ENSURING PERFORMANCE OF TIP POST-GROUTED BORED PILES (DRILLED SHAFTS) THROUGH A COMPREHENSIVE QUALITY ASSURANCE PROGRAM

Antonio Marinucci, PhD, MBA, PE, V2C Strategists LLC, Brooklyn, NY, USA. +1 (401) 261.9102, Email: antmarinucci@gmail.com
Silas C. Nichols, P.E., Federal Highway Administration, Office of Bridges and Structures, Washington, D.C. USA. +1 (202) 366.1554. Email: silas.nichols@dot.gov
Mary Ellen Bruce Large, P.E., D.GE, Deep Foundations Institute, Hawthorne, NJ USA. +1 (724) 942.4220. Email: melarge@dfi.org

Keywords: tip post-grouting, drilled shafts, bored piles, QA, performance

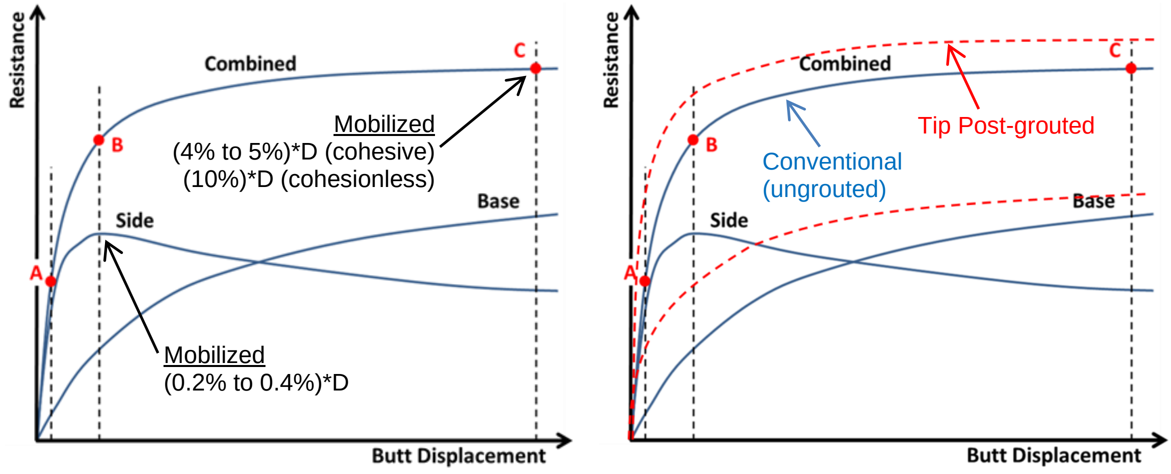
ABSTRACT: Tip post-grouting of bored pile (drilled shaft) foundations refers to a method where cementitious grout is injected beneath the tip of a shaft to improve the overall performance of the constructed foundation. This technique, when performed satisfactorily and in the appropriate ground conditions, enhances axial load-displacement performance by improving the mobilization of pile's resistance. Potential benefits associated with tip post-grouting include reduced settlement under loading, better alignment of load transfer curves, and improved ground beneath the base of the bored pile. However, to be able to realize the benefits attributed to this method, the design, construction, of both the bored pile and the post-grouting system must meet a minimum level for quality assurance. The various factors affecting the successful installation and performance of a bored pile (e.g., workmanship, base cleanliness, borehole integrity, and concrete placement) have been discussed by numerous practitioners and researchers in the available technical literature. For a conventional (i.e., ungrouted) bored pile, acceptance is based on a combination of visual inspection, material testing, and the results of integrity and/or performance testing of the constructed pile. A properly executed tip post-grouting program can be a relatively comprehensive and complex process, which is typically evaluated throughout the construction process based on the results of prior projects and/or on test pile(s) at the particular site. For tip post-grouting programs, verification procedures and acceptance criteria should be established during and incorporated into the design process to ensure design intent and objectives are achieved. Project specifications should be produced to ensure performance requirements are achieved. This paper will present and discuss factors affecting the successful execution of tip post-grouting, including grouting criteria, instrumentation, reliability and uncertainty with the method and outcome, and verification and acceptance.

INTRODUCTION

Constructing bored piles (drilled shafts) is increasingly more challenging given the lack of ideal site locations, tight project site confines, difficult or restricted access, greater demands on drilling equipment, and close proximity to adjacent structures. To evaluate the feasibility of bored piles as an appropriate foundation system, a myriad of factors is evaluated during design, including site conditions and constraints, budgeting and scheduling, reliability and risk exposure, presence of and depth to adequate load bearing soils/rock, and the magnitude of the imposed loading. Moreover, updated design codes increased load demand per element, and improved material strengths have led to more complex foundation designs, larger foundation elements, and significant increases in load magnitude. Monopile (monoshaft) foundations have been utilized where one large bored pile is used in lieu of a group of piles connected via a pile cap. In addition, to accommodate the design criteria, site conditions, and imposed loading, the geometry of the bored piles being designed and installed have been as large as 13 feet (4 m) or greater in diameter and to depths in excess of 260 feet (80 m).

Given the various concerns and uncertainty faced during design and construction, understanding load transfer in side and tip resistance and the factors that affect each component are essential to ensure the design is optimized and constructible as much as practical (or permissible). Some of the various factors affecting the successful construction and performance of a bored pile include borehole integrity, workmanship, base cleanliness, and concrete placement.

Even if a bored pile were to be constructed perfectly, designers often neglect either side or tip resistance (or reduce their respective contributions to the overall resistance) due to strain incompatibility in the mobilization of side and end resistances when subjected to axial compressive loading. When an axial compression load is applied to the top of a conventional (i.e., ungrouted) bored pile, an idealized load - displacement relationship can be represented by the "combined" curve shown in Fig. 1a. It has been well documented and established that, as the axial compressive load increases, the pile is compressed and displaced downward into the ground, and that the pile's resistance is first mobilized in side friction and then in tip resistance. Irrespective of ground type, side resistance is fully mobilized at relatively small displacements equal to about 0.2% to 0.4% of the pile's diameter. However, the tip resistance available when side resistance becomes fully mobilized is minimal, and it becomes fully mobilized at relatively large displacements equal to about 4% to 5% of the pile's diameter in cohesive soils and about 10% of the pile's diameter in cohesionless soils.

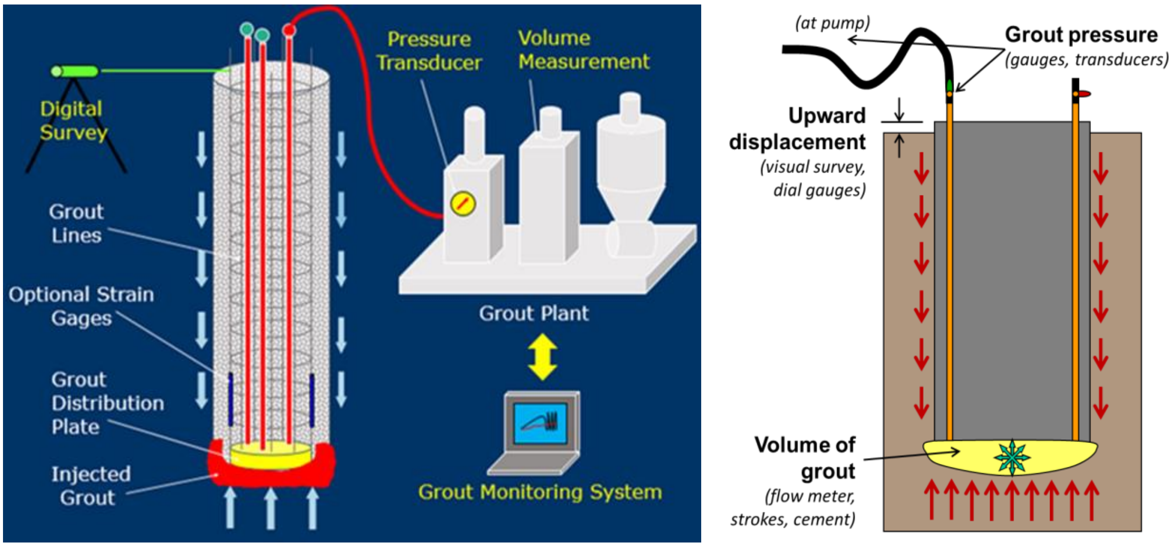


(a) **(b)**

Fig. 1. Idealization of load transfer (mobilization of side and end resistances) of a conventional (ungrouted) bored pile and (b) tip post-grouted bored pile due to axial compressive loading

An optimized maximum resistance (incorporating the full contributions of both side and tip resistance) cannot be realized with a conventional bored pile because the full side resistance is mobilized at very small vertical displacements, while the full tip resistance is mobilized at relatively large vertical displacements. Therefore, tip post-grouting of bored piles has been used to optimize the design and construction of bored piles, which would better align the load transfer curves in side and tip resistance to maximize their resistance to applied loading (Fig. 1b).

Tip post-grouting is a technique used to inject, under pressure, a neat cement grout beneath the base of a bored pile (Fig. 2a) to enhance or improve the axial load-displacement performance of the pile by improving the mobilization of side and tip resistance and/or by increasing the axial resistance of the pile. During the grouting operation, the bi-directional force induced by the pressurized grout on the bored pile and to the soil below results in negative side resistance and positive tip resistance (Fig. 2b). After the pile has been grouted, the tip resistance has been mobilized and there is a reversal of side resistance to resist axial loading and self-weight, such that there is positive tip and side resistance. The improvement of the axial compressive load-deformation response of bored piles due to tip post-grouting has been realized in a range of ground conditions from cohesionless soils to cohesive soils, even in rock. In addition to optimizing the load transfer curves, other benefits of tip post-grouting include stiffening the load-deformation response under working loads, reducing settlement of the pile under loading, decreasing the pile length, utilizing additional (or usable) tip resistance in design computations, verifying a lower bound of axial resistance, and improving the ground beneath the base of the pile.



(a) (b)

Fig. 2. Schematic depictions of (a) the setup used for tip post-grouting of bored piles; image courtesy of Applied Foundation Testing (Large, 2016), and (b) negative side resistance and positive tip resistance mobilized due to bi-directional force induced by the pressurized grout (grouting control criteria also shown).

Nonetheless, despite the numerous load test results and case histories published in the literature, many areas of concern regarding the execution and reliability of tip post-grouting remain unresolved. Different empirical and semi-empirical design methods have been proposed by different researchers (e.g., Mullins et al. (2006), China Academy of Building Research (2008), and Pando and Ruiz (2005)) based on select test data from local or regional geography. Furthermore, these predictive methods themselves are sources of uncertainty, as they require input of data that is difficult to define, and the methods may not explicitly consider the effect of different ground conditions, grout distribution systems, grout characteristics, grouting procedures, and other construction variables. The ideal manner to evaluate the efficacy and reliability of tip post-grouting is to perform, analyze, and compare results from full-scale load tests on conventional (ungrouted) piles and on tip post-grouted piles. However, developing and executing a comprehensive quality assurance (QA) program that addresses the known areas of possible concern and uncertainty will improve the reliability of tip post-grouted bored piles.

GROUTING EQUIPMENT

The equipment set up for typical tip post-grouting applications includes the grout plant (i.e., high speed / high shear mixers with two tanks), water pump, grout delivery system, and piston pump. To mix the neat cement grout thoroughly, the type of shear mixer used is extremely important to ensure proper consistency and quality, which is essential to minimize bleeding and segregation and to reduce the potential for plugging the grout lines. Two tanks are typically used with this type of operation: one is used to prepare a new batch of grout and the other serves as a storage tank from which the grout is pumped, and ensures that grout flow is uninterrupted during grouting. Single-/double-acting positive displacement piston pumps are ideal for these applications as they can achieve the desired high grout pressures (750 to 800 psi (50 to 55 bar)) as well as delivering the low flow rates (less than about 1 to 3 gpm (4 to 11 l/min)) during grouting. Grout flow volumes are measured using flow meters that are attached directly to the grout plant. If required as a backup system, the volume of grout can be recorded manually using a count of the calibrated strokes of the grout pump, but this requires calibration at the site prior to the commencement of grouting.

In essence, there are two types of grout delivery systems (open-type or closed-type) used for tip post-grouting applications. Irrespective of the system type, the device must be located at the base of the pile below the reinforcing cage and in contact with the in-situ soil to be able to perform as intended.

The water pump is used to flush the grout lines and delivery system prior to grouting and, again, if staged grouting is required; therefore, the pump must be sufficient to deliver water down to the delivery system and back up a return line to ensure there are no blockages in the system. Moreover, concrete may flow around and encapsulate the grout delivery system during placement, especially if a bottom plate separating the two zones is not used. Therefore, the concrete around the delivery system, if present, must be cracked using pressurized water before the concrete fully hardens to allow the tip post-grouting to function as intended. The pressure and volume used to crack the concrete should be recorded and used as a basis for the subsequent tip post-grouting. However, tip post-grouting cannot be performed until the concrete in the bored pile has fully hardened or has achieved an unconfined compressive strength (f_c') of at least 3,000 psi (20.7 MPa).

In an open-type system (i.e., sleeve-port or tube-á-manchette), which is applicable for all diameters especially larger piles, the grout is injected into the ground through small ports along the horizontal portion of the U-tube below the base of the pile. The key to this system is ensuring the flow of grout out into the formation and across the entire base of the pile. This grout flow is facilitated by using multiple grouting circuits for redundancy and better coverage across the bottom of the pile. In a closed-type system, which is applicable for smaller diameter piles (≤ 6 ft (1.8 m)), the grout is injected into an enclosed area that uses a steel plate on bottom of pile, and a flexible rubber membrane to protect the tubes during concrete placement and to provide separation between the grout and the formation. As grout fills and expands the space between the steel plate and rubber membrane, the membrane should rupture at relatively low pressure, which then allows the grout to flow out into the formation akin to the open-type system. The key to this system is ensuring the flow of grout across the entire base of the pile while the membrane is still intact.

Gravel bedding has been used with bored piles greater than about 6 ft (1.8 m) in diameter to facilitate the flow and distribution of grout across the base of the pile. In addition, the gravel bedding has been used to produce a level surface at the bottom of the borehole when construction tooling results in a contoured hole. The gravel bedding should be as thin as possible with a minimum thickness of about 4 to 12 in (100 to 305 mm), but no greater than about 24 in (600 mm). The bedding should consist of clean, coarse gravel (particle sizes between 0.625 and 1.25 in (16 to 32 mm)) that extends across the entire base of the pile, and the bedding should be tamped down prior to placement of the reinforcement cage with grout delivery system.

GROUT MIX CHARACTERISTICS

The grout mix used for tip post-grouting applications is neat grout mix, typically consisting of Type I/II Portland, water, and admixtures if required to control flowability, bleeding, and set time. The grout mix does not contain aggregates. The water-to-cement (w/c) ratio ranges from about 0.4 to as high as about 0.9. When the grouting operation first begins, higher w/c ratios (around 0.7 to 0.9) are typically used to ensure the grout delivery system, grout tubes, grout lines, and void space in the gravel bedding (if used) are full of grout (net volume). The net volume is defined as the amount in excess of the volume needed to ensure that the delivery system is filled, there is no blockage in the lines, and that the grout is reaching the base of the pile. As grouting continues, the w/c ratio is reduced gradually to a range between 0.4 and 0.6 to ensure control of the grout, and to facilitate delivery at the desired grout pressure. There should be flexibility in the specifications to modify the mix to adjust to conditions encountered in the field during grouting.

Some important characteristics of the grout mix should be monitored including flow (pumpability), specific gravity, viscosity, and compressive strength. Specific gravity and grout viscosity (indirect measurement of flowability and fluidity) are measured using a mud balance and a Marsh funnel, respectively, where both measurements may be made during and throughout the grouting operation to provide real-time indications of the properties of the fluid grout. Fluidity (or flowability) of the fluid grout is measured with a flow cone. Typically, project specifications do not mandate the quantity or frequency of tests performed during the grouting operation, but the tests should be performed at a frequency that ensures proper behavior and required properties of the grout are maintained.

Compressive strength testing of the grout is performed on cured samples of the grout. Typically, a minimum 28-day compressive strength may be specified between 2,000 and 4,000 psi (13.8 and 27.6 MPa)). The grout does not need to achieve similar strength as the concrete in the pile, but needs to be stiffer than the soil around the pile. That is, the post-grouting operation is intended to pre-mobilize end bearing. While it is a component of the development of load transfer along and at the base of the shaft, the grout is not a structural component of the shaft itself.

GROUTING PROCEDURES, VERIFICATION, AND ACCEPTANCE

The key consideration during any grouting operation is control of the grout, which, unfortunately, does not always occur for a variety of reasons. Mullins and Winters (2004) and Muchard and Farouz (2009) reported fluid grout flowing from the base, upward along the sides of the pile for distances of 60 ft (18 m) or more during tip grouting. As an unintended benefit, this upward flow of grout likely resulted in an increase in side resistance; however, control of the grout was lost and the system did not function as intended. In other instances, the grout has been found to have traveled some distance away from the edge of the pile. This outward flow of grout has generally been due to either hydrofracture or travel along a looser/weaker seam/void, and reflects a loss of control of the grout.

To ensure control of the grout and its effect on the load response behavior of the bored pile, various parameters are measured as a function of time, recorded, and analyzed throughout the grouting operation as part of termination criteria and the overall QA program. These main parameters include grout pressure, grout volume, and upward displacement of the bored pile during grouting (Fig. 3). The termination criteria for tip post-grouting includes a target grout pressure, net grout volume in excess of the amount to fill the delivery system and tubes yet below a maximum amount, and maximum upward displacement of the pile during grouting; however, the termination criteria typically vary from project to project based on the engineer's experience, site conditions, and the project requirements.

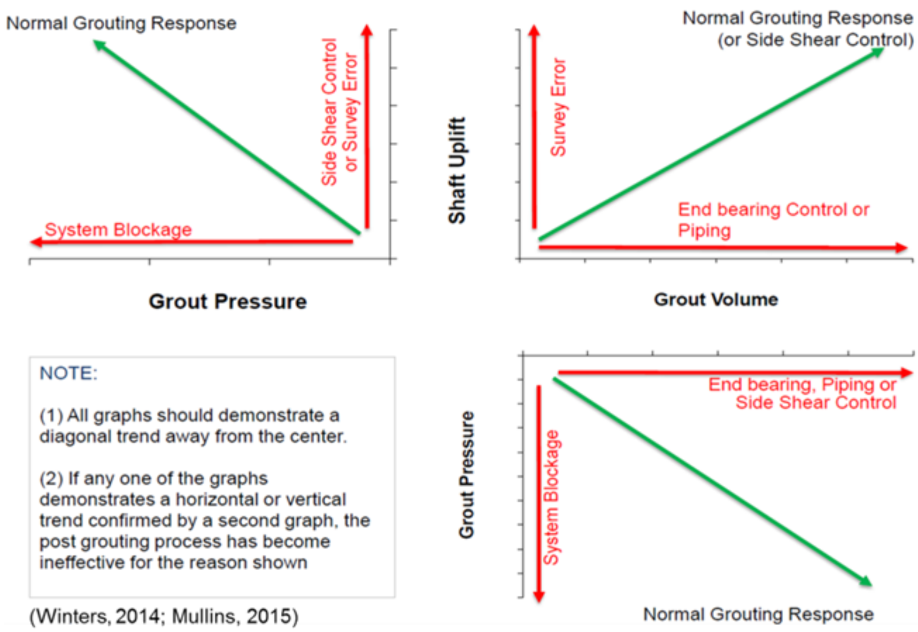


Fig. 3. Idealized graphs of grouting parameters measured during the tip post-grouting operation and analyzed in real-time (Winters, 2014; Mullins, 2015)

The target grout pressure is considered the most important parameter for tip post-grouting, and is a function of a variety of factors, including in-situ stress state, soil type, the presence of weak or soft layers, available reaction force (i.e., self-weight of the bored pile plus available side friction resistance), location of groundwater table, head losses in the system, and the hydrofracture potential of the in-situ soil. The greater the magnitude of the bi-directional load induced into the shaft during tip post-grouting results in an enhanced performance of the grouted shaft. Grout pressures used when tip post-grouting in sands and clays/silts have been reported as high as 2,180 psi (150 bar) and 1,160 psi (80 bar), respectively. As the grout pressure approaches / exceeds about 600 psi (45 bar), there is concern about the risk of clogging in the grout lines due to the squeezing out of water from and in front of the fluid grout mix. Commonly used upper limits of grout pressure are in the range of 750 to 800 psi (50 to 55 bar) and are measured using analog or digital pressure transducers or gauges attached directly to the grout plant at the discharge line and, at times, additional transducers or gauges are used near the connection at the top of the bored pile. In addition, once the target pressure has been achieved, it is sustained for a specified duration. The hold time is typically around 2 min in the U.S. but may vary considerably based on the contractor and geographical location to ensure that the grout below the base of the pile is pressurized and performing as intended. For open-type systems, the above process is repeated for each circuit in the grout delivery system in a continuous operation; however, the process is only performed once when used with closed-type systems.

In tip post-grouting applications, hydrofracture of the in-situ soil formation is highly undesirable, as this condition causes a loss of control of the grout. Hydrofracture can occur when the applied grout pressures become greater than the tensile strength or shear strength of the in-situ formation (and implicitly the overburden pressure) and is more likely to occur in low strength soils, fine-grained or granular soils with more than about 20 to 30% fines, in lower permeability soils were the grout remains more fluid for a longer period, and with higher mobility grouts. When hydrofracture initiates, observations include relatively large grout takes with little-to-no increase in the measured grout pressure along with small-to-no upward displacement of the pile. Different means to minimize the potential of hydrofracture include using a less mobile grout mix, using lower grout pressures, and performing staged grouting.

The target grout volume is dependent upon the diameter of the bored pile being grouted, the grout delivery system used, and the condition of the ground beneath the base of the pile (e.g., relative density, presence of a soft bottom, etc.). The target grout volume should be a net volume, which is typically in the range of 2 to 5 cu. ft (55 to 140 liter). The volume of grout being delivered and measured using flow meters attached directly to the grout plant at the discharge line location. Some specifications provide a maximum grout volume, which can vary greatly depending upon the diameter of the pile, engineer, and ground formation. Based on conversations with service firms and contractors performing this work, grout volumes have ranged from 5 to 30 cu. ft (140 to 850 liter). In practice, if the maximum specified grout volume is achieved at grout pressures considerably lower than anticipated, staged grouting may be required. However, when possible, it is advantageous to achieve the grout pressure in the initial grouting even if that means exceeding the maximum grout volume specified.

The upward displacement of the bored pile during the post-grouting is the third commonly monitored termination criterion. To minimize the potentially negative effects to side friction due to the reversal of side resistance, the upward displacement measured at the top of the pile during any one stage of grouting is limited to between 0.25 and 0.75 in (6 and 19 mm). If the upward displacement limit is reached prior to achieving the target grout pressure, staged grouting is performed. An excessive amount of upward displacement may be indicative of insufficient side resistance, which may negate the benefit of performing staged grouting below the base of the pile. To measure the upward movement at the top of the pile, displacement transducers or gauges are commonly used in conjunction with an independent reference beam. At times, an optical survey may be performed as a backup.

Staged grouting is an approach that is employed with open-type grout delivery systems when the grouting termination criteria are not achieved. Staged grouting entails performing a modified initial grouting sequence multiple times, but usually, no more than four, until the grouting termination criteria are achieved. As described in Figure. 4, the initial grouting is performed, then the grout in the grout tubes and delivery system is flushed using pressurized water. Two to four additional phases of grouting are then performed through the grout delivery system. The key is to perform the additional grouting phases before the previously injected grout fully sets but has achieved enough strength to seal off potential escape paths. It is preferable to avoid performing staged grouting, as doing so introduces additional concerns and uncertainties, including being able to deliver the pressurized grout across the full area of the base of the pile, to deliver the grout beyond the delivery system itself, and to determine the area over which the grout is being injected.

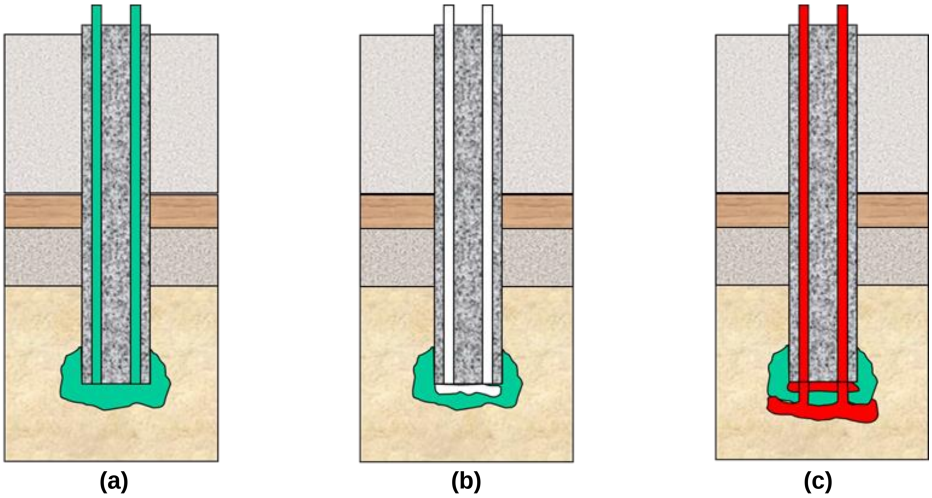


Fig. 4. Idealized depictions of the different phases of staged grouting: (a) initial grouting below base of bored pile, (b) flushing of grout in the tubes and in delivery system, and (c) additional grouting through delivery system (images courtesy of Applied Foundation Testing (mod. from Large, 2016))

Embedded within the bored pile, strain gages and/or telltale rods have been used to evaluate the effectiveness of grout distribution across the base of the pile, to evaluate load transfer along the length of the pile during the tip post-grouting or during load testing, and to provide an indication of a possible blocked circuit / line or hydrofracture during grouting. A multi-axis plot of grout pressure and strain measurements versus time during the grouting operation is presented in Figure 5. In the figure, the plot indicates eccentricity, but the average strain indicates excellent trending with the applied grout pressure. However, the use of strain gages and telltales is not common in current practice on production piles. Nonetheless, the use of strain gauges can provide an estimate of the relative displacement and axial load in the pile at their locations and can provide a measure of any relaxation as the grout cures.

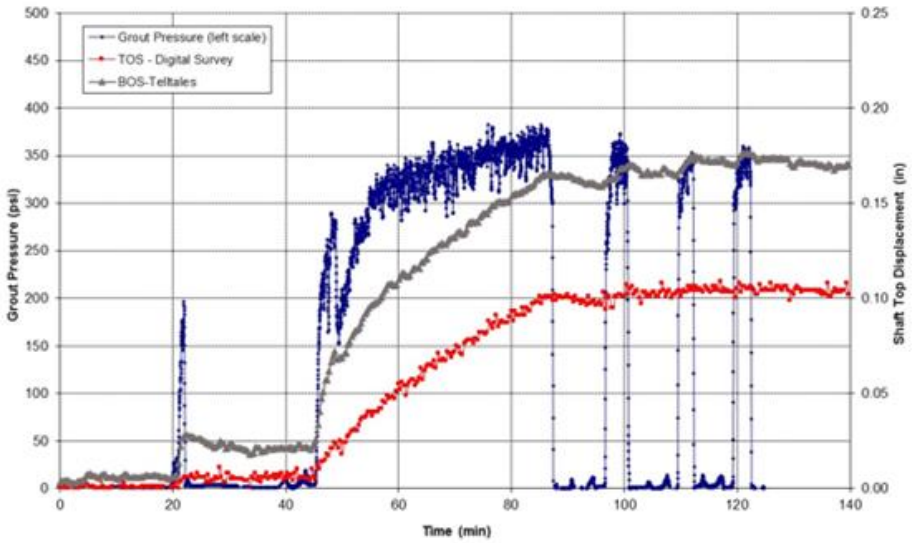


Fig. 5. Measurements of grout pressure (blue, left axis), top of shaft displacement from digital survey (red, right axis), and displacement near bottom of shaft from telltales (gray, right axis) versus time during grouting (Large, 2016)

RELIABILITY AND UNCERTAINTY – METHOD AND OUTCOME

A clear and rational process for assuring the quality of tip post-grouting is a clear obstacle to full implementation. The reliability of a tip post-grouted pile, as indicated through safety margins or resistance factors, should not be less than for an ungrouted pile, but is not as yet defined in practice. Understanding the elements of QA is necessary to ensure that the tip post-grouting process has occurred and is complete. However, an assessment of the reliability of the process is more complex. Typically, uncertainty in ungrouted bored pile construction is addressed by monitoring the means and methods for the construction of the pile. Demonstration or technique shafts are constructed to verify means and methods, and construction inspection and materials testing ensures repeatability. Some combination of performance and integrity testing allows the designer to assure reliability in bearing resistance.

Tip post-grouting provides a difficult problem for designers and owners since it is clear that the construction process clearly improves the performance of the foundation element. This leads one to conclude that any QA requirements for tip post-grouting would certainly be excessive. Acceptance of any foundation element must include assurance that the post-grouting process is performed consistently from element to element, and that bearing resistance can be reliably estimated. There are inherent difficulties in performing adequate QA to capture, quantify, and minimize the potential uncertainty resulting from a construction activity that is understood to absolutely improve the existing condition.

A QA program for tip post-grouting should try to achieve two goals. First, the means and methods must demonstrate that construction results in a pile that performs as expected in axial compression. Second, the means and methods must be repeatable for all elements. This means that the projects that use tip post-grouting should always have a test shaft that allows the contractor to demonstrate its construction means and methods along with some frequency of testing primary metrics (e.g., pressure, volume and displacement) to verify repeatability of the construction process.

CONCLUSIONS

Tip post-grouting has been demonstrated in different ground formations to provide various benefits and enhancement to the axial load-displacement response of a grouted bored pile compared to conventional (ungrouted) piles. It has been shown that this technique can increase the axial nominal resistance of the pile, improve the mobilization of pile's resistance, and better align the load transfer curves. The various factors affecting the performance of a tip post-grouted pile include the size (diameter and length) of the pile, grout delivery method, grout injection pressure, grout volume, and upward displacement during grouting. To achieve the myriad benefits, the construction of the bored pile and the implementation of the tip post-grouting program must be performed to a high level of quality and control throughout the entire grouting operation. Successful and reliable implementation of tip post-grouting will allow designers to optimize the design of a tip post-grouted pile by stiffening its end-bearing response and by allowing the maximum tip resistance at a downward displacement that is consistent with the maximum side resistance (i.e., optimizing of load transfer curves). Using these optimized load transfer curves, cost efficient bored piles can be designed leading to a reduction in the overall cost of, and greater reliability with, bored pile construction. However, tip post-grouting or any other enhancement or remedial technique should never be used in lieu of proper execution and good workmanship in the construction of a bored pile.

REFERENCES

Castelli, R.J., (2012). "Guidelines for Application of Base Grouting for Drilled Shafts"; *Proceedings of GeoCongress 2012*, ASCE, Recent Advances in Foundation Engineering, pp. 225-234.

China Academy of Building Research (2008). *Technical Code for Building Pile Foundations*, JGJ 94-2008, Architecture and Building Press, Beijing.

Large, M.E.B. (2016). "Workshop on Quality Assurance for Post-grouted Drilled Shafts." Submitted to the Federal Highway Administration. Report No. FHWA-HIF-16-015. 187 pp.

Loehr, J.E., Marinucci, A., Hagerty Duffy, P., Gómez, J., Robinson, H., Day, T.J., Boeckmann, A.Z., and Cadden, A.W. (2017). *Evaluation and Guidance Development for Post-Grouted Drilled Shafts for Highways*, Report No. FHWA-HIF–17-024, Federal Highway Administration. March. 158 pp.

Marinucci, A. and Nichols, S.C. (2016). "Optimized Drilled Shaft Design through Post-Grouting," ASCE/Geo-Institute *GeoStrata* Magazine. May/June.

Muchard, M.K. and Farouz, E. (2009). "Broadway Viaduct Design Phase Load Test Program for Post-grouted Shafts," 34th Annual Conference on Deep Foundations, DFI, Kansas City, Missouri.

Mullins, G. (2015). "Grouting Effectiveness – Construction QA/QC of Post-grouted Shafts." Presentation delivered at FHWA/Caltrans Workshop on Quality Assurance for Post-grouted Drilled Shafts. April 15-16. Oakland, CA.

Mullins, G. and Winters, D. (2004). "Post Grouting Drilled Shaft Tips – Phase II." Final Report to the Florida Department of Transportation.

Mullins, A.G., Winters, D., and Dapp, S.D. (2006). "Predicting End Bearing Capacity of Post-Grouted Drilled Shaft in Cohesionless Soils," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 132, No. 4, pp. 478-487.

Nichols, S.C., Marinucci, A., and Rivers, B. (2012). "Evaluating Post-Grouting to Improve Drilled Shaft Capacity." In *A Compendium of Research Reports and Invited Technical Papers*, Geo-Construction Conference Proceedings of the 2012 ADSC-IAFD Equipment Exposition and Technical Conference. A. Marinucci and W.T. Witherspoon, editors.

Pando, M.A. and Ruiz, M.E. (2005). *Study of axially loaded post grouted drilled shafts using CPT based load transfer curves*, Geotechnical Engineering Research Report No. CIRC/GT/05-02, Civil Infrastructure Research Center, University of Puerto Rico, Mayaguez, PR, June 2005, 287 p.

Ruiz, M.E. and Pando, M.A. (2009). "Load Transfer Mechanisms of Tip Post-Grouted Drilled Shafts in Sand", *Contemporary Topics in Deep Foundations*, Proceedings, 2009 International Foundation Congress and Equipment Expo, Orlando, Florida, ASCE, GSP 185, pp. 23-30.

Winters, D. (2014). "Selected Topics in Foundation Design, Quality Assurance, and Remediation." Ph.D. Dissertation, University of South Florida, Tampa, FL.