally 3 to 6 feet) and rebar cage sizes as well as an adjustable loading frame height based on the instrumentation extending out from the shaft top. The illustrated top-loading system is capable of applying uni-directional loads up to 1,800 kips (3,600-kip bi-directional load).

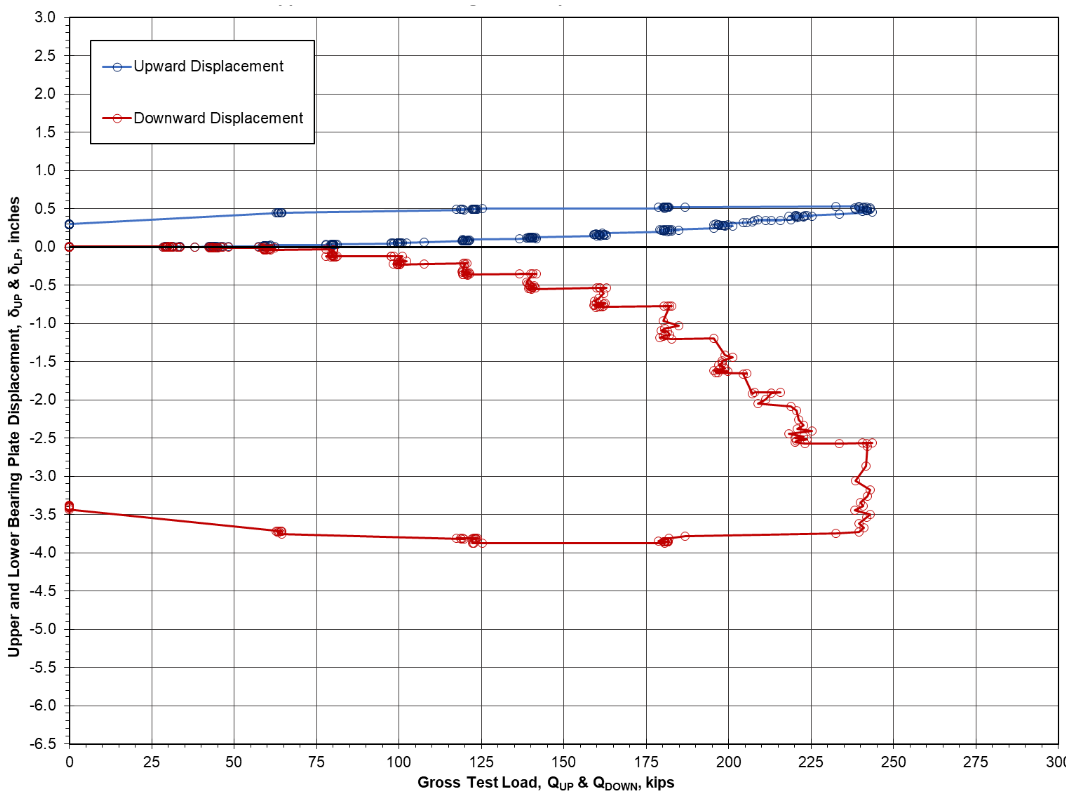

Fig 3. 2017 Conventional BDLT results - bearing plate displacements vs gross test load

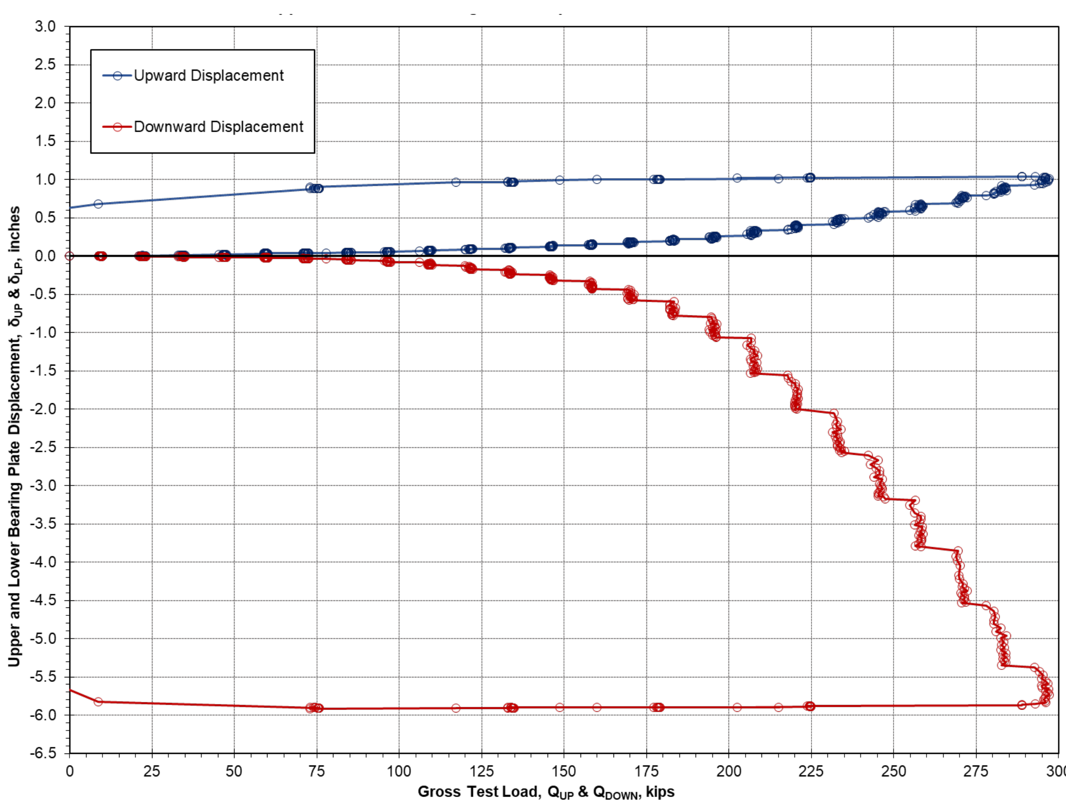

Fig 4. 2021 TLBT results - bearing plate displacements vs gross test load

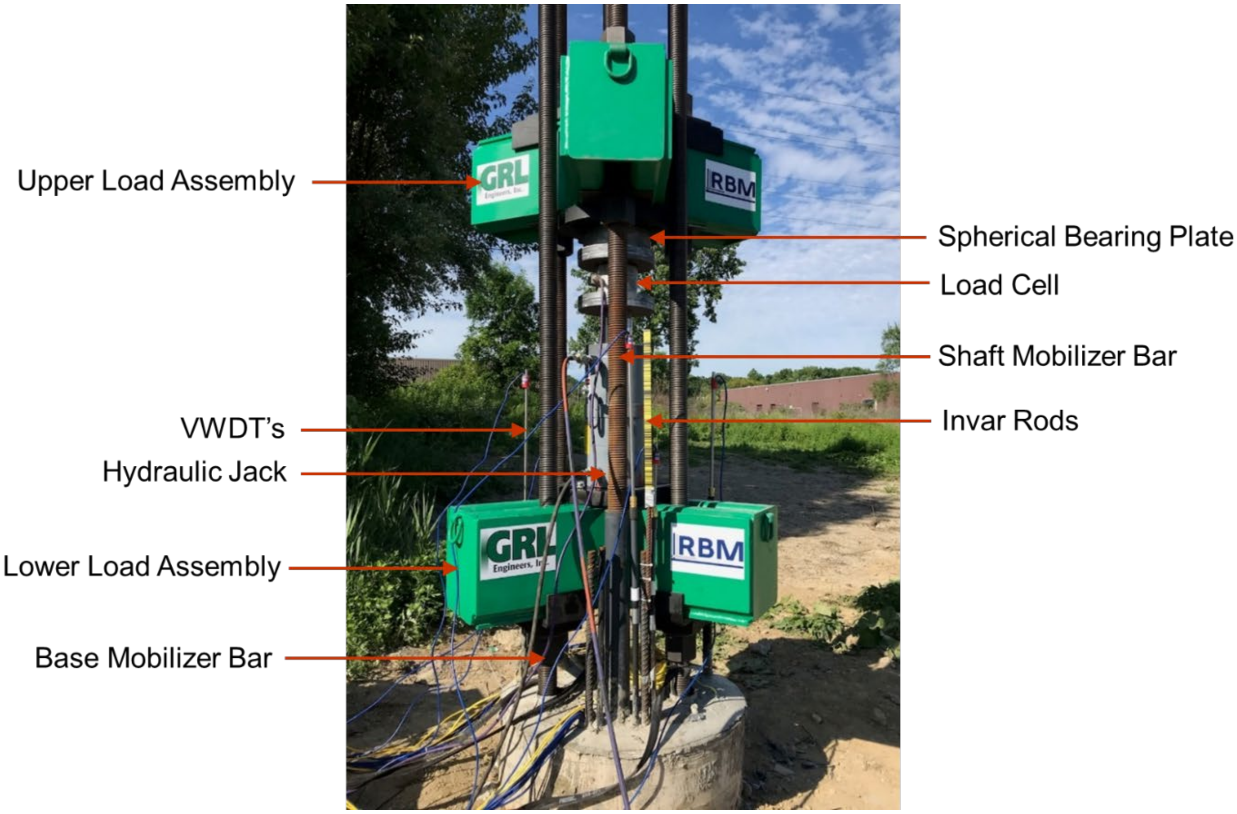

Fig 5. TLBT - load assemblies, hydraulic jack, load cell, and other components.

Load Transfer Profiles

In both tests, the measured strains were acquired from at least two sister-bar mounted vibrating-wire strain gages attached at diametrically opposite locations on the reinforcing cage. Identical strain gage elevations or levels were used in both tests. In the TLBT, an additional strain gage level was added at Elevation 103.5, a distance of one diameter above the bearing plate. This additional level, as well as the strain gage levels in the TLBT at Elevation 96.5 (one diameter below the bearing plate) and at Elevation 108.5 (two diameters above the bearing plate) each had four sister-bar mounted vibrating-wire strain gages to better delineate load transfer. The average measured strain at each level was converted to calculated internal forces using the incremental rigidity method, Komurka and Moghaddam (2020), Komurka and Robertson (2020). The resulting load transfer profiles versus elevation (site datum) are presented in Figure 6a for the conventional BDLT and in Figure 6b for the TLBT test shaft.

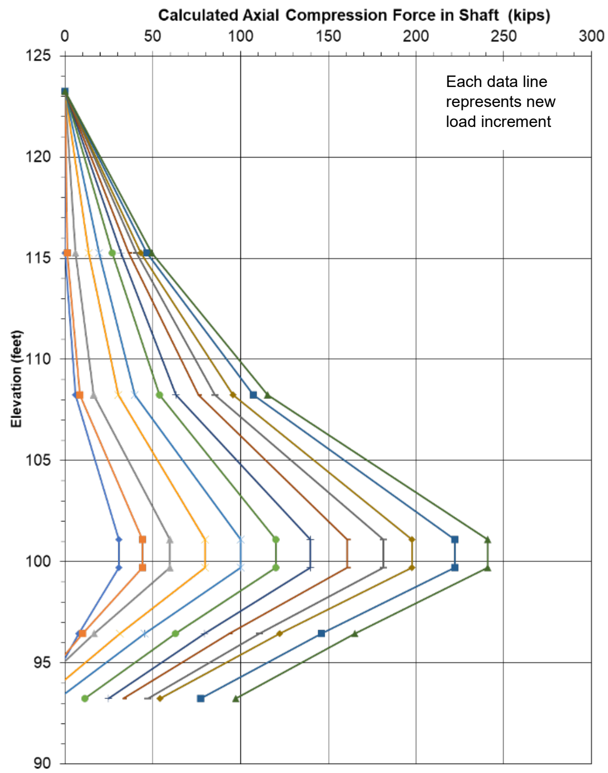

Fig 6a. Internal force profiles versus elevation for conventional BDLT.

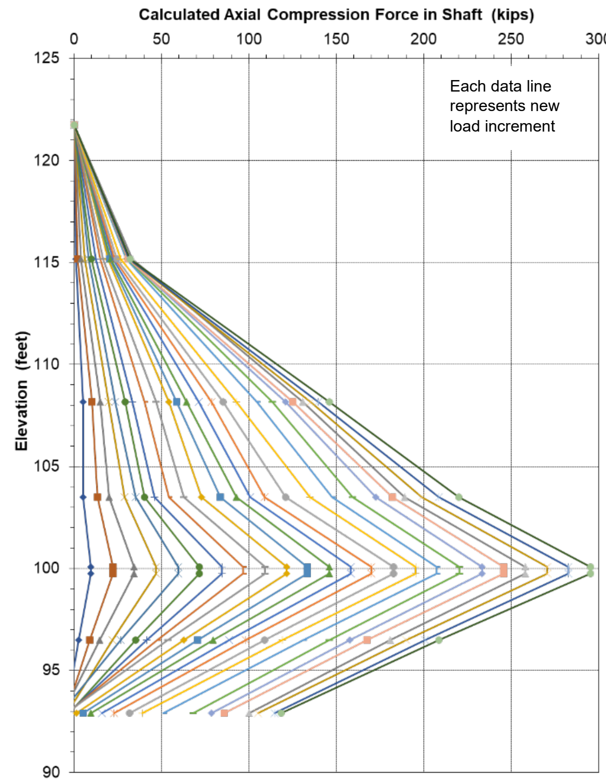

Fig 6b. Internal force profiles versus elevation for TLBT.

Equivalent Top Loading Curves

Figure 7 presents the equivalent top loading (ETL) curves for the conventional BDLT shaft, as well as for the TLBT shaft. The ETL curves were generated using the modified ETL method described by Seo, et al (2016). In the conventional BDLT, the maximum equivalent top load was 375 kips at a shaft top displacement of 0.55 inches. In the TLBT, the maximum equivalent top load was 490 kips at a shaft top displacement of 1.05 inches.

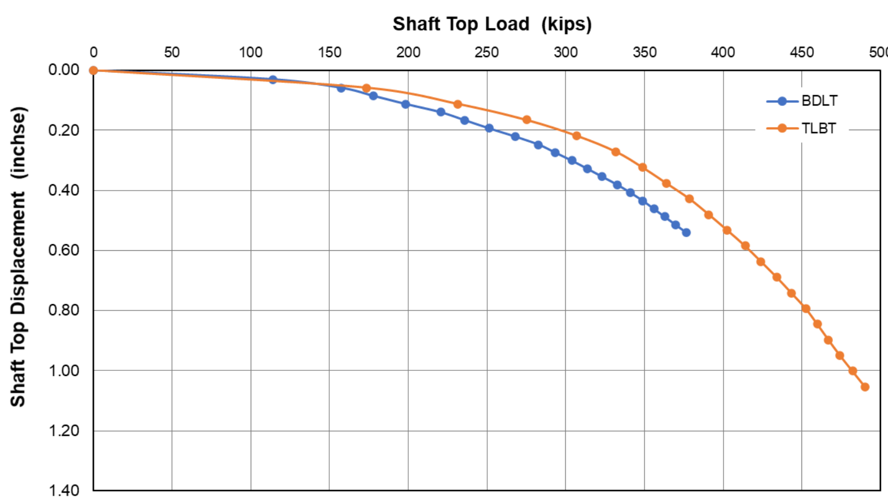

Fig 7. Equivalent Top Loading Curve Comparison for BDLT and TLBT

Measured Strains on Base Mobilizer Bars and Bearing Plate in TLBT

The strain near the bottom of each base mobilizer bar was measured at the center of a two-foot-long unthreaded section using four active gages in uniaxial stress field; two aligned with maximum principal strain and two "Poisson's" gages. The strain was then converted to force using the smooth steel bar cross-sectional area of 5.31 in^2 and the high strength bar manufacturer's recommended elastic modulus of 29,700 ksi. Figure 8 shows the instrumented base mobilizer bars with an epoxy coating over the instrumented section each with the flat cable used for signal transmission to the SLT data logger at the surface. Figure 9 presents a plot the individual force determined from each bar versus elapsed time. Note that two of the three bars have the same load throughout the test but that the NW bar, Bar 3, carries a reduced load until such time that the signal is lost from Bar 3 during the final load interval.

Fig 8. Strain gages attached to 2-foot-long unthreaded portion of TLBT base mobilizer bars

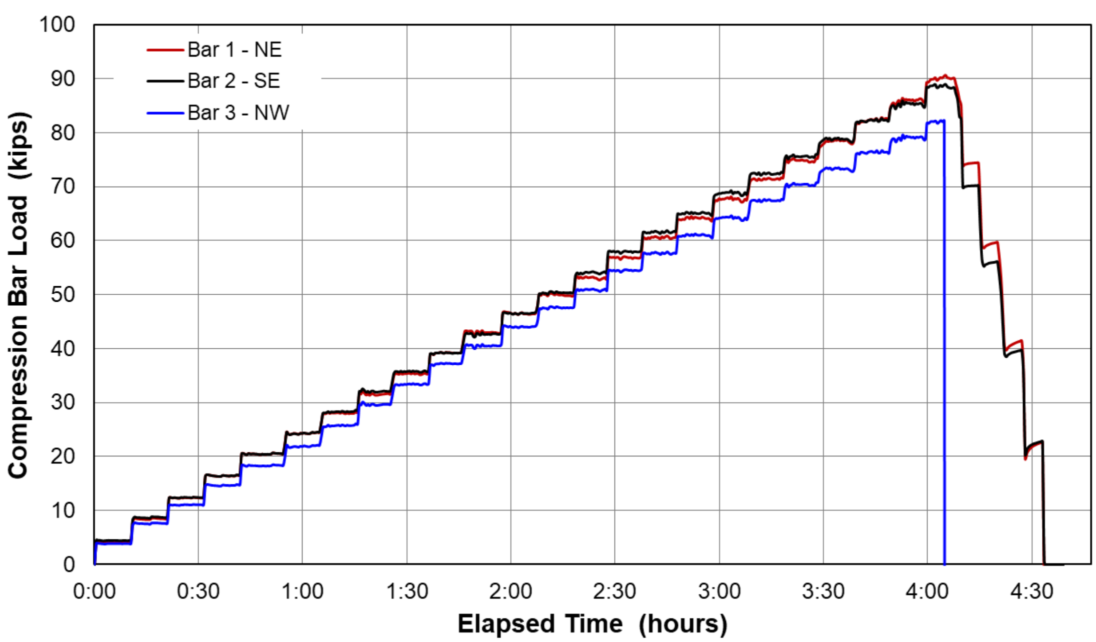

Fig 9. Loads on individual TLBT base mobilizer bars

Figure 10 contains a plot of the "measured" load vs elapsed time as determined from the calibrated jack, calibrated load cell, and the load summed from the three compression bars. Even though Bar 3 carried less load throughout the test, these "measured" load readings were reasonably similar over the first half of the test (up to 150 kips). After that point, the base mobilizer load summed from the three compression bars deviated from the calibrated hydraulic jack and load cell. As noted above, the reading from Bar 3 became unusable as the wire running from the instrumented section up along the bar was crushed. The 3.5-inch ID of the pipe surrounding the 2.5-inch OD compression bars was essential to pass the data cable to acquire the base mobilizer bar readings. Unfortunately, this was also detrimental in allowing greater than normal annular space for lateral movement. This annular space likely contributed to the difference in bar versus jack readings.

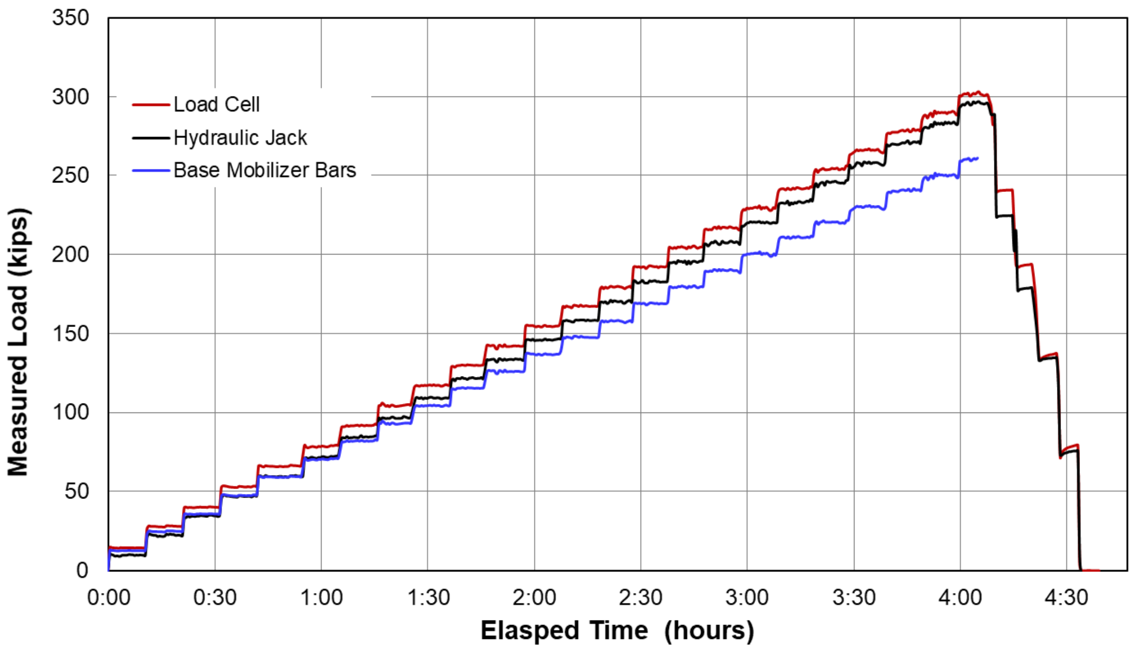

Fig 10. Comparison of hydraulic jack, load cell, and average base mobilizer bar loads in TLBT

Since the conventional BDLT incorporates one or more embedded hydraulic jacks, the applied jack loads are usually assumed to be uniformly distributed to the deep foundation. However, experience has shown that this may not always be true. Therefore, additional instrumentation was incorporated on the TLBT lower bearing plate for assessing anticipated plate deformations under a series of point loads and the influence of potential non-uniform stresses at some distance away from the load application. Stiffener plates were added below the base mobilizer bar locations solely for this purpose to characterize bearing plate response to the TLBT applied load. Only one stiffener plate was instrumented with multiple strain measurement locations. The instrumented stiffener plate was located below Bar 1, the NE bar.

Strain location S3 was located at the vertical center of the stiffener plate immediately below the load application point of a base mobilizer bar. Strain location S4 was located at the vertical center of the stiffener plate near the opposite, inside edge of the plate. Strain locations S1 and S2 were located at the horizontal center of the stiffener plate with S1 on the side face of the stiffener plate near the top edge and S2 on the bottom edge of the stiffener plate. These strain measurement locations are pictured in Figure 11 along with an orientation diagram. Strain locations S1 and S2 were oriented perpendicular to the load application direction and strain locations S3 and S4 were oriented parallel to the load application direction. A plot of these strain measurements versus elapsed time is presented in Figure 12.

Strain measurements were also made on three locations near the center of the lower bearing plate, oriented 120 degrees apart. Strain locations S5, S6, and S7 were located on the bearing plate between the load application points of the base mobilizer bars. These strain locations were not directly in-line with the load application points but were slightly offset toward the shaft center to accommodate the plate cutout locations for the shaft mobilizer bar hex nuts. Figure 13 presents the measured microstrain versus elapsed time for strain locations S5, S6, and S7. The change in microstrain around the 4:10 timestamp corresponds to the beginning of the unloading cycle. The measured microstrain for S5 and S6 terminated early due to transmission cable or gage loss. As anticipated by the strain measurement locations and orientations, the lower bearing plate was in compression throughout the entire test. The relative magnitude of the measured strains on the stiffener and bearing plate characterized the expected plate deformation under the applied loading condition. However, the influence of these observed deformations on shaft and base resistance mobilization cannot be solely assessed from these measurements.

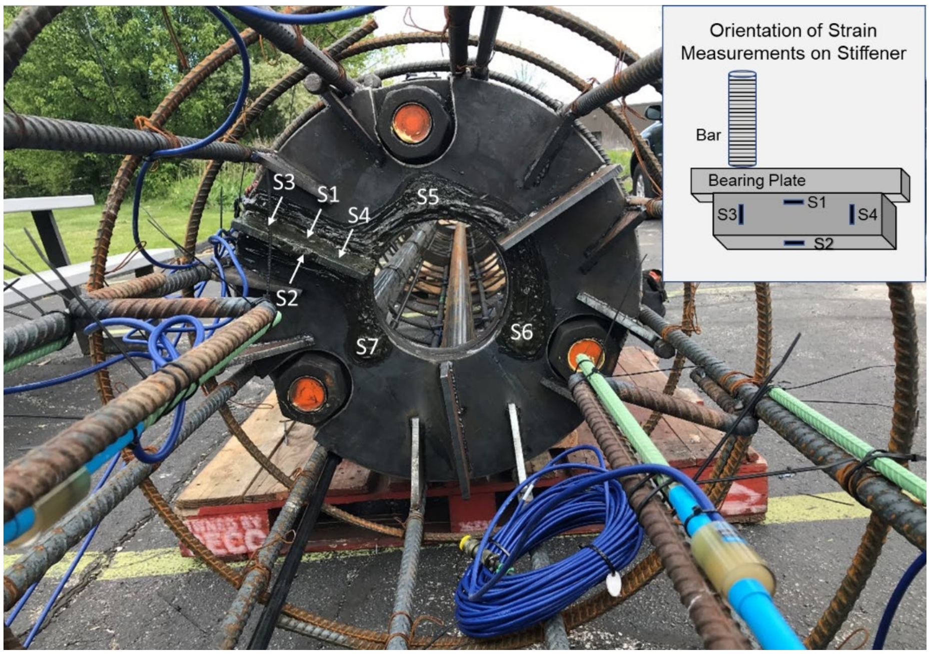

Fig 11. Strain gages attached to bearing plate and stiffener plate in TLBT

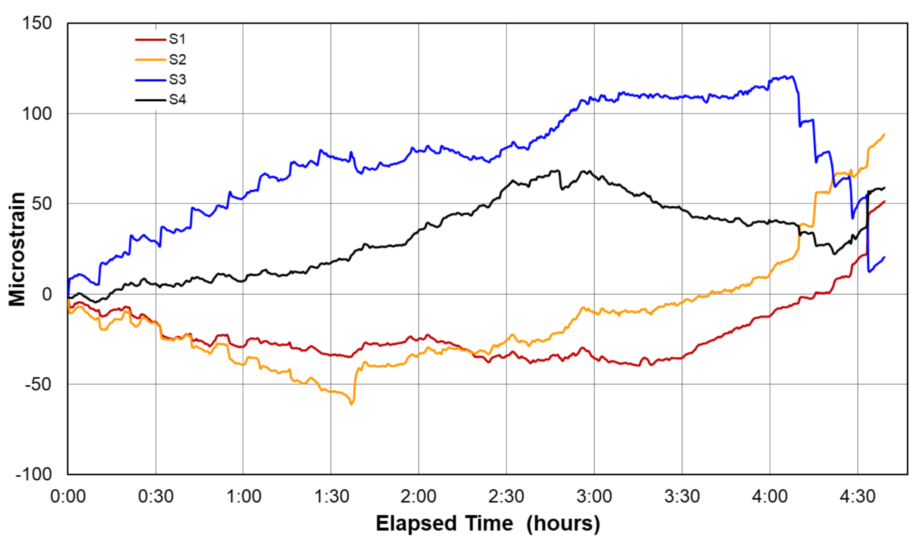

Fig 12. Strain measurements vs elapsed time on stiffener plate in TLBT

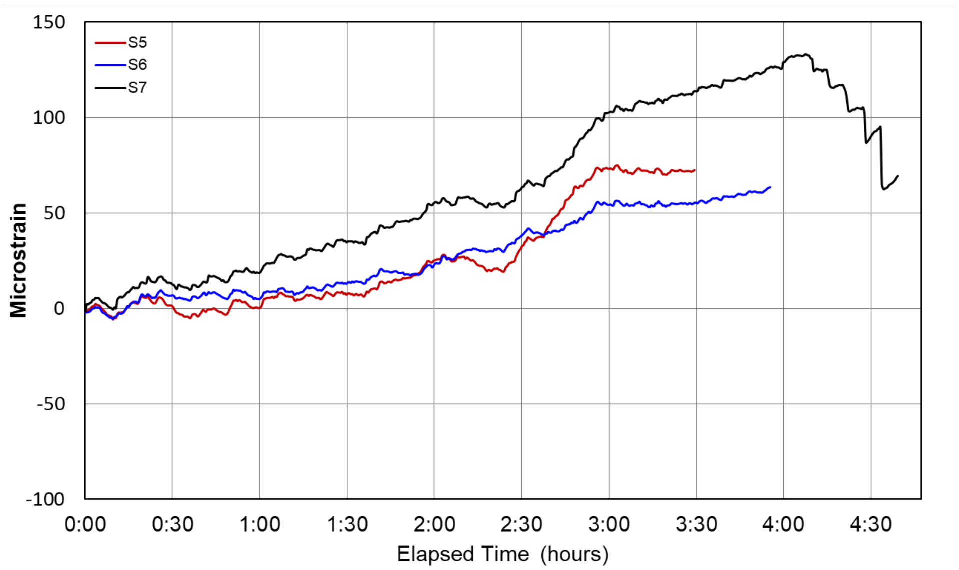

Fig 13. Strain measurements vs elapsed time on lower bearing plate in TLBT

As visible in Figure 11, two additional sister-bar mounted vibrating-wire strain gages were installed on offset rebar approximately nine inches inside the reinforcing cage towards the shaft center. These offset strain gages were located approximately 40 inches below the lower bearing plate. The purpose of these offset strain measurements was to compare the offset strain values with the average strain measured from four sister-bar mounted vibrating wire strain gages on the reinforcing cage. Figure 14 presents the cage and offset strain measurements vs time. Even though plate deformations were indicated by the strain measurements on the lower bearing plate, the strain distribution below base mobilizer bar point loads through the bearing plate and into the concrete was relatively uniform, indicating reasonable strain compatibility across the shaft cross-section under the TLBT applied load.

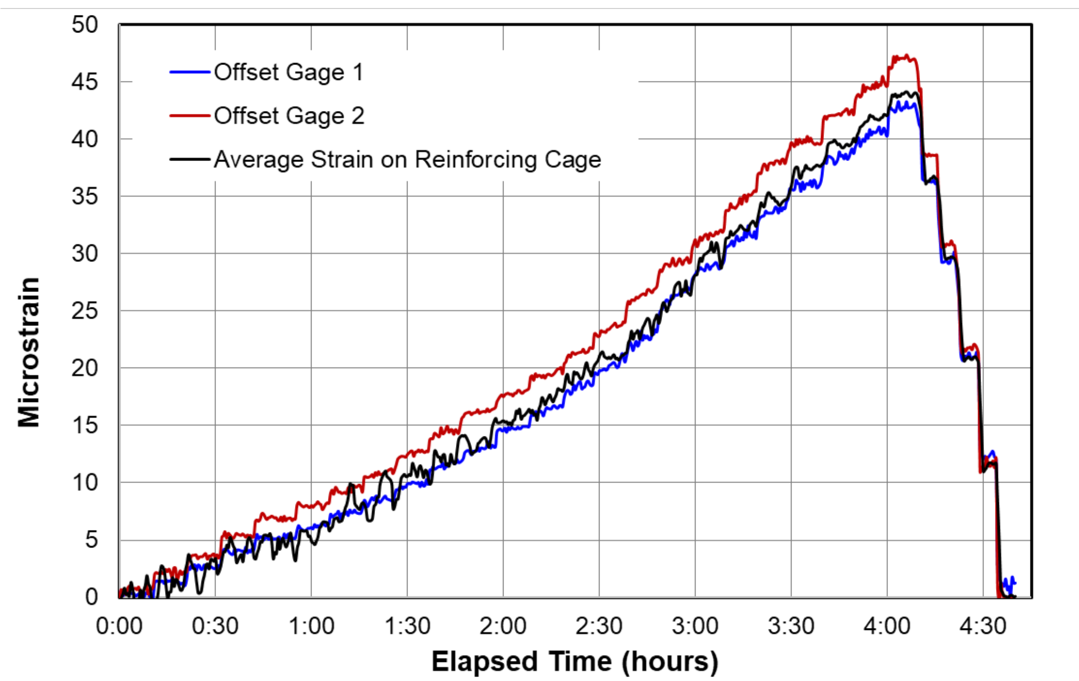

Fig 14. Comparison of average strain measurements on the reinforcing cage vs strain measurements offset near the shaft center in TLBT

Conclusions:

Bi-directional load tests were performed on two 3-foot diameter test shafts at a test site in Ohio. One shaft was load tested using a conventional BDLT and the other test shaft was load tested using a TLBT. In both test shafts, the top of the lower bearing plate delineating the break plane was located at the same elevation approximately 7 feet above the shaft base in the 30-foot-long shafts. The conventional BDLT shaft had a maximum uni-directional load of 240 kips at upper and lower bearing plate displacements of 0.5 and -3.8 inches, respectively. The TLBT had a maximum uni-directional load of 300 kips at upper and lower bearing plate displacements of 1.0 and -5.9 inches, respectively.

The BDLT and TLBT equivalent top loading curve responses at the maximum BDLT applied load were very similar when the encountered variation in base material resistance and typical construction variations are considered. At the maximum equivalent top load of 377 kips available from both ETL curves, the estimated shaft top displacement was 0.54 inches in the BDLT shaft and 0.43 inches in the TLBT shaft.

For research and development purposes, additional instrumentation was added to the TLBT base mobilizer bars and lower bearing plate. These measurements confirmed reasonably uniform load application behavior occurred in the TLBT.

At the maximum applied load, the load on two of the three base mobilizer bars was within 0.2% of one another whereas the load on the third base mobilizer bar, Bar 3, was 8.3% less than the average of the other two bars. This difference in bar load may be the result of horizontal alignment issues in the above grade top loading assembly, in the embedded bearing plates, or some other unknown cause. Even with this variation in bar load, the difference in jack load and the average bar load was only 12.0% at the maximum applied load

The TLBT method offers potential cost savings and reduced construction risk due to the elimination of the embedded hydraulic jack(s) and associated hydraulic lines. Embedded instrumentation requirements are essentially the same for both the TLBT and BDLT methods.

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