This report describes presentations and discussion sessions delivered during a workshop on quality assurance (QA) practices for acceptance of post-grouted drilled shafts. The 1½-day workshop was organized by Deep Foundations Institute on October 15-16, 2015 in Oakland, CA in partnership with California Department of Transportation (Caltrans), Federal Highway Administration (FHWA), and with support from International Association of Foundation Drilling (ADSC). The primary goals of the workshop were to identify and summarize the state of the practice for design, construction, inspection, verification, acceptance criteria, reliability and performance of post-grouting; and to identify gaps and needs in quality assurance that should be addressed for successful use of post-grouting.

Workshop presentations provided state of practice overviews and perspectives from owners, engineers and contractors on acceptance of post grouting methods for drilled shafts; and subsequent workshop discussions attended by a small invited group of participants focused on identifying areas of agreement and disagreement on post-grouting best practices, acceptance criteria, design and verification procedures, and inspection requirements. A partial list of attendees of the open and closed sessions is provided as Appendix A, and copies of presentations are included as Appendix B.
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INTRODUCTION

In partnership with California Department of Transportation (Caltrans), Federal Highway Administration (FHWA), and with support from International Association of Foundation Drilling (ADSC), Deep Foundations Institute (DFI) organized a workshop on quality assurance (QA) practices for acceptance of post-grouted drilled shafts in conjunction with DFI’s 40th Annual Conference on Deep Foundations. The 1½-day workshop was held on October 15-16, 2015 at the Oakland Marriott City Center in Oakland, CA.

Post-grouting, in the context of this workshop and report, refers to the alternative design and construction of base-grouted drilled shafts wherein a grout distribution system is installed during construction and used to grout the base under pressure after the drilled shaft concrete has gained adequate strength, resulting in a stiffer axial-compression load-displacement relationship and additional possible ground improvement effects.

The primary goals of the workshop were to

- Identify and summarize the state of the practice for design, construction, inspection, verification, acceptance criteria, reliability and performance of post-grouting.
- Identify gaps and needs in quality assurance that should be addressed for successful use of post-grouting.

This report is structured to follow the workshop program: workshop presentations outlined the state of practice and views from owners, engineers and contractors on acceptance of post grouting methods for drilled shafts; and subsequent workshop discussions attended by a small invited group of participants focused on identifying areas of agreement and disagreement on post-grouting best practices, acceptance criteria, design and verification procedures, and inspection requirements. A partial list of attendees of the open and closed sessions is provided as Appendix A, and copies of presentations are included as Appendix B.

FHWA and Caltrans are the primary audiences for this report, and its content will be used to develop a roadmap for deploying the findings into policy and practice. The secondary audience is the broader industry group, and the report content will be disseminated in a variety of formats.
EXECUTIVE SUMMARY

The workshop program consisted of presentations that outlined the state of practice and views from owners, engineers and contractors on acceptance of post grouting methods for drilled shafts, followed by workshop discussions attended by a small invited group of participants focused on identifying areas of agreement and disagreement on post-grouting best practices, acceptance criteria, design and verification procedures, and inspection requirements.

The Presentations section of this report provides an overview of the content as offered by the presenters. The statements contained within this section do not necessarily reflect consensus of the group or the discussions held during the workshop. Workshop attendees expressed various opinions, and consensus was reached on some topics and while disagreement remains on others. The report covers all of the discussions, and the generally agreed conclusions are summarized below. It is important to recognize when reading the Discussions section that the statements shown do not necessarily reflect consensus of the group.

The following were agreed upon regarding acceptance methods for post-grouting of drilled shafts:

- Grout pressure, shaft uplift (vertical displacement), and grout volume are the primary parameters to be measured during post-grouting.
- Grout pressure is considered to be most important, followed by shaft uplift, and then grout volume. In general, parameter monitoring trends must be stable.
- The design or target grout pressure should be a design element and a function of skin friction, shaft weight, soft layers, hydrofracture potential, soft/loose areas, and water table.
- To date, a maximum shaft uplift has been used as a limiting criterion to prevent a presumed potential for deterioration. However in side resistance it is recognized that movement at the top of the shaft (or from telltales in deep slender shafts) also provides assurance that grout is being distributed across the base sufficiently enough to result in a bi-directional load causing upward movement and mobilization of side resistance; thus, some minimum amount of upward movement is desirable.
- A minimum top of shaft displacement requirement is not always feasible because high side resistance may prevent shaft movement. Shaft movement is important to measure, and instrumentation at the surface or within the shaft is required to ensure upward shaft movement.
- Verification of load at the tip of the shaft is needed. Upward shaft movement confirms some volume of grout reached the tip of the shaft and some load was applied.
- Volume measurements are useful as a secondary control measure in that when the volume increase coincides with upward shaft movement, grout coverage across the base, and thus load transfer across the base, can be more reasonably assumed. It is important that net volume be specified and accurately measured.
- The net grout volume criterion should be the lowest value necessary to verify grout flow to the base of the shaft.
The following were agreed upon regarding design and verification for post-grouting of drilled shafts:

- Post-grouting can indicate that designed axial resistances are being achieved, but it cannot determine an “ultimate” resistance.
- Qualified and experienced post-grouting professionals must oversee the grouting process and prepare the documentation.
- It is important to recognize the role of a qualified project geotechnical engineer and the need for sound engineering judgment when establishing post grouting criteria and post grouting capacity.
- Static load testing (bi-directional load cell test) should be used to verify end bearing resistance and base displacement and creep response for projects that rely on post grouting to improve end bearing.
- Grout pressure at production shafts should be equal to or greater than the grout pressure observed at successful load test shafts; this may require specifying a lower grout pressure for load test shafts.
- The specified minimum grout pressure should be maintained for a minimum time period (2 minutes was suggested).
- Net grout volume at production shafts should be equal to or greater than the theoretical volume needed to fill the grout delivery system.
- Uplift should be observed at the top of the shaft, or at the bottom of the shaft when telltales are used.
- If a base gravel layer is used, the thickness of the gravel layer at production shafts should not exceed the gravel thickness used at the successful load test shaft.
- Staged grouting should be allowed, but avoided as a routine practice. Grouting criteria, particularly the minimum required grout pressure, should be selected to reduce the dependence on second stage grouting.

The following were agreed upon regarding inspection for the post-grouting of drilled shafts:

- The same standard of care and shaft bottom cleaning should be required at post grouted shaft installations as specified for non-grouted shaft installations.
- Post-grouting may improve loose material at bottom of the shaft and would normally be expected to provide a stiffer response to axial loading.
- Careful consideration of shaft cleaning procedures is required to minimize the possibility that loose material is trapped below the grout delivery system/plate/gravel pack due to reduced scouring by the tremie concrete.
- The contractor’s post-grouting installation plan must be reviewed by the owner’s engineer/representative.
- Use of gravel at the bottom of the shaft should be allowed. A minimum gravel bed thickness of 4 inches is needed to level the hole bottom. A maximum gravel thickness of 24 inches is recommended, and a thinner layer is preferred. The gravel must be sufficiently clean so that additional fines are not added to the shaft bottom, and the gravel must be tamped down. The grouting system plate should be in contact with the bottom of the shaft.
• Strain gauges are recommended, and the use of telltales is deemed helpful in test- and demonstration-shafts, and when sufficient indicative movement at the top of production-shafts might not manifest.
• The contractor needs flexibility with the water/cement ratio to achieve the desired improvement from post-grouting.
• Changes in water/cement ratio must be recorded during construction.
• Minimum grout volume must be a net volume that considers the grout volume required to fill the grout delivery system.

FHWA and Caltrans are the primary audiences for this report, and its content will be used to develop a roadmap for deploying the findings into policy and practice. The secondary audience is the broader industry group, and the report content will be disseminated in a variety of formats.
PRESENTATIONS

Early morning presentations on design, construction, and research were open to DFI Oakland Conference attendees, and subsequent sessions on FHWA/DOT perspectives and discussions were closed and attended by the small invited group of participants. Presentations are provided as Appendix B.

Many different terms are used in the industry to describe elements of the post-grouting process, including and not limited to the following:

- End bearing, base resistance, tip resistance, and end loading.
- Side resistance, side shear resistance, and skin friction.
- Initial grouting, stage grouting, and phase grouting.

The terms base resistance, side resistance, initial grouting and stage grouting are used throughout this report.

The Presentations section of this report provides an overview of the content presented by authors. The statements contained within this section do not necessarily reflect consensus of the group or the discussions held during the workshop.

Open Session Presentations

**Introduction and Workshop Purpose**

*Benjamin Rivers, FHWA*

Several state DOTs including Caltrans have expressed strong interests in better understanding the mechanisms of improvement due to post grouting and in implementing appropriate provisions for post-grouting drilled shafts. Questions related to quality assurance (QA) and acceptance criteria during the Gerald Desmond Bridge project, currently being constructed in Long Beach, CA, provided impetus for this workshop in Oakland. Other states have also used post-grouting for drilled shafts, and have had similar questions and concerns related to quality assurance. FHWA will use the results of this workshop in conjunction with an on-going FHWA/ADSC study to formalize guidance.

To develop appropriate and effective guidance, FHWA is focused on developing guidance for post-grouted drilled shafts with the following objectives:

- Bound current state of knowledge on use of post-grouting (what industry knows and does not know).
- Quantify improvement mechanism(s) for post-grouting.
- Establish design methodology(ies) for appropriate use.
- Define control/assurance/verification measures and acceptance criteria.

To this end, the workshop was conducted to
Identify and summarize the state of the practice for design, construction, inspection, verification, acceptance criteria, reliability and performance of post-grouting.

Identify gaps and needs in quality assurance that should be addressed for successful use of post-grouting.

United States State of Practice for Post-Grouting Methods
Mike Muchard (Applied Foundation Testing)

This presentation focused on the current state of the practice in the U.S. for post-grouting methods, and contains descriptions of processes, photographs of equipment, and plots of typical data collected. Post-grouting has been used by at least 19 DOTs on at least 36 bridge projects with over 32 load test programs conducted and 1,800 drilled shafts post-grouted to date. Usage began in late 1990s/early 2000s following a Florida DOT research project (Mullins et al., 2001; Mullins and Winters, 2004).

Muchard presented the grouting setup for typical post-grouted drilled shafts (Figure 1). A grout distribution system is installed on the bottom of the reinforcement cage, grout is injected under pressure beneath the tip of the drilled shaft after the concrete has set. Base resistance is engaged by the grout and reacted by side resistance. Muchard also showed and discussed measurements recorded in current standard of practice including: 1) grout pressure, 2) shaft upward displacement, and 3) grout volume. Optional measurements of supplementary instrumentation are sometimes performed including strain gages and telltales. Muchard also discussed the process of stage grouting (Figure 2). If the target grout pressure during initial grouting cannot be reached or maintained, repeated grouting attempts may be made (termed: stage grouting). In stage grouting, the grout pipes are flushed with water after initial grouting. After some waiting period in which the initially placed grout achieves set, the shaft is regrounded using the same procedure and recording the same measurements. This process is generally repeated until the target pressure is achieved. The terms phased grouting and multistage grouting are also used frequently. In this report, the terms initial grouting and stage grouting are used as indicated in Figure 2.

Figure 1. Typical grouting setup and measurements (from Muchard’s presentation).
Post-grouting is used to meet the following goals:

- Increase usable base resistance (resulting from any or all of the following mechanisms: Preloading the base; improving the soil below the base (compaction/permeation); increasing the tip area in some cases; the upward migration of grout increasing side resistance in lower portion of shaft).
- Decrease settlement.
- Improve reliability in base resistance.
- Reduce shaft length or diameter.
- Reduce construction risk by improving constructability.
- Save time and money.

Various techniques and equipment can be used to post-grout successfully. Each system has advantages and disadvantages, and the specialty contractor is best positioned to identify and demonstrate the most suitable technique for the shaft construction and ground conditions. Practical considerations include the post-grouting distribution systems as described below:

- Flat jack system
  - A rubber membrane wrapped around a steel grout plate provides a barrier so concrete does not get into the grout tubes during construction. Grout flows between the plate and rubber membrane, and the membrane ruptures very quickly (typically at small volumes and very low pressures). Initially the grout acts on the full plate area while the membrane is intact. But after rupture, it is an open grout distribution system like the Tube-à-manchette.
  - Scuff ring protects the edges of the membrane, but rubber tends to be easily damaged, e.g., not a very robust system.
  - Flat jacks are typically used on smaller diameter shafts (less than or equal to 6 feet).
  - Dedicated grout tubes are required.
- Not conducive to stage grouting.
- Tube-à-manchette (TAM, sleeve port) system
  - Grout may not act on entire plate area at the same time (zone coverage). Use of gravel bedding aids in grout distribution across the full base area (Figure 3).
  - Redundancy (through multiple independent U-tubes).
  - Robust system.
  - Well suited for stage grouting.
  - No limitation on shaft diameter.
  - Crosshole sonic logging (CSL) tubes may be used for grouting, thereby avoiding additional pipes.
- Gravel pack systems (bedding and baskets)
  - Gravel pack systems include either gravel bedding placed at the bottom of the excavation or basket-type systems in which gravel is enclosed within a fabricated metal container below and attached to the reinforcement cage with or without non-woven filter fabric.
  - Facilitate grout distribution at the shaft base.
  - Irregularity of shaft bottom impacts grouting effectiveness.
  - The process allows for correction by overdrilling.

![Diagram of Sleeve-Ports below steel plate with gravel pack (Sliwinski and Fleming, 1984).](image)

Other practical construction considerations include the following:

- Grout strength is less important than grout compressibility.
- Redundancy of grout pumps and mixers should be considered by the contractor based on the project specific circumstances to allow continuous operations, especially during flushing prior to stage grouting.

Reasonable expectations must be considered when establishing grouting criteria. Grouting process should be monitored and parameters plotted in real time by experienced personnel to demonstrate repeatability and identify problems in real time. The following grouting criteria and considerations reflect the current standard of practice in the U.S. for post-grouting:
1. Grout Pressure
   a. Minimum pressure for specified duration, e.g., 2 minutes.
   b. Value can vary based on the load demand of shaft.
   c. If pressure criterion cannot be achieved in initial grouting, then stage grout.
   d. May be limited by available shaft side resistance.

2. Upward shaft displacement
   a. Most commonly limited to 1/8 to 1/4 inch, measured at top of shaft. Limits are imposed so that skin friction is not negatively impacted.
   b. When displacement limit is reached, initial grouting is stopped and stage grouting may be done. (Note that when excessive shaft movement occurs, it is an issue of insufficient side resistance. Stage grouting may be performed but still may not solve the issue.)
   c. Criterion resets for each subsequent stage (displacement limit is not cumulative for grout stages).

3. Grout Volume
   a. A minimum volume value must be established to assure grout lines are not blocked, and grout is reaching the base of the shaft.
   b. An upper limit volume value is sometimes specified. If this upper limit is reached, stage grouting is initiated. (Note: this is rarely used in practice. It is always desirable to achieve the required pressure during the first stage).
   c. Large grout takes may indicate hydro-fracturing of the ground or grout flow up the side of the shaft.

Monitoring instrumentation typically includes an oil filled Bourdon pressure gauge, electronic pressure transducer, digital survey displacement measuring system, convention survey level (for redundancy), grout holding tank volume measurement, and grout flow meters. Grout Monitoring Systems which plot the grouting measurements on multi-axis plots in real time (Figures 4 and 5) are encouraged on all production shafts. Optional instruments such as strain gauges and telltales provide valuable insight, but a precise value from these devices should not serve as a specified acceptance criterion. Strain gauge/telltale data are used to provide a relative indication that the shaft tip is being stressed by the applied grout pressure. Pressure cells have been used in research settings but are not practical for production grouting. Eccentricities in the strain measurements are normal during grouting, no matter what type of grout distribution system is used. Muchard emphasized these measurements are during fluid grout state and do not represent the stress conditions of solid state grout. Based on load tests on grouted shafts, Muchard has not experienced negative effects on shaft performance as a result of these eccentricities. He related this to pile driving where there are always eccentricities present both during installation and from naturally variable bearing stratum surfaces, but piles still perform as intended. Typical strain response near the shaft base during grouting is shown in Figure 6.
Figure 4. Grout pressure and grout volume.

Figure 5. Grout pressure and shaft displacement.
Owner Perspective on Use and Acceptance of Post Grouted Drilled Shafts

Ray Castelli (WSP | Parsons Brinckerhoff)

This presentation focused on owner concerns related to post-grouting for drilled shafts. Castelli noted that the industry agrees that post-grouting is an excellent method to improve base resistance of drilled shafts and to promote early mobilization of resistance, especially for granular soils. However, owners do have practical concerns and suggest that the industry consider the following:

- Develop and adopt design standards for post-grouting that provide better predictions of drilled shaft performance.
- Define appropriate resistance factors. The methods used currently cannot capture all factors that influence base resistance. More data are needed to define the resistance factors for inclusion in AASHTO procedures.
- Develop construction standards for post-grouting that address qualifications of grouting specialists, and consistency of shaft installation (shaft excavation, bottom cleaning, and grout delivery system), and grouting procedures (grout mix, grout pressure, and stage grouting parameters). Standards should not be difficult or costly to implement, and should allow contractors flexibility in their means and methods for performing post-grouting.
- Recognize the role of a qualified project geotechnical engineer and the need for sound engineering judgment.
- Establish contractor pre-qualification requirements, where permitted.
- Provide well documented inspection during shaft installation since the performance of post-grouted shafts is related to shaft installation and grouting methods. More data are
needed to help assess the influence of construction methods on base grouting performance.

- Require demonstration and test shafts, and establish consistent grouting and verification procedures for test shafts and production shafts. While it is difficult to specify the same requirements for different projects, consistent construction and grouting procedures should be used within a single project. Recognize that not all construction procedures and grouting systems give the same results.
- Establish reasonable verification procedures in test programs that can be reproduced for production shafts. It is important to restrain test shaft parameters (grout pressure and grout volume) to reduce the risk of production shafts not meeting test shaft values, which would then raise questions regarding the adequacy of these production shafts.
- Establish codes. Although there are limitations of codes because of the number of factors to be considered for post-grouted shafts, codes help assure owners that standard procedures are being followed.
- Identify appropriate instrumentation and monitoring procedures.
- Recognize uncertainties in post-grouting processes and evaluate how they relate to performance, including
  - Influence of grouting methods, i.e., delivery systems, grout mixes, grouting procedures, lock-off or open pressure, etc. Data from Audubon Bridge load tests suggest that the details of the grout delivery system influence the performance of post-grouting.
  - Influence of grout pressure at a given site beyond a minimum grout pressure. (Little or no data are available for comparing shaft performance with different grout pressures while maintaining other installation variables and ground conditions constant.)
  - Effectiveness of stage grouting, i.e., effectiveness of pressure on subsequent grouting stages.
  - More research is needed to assess the above factors.

The following specific concerns were noted for each of the quality control parameters routinely measured:

- Grout pressure
  - The relationship between grout pressure and shaft resistance is not unique even within a given site, and is influenced by many factors.
  - How is the pressure determined? Should a sustained pressure for a defined time period be specified? A peak pressure spike does not necessarily improve shaft performance.
  - Is the ground being further improved as grout pressure rises, or do we achieve most of the improvement at a lower bound pressure?
  - How do we verify the effectiveness of applied pressure during second stage of grouting?
- Shaft displacement
  - Shaft top displacement is a good means for verifying the effectiveness of grouting.
For shafts with high side resistance, however, there may be little or no top of shaft displacement under grout loading. For such cases, telltales to measure upward displacement of the base of the shaft should be considered.

For shafts with low side resistance, the shaft may reach the maximum allowable displacement before the required minimum grout pressure is achieved.

Top of shaft displacement should be limited to avoid risk of reduction in side resistance.

- **Grout volume**
  - There seems to be no relationship between grout volume and grout pressure, or between grout volume and base resistance.
  - Minimum grout volume must be a net volume that considers the grout volume required to fill the grout delivery system.
  - Large grout volumes may not be indicative of good performance. Large grout volumes may result from hydrofracturing the soil.
  - Contractor needs flexibility to adjust the water/cement (w/c) ratio to achieve the project goals, but the w/c ratio likely influences the grout volume injected.
  - Grout volume should be used to verify grout flow to the base of the shaft, and not as a means of assessing base resistance.

- **Limitations of Strain Gages**
  - Strain gauge data are useful in assessing the effectiveness of the grouting, but the data are not definitive. Since the gages are located some distance above the bottom of the shaft, the base resistance must be estimated by assuming a unit side resistance below the gage level. Also, strain gages may indicate differential loading of the shaft due to non-uniform grout pressure on the base, or lateral pressure from grout that permeates up the side of the shaft.

- **Creep**
  - Considering the large load (prestress) applied to the soil beneath the shaft base during grouting, will the completed shaft experience greater base creep displacement under service loads?
  - Load test results show low creep limits at some post-grouted shafts, but this has also been observed at non-grouted shafts.
  - Creep must be considered in design.
  - More research is needed to assess creep at post-grouted shafts.

**Engineering Perspective on Use and Acceptance of Post Grouted Drilled Shafts**

*Dan Brown (Dan Brown and Associates, PC)*

This presentation focused on factors that influence the selection of post-grouting, quality assurance issues, and keys to successful implementation. Brown set this input against the background of his experience with design-build delivery and value engineering projects, and service as a contractor’s consultant and industry advocate for best practices.

Several factors influence the selection of post-grouting:

- Reliability of performance and design of the drilled shaft.
- Effectiveness in improving foundation performance.
Costs, especially with respect to the impact on field productivity, including management and execution. Costs associated with schedule delays can be significantly more substantial than those of other project changes. Designers must consider whether cost savings warrant increased risks.

Additional risk to the contractor because of increased project complexity and potential for issues with owner.

The following must be considered related to construction and quality assurance practices:

- Grouting is only one component of installing a good foundation.
- Variability should be expected and associated with the ground conditions, not necessarily the grouting, i.e., “only going to get what the ground will give you.”
- A grouted shaft is more reliable than an ungrouted shaft because grouting reduces construction variability.
- Unrealistic expectations by owners or owner’s engineers can discourage contractors from using post-grouting, or cause contractor to conduct grouting and/or testing activities that are unnecessary.
- Qualified and experienced post-grouting professionals must oversee the grouting process and prepare the documentation.
- The owner must have active involvement in quality assurance protocols to include activities such as maintaining good inspection records and providing qualified grouting supervision so that a foundation certification/stamp can be responsibly provided.
- Load tests should be conducted on ungrouted shafts since they have more variability than grouted shafts. More load tests are typically run on projects where problems are experienced or unexpected conditions encountered during shaft installation. It is important to consider the reliability of this sample set when analyzing data from these tests in relations to tests on other shafts installed without problems.
- Redundancy in the grout delivery systems, e.g., multiple pumps and gauges, is critical to ensure grouting continuity in the event of equipment breakdowns.
- The grout pressure applied during grouting should be appropriate for the specific need, accounting for shaft size and expected resistance. The trend line must be stable and reasonable. A loss of grout pressure occurs when the ground hydrofractures and grout travels up the side of the shaft. The contractor must have flexibility to modify grout water/cement ratio and open values to let grout circulate.
- A maximum top of shaft displacement should be stipulated to avoid too much movement or heaving the shaft. A small upward displacement of the shaft during grouting is desirable, but over 1/2-inch of movement is undesirable.
- It is important to recognize that strain gauges may not be indicating actual load. However, curvature can be extracted from the strain gauge readings, and axial load can be estimated.
- Sufficient grout volume is needed to ensure grout delivery and improvement at the bottom of the shaft.
- The grout volume for 1-inch of displacement can vary considerably, and large grout volumes may not be indicative of good performance.
Research Needs and Ongoing Studies  
*Prof. Erik Loehr (University of Missouri-Columbia)*

This presentation was based on findings from a two-phase project on post grouted drilled shafts funded by FHWA, and conducted by a team organized through ADSC: International Association of Foundation Drilling (ADSC). The Phase 1 work included a literature review, consultation with practitioners involved with post-grouting, collection and interpretation of results from full-scale load tests on post-grouted and conventional drilled shafts, numerical modeling to investigate and evaluate load transfer and improvement mechanisms for post-grouted drilled shafts, and development of design and construction recommendations. The Phase 1 report (currently unpublished) summarizes the current state of the practice for post-grouting of drilled shafts in the U.S., documents the analyses and evaluations performed in the study, and provides recommendations for future work. The Phase 2 work includes installation, grouting, and testing of full scale shafts. This second phase work is ongoing, and the final report is expected Spring 2016.

Loehr’s presentation focused on the improvement mechanisms that occur during post-grouting: pre-mobilization and ground improvement, and the assertion that considering these mechanisms separately can improve predictions and allow better post-grouting execution in field. These mechanisms are fully described in the Phase 1 report. Ground improvement through post-grouting occurs through densification, permeation, and the enlargement of the shaft tip. Pre-mobilization is improvement in shaft performance that results from load reversal during grouting and subsequent top-down loading (Fleming, 1993).

The presentation presented the bilinear idealization of the load displacement relationship during post-grouting and showed the breakdown of side resistance and base resistance. The redistribution of stresses during pre-mobilization improves shaft performance without increasing ultimate resistance. The degree of improvement depends on the load induced during grouting; therefore, load, as opposed to pressure, is the critical parameter to be assessed. Although grout pressure is a good indicator of load, there is not a direct correlation between grout pressure and load. Pre-mobilization is independent of material type or constitutive behavior, and may be more predictable than ground improvement. Dependent upon criteria used to assess the maximum load, larger or smaller improvement due to post-grouting may be expected.

Regarding other quality assurance parameters, there is a sound basis for using grout volume criteria, but recommendations should be used with engineering judgment. Upward displacement criteria are often unnecessarily strict.

**Post-grouting Effectiveness**  
*Prof. Gray Mullins (University of South Florida)*

Mullins’ presentation briefly overviewed design methods and then focused on field parameter monitoring during post-grouting. He presented methods for estimating base resistance due to initial grouting (Mullins et al., 2006) and stage grouting (Dapp and Brown, 2010). These design methods are dependent upon achieving a specified design grout pressure, and assume that the shaft tip area is fully grouted.
Field monitoring data provides information required for quality control and verification. All grouting parameters should be measured simultaneously to assess grouting effectiveness and ensure that the desired results are achieved. Idealized plots of grout pressure, grout volume, and shaft uplift (vertical displacement) are shown on Figure 7 (Winters, 2014). In general, green lines showing a diagonal trend away from the center indicate desired behavior and red lines trending horizontally or vertically indicate undesirable behavior for the reasons indicated. Eccentricity occurs when the shaft bottom is grouted in circuits; that is, one section of the shaft bottom is grouted at a time. Strain gauge readings may monitor non-uniform grouting. The presentation showed real time data plotting for two shafts where eccentric grouting manifests in the plot as horizontal and vertical trending lines. To minimize eccentricity, grout should be pumped simultaneously into as many lines as practical (at least on opposing sides of the shaft). It is important to recognize that initial grouting and stage grouting will provide different results.

Figure 7. Idealized plots of grouting parameters during post-grouting.

Shaft uplift is the strongest indicator of the global force emanating from the grout pressure. However, the top of shaft uplift may not always be able to be detected.

Grouting should be performed on cool shafts as concrete heat of hydration could flash-set grout in grout lines. Chilled water in the comparatively small diameter lines cannot offset the heat capacity in the shaft. It was suggested that retarders can be used in 1-inch diameter grout lines or use CSL tubes for post-grouting.
Closed Session Presentations
Quality Assurance Measures and Acceptance
Silas Nichols, FHWA

This presentation outlined FHWA’s perspective on quality assurance and acceptance processes for deep foundations, particularly related to post-grouted drilled shafts. An owner views acceptance as the means for justifying payment to a contractor. Quality assurance measures are influenced by

- Design and design verification (technique or demonstration shafts).
- Construction means and methods (submittals, contractor installation plans).
- Materials parameters (concrete and grout testing and sampling, manufacturer certificates).
- Construction control methods (tolerances, assuring contractor consistency and repeatability).
- Inspection and documentation (acceptance criteria, compliance with plans, documenting inconsistencies).
- Post-construction testing (load testing to verify predicted design loads, establish level of uncertainty in predicting resistance and establish controls for production foundations).

Shaft performance is impacted by shaft bottom cleanliness, prolonged exposure to slurries and excavation stability. Acceptance must be defined based on an understanding of the relationship between performance and means and methods.

Nichols encouraged the workshop attendees to consider the following questions:

1. Should the action of post-grouting be able to provide a direct indication of success of the effort?
2. Should acceptance be based on measurement of indicators that cannot be reliably controlled?
3. Are the current quality assurance metrics reliable enough shaft-to-shaft to consistently demonstrate successful post-grouting?

Caltrans General Practices for Foundation Acceptance and Specific Requirements for Post Grouted Drilled Shafts
Tom Shantz, Caltrans

Shantz outlined Caltrans’ overall approach to accepting driven and drilled deep foundations and then focused on specific acceptance considerations for post-grouted drilled shafts. For drilled shafts, different parameters are used for assessing quality of dry and wet holes. Dry holes are characterized as having less than 3 inches of water at bottom, with intrusion of less than 12 inches per hour. Non-destructive testing is not used on dry holes. The bottom is cleaned with a bucket (no air lift), and concrete is placed via free fall. Quality control tests include concrete gradation and slump tests. Quality assurance is built into the process by requiring conservative design.
For drilled shafts constructed in a wet hole, quality control tests include concrete gradation, slump and placement requirements, and drilling mud type, cleanliness, required head, and bottom clean out criteria are specified. Gamma-gamma testing is used for quality assurance. CSL is used to characterize anomalies identified by gamma-gamma testing. Sonic caliper is only used on test shafts. A shaft inspection device (SID) is used only if end bearing is relied on in determining design capacity.

Caltrans is comfortable with a conservative design. Considering a contribution from end bearing moves the design value less conservatively towards the ultimate load, but it is unclear how much closer. Unless a shaft is shallow and tipped in near-rock-like materials, Caltrans will often ignore end bearing for design capacity.

Typically, inspection tubes are tied to the cage and suspended 3 to 6 inches from the bottom of the hole. The source and receiver are located between 3 and 18 inches, respectively, above the bottom of the hole, so the bottom 12 inches of the shaft is unverified. Caltrans’ amendments to AASHTO LRFD limit end bearing to 50%$Q_{ult}$ (Figure 8), where $Q_{ult}$ is design capacity.

![Figure 8](image.png)

Figure 8. Caltrans definition of potential benefit from post-grouting.

Caltrans does not have standard specifications or special provisions for post-grouting of drilled shafts. Performance specifications are used, but include a lot of prescriptive influences depending on the grouting technique used. Quality assurance measures on production shafts are typically inferred from matching target values from test shafts; however, it is recognized that target values can vary significantly on a project as construction practices are refined. Post-grouting is used as another measure to help identify issues and to quantify skin friction limit on lower bound. While post-grouting provides some information about loading, it should not be considered a load test.
For the Gerald Desmond bridge project, the quality control parameters were determined from the test shafts, including water/cement ratio of grout mix, grout volume, grout pressure (maximum, sustained and residual), and top of shaft elevation. Due to a lack of repeatability on the Gerald Desmond Bridge, Caltrans Substructure Committee adopted this position: “It is suggested that Caltrans not allow the use of tip post-grouting for systems with low redundancy (higher risk) including Types I and II shafts, pile groups supporting single column bents, and pile extensions until further studies are conducted, and procedures are established and standardized to make the results predictable and repeatable.”

Studies are needed to refine resistance factors from current values that are back-calculated from allowable stress design using a factor of safety of 2. Caltrans is comfortable with these factors because no failures have been recorded due to capacity issues. No benefit is being taken due to load testing.

**Contractor Perspective on Influence of Post-grouting on Contractor Practices**

*August Beck (AH Beck)*

Beck provided opinion on the influence of the use of post-grouting on a contractor’s practices. It is important to note that this opinion does not necessarily reflect an industry consensus view. The following points were offered:

- A lot of problems can occur at the base of the shaft. He would not rely on end bearing in design without good quality control, CSL, gamma-gamma testing, load testing, or post-grouting.
- Some DOTs, e.g., Texas DOT, do not allow use of end bearing. Drilled shaft foundation designs may not be cost competitive without end bearing contributions, and foundations may be changed to driven piles.
- Post-grouting is a good verification tool, but post-grouting should be an indicator of performance, not an equivalent to a full load test.
- The contractor typically prefers a performance specification, but it is important to recognize that the contractor did not choose the site and has not performed the design.
- The contractor should be allowed to select the appropriate grout delivery system.
- Although the contractor can get equipment and materials into the ground, the contractor cannot know how the grout is distributed across the shaft cross section. Grout eccentricity during post-grouting occurs.
- A certain level of quality control forces the contractor to perform the post-grouting correctly. A good contractor likes a tough specification, i.e., one that is logical, reasonable and doable. A tough specification keeps post-grouting competition on a level playing field.
- Post-grouting is a niche technique, and the specification should require having a specialist, third party independent practitioner involved.
- Strain gauges are used effectively to indicate that load is being induced into the shaft from post-grouting. A few sacrificial strain gauges are inexpensive compared to the cost of a shaft.
- It is important to not push the limits of the test shaft because sometimes test shaft results are used to change how production shafts are judged.
• Non-destructive testing should be used to raise the standard and quality of the construction. CSL and gamma testing are extremely important and valuable techniques.

General Conclusions

The following general conclusions may be drawn from these discussions.

• Industry agrees that post-grouting can improve the performance of drilled shafts when properly controlled and used in appropriate conditions.
• There is variability in construction and acceptance of post-grouting for drilled shafts.
• Pressure, volume, and uplift are the three critical parameters that are currently measured during post-grouting.
• Strain gages and telltales provide valuable insight, but a precise value should not serve as a hard and fast acceptance criteria.
• The designer should set all grouting criteria with reasonable expectations, including considerations of necessary adjustments during construction to achieve design performance.
• Grouting system redundancy, including a back-up pump system, and efficient QA and acceptance procedures minimize the likelihood of delays.
• A grout monitoring system is encouraged on production shafts to demonstrate repeatability and determine solutions in real time. Manual measurements should also be performed for redundancy and verification. Post-grouting contributions from both ground improvement and pre-mobilization should be considered separately. Load, not grout pressure, is the primary parameter for pre-mobilization effects.
• The contractor should be responsible for selecting the grout delivery method.
• Post-grouting is a good verification tool, but post-grouting should be an indicator of performance, not an equivalent to a full load test or a proof test.
• Experience and qualifications of the personnel installing the drilled shafts and performing the post-grouting have a significant impact on the foundation performance. Pre-qualifications of experienced personnel should be used where permitted.
• Studies are needed to refine resistance factors from current values that are back-calculated from allowable stress design using a factor of safety of 2.
DISCUSSION

A small group of invited attendees held discussions related to acceptance methods, design and verification, and inspection requirements. Amplifying questions were developed on these topics, and the discussions focused on identifying areas of agreement and disagreement with the goal of establishing an industry consensus for preparing future guidance for practice and acceptance. Workshop attendees expressed various opinions, and consensus was reached on some topics and while disagreement remains on others. The report covers all of the discussions. Generally agreed upon conclusions are provided in the Summary and Conclusions section at the front of this report. It is important to recognize when reading the discussions below that the statements shown do not necessarily reflect consensus of the group.

Acceptance Methods

1. Why do post-grouted shafts get accepted? Rejected?
2. What is our current expectation for variability or uncertainty?
3. We currently measure volume, pressure and uplift as part of acceptance criteria. What is most important? Does this combination lead to consistency in constructed product?

Definition of Acceptance and Quality Assurance Goals

Acceptance indicates that the parameter being evaluated meets certain criteria to ensure adequate performance. Acceptance and verification procedures for a post-grouting program should be considered as part of the design process. Acceptance criteria should be established to assure design intent and that certain design objectives are achieved, and specifications are written to assure that construction means achieve these objectives. Two different questions should be asked when establishing the acceptance and verification program: 1) what tests will verify that the shaft meets the design criteria, and 2) which tests verify that the shafts are constructed correctly? CSL, for example, does not provide confirmation that design resistance is being achieved, but provides a check for anomalies, which verify the shafts are constructed properly.

Optimization, Risk, and Responsibility

With post-grouting, FHWA funded studies are aiming for a better understanding of mechanisms that impact design and to develop more cost effective methods that allow for optimized drilled shaft design. But, what are the costs versus risk for such optimization? It is important to consider other suitable optimization methods in addition to post-grouting, e.g., lengthening the pile. Base resistance is proportional to the square of the shaft diameter, and side resistance is proportional to diameter. It may be more effective to lengthen a shaft than to post-grout.

For a Caltrans project, the current structure policy is to limit application of post-grouting to redundant foundations. Caltrans is doing some in-house pilot studies to develop specifications for use, and when this is done and there is more information and familiarity with the processes, Caltrans may move to less redundant systems.
Currently, most post-grouting work is conducted in the design-build arena. Industry is concerned with Caltrans, or other agencies, writing policy that may unnecessarily restrict the use of post-grouting. By educating owners and practitioners with the current state of knowledge of post-grouting, reasonable constraints and control measures can be established, while recognizing that future studies will further develop and refine practice.

**Acceptance Criteria for Initial Grouting**

Correctly executed post-grouting is a relatively elaborate process. For an ungrouted shaft, acceptance is based on material testing and evaluations conducted after the shaft has been constructed. By contrast, post-grouting must be accepted based on parameters measured during the construction process. Criteria are set currently with reference to prior work or through test shafts. Because we do not completely understand the mechanisms for improvement due to post-grouting, additional quality control is needed. As more results become available and the body of knowledge increases, testing requirements can be adjusted to better accommodate acceptance needs. Procedures and measurements must be established such that engineering judgment can be used, but also provide a consistent or uniform process that can be implemented widely by all practitioners.

The group agreed that grout pressure, shaft uplift (vertical displacement), and grout volume are the primary parameters to be measured during post-grouting. Grout pressure is considered to be most important, followed by shaft uplift, and then grout volume. In general, parameter monitoring trends must be stable. If grout pressure and shaft uplift criteria are met, the post-grouting work should be acceptable. This assumes that a minimum volume of grout has been delivered to the tip of the shaft. To date, maximum shaft uplift criteria has been a limiting criterion to prevent potential deterioration due to excessive deterioration of side resistance; however, it is recognized that movement at the top of the shaft (or from instrumentation in deep slender shafts) provides assurance that loading at the base has mobilized side resistance, and thus some minimum amount of movement is desirable.

The grouting means and methods should be left to the contractors, but clear thresholds for acceptance criteria must be established. Clear thresholds help to avoid delays. When criteria are not met, a third party geotechnical firm should review the data and suggest additional investigation if needed for certification (as is done for conventional shafts).

**Grout Pressure**

- The design or target grout pressure should be a design element and a function of skin friction, shaft weight, soft layers, hydrofracture potential, soft/loose areas, and water table.
- A minimum grouting pressure should be determined as part of design, but it is desirable to exceed the minimum (except at test shafts). Pressure should be maintained over a sustained period of time.
- Grout pressure should be used as an indicator of performance. Selected design pressures should reflect consistently achievable minimum target pressures, while recognizing that, during production, it is desirable to exceed these design pressures, often to the highest pressure practicable.
• Measuring pressure is not always a good indicator of force at the tip of the shaft, and this is the parameter in which we are most interested for success.

• The design grout pressures should be verified during construction with load tests where practical. At load test shafts, the minimum target pressure should be achieved and not exceeded to verify performance at the minimum requirement. Consideration should be given to specifying a lower grout pressure for load test shafts.

• Soil and grout will relax when pressure is released; however, locking off the pressure may not necessarily avoid relaxation.

Shaft movement

• It was agreed that shaft movement is important to measure, but the question is where along the shaft to measure movement.

• A minimum top of shaft displacement requirement is not always feasible because high side resistance may prevent upward movement at the top of the shaft.

• In special cases, shafts with high side resistance may prevent detectible movement at the shaft top, shaft movement can be measured at bottom of shaft using telltales. In some cases, telltales at depth showed movement, but no movement was recorded at shaft top.

• For cases where shaft side resistance does not control, monitoring top of shaft displacement would be acceptable.

• Considering the cost of drilled shafts, the cost and effort for installing and monitoring telltales in test shafts and production shafts are considered incidental. As a minimum, install telltales in the test shafts to determine if they may be needed at production shafts.

• If upward shaft movement occurs, then an assumption can be made that the grout can flow across and cover the bottom of the shaft (cavity expansion). If the grout can cover the bottom of the shaft, then you can achieve more uniform pressure on base of shaft. Shaft movement also confirms some volume of grout was injected below the tip of the shaft and some load was transmitted to the tip.

• Currently, upward movement at the top of shaft has been commonly limited to ¼-inch to ½-inch. There was general consensus that more movement could be allowed without negatively impacting shaft side resistance. Results from the FHWA Phase 2 load testing program may provide supporting data for this assertion.

Grout Volume

• Volume is less critical to the success of post-grouting. However, it is important that net volume be specified and accurately measured to ensure that delivery lines are full and grout reaches the shaft base.

• A greater net grout volume is needed if a gravel distribution system is used due to the void space in in the gravel matrix.

• A target net volume can be calculated for the selected grout distribution system.

• The net grout volume criterion should be the lowest value necessary to verify grout flow to the base of the shaft. Specifying a high net volume value may raise unnecessary concern regarding the adequacy of a production shaft when the specified minimum volume is not obtained.

• Volume measurements are useful as a secondary control measure in that when volume increase coincides with upward shaft movement, grout coverage across the base, and thus load transfer across the base can be assumed.
The grout volume used is also related to the water/cement ratio. A typical range of water/cement ratio is 0.4 to 0.75. The contractor adjusts the water/cement ratio to thin or thicken the mix in accordance with grout take (volume injected). Specifying tight water/cement criteria could constrain the contractor. The contractor needs flexibility with the water/cement ratio to achieve the desired improvement from post-grouting.

Stage Grouting Considerations

Stage grouting is used for the following various reasons, and the responsibility for each of these lies with different parties:

- Initial grouting acceptance criteria were not met.
- Target minimum grout pressure criterion was set too high.
- Hydro-fracturing of the soil or grout flow up the side of the shaft prevents development of specified minimum grout pressure.
- Highly permeable soil stratum causes grout loss.
- Unanticipated ground conditions (more permeable soil strata).
- Construction equipment had problems (e.g., failure of grout pump).

Quality assurance requirements are different for initial grouting and stage grouting:

- Stage grouting is performed within specified time limits, a minimum of 3 to 4 hours after initial grouting and a maximum of 24 hours after initial grouting.
- Grout is allowed to set between grouting stages.
- Often higher pressures are achieved in stage grouting to re-initiate grout flow, but not always. Using the same pressure for both initial grouting and stage grouting may not induce the same load due to head loss through fractured grout and reduced area over which the grout pressure is applied. Although stage grouting may achieve the specified pressure criterion, the same load may not be getting into the shaft because the effective shaft bottom areas may not be the same as during initial grouting.
- Stage grouting probably provides more ground improvement benefit than preloading benefit. But overall some benefit is achieved.
- The goal in stage grouting is to seal off the bottom pathways of grout from hydrofracture or open formations like gravel and thereby allow pressure to build and improve the ground.
- There is more uncertainty in interpreting results of subsequent stages, therefore it is difficult to know if we are getting a connection between pressure and load.
- The presence of gravel in the bottom of the hole can make stage grouting more difficult and less effective.
- Top (or bottom) of shaft displacements, and strain gauge monitoring provide means for evaluating the effectiveness of stage grouting.

It is difficult to include stage grouting into a construction contract. Florida DOT has a stage grouting specification, and Wisconsin DOT has a specification that includes a pay item for stage grouting. The designer can mitigate the need for stage grouting by having a conservative (lower)
minimum grout pressure criterion, one or more borings at each shaft foundation location, and a lower minimum specified grout volume.

From a contractual point of view, stage grouting could be specified as a remedial measure for an initial grouting stage that does not meet the target grout pressure criterion. This could be similar to how, on design-build projects, remediation grouting is recommended when CSL results indicate anomalies at the base of a shaft. However, for stage grouting to be a viable remedial measure, the design, inspection and construction team must have sufficient expertise and be available to quickly review the installation records within the time constraints for stage grouting (typically a minimum of 3 to 4 hours to a maximum of 24 hours after initial grouting). A similar mechanism could be applied to uplift or other acceptance criteria.

Discussion was held on whether classifying stage grouting as a remedial measure is correct because it could imply that some task has not been executed correctly. As mentioned above, the contractor may not be solely responsible for non-compliance with the acceptance criteria. Since acceptance is a pay item, it is important to recognize the cost implications/reductions in payments that would be imposed for non-compliance. Consensus of the group was that stage grouting, when needed, should be considered a step in the post-grouting process, and not a remedial measure. In general, measures to minimize the need of stage grouting are desirable.

**Specifications and Submittals**

Different states have different requirements for quality assurance of drilled shafts. Caltrans has defined a comprehensive procedure for acceptance that includes identifying anomalies and determining if there will be an impact on performance. Florida DOT writes a letter certifying that the constructed foundation was built in accordance with the project requirements upon completion of quality assurance procedures.

Florida DOT has a standard technical provision that can be tailored to other project specific requirements for post-grouting. For Caltrans, routine load testing is not currently incentivized. Caltrans will need policies and standard procedures to take better advantage of post grouted drilled shafts.

The group suggested Caltrans start with collecting and reviewing existing DOT specifications. It was suggested that a library of specifications be prepared and reviewed.

There were differences of opinion expressed regarding performance versus method specifications in deep foundation construction. It was suggested during the meetings that Caltrans should specify means and methods since Caltrans has the design experience. It was noted that the grout volume risk is a disincentive for contractor to bid post-grouting. The general consensus, however, was that the means and methods of post-grouting should remain the responsibility of the contractor; the owner or designer would set performance criteria, not the means and methods for achieving these criteria.
A qualifications/experience requirement should be developed and included in specifications, when possible, and owners need to do a degree of due diligence to qualify contractors in the performance of post-grouting work.

Pricing and Pay Items

It was suggested by one of the contractors that projects should not have post-grouting bid as a lump sum item because contractor has risk with respect to grout volumes. A clear volume pay item must be established. One contractor suggested that contractors do not have the experience to price the post-grouting work. Bids will be priced higher to cover the contractor’s risk, and so there will be less economic benefit for doing this work while the technology is in the initial stages of deployment. For these projects, it is typical to bid the initial grouting on a per shaft basis, and stage grouting on a per incident basis with a minimum volume of grout injected. A second contractor indicated that grout volume is not a high pay item, and so should not be a high risk. It was suggested that at a worst case, the grout volume is 100 bags, which is not a significant cost item, and incidental to the cost of shaft installation and grouting.

Design and Verification

1. Based on research to date, FHWA is considering limiting the design of post-grouted drilled shafts to considering only the improvement attributed to pre-mobilization. What metrics should be required to assure that predicted resistance is consistently achieved?
2. Should there be effort placed on the “reliability” of any particular prediction method?
3. Should QA methods focus on something different that can correlate to success?

Design Methods

Some guidance on post-grouting is included in FHWA’s Geotechnical Engineering Circular (GEC) No. 10 Drilled Shafts: Construction Procedures and LRFD Design Methods (Brown et al., 2010). This guidance is relatively vague and therefore often misused. FHWA will modify GEC 10 eventually to include FHWA/ADSC report findings. The terms tip resistance and base resistance are used interchangeably within the documents.

The study outlines design methods typically used for predicting the nominal resistance of a post-grouted drilled shaft, including estimating a target grout pressure. Most methods include multiplying the nominal resistance for a conventional drilled shaft by an empirical multiplier to predict the nominal resistance for a similarly sized post grouted drilled shaft. The actual nominal resistance of the post-grouted drilled shaft is then demonstrated through a site-specific test program.

The group discussed the following approach to calculating the target grout pressure:

- The grout pressure is limited by side resistance and the self-weight of the shaft. The designer first estimates the nominal side resistance for the ungrouted shaft using any appropriate method as outlined in AASHTO (2012). Each method has a deflection
criterion embedded/included in the design, e.g., Davisson (1972), 5% of shaft diameter, etc.

- The maximum grout pressure is determined by dividing this estimated side resistance (including the self-weight of the shaft) by the shaft tip area (calculated based on the shaft diameter).
- Limitations due to potential for hydrofracture during post-grouting and unit base resistance should be considered. A maximum practicable pressure can then be determined.
- The target design grout pressure might then be reduced from the maximum practicable pressure to assure criteria can be consistently achieved.

Design methods for predicting the nominal base resistance of the grouted shaft from the nominal base resistance of the ungrouted shaft were also discussed. Note that the following captures general discussion, and is not intended to reflect guidance nor consensus:

- The base resistance of the ungrouted shaft is estimated using the empirical relationship of 1.2 $N_{60}$, where $N_{60}$ is the uncorrected standard penetration test (SPT) N-value for soil beneath the shaft tip (in blows/ft) <= 75 blows/ft (Reese and O’Neill, 1988).
- A grout pressure index (GPI) is calculated as the maximum sustained grout pressure divided by the nominal unit base resistance for an ungrouted shaft.
- The designer can estimate an improvement factor, e.g., a tip capacity multiplier (TCM), using the GPI and the maximum allowable displacement (expressed as a ratio of shaft diameter) using either the Mullins et al. (2006) or Dapp and Brown (2010) (for sands, post grouting would typically not be used in clays) approaches. It is important to note the assumptions inherent to both (including the backbone curve and ungrouted shaft unit base resistance equation by Reese and O’Neill (1988) and specific load test data) and the need to modify for actual conditions (geology, grouting process). The Mullins et al. and Dapp et al. approaches calculate resistances at different displacements, which may or may not reflect actual conditions. These methods are based on a disturbed shaft bottom, so the benefit of improving the bottom is already taken into account in these methods.
- The designer then calculates the nominal base resistance of the grouted shaft by multiplying the TCM by the estimated base resistance of the ungrouted shaft.

Based on past project experience, improvement factors for granular soils typically range from 2.0 to 3.0. As a design guideline, consideration should be given to limiting the improvement factor to no more than 2.5. Pressure should be limited to 750 to 800 psi. There is a greater risk of clogging when grout pressure exceeds 600 psi.

Side resistance typically increases with depth in a uniform sand deposit. Side resistance increases non-linearly as a function of increased effective vertical stress. Pressure applied to the base will mobilize side resistance. The applied grout pressure therefore confirms some or full side resistance is mobilized. If base resistance exceeds side resistance, the shaft will be displaced out of the ground. The positive effects of post-grouting are limited by the total side resistance.
Designers need to provide additional consideration to residual stresses locked in during grouting when interpreting bi-directional load test results on post-grouted shafts. The degree of base improvement is dependent on residual stresses. Not considering the residual stresses will under-represent the base resistance and over-represent the side shear resistance calculated from the load test data.

In addition to grout pressure, grout volume take should coincide as side resistance mobilizes. If a large volume of grout is injected, the soil is likely hydrofracturing. This may be less likely if a small grout volume is injected.

**Predicted versus Measured Performance**

The mobilized base resistance due to post-grouting can be estimated as the maximum sustained grout pressure multiplied by the shaft tip area (may be less for stage grouting). The overall nominal resistance of the post-grouted drilled shaft could be estimated by adding this mobilized base resistance to the estimated side resistance.

Separating ground improvement and pre-mobilization components during post-grouting allows for more reliable prediction than when these components are combined. Pre-mobilization is measurable and repeatable, whereas the ground improvement contribution may vary widely. The benefit from ground improvement may be significant (and potentially greater than pre-mobilization effects), particularly since it may correct any soil disturbance and consolidate soft sediments at the base of the shaft created during shaft construction.

Nominal base resistance is defined as the value of base resistance at the strength limit state, which is typically defined as the base resistance at a displacement equal to a percentage of the shaft diameter. Ultimate resistance can be defined by various means, which are not definitive.

Figure 9 provides a conceptual illustration of a mechanism by which post-grouting can improve nominal base resistance without any change to the backbone relationship of resistance and deflection. The solid curve is the base resistance versus displacement curve for an ungrouted shaft, which would provide a nominal base resistance, $R_{n,1}$ at a displacement associated with the nominal strength, $\Delta_n$. Consider a load applied at the tip to mobilize a resistance to point A (as with base grout pressure, for example) and then removed, resulting in an unloading to point B as shown. Upon a subsequent reloading from point B, the relationship of mobilized base resistance and deflection follows the reload curve, eventually returning to the backbone curve at values of mobilized base resistance exceeding point A. This reloading to a displacement associated with the strength limit state would result in a nominal base resistance $R_{n,2}$ that exceeds the magnitude of the nominal strength $R_{n,1}$ associated with the ungrouted base resistance. Ultimate base resistance is not specifically defined on this plot.
Figure 9. Conceptual illustration of a mechanism by which post-grouting can improve nominal base resistance.

The design method used is important even though the shafts are tested and verified. Design values are used to predict the grout pressure and establish the field testing process. The designer estimates a target pressure and converts it to base resistance that can be verified in the field. The design procedures are less important than the verification procedures. It is important when predicted design values are compared to measured values that results are compared to the constructed case. Shaft verification load testing should be specified for all post-grouting shaft applications.

Shaft resistance predicted from the various static analysis methods vary widely. Good data are needed to justify local/regional use of base resistance. It was suggested that instead of correlating field data with nominal resistance, perhaps grout pressure could be estimated directly from field characterization parameters (blow counts, etc.)

The question is how reliably can we predict load due to grouting at the shaft base and soil resistance at the bottom of the shaft? Strain gauges can give an indication of this load but they are not fully accurate because of stress distribution within the shaft, side resistance between the gauges and the bottom of the shaft, composite modulus, and non-uniform distribution across the bottom of the shaft, and that we are measuring stresses while grout is fluid which can be different than conditions after it cures. Measured strains are typically too low, and strain gradients are
present. The shaft area and modulus of concrete values must be estimated, and strain is not as high as suggested by values equal to pressure times modulus.

Gauge placement affects measured strain values. Strain gauges should be placed near the bottom of the shaft on the reinforcement cage, but not so close that the data is influenced by end effects. When gauges are far enough away, side resistance below the gauges diminishes the load at the level of the gauges. Side resistance predictions may be more reliable than base resistance estimates, although grout moving up the side of the shaft may significantly affect side resistance near the base of the shaft. When grout hardens on the side of the shaft, side resistance is improved. All of these factors make strain gauges a qualitative not quantitative indicator. The use of telltales is most reliable to determine shaft base movement.

The group discussed whether increased pressure continues to provide performance improvements or whether the relationship becomes asymptotic after a certain pressure, e.g., 400 to 600 psi. Understanding this mechanism could also provide insight into the stage grouting process, especially when stage grouting is used to reach a certain specified pressure criterion. Although there is an emphasis on achieving a target pressure, the influence of pressure is not known well. Since pressure is an important measure in the post-grouting process, this is an area where further research is needed.

Test Shaft Programs

The focus of a test program should be on verifying the design. The contractor has some constraints during the test program. Sometimes access limitations occur during the initial stages of the project, and the contractor may not have access to the entire site. The test shaft is not always in the optimum design location, but the test shaft should be installed in the poorest ground conditions.

Enough shafts should be tested to demonstrate means and methods in different site conditions. Similar to ungrouted drilled shafts, at least one test shaft should be conducted per site on any project to reduce the influence of site variability. Tests should be highly controlled and should be designed appropriately so that means and methods can be demonstrated and used successfully on production shafts. Caution should be used to ensure that the test shaft results are applicable to the production shafts. Contractor needs to have some ability to accommodate changes in shaft loads, lengths and diameters, etc., but test shafts with comparable features are required. Extrapolating data for shafts of significantly different lengths can stretch the applicability of the test shaft results.

A test shaft truly representative of the construction processes for the production foundations is needed, not one that is constructed to reach a maximal quality and capacity. For deep shafts, more pressure is needed to ensure that grout is under the entire shaft, and so the grouting criteria for that shaft will be different from shafts at much shallower depth. When stress and grout pressures are significantly different, we have less confidence in extrapolating the test results. Records need to note when an interpolated value is used, and this information should be reflected in the design method used.
Some judgment must be allowed in assessing whether the original test results can be used or modified. There needs to be an understanding of when there is enough change from the test shaft to warrant another test shaft for the different location. Truly changed conditions (size of shaft, ground conditions, etc.) warrant additional load tests.

It is recommended that the grouting parameters (grout pressure and volume) at load test shafts be restrained to avoid setting the bar too high for the production shafts. Since grout pressure is recognized as the most important parameter for assessing the success of post-grouting, there will be uncertainty in the adequacy of any production shafts that fail to achieve at least the grout pressure applied at the related test shaft.

Variability and Reliability

A high level of reliability is needed because there is inherent variability across sites and in grouting practices. If foundations are redundant, then individual shafts are less critical. If foundations are not sufficiently redundant, each shaft is more critical. The designer must consider variability in both the design and in the site conditions and use engineering judgment to set the grouting parameters and acceptance values to achieve acceptable results in all shafts. Some values could be too high for some and too low for others; for instance, a layer prone to hydrofracturing may limit the practicable grout pressure in one area, but that layer may not be near the base at other locations where higher pressures may be easily achievable. Additional testing may be needed to address wide variability on a project.

For ungrouted shafts, the industry has improved its construction methods, and less disturbance is being developed at the bottom of the shaft. But, even with less disturbance, an open drilled shaft excavation experiences stress relief. Post-grouting restores the stress conditions. It was agreed that post-grouting improves loose material at bottom of the shaft and provides a stiffer performance response. Grouting creates a more uniform response across the site if all shafts are grouted to at least the specified minimum pressure, thereby reducing variability in base resistance.

Standards are needed to assure the owner of the reliability and repeatability of the design and construction, and that the completed shafts meet the specified foundation performance requirements. DOT owners need assurance that the production shafts will perform as well as test shafts. For design-build projects there are different levels of risk between the owner, designer and contractor. If design-bid-build process is used, a more conservative design should be considered since contractor experience and capabilities are not known during design. For design-build, the owner needs to address requirements in the contract performance specifications.

Inspection Requirements

1. Are the current standards regarding drilled shaft construction sufficient if post-grouting will occur (e.g., bottom cleanliness)?
2. What does an inspector need to observe and record as part of post-grouting (in addition to normal shaft inspection)?
3. Should there be instrumentation requirements?

Shaft Bottom Preparation

The general consensus was that post-grouting should not be used to compensate for poor construction, and contractors should clean the bottom of every shaft in accordance with requirements for non-grouted shafts. Shaft bottom cleanliness requirements for post-grouted drilled shafts are the same as for any well-constructed shaft. The potential for sediment/soft or loose material to become trapped below the grout delivery system/plate/gravel pack due to less effective scouring by the tremied concrete must be recognized.

Grout Delivery System Requirements

Flat jacks are limited to smaller diameter shafts. Flat jacks promote more uniform initial pressure distribution along the bottom of the shaft, but they can be damaged easily. Sleeve ports or tube-a-manchette (TAM) systems also incorporate a plate. They can be used for any size shaft but are typically used for larger diameter shafts. TAM systems are more robust and have multiple semi-autonomous circuits in comparison to flat jacks that have multiple ports and a single diaphragm. The distribution system must be in contact with the bottom of the hole. The contractor should decide the most suitable grout delivery method.

A gravel bed can be used to level the shaft bottom, particularly for shafts excavated with a hammer grab. The irregular base created by the hammer grab can also be mitigated by airlifting, drilling tools, or tamping to provide more effective and repeatable base grouting. Rotary drilling methods usually provide flat shaft bottoms.

Gravel can add another variable to the process, so gravel pack and preparation needs to be similar for all shafts. A grouting system which includes gravel bedding should be demonstrated with load testing. Gravel requirements were discussed and include the following:

- Gravel must be sufficiently clean so that additional fines are not added to the shaft bottom.
- Gravel must be tamped down.
- A minimum gravel bed thickness of 4 inches is needed to level the hole bottom. (A thicker layer is needed for shafts excavated and completed using a hammer grab.)
- The bed must be thick enough to cover the scuff-ring height plus 2 inches. A thickness between 4 inches and 24 inches is recommended.
- A maximum gravel thickness of 24 inches is recommended, and a thinner layer is better. Larger gravel bed thicknesses increase overall required grout volume and could make reaching higher grout pressures more difficult.
- Since the thickness of the gravel layer may influence the performance of post-grouting, the gravel thickness at production shafts should be the same or less than the thickness at the corresponding load test shaft.

The grout tube and scuff-ring must be on the bottom. Overdrilling may be needed for the gravel layer since the post-grouting system is mounted on the bottom of the cage. The length of the
cage or the location of grout delivery system may need to be adjusted accordingly. Gravel may be used to mitigate overdrilling. The Schuyler Heim Bridge replacement project in the Port of Long Beach, CA, has a specification for this.

The type of tube used in the delivery system is important, and the following recommendations were offered:

- Delivery tubes must be equal to or greater than 1 inch ID.
- CSL tubes may be used (1.5-inch ID steel).
- PVC gamma-gamma tubes may be used (2-inch ID PVC), but the PVC tubes will limit the grout pressures that can be applied.
- It is important that hot shafts are not grouted to avoid flash set of the grout.
- CSL tubes are typically used because they are steel tubes; however grouting cannot be initiated until after CSL testing is complete.

Ideally, pressure and volume should increase steadily during grouting. The contractor should have flexibility to adjust the water/cement ratio to ensure steady pressure buildup. The inspector should note when the water/cement ratio of the grout changes and understand the effect of changing the water/cement ratio on the grouting process. He should know the approximate volume of grout needed for filling the delivery system, so that net volume injected can be calculated. Inspector should be documenting the work through inspection records.

Flow meters are used for grout injection, but are often unreliable. Tank meters are more reliable. All measurement systems should have a backup. Automated monitoring equipment is typically used and preferred due to its ease, economy and digital measurement trace (dependent upon shaft size and criticality), but key data should also be recorded on written records as backup. To measure pressure, volume, and displacement (perhaps in more than one place), use of a digital level is recommended.

**Displacement and Strain Gauge Measurement**

The following issues related to displacement measurement were discussed:

- Movement at the top of the shaft is always measured, but the shaft top does not move if side resistance is too high.
- For shafts with high side resistance, consideration should be given to using telltales extended to the bottom of the shaft.
- Strain gauges give a qualitative measure that load is being applied at bottom of shaft, and data should not be used to definitively quantify load.
- Strain gauges, telltales, or both should be used with demonstration shafts, load test shafts and for critical, non-redundant production shafts.
- Strain gauges could be installed in all shafts, but this may not be cost effective.
- Strain gauges should be placed near the shaft bottom, although the stress regime is variable at the bottom. Strain gauges are typically installed on 4-foot long sister bar, 1½ diameters above the shaft bottom, and readings are collected every 1 to 5 seconds.
• Resistance gauges are preferred, but vibrating wire gauges can also be used.

Submittals

There should be a submittal for entire post-grouting process, including

• Grout materials.
• Delivery system components and arrangement.
• Measurement systems.
• Grouting system redundancy.
• Construction process.
• QC/QA procedures.
• Qualifications and experience profile for the grouting personnel and inspector.
• Inspection plan prepared by the personnel grouting personnel in response to the design/specification.

The installation plan must be reviewed, and the inspector must ensure contractor compliance during construction. Detailed records are obtained by the grouting specialist. It is often difficult for the inspector to record the grouting data independently, and usually the inspector will rely on the grouting specialist’s records.
RESEARCH NEEDS

Additional research in stage grouting does not appear to be a priority for furthering the deployment of post-grouting to DOTs. Some topics discussed include:

- Continued studies to isolate post-grouting mechanisms (ground improvement and pre-mobilization) that contribute to improvement in drilled shaft performance due to post-grouting.
- To date, emphasis in practice has to be largely on achieving high target grout pressures, and there is not much data to determine whether similar improvement effects might be achieved at lower pressure. For instance, does the rate of improvement diminish after some percentage of the maximum pressure is achieved? Since pressure is an important measure and limiting grout pressure is sometimes necessary, this is considered to be a significant area for further research.
- A method to reliably measure force at the shaft base during grouting and to observe the migration of grout around the base area are desirable in addition to pressure measurements at the top of the shaft.
- The type of grout distribution system likely influences the results of post-grouting. Research is needed to compare the currently used grout distribution systems on performance of the completed shafts.
- Development of appropriate resistance factors for design of post-grouted shafts.
- Post-grouting imposes very high stresses on the soils beneath the shaft base. Does this cause increased creep under service loads?
- Consider research into a) how to reduce the need for stage grouting, and b) how to have greater confidence in the effectiveness of stage grouting when it is performed. Can we reduce the frequency of stage grouting by limiting grouting parameters, but without affecting the performance of the completed shaft? Do the higher grout pressures developed during stage grouting reflect true improvement and pre-mobilization, or are they simply the consequence of more resistance to grouting caused by the setting of the initial grout? Should the maximum time for performing stage grouting be reduced from 24 hours?
INDUSTRY FEEDBACK FORMS

Industry feedback forms were distributed for written input to the workshop, and an online survey for electronic feedback is posted on the DFI Drilled Shaft Committee webpage at http://www.dfi.org/commhome.asp?DRSH and http://survey.constantcontact.com/survey/a07ebk7769tjemzl3ue/start

The following industry feedback was received:

<table>
<thead>
<tr>
<th>NAME, COMPANY</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwight Metcalf</td>
<td>Excellent workshop</td>
</tr>
<tr>
<td>Kiewit Construction</td>
<td></td>
</tr>
<tr>
<td>Lisheng Shao</td>
<td>The key of shaft post grout is “control.” There are several advanced grout control systems in the grouting industry, such as i-grout, Intelligrout, etc. I suggest combining the experience/practice of the grouting industry with the drilled shaft industry.</td>
</tr>
<tr>
<td>Hayward Baker, Inc.</td>
<td></td>
</tr>
<tr>
<td>Tom Richards</td>
<td>Evaluate Castelli plots of capacity further. Consider pressure x volume (this is like input energy) versus load.</td>
</tr>
<tr>
<td>Nicholson Construction</td>
<td></td>
</tr>
<tr>
<td>Walter Paniagua</td>
<td>Which would be the QC/QA criteria for post-grouting end bearing slurry walls? Barrettes? This type of work is going on in Mexico City, nowadays.</td>
</tr>
<tr>
<td>Pilotec</td>
<td></td>
</tr>
<tr>
<td>Gerald Verbeek</td>
<td>Include what is done outside of the U.S.</td>
</tr>
<tr>
<td>Allnamics</td>
<td></td>
</tr>
</tbody>
</table>
OUTREACH AND DISSEMINATION

The audience for this report is FHWA and Caltrans, who will use this report as a summary of the state of practice described by subject matter experts for acceptance of post grouted drilled shafts. FHWA’s road map is outside the scope of DFI report.

A secondary audience for the report is the broader industry group with the goal of educating owners, practitioners and contractors on how to execute post-grouting work and how the work will be accepted.

Several outreach efforts were discussed including:

- Post report online through government and private website.
- Publish a *DFI Journal* article.
- Deliver presentations at regional DOT and Transportation Research Board conferences.
APPENDIX A: PARTIAL LIST OF ATTENDEES

Small invited group attendees who participated in the full workshop discussions are marked in yellow.

Bubba Knight (Loadtest)
Andrew Bro (Fugro)
Paul Axtell (Dan Brown and Associates, PC)
Ray Wood (Fugro)
Peggy Hagerty Duffy (ADSC/Hagerty Engineering)
Walter Paniagua (Pilotec)
John Lemke (Geodaq)
Ray Fassett (Condon Johnson and Associates, ADSC West Coast Chapter)
Allen Cadden (Schnabel Engineering)
Helen Robinson (Schnabel Engineering)
John Wysockey (Thatcher)
Al Rasband (Malcolm Drilling, ADSC President)
Tom Richards (Nicholson Construction Company)
Erik Loehr (University of Missouri-Columbia)
Mike Moore (ADSC)
August Beck (AH Beck)
Mike Muchard (Applied Foundation Testing)
Peter Faust (Malcolm Drilling)
Dan Brown (Dan Brown and Associates, Inc.)
Ray Castelli (WSP|Parsons Brinckerhoff)
Antonio Marinucci (Consultant)
Tom Shantz (Caltrans)
Amir Malek (Caltrans)
Sarah Skeen (FHWA)
Ryan Turner (Caltrans)
Tracy Brettmann (AH Beck)
Kirk McIntosh (AMEC)
Lisheng Shao (Hayward Baker)
Arthur Patch (Geokon)
Gerald Verbeek (Allnamics)
Don Robertson (Applied Foundation Testing)
Dylan (West Coast-based Helical installer)
Alex Gerki
Rusty Lucido (Shimmick)
Dwight Metcalf (Kiewit Construction)
Silas Nichols (FHWA)
Ben Rivers (FHWA)
Mary Ellen Bruce Large (DFI)
Gray Mullins (University of South Florida, via phone)
APPENDIX B: WORKSHOP PRESENTATIONS

Introduction and Workshop Purpose
Benjamin Rivers, FHWA

United States State of Practice for Post-Grouting Methods
Mike Muchard (Applied Foundation Testing)

Owner Perspective on Use and Acceptance of Post Grouted Drilled Shafts
Ray Castelli (WSP | Parsons Brinckerhoff)

Engineering Perspective on Use and Acceptance of Post Grouted Drilled Shafts
Dan Brown (Dan Brown and Associates, PC)

Research Needs and Ongoing Studies
Prof. Erik Loehr (University of Missouri-Columbia)

Post-grouting Effectiveness
Prof. Gray Mullins (University of South Florida)

Quality Assurance Measures and Acceptance
Silas Nichols, FHWA

Caltrans General Practices for Foundation Acceptance and Specific Requirements for Post Grouted Drilled Shafts
Tom Shantz, Caltrans
Workshop: Quality Assurance for Post-Grouted Drilled Shafts
Why a workshop on QA for PGDS?

1) Caltrans and other DOTs are interested in QA
Evaluation and Guidance Development for Post-Grouted Drilled Shafts for Highways

- Primary objectives
  - Bound use of post-grouting for current state of knowledge
  - Quantify improvement mechanism(s) for post-grouting
  - Establish design methodology(ies) for appropriate use
  - Provide control/assurance/verification measures
Why a workshop on QA for PGDS?

1) Caltrans (and other DOTs) are interested in QA
2) Timely to FHWA/ADSC development efforts
3) DFI’s 2015 International Conference on Deep Foundations – Oakland, CA
Workshop Objectives

- Identify and summarize the state of the practice for quality assurance in post-grouting
- Identify gaps and needs in quality assurance that should be addressed for successful use of post-grouting
Set your minds at work on...

- What we know…and don’t know
- How we design and verify expected performance
- What acceptance criteria should look like
- What control measures, assurances and inspection requirements are necessary to adequately account for reliability and performance of post-grouted drilled shafts.
Presentations

State of the Practice: Design and Construction
- Mike Muchard, Applied Foundation Testing
- Ray Castelli, PB Americas Inc
- Dan Brown, Dan Brown and Associates

QA Requirements: What to Measure
- Erik Loehr, University of Missouri-Columbia
- Gray Mullins, University of South Florida
Post Grouted Drilled Shafts
Overview of Current Techniques

By: Mike Muchard, P.E.
Applied Foundation Testing, Inc.
Review of Post Grout Experiences

- 36 Bridge Projects
- 19 State DOT’s
- 32 Load Test Programs
- 1,800 Shafts Grouted to Date

- Alabama
- Arkansas
- California
- Colorado
- Florida
- Hawaii
- Indiana
- Iowa
- Louisiana
- Minnesota
- Mississippi
- Missouri
- Nebraska
- North Carolina
- South Carolina
- Texas
- Utah
- Virginia
- Wisconsin
Digital Survey

Grout Lines

Strain Gages

Grout Distribution Plate

Injected Grout

Pressure Transducer

Volume Measurement

Grout Plant

Grout Monitoring System
Stage Grouting

Stage 1
Initial Grouting

Flushing

Stage 2
Re-Grouting
Why Base Grout

• Increase Usable End Bearing
  • Pre-load Base
  • Improve Soil Below Base
    • Compaction
    • Permeation
  • Increase Tip Area (some cases)
    • Upward Grout migration increases shear in lower portion of shaft
• Decrease Settlement
• Heighten Reliability in Tip Resistance
• Reduce Shaft Length or Diameter
• Make more Constructible Reduce Risk
• Save Time and Money
Focus of the Rest of Presentation

• Grout Systems in Current US Practice
  • Flat Jack
  • Tube-a-Manchette (TAM)
• Grout Equipment
• Grout Mix
• Measure of Grouting Performance:
  • Data Acquisition
  • Instrumentation
Grout Distribution Systems
Flat Jack Type
Grout Distribution Systems
Tube-a-Manchette w/Plate
Record Size Grout Plate

Copyright (2013) Applied Foundation Testing
Use of Gravel in Post Grouted Drilled Shafts

- Aid Grout Distribution
- Contoured Shaft Bottom
- Overdrill Correction

Sleeve-Ports Below Steel Plate with Gravel Pack, Sliwinski and Fleming, 1984
Placing Gravel Bedding
Tube-a-Manchette with Gravel Basket

Pre-Load Cell with Gravel Pack, Bolognesi and Moretto, 1973
Tube-a-Manchette / without Plate
Summary of Grout Systems

• FlatJack
  • Grout acts on area of plate at the same time
    • Benefit and also limitation – (I’ll explain later)
  • Small diameter shafts only
  • Requires separate grout tubes
  • Not conducive to stage grouting
  • Not very robust
Summary of Grout Systems

- TAM w/ Plate and w/ Gravel Bedding
  - Redundancy (through multiple independent U-tubes)
  - Robust
  - Well suited for stage grouting
  - No limitation on shaft diameter
  - Allows use of existing CSL tubes
  - Grout may not act on entire plate area at the same time
    - (Zone Coverage) Benefit and perceived limitation
  - Gravel bedding aids in grout distribution

- TAM with Gravel Basket
  - Way to circumvent gravel bedding
  - Difficult to stage grout

TAM without Plate – not used in USA
Grout Mix Designs

• Portland Cement and Water
• No Sand
• Water / Cement Ratio 0.75 to 0.4
• Admixtures sometimes
• Typical strength requirement 2,000 to 2,500 psi
• Sampling and testing per ACI
Variety of Grout Equipment
Redundant Pumps
Standard of Practice - Grouting Criteria

1) Grout Pressure
   1) Minimum value for some duration such as 2 minutes
   2) Can vary based on load demand of shaft
   3) If pressure can not be achieved stage grout

2) Upward Shaft Displacement
   1) Most common 1/8” to ¼” at Shaft Top
   2) If limit reached stop and prepare for stage grouting
   3) Value resets for each subsequent stage

3) Grout Volume
   1) Minimum only to assure no line blockage
   2) Upper limit field determined for stage grouting
QA/QC Measurements During Grouting

- Grout Pressure
- Upward Displacement
- Grout Volume
- Strain Gages (Optional)
  - Multi-Axis Plots
- Real Time
- By Experienced Individual who can interpret data in the field and make immediate decisions
Post Grout Field Log

- Capture a range of measurements that adequately depicts the grouting event.
QA/ QC Instruments

- Pressure
- Displacement
- Grout Volume
Optional Instrumentation Used

- Strain gages
- Telltales
- Pressure Cells (For Research)
Grout Pressure Measurements
Grout Pressure and Volume
Grout Pressure and Displacement
Strain Measurements and Grout Pressure
Single Circuit
Grout Pressure and Volume

[Graph showing grout pressure and volume over time]
Example - Grout Measurements Indicating Problems
Topics for Discussion

- Many ways to successfully post grout – leave up to specialist / contractor to demonstrate method
- Grouting criteria with reasonable expectations
- Grout Monitoring System encouraged on production shafts to demonstrate repeatability and determine problems in real time
- Strain gages / telltales provide valuable insight but a precise value should not serve as a hard and fast acceptance criteria
The End

Applied Foundation Testing, Inc.
Post Grouted Drilled Shafts Owner Concerns

Ray Castelli

October 15, 2015
Generally Accepted Principles

- Improved End Bearing Resistance
- Early Mobilization of Resistance
- Best Suited for Granular Soils
Owner Concerns

- Lack of Reliable Design Methods
- No Standards for Base Grouting
- Influence of Grouting Method (Delivery System, Grout Mix, Grouting Procedures, Lock Off Pressure?, etc.)
- Influence of Shaft Construction Methods
- Reliance on Pressure during Staged Grouting
- Limitations of QC Methods at Production Shafts
QC Parameters

- Minimum Grout Pressure (Initial & Staged)
- Minimum Grout Volume
- Grout w/c Ratio Range
- Maximum Top of Shaft Displacement
- Strain Gages Near Bottom of Shaft (Demo & Test Shafts)
Influence of Grout Delivery System

Base Resistance (MN)

Downward O-Cell Displacement (mm)

1 mm = 0.3937 in.  Audubon Bridge, LA  1 MN = 224.7 kips
Limitations of Grout Pressure Criteria

Audubon Bridge, LA

![Graph showing the relationship between grout pressure and resistance/displacement. The x-axis represents grout pressure (psi) ranging from 400 to 1000 psi, while the y-axis represents resistance/displacement (ksf/inch) ranging from 0 to 120. The graph shows a scatter plot of data points at various grout pressures and resistance/displacement values.]
Limitations of Strain Gages

Audubon Bridge, LA
Limitations of Strain Gages

Audubon Bridge, LA
Limitations of Grout Volume Criteria

Audubon Bridge, LA
Limitations of Grout Volume Criteria
Limitations of Grout Volume Criteria

Gerald Desmond Bridge, Long Beach CA
Limitations of Shaft Displ. Criteria

- High Side Resistance: Little/No Top of Shaft Displacement
- Low Side Resistance: Maximum Displacement Reached Before Achieving Minimum Grout Pressure
Creep

Honolulu Transit Project

Apparent Creep Limit
1,300 kips at 0.07 inches displacement

4 to 8 Minute Creep (in)

O-cell Load (kips)
Design Standards

- Develop & Adopt Design Standards
- Design Methods Need to Better Predict Drilled Shaft Performance
  - (Performance Influenced by Grout Delivery System Used & Construction Method)
- Define Appropriate Resistance Factors
Construction Standards

- Qualifications of Grouting Specialist
- Consistency of Shaft Installation
  - Shaft Excavation
  - Bottom Cleaning
  - Grout Delivery System
- Consistency of Grouting Procedures
  - Grout Mix
  - Grout Pressure
  - Re-Grouting (tube flushing; time limits)
Construction Standards

- Requirement for Demo & Test Shafts
- QC Verification for Production Shafts
  - Inspection of Shaft Installation
  - Grout Properties
  - Grout Pressure > Pressure at Test Shafts
  - Minimum Grout Volume (only to verify flow)
  - Max. (& Min.) Upward Shaft Displacement
- Instrumentation Monitoring
  - Top of Shaft Displacement (Precision)
  - Telltale for Shaft Bottom Displacement ??
  - Strain Gages at Bottom of Rebar Cage ??
Final Thoughts

- Further Research Needed
- Standards should not be Difficult or Costly to Implement
- Limitation of Codes
- Role for Project Geotechnical Engineer
- Need for Engineering Judgment
Thank You
Perspectives on Base Grouting of CIDH Piles

Dan Brown, P.E., PhD
Outline

- Factors influencing selection of base grouting
- Q/A issues
- Keys to successful implementation
My perspective

- Responsible designer, often with design-build delivery or VE proposal
- Contractor consultant
- Industry advocate for best practices
Factors influencing selection of base grouting

- Reliability
- Effectiveness in improving foundation performance
- Costs, including (especially) impact on productivity
- Risks

![Graph showing load tests and downward displacement for grouted and non-grouted shafts.](image)
Q/A issues

- Pressure achieved during grouting (appropriate for specific need) and trend line is stable, reasonable
- Upward displacement of shaft
  - Small movement good; upward over ½ inch undesirable
- Enough volume to ensure grout delivery to base
- Oversight & documentation by qualified and experienced base grouting professional
Keys to successful implementation

- Oversight by qualified and experienced base grouting professional
- Redundancy in grout delivery system
- Stage grouting plan & ability to implement as needed
- Flexibility in the design to accommodate variability in conditions
Shafts constructed with Oscillator and Grab

Utilized Gravel Bedding between 6” and 24” in thickness

Sleeve port delivery with four circuits
Honolulu

Mobilized Unit End Bearing
Test Shaft 7T - HHCTC Farrington Guideway - Waipahu, HI

90ksf = 625psi

With $E=4,000\text{ksi}$,
$65\mu\varepsilon \approx 260\text{psi}$
What is it that I actually worry about?

- Damage to grout delivery during construction
- Grout system plugs during grouting
- Hydrofrac along sidewall or to a weak seam
- Unrealistic expectations or acceptance requirements by others
QA to Owner

- Inspection records and grouting supervision
- Responsible EOR Certification

4 October 2012

Parsons Transportation Group, Inc.
Baldwin Point Building
2420 Lake mantle Avenue, Suite 450
Orlando, FL 32814

Attn: Ted Davidson, P.E.

Re: Certification for Shaft 118 WB
Lee Roy Selmon Crosstown Bridge Widening and Deck Replacement
Tampa, Florida

DBA Project No.: DBA-10-006D
FPN: 416361-2-32-01
Bridge No.: 100332 (WB) and 100333 (EB)

Mr. Davidson:

The 3.5 ft nominal diameter shaft at Pier 118 WB has been constructed, and quality testing has been completed. It is the opinion of DBA that this shaft meets the resistance and integrity requirements.

The construction/concreting logs and the mini-SID inspection report are included as ATTACHMENT 1. The CSL Testing results are included as ATTACHMENT 2, and the Thermal Integrity Testing results are included as ATTACHMENT 3. To follow is a summary of construction and testing of this shaft:

- Casing tip estimated Elev. 42 ft, while actual was Elev. 41.74 ft (0.26 ft less).
- Shaft design tip was Elev. 51 ft. (Adden. 2 Rev. 2), while actual was Elev. -31.04 ft (essentially equal to).
- The mini-SID inspection passed.
- No construction/concreting issues were noted.
- The CSL and Thermal testing did not indicate any significant integrity deficiencies.

Regards,

Steven D. Dunn, P.E., Ph.D.
Florida PE No. 59298
Final Thoughts

- Base Grouting is a great tool
- Effective implementation requires engineering involvement and skilled, experienced specialists
- Please don’t kill it with unrealistic expectations or requirements
Improvement Mechanisms for Post-grouted Drilled Shafts

J. Erik Loehr
University of Missouri & Dan Brown and Associates

DFI-FHWA Workshop on Quality Assurance for Post-grouted Drilled Shafts
Oakland, CA
October 15-16, 2015
Improved performance for PGDS can be attributed to two general mechanisms:

- **Ground improvement**
  - Densification
  - Permeation
  - Enlarged tip
- “Pre-mobilization”

Separate consideration can lead to improved predictions and execution.
Top-down Loading – Conventional Shafts

Load (kips)

Tip Resistance (kips)

Displacement (inches)

Side Resistance (kips)

Displacement (inches)
Loading due to post-grouting

![Graph showing loading due to post-grouting with two charts: one for Side Resistance (kips) vs Displacement (inches) and another for Tip Resistance (kips) vs Displacement (inches).]
Top-down Loading - PGDS

- Side Resistance (kips) vs. Displacement (inches)
- Tip Resistance (kips) vs. Displacement (inches)
- Load (kips) vs. Displacement (inches)
Characteristics of Pre-mobilization

- Improves performance without increasing ultimate resistance
- Redistribution of usable resistance
- Degree of improvement dependent on bi-directional load induced during grouting
- Independent of material type or constitutive behavior
- More predictable than ground improvement (??)
Influence of Induced Load

![Graph showing the influence of induced load on displacement](image)

**Load (kips)**

**Displacement (inches)**

- Conventional
- 200 kips
- 400 kips
- 600 kips
- 715 kips

**Davisson Criterion**

10% Diameter
Load Transfer for PGDS
Load Transfer with Relaxation
Improvement with Relaxation

Load (kips)

Displacement (inches)

Conventional

715 kips
Ground Improvement Ratio, \( G/\bar{R} \)

- Clay Cases
- Sand Cases

<table>
<thead>
<tr>
<th>Location</th>
<th>GIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAMU Sand</td>
<td>0.0</td>
</tr>
<tr>
<td>UH Sand</td>
<td>0.2</td>
</tr>
<tr>
<td>Broad. Viad.</td>
<td>0.4</td>
</tr>
<tr>
<td>PGA Blvd.</td>
<td>0.6</td>
</tr>
<tr>
<td>TAMU Clay</td>
<td>0.8</td>
</tr>
<tr>
<td>UH Clay</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Legend:**
- Clay Cases
- Sand Cases
“Total” Improvement

Total Improvement Ratio, TIR

Clay Cases
Sand Cases

TAMU Sand
UH Sand
PGA Blvd.
TAMU Clay
UH Clay
Broad. Viad. O-Cell
Zoo CTS3-4
Zoo CTS1-2
Zoo WTS1-2
Implications for QA/QC

- Maximizing induced load is key to performance
- Upward displacement is not a bad thing
Personal Perspectives on QA/QC

- Pressure criterion is logical, but
  - not always a one to one correspondence with load
  - have to carefully consider pressure that can practically be achieved

- Volume criteria also have a sound basis, but
  - Historic application appears to be somewhat ad hoc
  - Should be made thoughtfully

- Upward displacement criterion is often unnecessarily strict
Thanks for your attention
Grouting Effectiveness
Construction QA/QC of Post Grouted Shafts

Gray Mullins, Ph.D., P.E.
Problem Statement

- Post grouted drilled shaft tips have amazing benefits:
  - increased end bearing,
  - reduced foundation cost,
  - increased design confidence, etc.
- However, grouting must be effectively performed requiring field monitoring measures to aid both quality control and verification.
Grouting Processes

- **Single stage**
  - Grout pressure is achieved in first application.

- **Multi-stage (stage grouting)**
  - Grout pressure is not achieved in first application requiring subsequent cycles/stages to achieve design pressure
Design Options (Conservative)

- **End Bearing** = \( \phi A_{tip} P_{grout} \)
  - \( A_{tip} \) = Area of the shaft tip
  - \( P_{grout} \) = Applied grout pressure
- Approximate 3 times more capacity than ungrouted tip
- Proof tested to design capacity
- Applicable to stage grouting process
- \( \phi \) not properly determined
Design Options (Empirical)  
Mullins et al. 2006; Dapp and Brown 2010

- **End Bearing = φ TCM qungrouted**
- Up to 5-10 times more capacity than ungrouted tip
  - Mullins et al developed from tests on shafts grouted with single stage
  - Dapp and Brown cite use of stage grouting resulting in lower predicted strength equation
- φ not properly determined
Design Methods

- Methods depend on achieving a specified design grout pressure

- Require grouted area to fully form beneath shaft tip.
Present Quality Control Measures

- Must achieve and hold design grout pressure.
- Must place a minimum net grout volume to indicate sufficient grout area (soil dependent)
- Should stay within safe uplift limits (soil dependent; wide range of acceptability)
- Present methods do not verify effectiveness
Effective Grouting

- Should show increase in pressure with increase in volume
- Should show increase in uplift (or strain) with increased pressure
- If both above are true, then increases in volume are registered as increases in uplift

Large amounts of scourable or liquefiable overburden make strain more appropriate than uplift measurements
Grouting Concept
Normal Balanced Grouted Shaft Design in Sand
(Side Shear Controlled)

Mullins and Winters 2004
Normal Grouting Response

Grout Pressure

System Blockage

Side Shear Control or Survey Error

End bearing Control or Piping

Shaft Uplift

Grout Volume

End bearing, Piping or Side Shear Control

Grout Pressure

System Blockage

Survey Error

Normal Grouting Response

NOTE:

(1) All graphs should demonstrate a diagonal trend away from the center.

(2) If any one of the graphs demonstrates a horizontal or vertical trend confirmed by a second graph, the post grouting process has become ineffective for the reason shown.

Winters 2014
Increased Volume w/o pressure or displacement
Increase Pressure w/o volume or displacement
Example 2
Toe Strain Gages
Thermal Integrity Profiling
Confirmed more grout on one side

Before Grouting

After Grouting

Bottom of Shaft
Multi-Stage Grouting

- Note change in P-V slope
- Original grout bulb acts to distribute shaft tip pressure to a lesser value at soil
- Second Stage produces pressure to shaft tip but no new pressure to soil
- No further soil improvement is achieved
- Second Stage DOES PROOF LOAD to that level (e.g. $P_{\text{grout}} A_{\text{tip}}$)
Conclusions

- Field monitoring and plotting of P, V, and U as shown can directly confirm effective grouting.

- However, grout should be pumped into as many lines as practical (at least opposing sides).
Conclusions

- Uplift is the strongest indication of global force emanating from grout pressure

- However, unbalanced designs with large amounts of scour-able or liquefiable overburden need an alternate measurement as top of shaft uplift may not be detectable
Conclusions

- Multi-stage grouting is not the same as single stage grouting.
- Supported by lower TCM value derived for stage grouted shafts (Dapp and Brown 2010)
- Design should account for the use of stage grouting (if used) at design phase or effects should be shown by test shaft
Conclusions

- Where possible grouting should be performed on cool shafts to prevent flash-set grout line blockages.
- For test programs on fast track schedules, use chemical retarders or larger grout lines less prone to blockage.
- Chilled water or grout in small grout lines cannot offset heat capacity of shaft.
References


Questions

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Quality Assurance and Acceptance of Drilled Foundations

Silas Nichols
Principal Geotechnical Engineer
Federal Highway Administration
How We Define Acceptance

• Means for justifying payment to a contractor

• Influence by several components:
  • Design and design verification
  • Construction means and methods
  • Materials quality assurance
  • Construction control methods
  • Inspection and documentation
  • Post Construction Testing
Quality Assurance Measures

Review of Contractor Installation Plans
  – Details means and methods

Technique or Demonstration Shafts
  – Contractors ability to perform function

Load Test Programs
  – Verify predicted design loads
  – Establish level of uncertainty in prediction of resistance
  – Establish controls for production foundations
Quality Assurance Measures

Visual Inspection and Documentation
- Compliance of construction activities with installation plan and agency governance
- Document inconsistencies in construction

Materials Testing
- Concrete sampling and testing
- Slurry sampling and testing
- Manufacturer certifications
Quality Assurance Measures

Post-Construction Evaluations
- Assure contractor consistency
- Assure consistency within element

Additional Issues
- Tolerances and acceptance criteria
Issues and Concerns

• Note that there is no such thing as a perfect drilled shaft
• Acceptance requires understanding relationship between performance, and means and methods
• Drilled shaft performance impacted by:
  – Shaft bottom cleanliness
  – Prolonged exposure to slurries
  – Ability to maintain stability of the excavation
Effect of Post-Grouting

1. Should the action of post-grouting be able to provide a direct indication of success of effort?

2. Should acceptance be based on measurement of indicators that cannot be reliably controlled?

3. Are the current quality assurance metrics reliable enough shaft-to-shaft to consistently demonstrate successful post-grouting?
Thanks!

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Workshop Discussion Slides
Acceptance Methods

1. Why do post-grouted shafts get accepted? Rejected?
2. We currently measure volume, pressure and uplift as part of acceptance criteria. What is most important? Does this combination lead to consistency in product?
3. What is our current expectation for variability or uncertainty
Design and Verification

1. FHWA is considering limiting the design of post-grouting to only the pre-mobilization at the tip. What metrics should be required to assure that predicted resistance is consistently achieved?

2. Should QA methods focus on something different that can correlate to success?

3. Should there be effort placed on the “reliability” of any particular prediction method?
Inspection Requirements

1. What does an inspector need to observe and record as part of post-grouting (in addition to normal shaft inspection)?
2. Should there be instrumentation requirements?
3. Are the current standards regarding drilled shaft construction sufficient if post-grouting will occur (e.g., bottom cleanliness)?
Overview of Caltrans Quality Assurance Practices for Deep Foundations

FHWA/DFI Workshop on Quality Assurance for Post Grouted Drilled Shafts
October 15-16, 2015  Oakland CA

Tom Shantz, P.E., G.E.
Caltrans Division of Research, Innovation, and System Information
tom.shantz@dot.ca.gov
Driven Piles

Quality Assurance focus -> Axial capacity

**Standard Plan pile ($\phi < 18''$):**  
Energy Method (Mod. Gates)  $\rightarrow$  Pass....Accepted  
\[\downarrow\]  
Fail  $\rightarrow$  PDA  $\rightarrow$  Pass....Accepted  
\[\downarrow\]  
Fail  $\rightarrow$  Static Load Test  $\rightarrow$  Pass....Accepted  
\[\downarrow\]  
Fail  $\rightarrow$  redesign

**Non-std. plan pile $18'' < \phi \leq 36''$:**  
PDA  $\rightarrow$  Pass....Accepted  
\[\downarrow\]  
Fail  $\rightarrow$  Static Load Test

**Pile $\phi > 36'':**  
Static Load Test

Engineer can require PDA or Static Load Tests in Special Provisions (regardless of pile dia.)
Driven Piles

On larger projects, static load tests will be used to calibrate GRLWEAP via PDA/CAPWAP to generate field acceptance curves. (In some cases CAPWAP predictions will be used instead of static load tests.)
Driven Piles Summary

Quality Control specs...

• Measurement of hammer stroke or bounce chamber pressure

• Specs on use of pile cushions and WEAP analysis to avoid overstressing the pile

• Use of predrilling and center-relief drilling

Quality assurance -> Modified Gates / PDA / Static Load Test. Driving pile to tip elevation
Dry holes (< 3” water at bottom, intrusion < 12” per hour ):

- Visual inspection from top of hole
- No non-destructive evaluation (no NDE)
- Bottom cleaned with clean out bucket...no air lift
- Concrete placed free fall

QC -> concrete gradation, slump

QA -> ...
Drilled Shafts - CIDH (Cast In Drilled Hole)

Wet holes:

• QA relies primarily on gamma-gamma testing
• Cross hole sonic used only to characterize anomalies identified by gamma–gamma testing
• Sonic caliper is used only on test shafts
• Shaft Inspection Device (SID) is used only if end bearing is used for design capacity.

Courtesy of Dan Brown and Associates
Gamma – Gamma testing

2” PVC inspection tubes are required (about 1 tube per foot of diameter).

Radius of detection
3” to 4.5”
Gamma – Gamma testing

Counts correlate to density

Gamma-Gamma Probe

Access Tubes
Cast into Shaft

Read-out Unit

Detector

Radioactive Source

152 pcf
Caltrans identifies anomalies as 0.5 feet of consecutive readings below 3 standard deviations.

Any anomalies are forwarded to various functional units for input on mitigation and need for cross-hole sonic testing.
Evaluation of Anomalies

Potential geotechnical, structural, and corrosion impacts are assessed

Decision is made to either require repair or allow payment deduction
Wet Spec Summary

Quality Control specs...

• Concrete gradation, slump, placement

• Drilling mud type, cleanliness, required head

• Bottom clean out

Quality Assurance-> integrity testing

Performance spec, not a method spec
Post Grouting of Shafts

- No Standard Specifications or Special Provisions
- Gerald Desmond Br. -> QC parameters determined from test shaft

Quality Control ...

- Grout mix (water-cement ratio)
- Grout take
- Grout pressure (max, sustained, residual...)
- Top of shaft elevation

Quality Assurance -> inferred from matching target values from test shaft

Challenge: Target values can vary significantly across a job site as well as over time as construction practices are refined.
Substructure committee position on use of post grouting

“It is suggested that Caltrans not allow the use of tip post-grouting for systems with low redundancy (higher risk) including Types I and II shafts, pile groups supporting single column bents, and pile extensions until further research is conducted, and procedures are established and standardized to make the results predictable and repeatable.”
Utilization of End Bearing for Design

Unless the shaft is shallow and tipped in near-rock-like material, the engineer will often **ignore** end bearing for design capacity.

Caltrans amendments to AASHTO LRFD limit end bearing to 50% $Q_{ult}$. 

~9”-18” unverified
Potential benefit of post grouting

End Bearing

$Q_{ult}$

Post grouting

$\delta Q$

Net increase for Caltrans wet spec shafts

50% $Q_{ult}$ assumption

5% $Q_{ult}$ assumption

0% $Q_{ult}$ assumption

Settlement at base ($\Delta/B$)
Improve reliability by ...

- Requiring use of near-tip strain gauges in a portion of production shafts?
- Limiting grout pressures to “modest” levels?
Thank You
Verification

- How many strain gauges (SG) per shaft?
- What type?
- SG attachment. Sister bar? SmartPile type?
- What elevation? (Near tip concrete will be non-uniform)
- Required percentage of instrumented production shafts (non-redundant->100%, < 6 shafts -> 50%, > 20 -> 20%)
- How do we interpret time varying signals?
- How do we handle inconsistent readings between gauges?
- Do we include temperature sensors?
- Require telltales?
- Young’s modulus determination
- Need standard data output and real-time interpretation software
Design

Need LRFD resistance factor that is consistent with...

- Higher level of ultimate capacity utilization
- Improved estimate of capacity
Misc.
ACKNOWLEDGMENTS

The workshop was sponsored by the FHWA Office of Infrastructure. Deep Foundations Institute recognizes the valuable efforts of Messrs. Silas C. Nichols and Benjamin S. Rivers and Ms. Sarah Skeen (FHWA) who guided the organization and execution of the workshop and provided detailed review and critique of the workshop report. We appreciate the contributions of Mr. Tom Shantz (California Department of Transportation) who partnered with FHWA in organization and execution. ADSC provided a financial contribution to the workshop, and their support and participation in the workshop activities are valued. The conscientious input from Dr. Antonio Marinucci (Consultant) and Ms. Skeen who assisted in recording notes during the presentations and discussions was vital to the accuracy of the report. The presenters and attendees openly and constructively shared their broad knowledge and extensive experience in quality assurance of post grouted drilled shafts to make this workshop successful. Their commitment of time and resources are gratefully acknowledged.
REFERENCES


