New Design Method Gives Drilled Shafts a Boost

By Gray Mullins, Ph.D., P.E., Associate Professor, University of South Florida

Drilled shafts have seldom been cost effective in sandy soils due to the merits of driven piles in such conditions. This is in part due to the relatively poor end bearing performance of shafts caused by the large displacement required to mobilize the ultimate capacity. Recently, a new design method has revitalized a construction method that significantly improves the end bearing capacity of shafts in virtually all scenarios. This article will summarize the design and construction of drilled shafts using this technique.

INTRODUCTION

The end bearing of drilled shafts (especially in sands) has long been discounted due to a variety of reasons such as borehole cleanliness and the like. However, even in the ideal conditions of perfectly clean excavations, the end bearing in virtually all soil types is only partially available due to the large displacements required to develop that capacity. Simply stated, the side shear and end bearing components of the drilled shafts are analogous to side-by-side spring systems with vastly different characteristics. As such, the side shear is like a series of short-stroke, high stiffness shear springs where more shaft length incorporates more of these springs. The end bearing is more like a single long-stroke, low stiffness spring that can develop enormous loads, but only at very large displacements (Fig. 1). This article addresses a construction method that significantly improves the stiffness of the end bearing "spring."

BACKGROUND

As far back as 1961, engineers around the world have targeted improving the end bearing of drilled shafts using post construction, high pressure grouting beneath the shaft tip (also called post grouting or base grouting). The first published citing was much later in 1973 by Bolognesi and Moretto. These early test programs showed that post-grouting large diameter shafts led to increased ultimate load capacity up to three times in both sands and clays. As a result, post-grouting techniques have become a routine construction process in many parts of the world. However, the notable absence of the practice in the United States has been attributed to no recognized design approach.

Post grouting drilled shafts targets the mechanisms intrinsic to drilled shaft construction that make the end bearing only minimally usable. These mechanisms include: (1) soil relaxation beneath the shaft tip due to excavation, (2) debris remaining after clean out, and (3) strain incompatibility between the side shear and end bearing (mobilizing displacement mismatch). By precompressing the soil after construction, it is clear how the first two mechanisms can be mitigated. However, the third is better understood via illustration. Fig.1 shows four states of a drilled shaft from the perspective of the displacement required to distribute load. It includes: (a) the post construction state where no load is applied, (b) the fully loaded state of a conventional, ungrouted shaft, (c) the conditions just after post grouting, and (d) the loaded state of a grouted shaft.

The conventional, ungrouted shaft (b) shows little end bearing contribution based on the displacement required to obtain ultimate capacity. In this case, the ultimate side shear displacement and/or the permissible service limits are exceeded far before the end bearing can contribute. Consequently, little to no end bearing is typically considered for design. Fig. 1(c) shows two significant features: (1) the end bearing strata can be pre compressed to access more of the ultimate capacity, and (2) the upward movement of the shaft during grouting may lock in negative skin friction that when loaded will increase the permissible downward movement (up to 2% diam.) without exceeding the ultimate side shear displacement. This helps to transfer load to the toe while balancing the displacement at ultimate side shear and end bearing. However, from a "nuts and bolts" perspective, the upward movement should be monitored and limited based on a pilot grouting program at the beginning of construction. Interestingly, Fig. 1(d) depicts the full structural load applied to the foundation while mobilizing significant end bearing and minimizing overall displacement. By engaging a large fraction of the ultimate end bearing, shafts can either be shortened for a given load or can provide higher capacity for a given length.

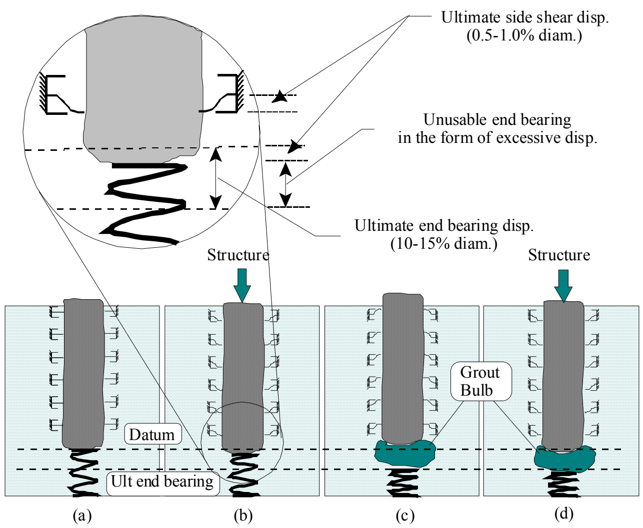

Fig. 1 Spring analogy of the loading states of drilled shafts (grouted and ungrouted)

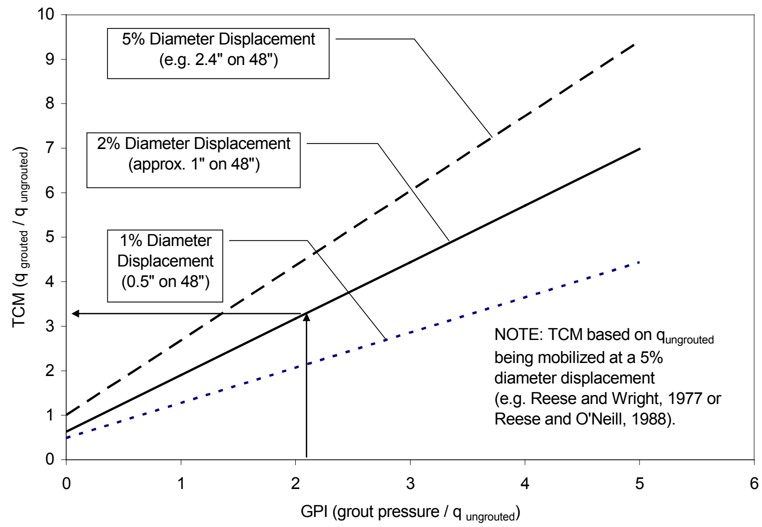

Fig. 2 Correlations used in Step 6 to establish TCM (Mullins. et al., 2001)

DESIGN AND CONSTRUCTION PROCEDURE

In 1998, the Florida Department of Transportation (FDOT) requested the University of South Florida to submit a proposal to investigate the use of post grouted drilled shafts. At the conclusion of the first phase of research (in 2001), a viable design and construction procedure was made available to consultants that incorporated these findings. Within the two short years that followed, four bridge projects using post grouted shafts have been undertaken with over twenty general contractors having given it serious consideration. A brief overview of both the design and construction procedures are presented below.

Design. The design of post-grouted drilled shaft tips can be easily summarized in the following seven steps:

(1) Determine the ungrouted end bearing capacity in units of stress.
(2) Determine the permissible displacement in units of percent shaft diameter (disp/diam*100%).
(3) Evaluate the ultimate side shear resistance for the desired shaft length in units of force.
(4) Establish a maximum grout pressure that can be resisted by the side shear in units of stress (*Step 3 / Tip Area*).
(5) Calculate the Grout Pressure Index, *GPI*, defined as the ratio of grout pressure to the ungrouted end bearing capacity (*Step 4 / Step 1*).
(6) Using design curves from Fig. 2, determine the Tip Capacity Multiplier, *TCM*, using the *GPI* calculated in *Step 5*.
(7) Calculate the grouted end bearing capacity (ultimate) by multiplying the *TCM* by the ungrouted end bearing (*TCM * Step 1*).

The design procedure affords the designer the ability to select the "usable ultimate" capacity as a function of permissible settlement (Fig. 2; larger displacement yields higher *TCM*). Therein, unless using very small diameter shafts (or high % diameter), reserve capacity will exist should more settlement occur.

Construction. The construction of grouted drilled shafts varies only slightly from conventional shafts: (1) during cage fabrication a grout distribution cell is installed at the base of cage with grout tubes that extend to the top of shaft, Fig. 3, (2) no spacer feet are required below the cell but rather the cell rests on the bottom of the excavation, and (3) after the shaft concrete has cured to sufficient strength, neat cement grout is pumped to the base of the shaft until the design pressure is achieved, Fig. 4.

Fig. 3 Installation of grout distribution cell (Courtesy of Applied Foundation Testing, Inc.)

The grout pressure can be locked in using sacrificial in-line valves, but it is not necessary.

Fig. 4. Top of shaft receiving grout

The first shaft grouted on site is usually used to set the grouting/construction criteria for proper shaft design and installation. Aside from verifying a designated grout pressure, a pilot program will provide criteria including the maximum permissible uplift and the minimum acceptable grout volume. These are set on the basis of field data such as that shown in Fig. 5. The maximum uplift criterion should minimize the adverse effects of over-stressing the side shear (in this case 0.1 inches). The minimum grout volume criterion is intended to assure that a reasonable volume is pumped to the base of the shaft as the design pressure is achieved. This prevents a grout line blockage from artificially satisfying the design grout pressure criterion. In the case shown in Fig. 5, a minimum of 2 cubic feet would suffice. This type of information can also be used to estimate the grout volume that the contractor may expect to use per shaft (approximately 10 CF at 0.1 inches).

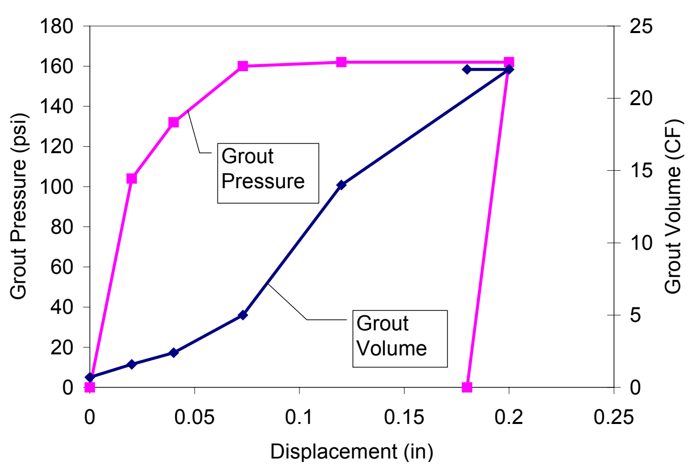

Fig. 5 Typical field measurements for QA/QC

Quality Assurance. Post grouting drilled shafts provides a level of quality assurance that is unparalleled by other shaft integrity methodologies. The information in Fig. 5 can and should be collected for every shaft installed to provide verification of shaft performance. Therein, the side shear and end bearing resistance of the shaft are proven for every shaft up to the level of the applied grout pressure. At a minimum the shaft capacity is therefore capable of resisting 2 times the product of the grout pressure and the end bearing area. This lower limit of the shaft capacity is often more than the service loads thus providing 100% certainty of competence.

CASE STUDIES OF END BEARING ENHANCEMENT

Within the two years that this end bearing enhancement procedure has been available, several bridge projects have incorporated post grouting into the drilled shaft design. These include: (1) Royal Park Bridge, Palm Beach, FL; (2) PGA Blvd, West Palm Beach, FL; (3) Natchez Trace Parkway, Natchez, MS; and (4) FM507 Bridge, in Willacy County, TX. Additionally, the post grouted shafts have been tested in sands, silts, and clayey soils with shafts 2', 2.5', 3', 3.5', 4', and 6' in diameter. Figs. 6 - 8 show the results of load tests on both grouted and ungrouted shafts with diameters of 2', 3', and 4', respectively.

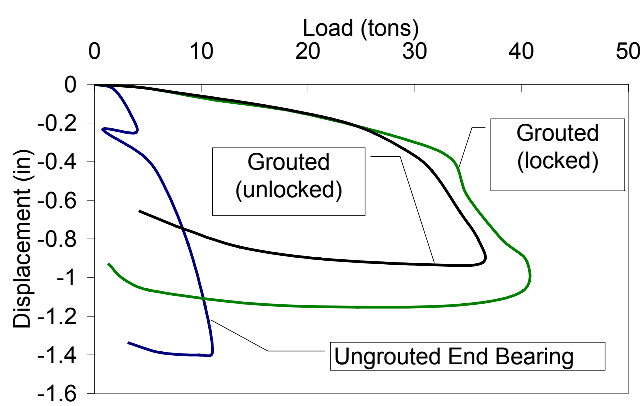

Fig. 6 End bearing capacity in silty sands (2' diam., Dapp, 2002)

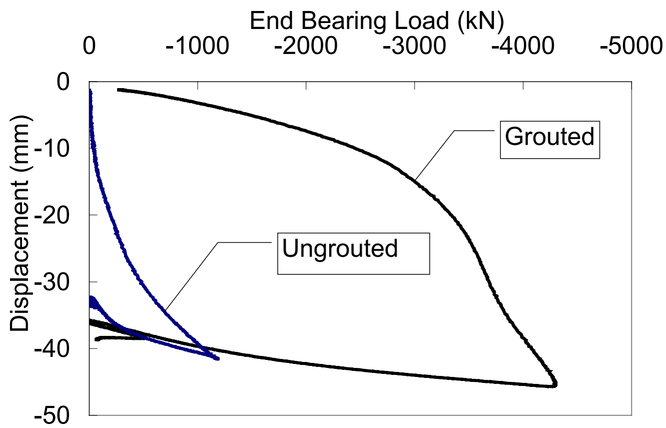

Fig. 7 End bearing capacity in shelly sands (3' diam., Mullins, et al., 2003)

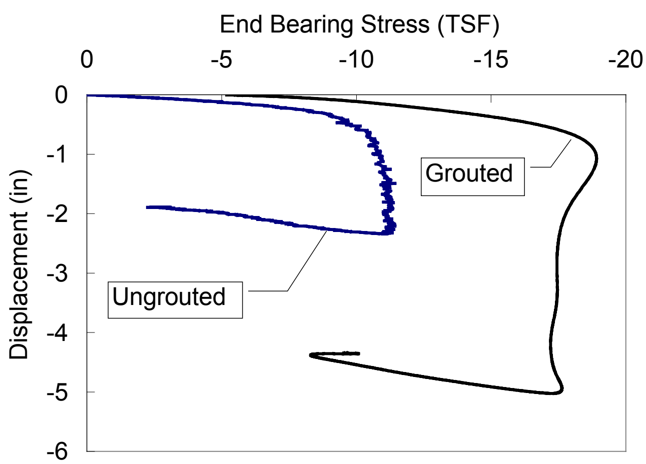

Fig. 8 End bearing capacity in clay (4' diam., Mullins and O'Neill, 2003)

Figs. 6 and 7 (in sandy soils) show significant improvement in both ultimate capacity and stiffness. Fig. 6 shows only a moderate difference between locking in the grout pressure and not. In clayey soils (Fig. 8) increased stiffness may be expected with more modest improvement in ultimate end bearing.

CONCLUSIONS

Although pressure grouting drilled shaft tips has been proven successful worldwide, its use in the U.S. has only recently evolved largely due to the availability of a new rational design approach. Case studies have confirmed the findings of the research that led to this method while also accenting the merits of a tremendous quality assurance mechanism.

ACKNOWLEDGMENTS

The author would like to gratefully thank FDOT, Applied Foundation Testing, Inc., A. H. Beck Foundation, Inc., Coastal Caisson Corp., Earth Tech, Inc., and Treviicos South for their support of this research.

GENERAL REFERENCES

Bolognesi, A. J. L. and Moretto, O. (1973) "Stage Grouting Preloading of Large Piles on Sand" Proceedings of 8th ICSMFE, Moscow.

Dapp, S. (2002). "Pressure Grouting of Drilled Shaft Tips in Sand," Doctoral Dissertation, University of South Florida, Tampa, pp. 358.

Dapp, S., and Mullins, G., (2002). "Pressure-Grouting Drilled Shaft Tips: Full-Scale Research Investigation for Silty and Shelly Sands," *Deep Foundations 2002: An International Perspective on Theory, Design, Construction, and Performance*, ASCE Geo Institute, GSP No.116, Vol. I, pp. 335-350.

Mullins, G., Dapp, S., and Lai, P. (2000), "New Technological and Design Developments in Deep Foundations, Pressure-Grouting Drilled Shaft Tips in Sand," American Society of Civil Engineers, Denver, Colorado.

Mullins, G. and O'Neill, M. (2003). "Pressure Grouting Drilled Shaft Tips: A Full-Scale Load Test Program," Final Report submitted to Texas Department of Transportation for A.H. Beck, Inc. May, pp.299.

Mullins, G., Muchard, M., and Khouri, B (2003). "Post Grouted Drilled Shafts: A Case History of the PGA Boulevard Bridge Project," Proceedings of the 28th Annual Conference on Deep Foundations, Deep Foundations Institute, October 22 - 24.