EXPERIENCES WITH BASE GROUTED DRILLED SHAFTS IN THE SOUTHEASTERN UNITED STATES

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The use of base grouting (tip grouting) to enhance the axial capacity of drilled shaft foundations can achieve improvements in economy and reliability for many types of projects and soil profiles. Recent experiences on a range of different construction projects in the Southeastern U.S. illustrate the most attractive opportunities for utilizing this technique and some limitations of the method. The quality assurance provided by measurements obtained during post grouting the pile toe is another important aspect favoring its use; the base grouting is shown to identify weaker piles and provide a means of remediating some deficiencies so that increased foundation reliability is achieved. This paper provides an overview of the methods used to evaluate and design for base grouted shafts along with lessons learned from several case histories.

Introduction

The use of drilled shaft foundations in the U.S. has increased in large part due to their ability to resist the large load demands in a small footprint and due to consideration of scour for highway bridges. In routine practice, many engineers use a very conservative assessment of the end bearing resistance due to concerns relating to soil variability, bottom hole cleanliness, and the magnitude of the displacement required to mobilize end bearing resistance. The use of pressure grouting at the shaft base has been proven to be an effective method for verifying the base resistance, achieving improvement where needed due to loose deposits at the shaft base, and preloading the shaft base to mobilize significant end bearing resistance at relatively small displacements.

Base grouting of drilled shafts has been utilized worldwide for some time to allow for the development of end bearing within displacements that are “useful” for structural support. Its revitalization in the United States in the past few years can be attributed to the increased reliability provided, as well as the enhancement of end bearing. There are a variety of drilled shaft quality assurance tools available (cross-hole sonic logging, sonic integrity testing, Shaft Inspection Device SID, etc.), but no other method provides, with such practicality, the assurance that the design capacity has been obtained in all the drilled shafts on a jobsite.

Six years of research on base grouting conducted at the University of South Florida, on behalf of the Florida Department of Transportation, has produced a reliable methodology for predicting the end bearing development of base grouted shafts (Mullins et al 2006). Since then many projects, both public transportation and private sector, have utilized base grouting with great success, and have further verified the design methodology.

The experiences described in this paper are based on ten projects performed by AFT since 2003 involving post grouted drilled shafts in the Southeastern United States. Six of these projects were Department of Transportation bridges in Florida, Mississippi, Texas and South Carolina. Four of these were commercial projects completed in Florida. A review of these post grouted drilled shaft project experiences includes 17 full scale load tests and nearly 600 post grouted drilled shafts. In all of the projects to date, post grouted shafts were used as a value engineering or value added alternate to competing foundation systems or to reduce numbers and/or lengths of conventional drilled shafts.

Base Grouting Process

The post grouting process entails installation of a grout delivery system during the reinforcing cage preparation. The shaft is constructed as normal, and grout is injected under high pressure once the concrete has gained sufficient strength. Reaction for the grout pressure acting at the base is supplied by negative side shear, and thus the shaft is pre-compressed. The in situ soil at the toe is densified and any debris left by the drilling process compressed. As a result, the ultimate end bearing resistance can typically be developed within service displacement limits.

Base grouting mechanisms generally fall into two broad categories: the flat jack, or the tube-a-manchette (also known as a sleeve-port in U.S. practice). A flat jack usually consists of grout delivery tubes to a steel plate with a rubber membrane wrapped underneath. A tube-a-manchette typically consists of 2 to 4 "U-tubes" arranged below the shaft toe in various configurations. U-tubes are perforated for grout release and covered by a tight fitting rubber sleeve. Note that conventional shafts that may be found to be substandard in resistance may be base grouted after-the-fact by coring to the tip and stem grouting. While this is a viable remediation technique, it is preferred to base grout using a pre-designed mechanism installed in the cage prior to shaft construction.

Occasionally concerns have been raised during projects where the grout pressure has been released from a flat jack prior to cure. Note that this not a consideration for a tube-a-manchette as the rubber sleeve acts as a check valve. Experience in the U.S. has shown that there is little difference in the resulting load displacement performance, (Dapp, 2000, Muchard 2005). The toe response will continue on the virgin compression curve with subsequent application of the structural load when the pressure is locked in. Similarly, the toe response will return to the virgin compression curve on a much stiffer rebound (reload) curve if it is not locked in. In either case, the base resistance is developed with relatively small displacements. This is more thoroughly detailed in (Mullins, et al 2006). In reality the toe response is believed to lie somewhere between these two limits due to soil beneath the shaft toe experiencing some amount of relaxation prior to the structural loading.

Recent Base Grouting Practice in the U.S.

Common practice in the Southeastern U.S. is to use a flat jack type grouting mechanism with typically 3 to 4 one inch (25 mm) diameter PVC pipes for delivery of the grout. Should stage grouting become necessary, fluid grout in the lines may be flushed out with water. Although stage grouting with a flat jack has been accomplished successfully, the tube-a-manchette system may better suited for conditions where stage grouting is anticipated.

Early research efforts as well as subsequent projects in the U.S. have shown benefits of a "scuff-ring" located around the perimeter of the flat jack plate. The scuff-ring protects the rubber membrane during placement of the re-bar cage into the excavation. It also provides an initial grout flow zone beneath the shaft toe due to its "cookie-cutter" action into the material at the bottom of the shaft excavation.

Alternatively, tube-a-manchette (sleeve-port) mechanisms have also been utilized in the Southeastern U.S. The ease of flushing the U-tube delivery system along with the re-sealing capability of the rubber sleeve (in essence a check valve) makes this device particularly user friendly if stage grouting should be needed. Current practice in the Southeastern U.S. is to include a plate above the tube-a-manchettes, also with a scuff ring attached. Although the rubber sleeves are not as susceptible to damage as the rubber membrane of the flat jack, the scuff ring is still utilized to provide an initial grout flow zone beneath the shaft toe.

The main advantage of incorporating a plate is that a more reliable correlation of the grout pressure to the uplift force exerted on the shaft is obtained during the grouting process. For many engineers, this verification test is an attractive aspect of the base grouting process. A typical upward load deflection curve obtained during a flat jack type grouted shaft is shown in Figure 1. The force is determined by means of both the grout pressure acting on the nominal shaft diameter and by embedded strain gages just above the shaft base. It is interesting to note that the measurements capture the pumping and retracting action of the single stage grout pump, which is understandably less prevalent in the strain gage data than in the grout pump gage.

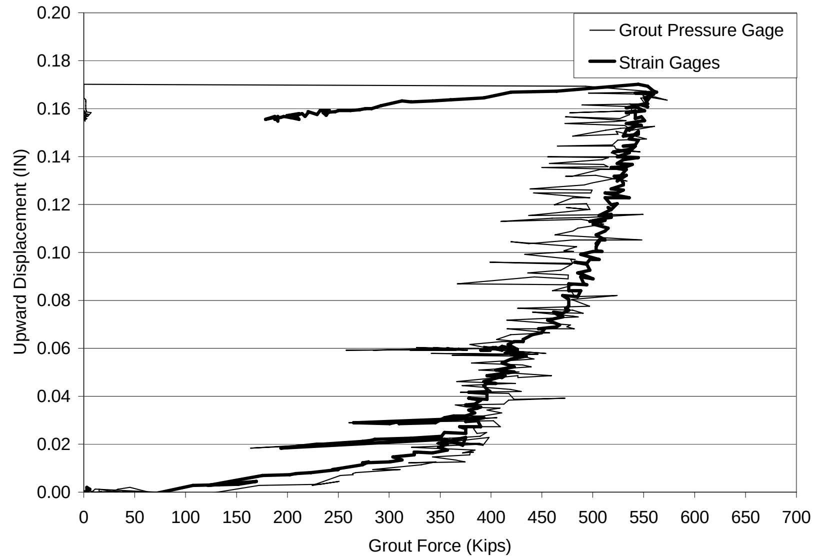


Figure 1. Comparison of upward shaft deflection vs. tip force based on measurements of grout pressure at the pump, and strain gages at the shaft base (1 in = 25 mm, and 1 kip = 4.4 kN).

Tube-a-manchette devices have been planned to be utilized in the Southeastern U.S. without a plate in instances of particularly large shafts where the plates become too large to be practical, or for shaft designs which have limited side shear available to provide reaction for the base grouting process. Without the plate to provide initial grout distribution across the entire shaft base, staged grouting of individual U-tubes may be carefully sequenced to allow for the entire shafts side shear to provide reaction for the individual portions of the shaft tip being grouted. A draw-back to this technique is that a direct observation of the load deflection characteristics is not possible, as the area being acted upon by the grout pressure is not as apparent. Another consideration is the bending stress locked into the shaft.

The End Bearing Dilemma in Drilled Shafts

While the ultimate end bearing resistance of large diameter drilled shafts may be many times greater than the side shear component; the end bearing contribution must often be greatly discounted or discarded entirely from a conventional drilled shafts "useful" resistance. The dilemma is that, without base grouting, the end bearing resistance most often can not be reliably depended upon within typical service limit displacements for a variety of physical and construction limitations.

(1) A basic strain incompatibility exists with the side shear resistance. For soils, the development of side shear can typically be fully developed within 0.5 % to 1.0 % of the shaft diameter, while the end bearing may require displacements on the order of 10 % to 15 % of the shaft diameter. Thus, the end bearing requires 10 to 30 times more displacement to develop than the side shear.

Further, if greater displacements were allowed in order to develop the end bearing, these greater displacements may be detrimental to the side shear resistance if strain softening materials are present (primarily cemented or clayey materials).

(2) Soil stress relaxation occurs at the shaft base due to excavation of the overburden. Other causes may include inflow of groundwater due to insufficient hydrostatic head or rapid removal of the excavation tooling during the construction process. This disturbance is detrimental primarily to cohesionless soils.

(3) Toe cleanliness issues contribute greatly to construction risks and end bearing reliability. Even during normal conditions, construction methods may often leave soft debris/deposits at the bottom of the excavation due to factors such as sand content; drilling mud precipitating out; and sloughing off of soil from the sidewalls. These conditions may all be exacerbated by prolonged time requirements for rebar cage and/or concrete placement of particularly deep and/or large diameter shafts. Note also that a non-uniform

distribution of compressible toe debris would cause an initially reduced shaft bearing area. The non-uniform distribution is most often due to either the tremie wash creating a ring of compressible material at the perimeter of the toe causing a “bullet nose”, or compressible material left in depressions caused by the tooling.

The Benefits of Base Grouting and Favorable Conditions

The primary motivation for post grouting drilled shafts in the Southeastern U.S. has been to realize the significant end bearing capacity increase. The economics associated with the end bearing capacity enhancement has proven especially attractive to design build teams and contractors providing value engineering option for savings over a competing foundation technology.

The benefits derived from the heightened quality assurance of proof testing every shaft on a project has had particular appeal to Department of Transportation (DOT) clients. The increased reliability has the potential to be much farther reaching that just the economics associated with the end bearing capacity enhancement, especially when it comes to reliability based design methods. The proof test of every shaft on a project, provided by base grouting, allows for a more reliable design with lower safety factors, or alternatively higher resistance factors in LRFD (Load Resistance Factored Design). At present, design codes used in practice do not provide guidelines for base grouting.

The most significant end bearing capacity enhancement from base grouting is realized in cohesionless soils. Base grouting gains a substantial economic advantage if a sandy bearing stratum is available at appropriate depths to tip the shafts in. Base grouting in cohesive soils, while resulting in much less improvement in end bearing capacity, may be an economically viable option when considering the increased reliability.

If a rock bearing stratum exists at relatively shallow depths, base grouting will provide limited benefit; the grout pressure provides no improvement of the native bearing materials and the shallow depth limits the magnitude of the base pressure that can be achieved due to the limited uplift resistance of the shaft. However, deep shafts in rock can provide benefit in verifying that the end bearing resistance is achieved. Where there may be difficulty in achieving a thorough cleaning of the rock bearing surface, or where the rock can include layers or seams of weathered materials that is difficult to detect, base grouting can be used to minimize the risk of adverse consequences from these conditions. From the contractor’s perspective, this technique can reduce their risk of delays or disputes arising from downhole inspection cameras or crosshole sonic logging tests. These factors of increased reliability in end bearing and reduced risk are important for projects with deep and expensive shafts, construction times far in excess of normal, and single column foundations with no redundancy in the foundation elements.

Quality Assurance Program

The quality assurance program practiced in the Southeastern U.S. consists of a pilot grouting and load testing program conducted on the initial shafts constructed at the site, followed by a less rigorous grout monitoring program during construction of all the remaining production shafts. The pilot grouting and load test program is performed on dedicated test shaft(s) installed in advance of production shafts to: 1) corroborate the design; 2) evaluate the drilled shaft construction method; and 3) establish grouting criteria for production shafts.

The test shaft(s) of the pilot program are instrumented with multiple levels of strain gages (to include a level as close to the tip as possible), as well as transducers for top of shaft movement, grout pressure, and grout volume. Testing is two fold: first monitoring during the base grouting process, second performing a downward axial compression load test. STATNAMIC® load testing has been used exclusively for load testing post grouted drilled shafts in the Southeast United States due to its economy, efficiency and reliability, although other methods of applying top-down force could be used. Remaining production shafts then require only monitoring of top of shaft movement, grout pressure and grout volume.

Using the load test data, grouting criteria are developed consisting of three main components: 1) Grout Pressure; 2) Upward Displacement; and 3) Minimum Grout Volume. The grout pressure is the most important component since the capacity improvement is directly related to the applied pressure. Also, the level of verification of side shear and end bearing resistance (proof testing) is governed

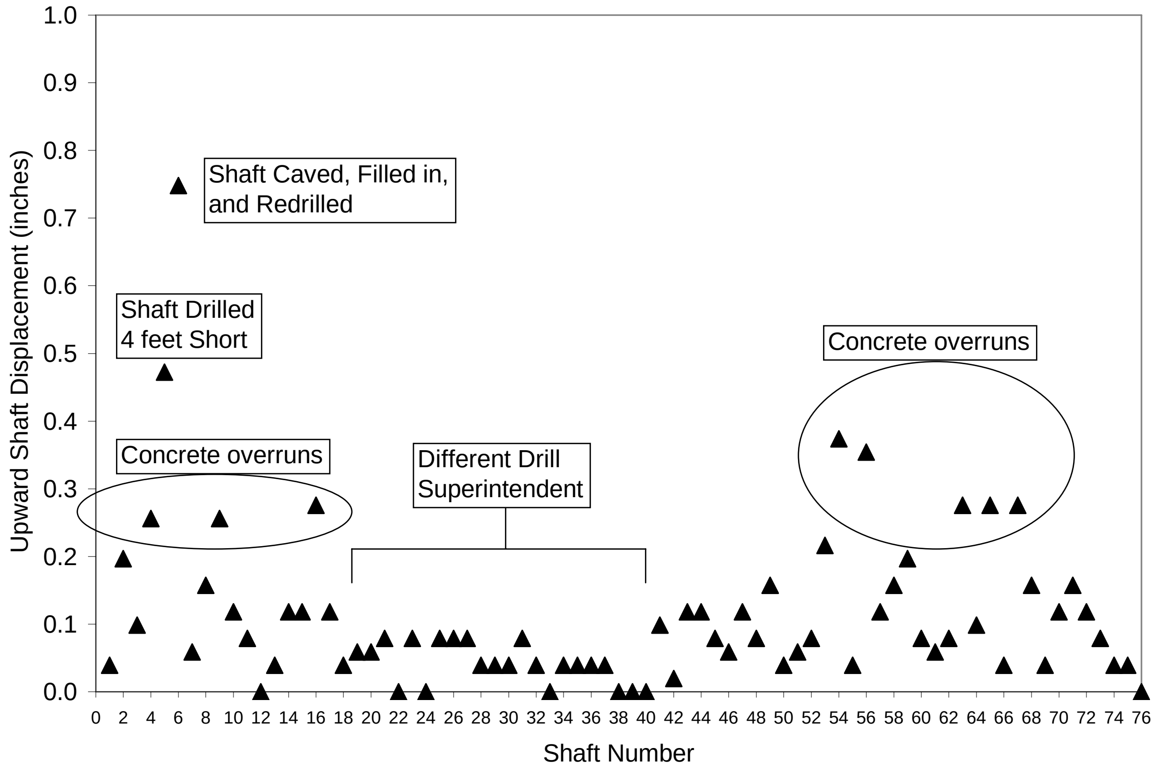


Figure 2. Post-grouted drilled shaft upward displacement summary for 76 shafts (1 in = 25 mm).

by the maximum achievable grout pressure. Grouting of the test shaft provides a basis for establishing the required pressure for all production shafts. The maximum achievable pressure is also evaluated with respect to the available side shear.

Evaluation of the side shear behavior is also necessary to determine the target maximum upward shaft displacement criterion. The pilot grouting upward test and subsequent downward load test each load the shaft side shear in opposite directions. It is thus important to evaluate effects of loading direction which can be significant (O'Neill, 2002) and find the level of displacement in which the friction degrades or goes residual. This information provides a basis for setting an upward displacement limit. This value is typically around a ¼ of an inch (6.3 mm), but as much as ¾ inches (19.0 mm) may be allowed in very clean sand materials.

Staged grouting technique has been successfully performed in cases where this upward displacement was met or when excessive grout volume was placed prior to achieving design grout pressure. As shown in the ensuing examples, situations with larger than expected upward displacements are typically synonymous with unforeseen problems.

Selected Case Histories from the U.S.

The grouting process provides a measure of shaft end bearing and side shear resistance. This information on every production shaft on a project provides insight into the routine construction factors that can affect axial load resistance. In most cases, the grouting operation also serves to mitigate unforeseen problems.

Case 1

The bridge project in example 1 provided measurements of upward displacement for 76 post grouted shafts during construction. A graphical presentation of displacement measurements for the drilled shafts on the project is provided on Figure 2. Shafts that were constructed with no obvious difficulties performed very well, as is evident by small upward displacements during the grouting (indicating high side shear capacity). Those with somewhat higher upward displacements were typically linked to some form of

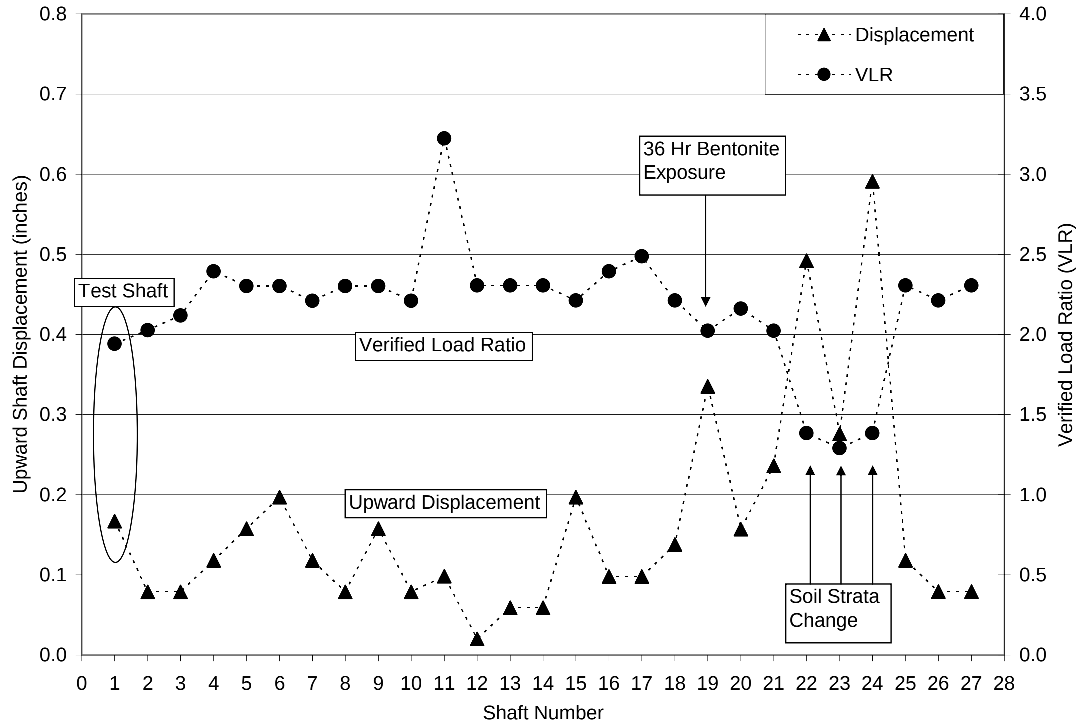


Figure 3. Post-grouted drilled shaft upward displacement and VLR summary for 27 shafts (1 in = 25 mm).

construction difficulty as indicated on the figure. In spite of the deviations, all shafts demonstrated full capacity by developing design grout pressures within the recommended upward displacement limit. However, it is interesting to note that concrete overruns do not equate to higher capacity in spite of the obvious increase in dimension. This can be attributed to the radial disturbance (loosening) caused by excavations that become slightly unstable and subsequently slough soil into the bored hole. Each shaft was constructed within tolerances of the project specifications.

<u>Case 2</u>

Case 2 is a bridge project which encountered variations both in construction technique and in soil conditions. The upward displacement for all post grouted shafts on the project is presented on Figure 3. To evaluate the level of capacity verification for each shaft, the ratio of the bi-directional grout force over the required design load is plotted along with the upward shaft displacement. The “Verified Load Ratio” (VLR) is defined as:

$$VLR = \frac{Applied \quad Grout \quad Force}{Design \quad Load}$$

The Applied Grout Force is the total of the upward and downward grouting force, and thus equal to two times the grout pressure times the nominal shaft diameter. The applied grout force can be considered as a verification of load capacity, given that downward directed side shear is as least as great as the mobilized side shear from the upward portion of the grout force.

The magnitude of the VLR is dependent on the available side shear to resist the grouting forces. In this case, scourable upper soils provided extra reaction to the grouting force so elevated pressures could be achieved in most cases. The shafts constructed with no apparent deviations from expected performed very well with VLR’s around 2.0 or greater. Those with higher upward displacements are a result of construction method and variation in the subsurface conditions.

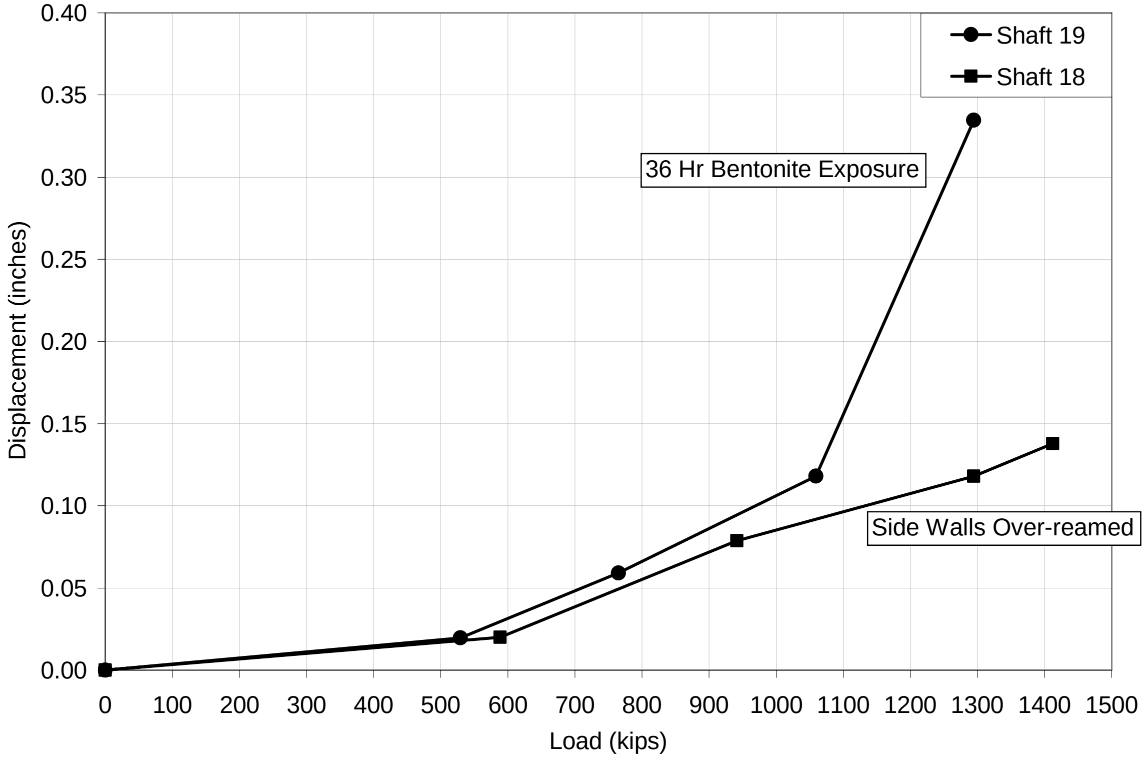


Figure 4. Grouting measurements show effect of prolonged side wall exposure to Bentonite drilling fluid versus over-reaming (1 in = 25 mm, and 1 kip = 4.4 kN).

Shaft numbers 18 and 19 are side by side shafts in the same bridge bent. Both shafts were constructed with Bentonite drilling fluid and both shaft excavations were left open with the side walls exposed to the drilling fluid for approximately 36 hours. However, Shaft 18 was over-reamed prior to pouring concrete and Shaft 19 was not. The resulting decrease in side shear resistance from the prolonged side wall exposure to Bentonite drilling fluid versus over-reaming was measured during the post grouting. The more detailed measurements recorded during post grouting from these two shafts are shown in Figure 4. This information helped the Contractor ensure the quality of their product was maintained by keeping the fluid exposure time to a minimum.

Through the quality assurance data obtained during post grouting, variation in the subsurface conditions was also identified in shafts 22 through 24. Overburden soils in this area had slightly lower side shear resistance, thus lower grout pressures were obtained with corresponding larger uplift displacements. Having this information provided a basis for further evaluation and decision making. As opposed to conventional projects that would not have known of this variation.

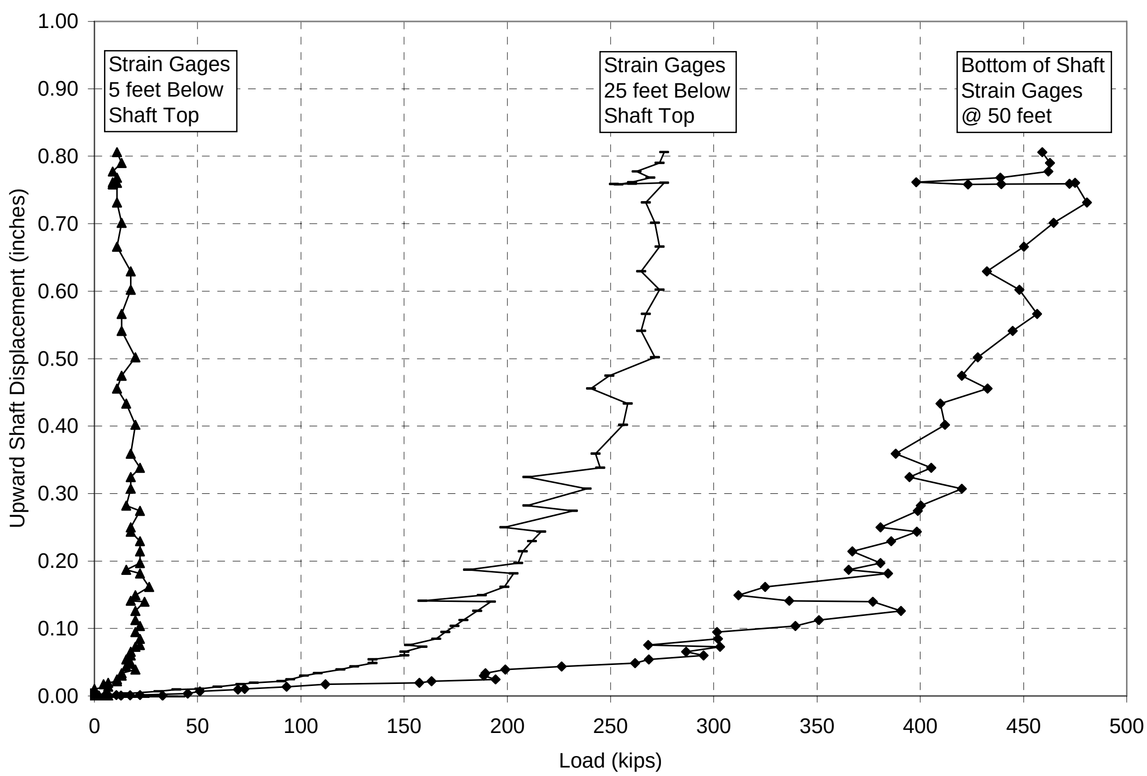
<u>Case 3</u>

Case 3 is an example in which post grouted shafts replaced CFA piles to support a high rise building. The clean sands found at this site afforded large end bearing improvements. The quality assurance aspect of post grouting provided the project engineer with added confidence regarding the use of drilled shafts, which were an “unfamiliar” foundation system for this engineer. The value engineering alternate was accepted.

This project also provides an illustration of the way in which base grouting can evaluate the potential effect of construction problems on performance. Drilled shafts were uncommon in this geographic area and the local concrete supplier did not have recent experience with drilled shaft concrete mix designs. During construction of the test shaft, the concrete flash set upon completing the pour. During the subsequent post grouting, a lower than anticipated (but still acceptable) grout pressure of 450 psi (3,100 kPa) was achieved.

As shown in Figure 5 the shaft upward displacement was unusually large at 0.8 inches (20 mm). The side shear resistance of 475 kips (2,113 kN), a unit side shear of 1.0 ksf (48 kPa), achieved during grouting was still reasonable for the loose to medium dense sands, but this limited side shearing resistance limited the magnitude of grout pressure that could be applied. As a result, the significant increase in end bearing that was achieved was not evident from the grouting operation.

The subsequent rapid (STATNAMIC®) load test results shown in Figure 6 confirmed that substantial end bearing was provided by this shaft and also documented the lower than expected side shear resistance. Only after the post grouting data from production shafts became available did the effects on side shear capacity from the concrete problem surface. The data presented on Figure 7 indicates that this shaft had much larger displacement and lower grout pressures compared to the production shafts.



<u>Figure 5.</u> Grouting force distribution (from embedded strain gages) versus upward shaft displacement on pilot grout test shaft (1 in = 25 mm, 1 kip = 4.4 kN).

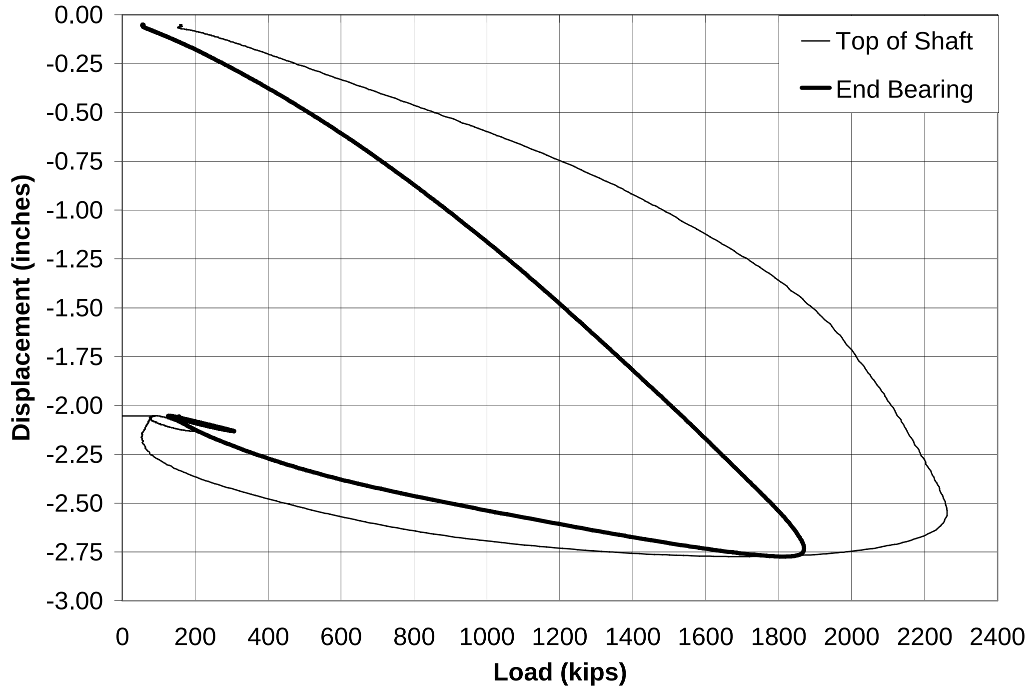


Figure 6. **STAT*NAMIC*® (or Rapid) load test results on same shaft after post grouting confirming relatively low side shear and large end bearing improvement (1 inch = 25 mm, 1 kip = 4.4 kN)**

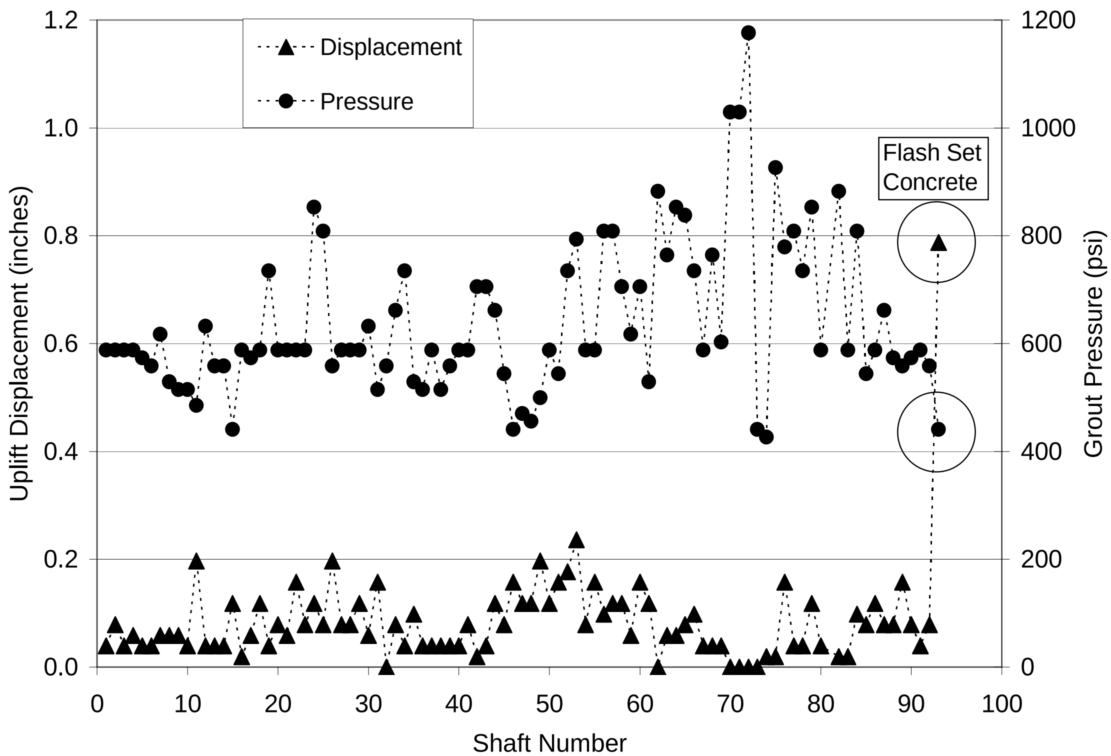


Figure 7. Post-grouted drilled shaft upward displacement and grout pressure summary for 94 shafts (1 in = 25 mm, 1 psi = 6.9 kPa).

Conclusion

The authors experiences on the case histories described in this paper and on other similar projects in the southeastern United States have demonstrated that base grouting is a valuable and effective technique for use with drilled shaft foundations. In addition to achieving soil improvement, base grouting increases the usable end bearing resistance by mobilizing and preloading base resistance. The technique enhances quality assurance by providing a direct measure of axial resistance for each production shaft. This assurance of load resistance on every production drilled shaft enhances reliability and can mitigate delays or costly remediation relating to unforeseen construction problems. In some cases, construction problems relating to bottom hole cleanout are directly mitigated by the base grouting process. In the authors' opinion, base grouting of drilled shafts represents a new form of quality assurance that should enhance confidence in end bearing resistance and improve the quality of drilled shaft construction with the result of overall greater reliability for drilled shaft foundations.

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