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BASE GROUTING CASE STUDIES INCLUDING FULL SCALE COMPARATIVE LOAD TESTING

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ABSTRACT

Base grouting is becoming more widely promoted in the drilled shaft industry as a means to improve shaft response to load. There are a limited number of full-scale field comparisons of test shafts which have been base grouted and adjacent test shafts which have not. This paper presents several case histories of full-scale static load test shafts as well as the results of the tests conducted on adjacent shafts with and without base grouting. The paper compares six pairs of adjacent grouted and ungrouted shafts on 5 separate projects in various parts of the United States. All tests were performed using the Osterberg cell (O-cell) test method. The comparisons yielded some intriguing results. In some cases the results matched theory quite well and showed some improvement to stiffness and overall capacity. In other cases this was not the case. Among other conclusions, the paper illustrates the need for further load testing and research to better understanding how drilled shaft capacity is affected by base grouting, particularly how the capacity is affected by technique, methods and quality control in various materials.

INTRODUCTION

Post-construction base grouting (or tip grouting) of deep foundation elements, typically drilled shafts (bored piles), is becoming more and more common in the Unites States. Although the practice of base grouting is not new, its rising popularity has lead led many, including the authors to ponder whether the state of knowledge is keeping up with application. There is a limited amount of direct comparisons between grouted and ungrouted shaft performance available in the literature (Dapp & Mullins 2002 and Dapp & Brown 2010 are two of the only examples found by the authors).

Loadtest has conducted over 3,500 load tests around the world in the last twenty years. It could be reasonably argued that Loadtest has a significant and advanced understanding of shaft behavior. The data suggests to us that base grouting may not always deliver the improvements that are sometimes promised. The reasons for this were more speculative until recently, when comparative test results have become available.

In the past five years Loadtest has performed bi-directional load tests on a variety of projects where base grouting was performed. On several projects, multiple shafts were tested, some base grouted and some not. Most of these “comparison shafts” were the same diameter and depth, and in the one instance where this was not true, the authors applied analytical techniques to compute equivalent capacities. All comparison shaft pairs were tipped in similar material.

Case studies of these projects and specifically the comparison shaft pairs are presented herein. It is neither the authors’ intention to present a comprehensive study on this complex subject nor to come to specific detailed conclusions. However, a detailed analysis of the load test results did produce some very interesting results. Those are presented at the end of the paper.

BACKGROUND

Loadtest specializes in bi-directional axial compressive load testing using Osterberg cell technology. A common test configuration consists of an O-cell at or near the base of a drilled shaft. The test shaft is excavated and concreted in a similar fashion to production drilled shafts. The O-cell is encased and surrounded by concrete (see Figure 1). Instrumentation is embedded around the O-cell to measure expansion. Strain gages are often installed at various depths within the drilled shaft to measure strain and ultimately compute load at different depths.
When the concrete is sufficiently hardened the test is performed. The O-cell is pressurized until the concrete around

the cell is fractured and the O-cell is immediately unloaded. The two shaft components above and below the O-cell are now free to move with only the shaft's reaction to resist the movement. Movement curves are then generated relating applied load to upward and downward displacement. Load is derived by relating the pressure to the O-cell's calibration curve.

The top of shaft movement is monitored with high precision digital survey levels. The shaft compression is measured using traditional telltales. The upward top of O-cell movement is computed by adding compression and top of shaft movement. The downward movement is calculated by subtracting the expansion from the upward top of O-cell movement. T-z curves can also be generated if strain gages are installed.

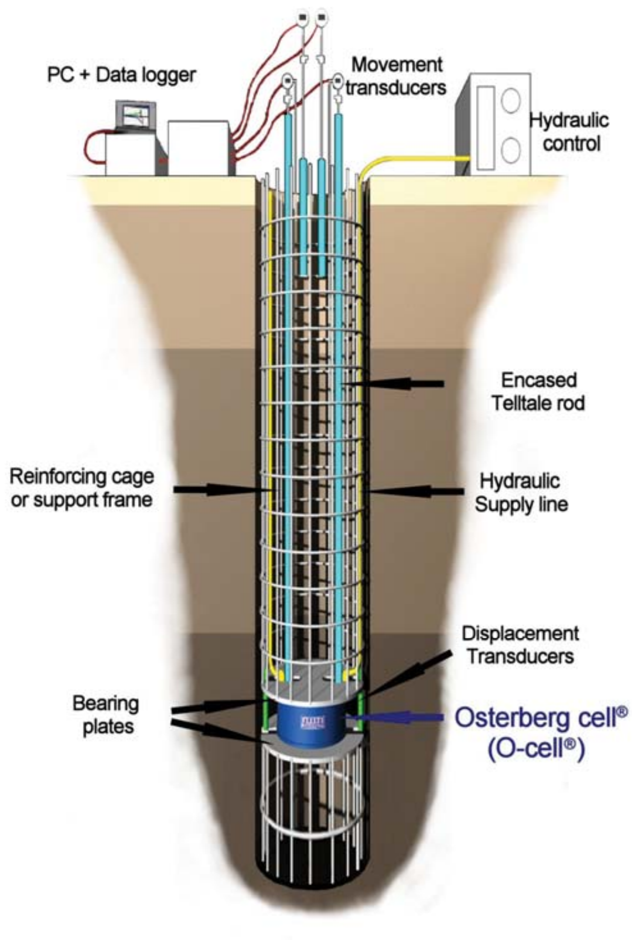

Fig. 1. Schematic representation of an o-cell test shaft (concrete not shown for clarity)

Finally, a unit end bearing curve is generated. The accuracy of this curve depends on how close to the tip of shaft the O-cell is and how well known the unit shear is between the O-cell and shaft tip. For all the case studies presented herein, the accuracy of unit end bearing is considered to be high, since the O-cells are close to the tip and strain gages were employed to evaluate the unit shear near the O-cell.

CASE STUDIES

<u>Sandy River Bridge</u>

Location: Troutdale, OR

General Contractor: Hamilton Construction

Drilling Contractor: Malcolm Drilling

The Oregon Department of Transportation (ODOT) is replacing the aging Interstate 84 bridges over the Sandy River with two new steel box girder bridges. Some design considerations, included seismic, environmental and flooding concerns. This created the need for smaller and fewer shafts.

One solution was to try to improve the capacity of the shafts by base grouting. Another was to verify that the aggressive drilled shaft design was sufficient. The original plan was to test two grouted test shafts after the grout was pressure injected and allowed to harden. Serendipitously, it was decided that one shaft could be tested without base grouting.

Each test assembly consisted of three 6,000 kip O-cells on a single level. Test Shaft 1 was not tip grouted and Test Shaft 2 was. Malcolm Drilling excavated the shafts and performed the tip grouting using a tube-a-manchette system (see Figure 2).

Fig. 2. Malcolm Drilling's tube-a-manchette system

Both shafts were tipped in similar materials (dense sand) at similar depths. The shafts were to be tipped in the Troutdale Formation (partially cemented glacial till). However, upon examining the soil cuttings from the base of the shafts, the material resembled very dense sand more than classic Troudale Formation in both test shafts.

The shafts were constructed and tested on a work trestle. Malcolm Drilling used a 2,500-mm (98-inch) diameter temporary sectional oscillator casing which was advanced to tip and a grab to excavate and clean the shaft bottom under water (see Figure 3). For the base grouted shaft the grouting occurred a few days after concreting. Both test shafts were approximately 120 feet deep.

Fig. 3. Malcolm Drilling's clam shell grab

The results of the first O-cell test (ungrouted shaft) served to confirm the engineering design assumptions. The second test showed an improved stiffness response but only a small improvement to the ultimate capacity (see Figure 4). Because of the way LRFD design was employed in this project, the Engineer was unable to leverage the improvements. Based on their analysis, it was not enough to justify the cost and effort required to base grout the shafts.

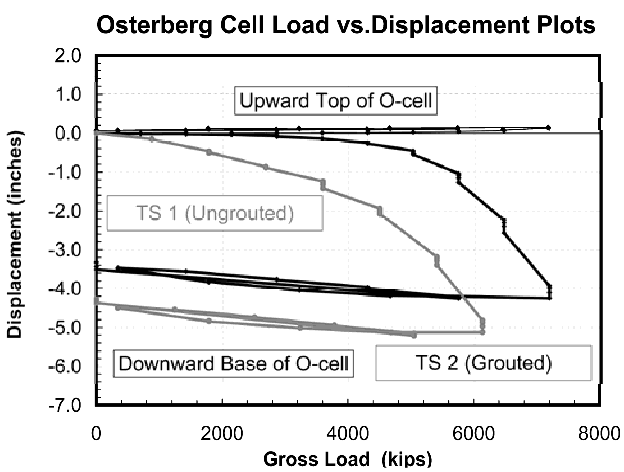

Fig. 4. Load-Movement curves for Sandy River

Subsequently, both test shafts were used as production shafts. This was critical to the project since there were only eight shafts on the bridge's main span and each shaft was costly to construct.

<u>Broadway Viaduct</u>

Location: Council Bluffs, Iowa

Drilling Contractor: Longfellow Drilling

The Broadway Viaduct is a true gateway bridge originally built in 1955, carrying well over 30,000 vehicles daily. Optimizing the design of the new bridge required addressing several project constraints, including the existence of nearby historic structures, and the numerous streets and railroad tracks that run under the bridge. Four column piers with base grouted drilled shafts were proposed as the foundation solution. Driven piling was undesirable on the project for a variety of reasons.

Subsurface conditions at the two test shaft locations were very similar and consisted primarily of sands and silty clay. Longfellow Drilling constructed the two 75-foot deep dedicated drilled test shafts under polymer slurry. The shafts were tipped into fine to coarse sand. Applied Foundation Testing (AFT) performed base grouting on one of the two shafts.

Each test shaft was equipped with a 24-inch diameter, 3,000 kip capacity Osterberg cell (O-cell) installed at a depth of 60 feet. Loadtest then conducted O-cell load testing on both 60-inch shafts in order to compare the load response of the conventional drilled shaft to the base grouted drilled shaft. Representatives of the Iowa Department of Transportation observed construction and testing of both shafts.

Fig. 5. AFT's tip grouting apparatus being installed in the shaft excavation along with the rebar cage and instrumentation

Since the use of base grouting was expected to increase the capacity and performance of drilled shafts, the confirmatory load tests provided useful design data that allowed shorter drilled shafts to be used without losing end bearing capacity (see Figure 6). This led to reduced construction and material costs. The Broadway Viaduct replacement project was the first in which the Iowa Department of Transportation utilized base grouting of drilled shafts.

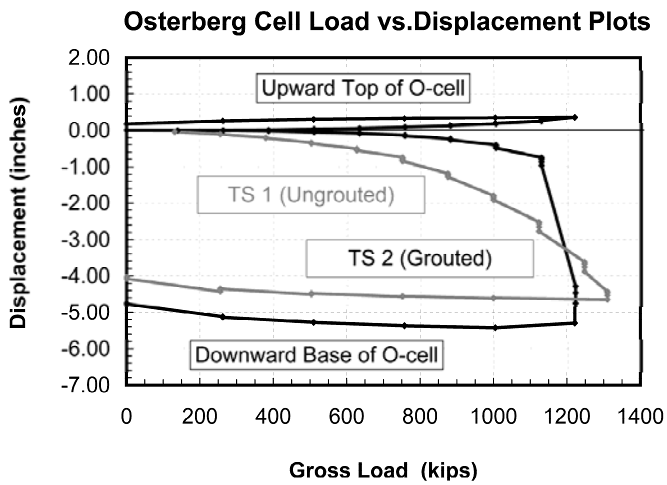

Fig. 6. Load-Movement curves for Broadway Viaduct

However, careful study of Figure 6 reveals some interesting features. Note that while some improvement did occur at the service limit state, the displacement was very rapid after 1,100 kips; much more than for TS-1 (ungrouted). Further, the ultimate capacity seemed to be higher in the ungrouted shaft.

Wisconsin Zoo Interchange

Location: Milwaukee, WI

Client: CH2M Hill

Drilling Contractor: Malcolm Drilling

The Zoo Interchange, which originally opened in 1963, is Wisconsin's oldest and busiest interchange, combining three major freeways and carrying over 300,000 vehicles daily. The enormous undertaking of its reconstruction is a task that prompted WisDOT to seek numerous design alternatives. Loadtest assisted in the facilitation of the most efficient foundation design for structures along both the Core and the West Leg of the Zoo Interchange.

Three pairs of dedicated tests shafts, ranging in diameter from 48-inch to 98-inch, were installed, with one of each pair base grouted. All shafts were outfitted with a single O-cell. The primary objective was to compare the pressure-meter testing (PMT) at each pair. Since base-grouting methods have been purported to substantially increase the shaft and base resistance in drilled shafts, the secondary objective was to compare and determine the potential improvement of the shaft and base resistance due to base grouting. Results from two of the three pairs are analyzed in the next section (the third pair of tests did not yield data useful to the analysis).

Fig. 7. O-cell and tube-a-manchette system in rebar cage

The shafts were constructed under water by advancing segments of oscillated casing into the ground and removing the soil inside with an auger. Sub-surface conditions consisted primarily of loose silt and soft clay underlain by medium to very stiff clay with trace gravel. The casing was advanced in this manner to the tip of the shaft and removed during concrete placement. Malcolm Drilling performed the shaft construction and base grouting (see Figure 7).

The bi-directional O-cell technology helped provide very precise separation of side friction and end bearing resistance. Figure 7 shows how close the O-cell was to the tip grouting apparatus and thus the tip of shaft. The error associated with the side shear component of load resistance is very small and the error assuming a reasonable side shear value even smaller.

Fig. 8. Installed Test Shaft CTS-1

Results of the testing program indicated that the base resistance was greater in all of the base grouted drilled shafts, which allowed for more robust design parameters. Furthermore, since shafts of different diameters were tested, the results provided flexibility in optimizing the foundation design for a complex series of bridges and structures for this project, the results of which will benefit WisDOT far into the future.

Missouri DOT Research Project

Location: Frankford and Warrensburg, MO

Client: University of Missouri

The Federal Highway Administration, and many others, has recently recognized the need to better quantify the proper utilization of base grouting drilled shafts for highway design; specifically where heavily loaded deep foundation elements are required for bridge main spans and abutments.

As a result of this need and dearth of available data, the Missouri DOT and the University of Missouri undertook an extremely ambitious project to develop improved design parameters and procedures. As part of the field testing aspect of this project, Loadtest performed testing at two different test sites in Missouri that were chosen to reflect the potential range of ground conditions where base grouting is likely to be effective.

Subsurface conditions at the Frankford test site consist of low variability, with very weak shale overlying competent shale. In contrast, the Warrensburg site was chosen for its irregularity, with 15 feet of overburden overlying thick, highly variable shale.

Fig. 9. Multiple O-cell load test assemblies ready for installation.

A combined total of 25 test shafts were constructed at the two sites in Frankford (10) and Warrensburg (15), MO. At each site the contractors were able to drill the shafts in the dry with very limited use of casings. The Warrensburg site included five base grouted shafts to help determine any potential improvement in shaft performance and to determine the reliability of any improvement that may be realized.

In general, the results of this project are used in a final FHWA report that includes recommendations for the proper use of base grouted drilled shafts, as well as a means to verify specific design methods. The O-cell testing helped provide extensive site characterization that is now being implemented in the new and improved guidelines, confirming the use of shorter drilled shafts that will produce considerable cost-savings in some cases.

The State of Missouri and the University of Missouri expended a lot of effort and capital on this research. Although there is a wealth of data available to the authors, we recognize that other papers and reports have been written considering the results of this research program. We selected only two test shafts, one grouted and one ungrouted, that represent the best pair to add to our analysis and case studies.

The two test shafts were both 36 inches in diameter and roughly 30 feet deep. They were cased to top of shale (roughly 15 feet). W6 was grouted and W2 was not. The shafts were drilled with an auger and core barrel and cleaned with an auger. Grout was installed at the tip and concrete above the cells. The downward load movement plots for each shaft are presented in Figure 10.

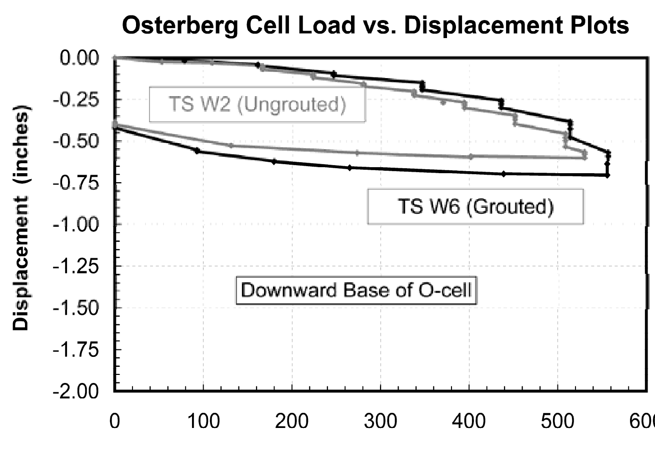

Fig.10. Downward Load-Movement Curves for Missouri Research Project

Gilmerton Bridge Replacement Project

Location: Chesapeake, VA

Drilling/General Contractor: PCL Civil Constructors, Inc.

Owner: Virginia DOT

Consulting Engineers: Parsons Brinkerhoff, Dan Brown & Associates.

Gilmerton Bridge is the Military Highway span over the Southern Branch of the Elizabeth River. The existing bridge was constructed in the 1930's. The replacement bridge is nearly 2,000 feet long and will be wide enough to handle six lanes of traffic.

PCL constructed a 62-inch and a 144-inch production shaft for the project. The smaller shaft was excavated to a tip elevation of -80 feet, and not base grouted. The larger shaft was excavated to a tip elevation of -112 feet, and was base grouted. The shafts are approximately 90 feet apart and tipped into similar material (the Yorktown Formation, a dense silty sand).

The 62-inch diameter shaft was started with a 62-inch diameter, 1-inch thick permanent casing driven with a hydraulic impact hammer. The shaft was excavated with a spherical grab to a depth of 81 feet below river bottom. There are a few unique features of this test shaft which should be explained. The O-cell was actually placed inside the permanent casing several feet. Measures were taken to minimize resistance to downward movement but it is unknown how much load was transferred to the casing. Additionally, there were some concreting stopping and starting issues during the initial pour.

The O-cell assembly and frame were removed at one point and the shaft re-cleaned. The shaft pour was begun with grout until the grout level was above the O-cell. Concrete was then poured through a tremie inserted into the wet grout. The authors believe this test shaft yielded very useful comparative data despite these issues and added to the diversity of the data.

Fig. 11. Tip grouting apparatus installed at the cage tip.

The 144-inch test shaft was excavated with a grab and sectional oscillated casing. The last 10 feet was excavated with a bucket. The casing was advanced as material was removed to a depth of 112 feet. A seating layer of gravel was placed at the tip and tamped to compact it. Applied Foundation Testing (AFT) grouted the shaft tip approximately one month later. The shaft was then allowed to sit for another month prior to testing. The test shaft included four O-cells on a single level three feet above the tip.

Movement curves for these test shafts are not included here as they were sufficiently different so as to require a more detailed analysis. They are included in Figures 12 and 13 below as part of the paper's analysis of all twelve test shafts.

ANALYSIS

In each of the case histories presented in the previous section, one or more pairs of adjacent test shafts were constructed, one shaft which was base grouted and the second which was not grouted. Unit end bearing data was derived for every test shaft by computing the shear component of the shaft section below the O-cell using strain gage data, and subtracting it from the applied O-cell load.

All of the test shaft pairs were of the same diameter, with the exception of the Gilmerton Bridge Replacement Project. Since the scaling effect will affect the shaft load-settlement behavior (see for example, Sinnreich 2011), an equivalent unit end bearing must be computed for the smaller (60-inch base diameter) ungrouted shaft, in order to compare the results to the larger (144-inch base diameter) base grouted shaft. Based on the theory of elasticity (Davis & Selvadurai 1996), the settlement **w** of a rigid disk of diameter **D** subject to a uniform pressure **q** and fully embedded in an elastic medium which has a Young's modulus **E** and Poisson's ratio ν is given by:

$$w = \frac{qD(3-\nu-4\nu^2)}{8E(1-\nu)} \qquad (1)$$

Although the actual end-bearing load-displacement curve is obviously not linear-elastic, the simple analysis given by Equation 1 suggests that, all other parameters being equal, an inverse relationship between **q** and **D** exists. Therefore, for the measured downward displacement of the 60-inch (5-foot) diameter base of the shaft, the unit end bearing is scaled to a 144-inch (12-foot) diameter equivalent by multiplying by the ratio of the shaft diameters (0.4167 - see Figure 12).

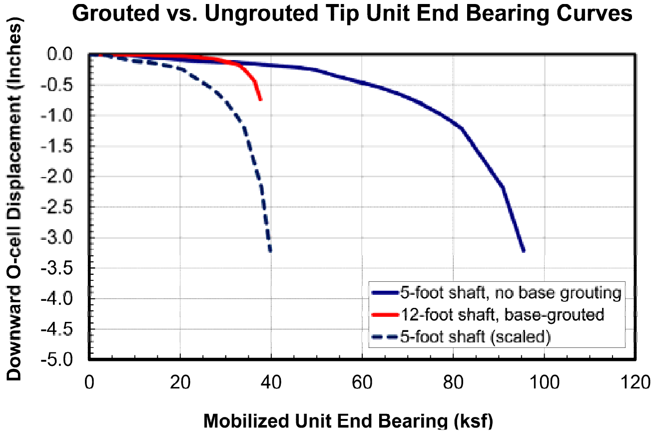

Fig.12. Gilmerton Bridge Project Scaling of Unit End Bearing Curves for Shafts of Different Diameters

In order to compare the results, not just of each pair of matched test shafts but across the whole data set of six pairs, all of the unit end bearing curves are normalized in the following manner:

First, a hyperbolic curve-fit to the unit end-bearing data is applied in order to smooth out the data (see Fleming 1992 for a discussion of the hyperbolic curve-fitting method). The form of the hyperbolic curve-fit function is given by Equation 2:

$$w/q = \beta_1 q + \beta_2 \qquad (2)$$

where **w** and **q** are the displacement and unit end bearing, same as in Equation 1, and the terms β_1 and β_2 are constants which are determined using the least-squares method.

Second, the hyperbolic function is extrapolated in order to estimate the ultimate unit end bearing capacity. Third, for each paired data set, both unit end bearing capacities are normalized to the ungrouted shaft's ultimate end bearing capacity. Fourth, for each paired data set, both displacements are normalized to the ungrouted shaft's initial displacement slope **m** (the tangent to the curve near the origin).

The net result of this normalization is that all of the ungrouted end bearing vs. displacements effectively plot on the same curve (see Figure 13). The thick black line represents all six ungrouted unit end bearing curves. The base grouted end bearing vs. displacement curves are also plotted on Figure 13, each normalized using the parameters of its corresponding ungrouted shaft, in order to visualize the relative change in unit end bearing performance after grouting.

Examining the plots, it is apparent that in all cases base grouting increased the initial stiffness of the end bearing vs. displacement curve relative to the ungrouted shaft, in some cases slightly and in others significantly.

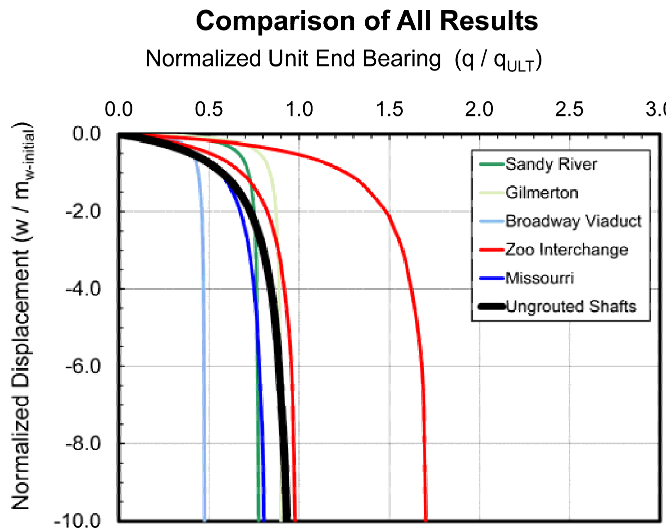

Fig.13. Normalized Displacements vs. Unit End Bearing

For all but two cases, the ultimate capacity appears to be similar to the ungrouted shaft (within normal variation of shaft construction). This result correlates well with the analysis of Fleming 1993, which postulated that pre-stressing of the shaft base does not increase the capacity, only changes the shape of the load-displacement curve. In one instance, the base grouted ultimate capacity increases significantly, and in one case it *decreases* significantly.

In all the case histories discussed here, the pressure was not maintained in the grout lines after the completion of grouting. Therefore the shaft is loaded and unloaded by the grouting operation, then re-loaded when tested using the O-cell. As in any multi-cycle load test, subsequent load-displacement curves are stiffer than the initial curve, but only up to the previous maximum load (generated by the maximum grouting pressure, in these cases). This probably accounts for at least some of the observed stiffness increase in all of the grouted test shafts relative to the ungrouted shafts in the initial portion of Figure 13.

CONCLUSION

Post-construction shaft base grouting is becoming common in many deep foundation projects. This paper presents several case histories which cover a large spectrum of construction technique, grouting procedure and geographic area. In each project discussed herein, one or more pairs of adjacent shafts of equivalent diameter and tipped in similar material were constructed. One shaft of the pair was base grouted, while the other was not. Each shaft was then tested using the O-cell method, and the resulting unit end-bearing curves compared. In order to assess the impact of base grouting, all of the results were curve-fit in order to estimate ultimate end bearing capacity and then normalized in such a way that all of the ungrouted unit end bearing data plotted on essentially the same curve. This allows for an assessment of the relative impact of grouting on all of the tested shafts, independent of actual total settlements or capacities.

The results of the comparison analysis are ambivalent. In four cases, it is apparent that base grouting improved the initial bearing stiffness of the shaft but did not affect the ultimate capacity significantly. In one case the ultimate capacity was significantly improved, and in one case it was apparently degraded. No obvious correlation to soil materials, construction technique or grouting procedure was discerned by the authors. It may be concluded that further research into the mechanics of post-construction base grouting and its impact on shaft capacity is needed, coupled with systematic testing of drilled shafts, both grouted and ungrouted, in order to accurately assess the true benefits of base grouting.

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