

WHAT QUALITY REALLY MEANS IN DRILLING, GROUTING, MICROPILING AND ANCHORING

Abstract

The pursuit of quality in every phase of a project is synonymous with achieving the mutual goals of schedule, cost, and compliance. Quality – either by control or assurance – is not something that happens only in the field. It must pervade each successive process on the way to building a product which satisfies the specifications and is fit for purpose. The underlying themes of quality are:

- avoiding rework by doing every task correctly the first time, and optimizing each successive process.
- devising plans and specifications which are sensible and constructable, and which allocate risk sharing in an equitable manner between all parties in the contract.
- conducting and clearly reporting upon an adequate site specific hydrogeological investigation.
- designing and implementing each task in compliance with the contract documents.
- preparing comprehensive Work Plans, which are fully understood, and approved, by the Engineer/Regulator.
- conducting the work in accordance with the Work Plans, based on the referenceable standard of care for the industry.
- using real time methods of QA/QC/verification which are pragmatic and related specifically to the product being built.
- providing comprehensive records in a Post-Construction Report: this will be invaluable for future generations who happen upon the particular project.

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The authors trust that this paper will serve as a guide to practitioners, and as an encouragement to younger professionals striving to make sense of the hectic world of specialty geotechnical construction. In addition to providing this general guidance, recommendations specific to the four specialty construction techniques cited in the title of this paper are provided.

1. Background

During this Conference in 2023, one of the current authors presented a paper based on innovative contractor procurement practices (Bruce, 2023a). At the heart of that paper was the admirable concept of Total Quality Management (TQM) and how that could influence the procurement process for the benefit and enjoyment of all project shareholders. The current authors would recommend that the 2023 paper should be read in conjunction with this 2024 paper.

This paper focuses on different applications of the principles of TQM as related to aspects of project design, specification, construction, verification and record keeping. The field of specialty geotechnical construction is wide, and in consideration of the techniques probably most often utilized by attendees to this conference, the authors have chosen to focus on only drilling, grouting, micropiling and anchoring: in effect, the “small hole” drilling related processes. We trust our colleagues involved in other specialty construction techniques such as large diameter bored piles, driven piles, diaphragm walls, Deep Mixing, vibroflotation and the wide world of proprietary ground modification techniques will not take umbrage, and hopefully, will be able to find nuggets of value in the restricted scope of this paper. This is not an unreasonable hope since the basic principles of TQM apply across the whole field of construction, supply chain and manufacturing processes¹.

In essence, two fundamental principles of TQM are (i) eliminate “rework” (i.e., do it right the first time), and (ii) optimize the quality of each successive step or process used in the creation of a product (you can’t inspect quality *into* the as-built product). In recognition of more recent trends, the authors would add a third element: beware of “internet experts” – the ability to use a

¹ The interested reader is referred to the classic book “Total Quality Management for Engineers” by Mohamed Zairi (1991).

Google Search tool does not grant the experience or judgement necessary to properly exploit the results of the search, especially in a field such as geotechnical engineering. In this regard, the authors believe that being a *member* of a committee of a trade association which publishes some type of “guideline” – often obsolescent on arrival – does not qualify as an authoritative voice for defining best practices. We find that the *leaders* of such committees are typically very experienced and worthy practitioners, and so most typically, contribute the great majority of the work products: this is a saving grace!

Quality is not to be conflated with the field QA/QC testing that is conducted during construction. Quality must pervade each successive process or phase of a project from conception to final verification so that the completed product meets the specifications and is truly fit for purpose.

The authors provide an overview of each of these successive steps. Within each step, specific points are raised for each of the four specialty construction techniques addressed in the scope of the paper.

2. Conceptual Design

2.1. General Observations

The design concept must be constructable, cost effective, and in accordance with prevailing codes, standards and recommendations. It must be developed by a consultant who is an experienced specialist in the techniques which are fundamental to the safe construction and performance of the works. In this regard, the consultant should always consider the employ of specialty subconsultants and/or peer review panels to provide expert guidance. Often, contacts with specialty geotechnical contractors can prove invaluable at this stage (provided these contractors are not thereby disqualified from bidding the subsequent work). The authors have found that even in the Conceptual Design Phase, and indeed even up to, say, the 30% Design stage, focused workshops reviewing construction alternatives, and construction potential failure modes represent excellent value for money, at a crucial phase of the project’s evolution.

2.2. Specific Recommendations

Even at the Conceptual Design Phase, the drilling methods foreseen should be closely evaluated for their viability and admissibility. This is especially true for construction in variable overburden materials (both natural and placed), in particularly difficult lithologies (e.g., karstic limestone) and/or for remedial projects (for water retaining structures and in urban settings). For example, the use of air flush should not be permitted in earth embankments, or for overburden drilling adjacent to existing structures, or for drill holes to be used for rock mass fissure grouting. This may also hold true in rock foundations characteristic of features that have the potential to accommodate the re-direction or channeling of damaging pressurized air.

At the Conceptual Design Phase, it is essential that the construction assumptions are compatible with what contractors can realistically deliver. In this regard, there is a wealth of information to inform reasonable expectations for prestressed anchor (e.g., PTI, 2014; CEATI, 2023) and micropile capacities (e.g., FHWA, 2005). For soil grouting there are excellent publications on compaction (ASCE, 2019), jet (ASCE, 2016) and permeation grouting (Xanthakos et al., 1994), while other publications (e.g., Weaver and Bruce, 2007 and USACE, 2017) define achievable residual permeabilities for grouted cut-offs in rock. Such evaluations, usefully conducted during the preliminary alternatives assessment process, will either confirm the design basis is sound, or may require the conceptual design to be heavily modified, or even abandoned in favor of a different approach.

3. Site Investigation

3.1. General Observations

The mention of this topic inevitably arouses statements such as:

- “There are never enough boreholes” (and even if there were, they are in the wrong place, and inappropriately oriented).
- “If you’re preparing a cross-section, assert that the connections between the borehole “stick logs” are no guarantee of conditions between these boreholes’ (instructions to young geotechnical engineers).

- “Beware of presenting average values of parameters” – especially permeabilities for ground to be treated by a technique involving grouting or diaphragm walling (advice from a technical reviewer).

The results from the site investigation are the basis of determining the Potential Failure Modes (construction – and performance related), and so are the underpinning of the design. There is the classic cartoon showing two Italian engineers discussing the plans for the construction of the Tower of Pisa: “So we’ve saved another 100 lire by missing out this site investigation thing. No one will notice”.



The scope of any site investigation is restrained by cost, access and the variability of the ground, unfortunately not always in that order, and this is the reality of our business. Nevertheless, the following recommendations are given to improve the quality and thoroughness of the investigation and its subsequent reporting:

- (i) The scope of the field investigation, including the follow-up laboratory testing, must reflect the specific needs of the construction technique to be employed as discussed in Section 3.2, below. It also needs to be broad enough to inform the decision for determining the technique that will best satisfy the requirements of the project and deliver the maximum results.
- (ii) It is a cardinal responsibility for the site investigation data to be presented in a Geotechnical Data Report. Equally important is the resultant Geotechnical Interpretive Report (GIR) since it is appropriate and correct for the Engineer to present his interpretation of the Owner's ground, and not leave the analysis to the bidding contractors, who should not be deemed to possess "superior knowledge" of the site. Depending on the nature and scale of the project, a Geotechnical Baseline Report (GBR) is also prepared, most commonly and consistently for tunnel-related projects. Since the GBR is deemed to have contractual precedence, the decision to produce one is not to be taken lightly.
- (iii) All historical investigatory information on the site should be studied and assimilated in the GIR, with clear statements regarding its quality and relative priority.
- (iv) All site investigation knowledge must be disclosed to bidders in the Contract Documents to a) improve the quality and responsiveness of the bids and b) avoid damming embarrassment during the Discovery phase of a litigation.
- (v) Soil and rock samples must be securely maintained and made available for inspection by prospective bidders during the (mandatory) prebid site visit.

Implementation of all these recommendations will help greatly in the development, completeness, and reliability of the geotechnical investigation.

3.2. Specific Recommendations

As alluded to in Section 2.2, above, the selection of the drilling methods is critical, for the site investigation program itself, and during the subsequent specialty construction activities. The investigation and description of the ground and its engineering properties should match the requirements of the specialty construction technique(s) to be used, as well as confirming the viability of the conceptual design elements. For example, in a rock anchor project, it is essential

to qualify the lithology, structure, strength, permeability and durability of the rock mass, and the extent of weathering. Given that the majority of micropile drilling is conducted in overburden in urban locations, it is essential to establish the stratification of the site, the density of the various strata, the presence of obstructions, and the hydrogeological and environmental conditions. The world of grouting is indeed very wide, and so the basic information necessary to plan and construct varies accordingly. Whereas the information needed for the variety of soil grouting techniques will be similar to that for micropiles, the data needed for a rock mass fissure grouting program will be more akin to those for a rock anchor project.

Particularly informative and high quality guidance for the design and scope of a site investigation program is provided in PTI (2014) and USACE (2014).

4. Design Development and Documentation

4.1 General Observations

A high quality design must address:

- (i) consistency with the site conditions, above and below ground,
- (ii) consistency with the goals of the project (both engineering and environmental),
- (iii) consistency with the most up-to-date relevant standards, guidelines and regulations,
- (iv) the realities of cost and schedule,
- (v) ability to be modified – in some extent – in the event that the field conditions as revealed during construction are different from those foreseen or anticipated,
- (vi) ability of the built project to be verified as being “fit for purpose”.

In essence, a high quality design is a warrantee of constructability, as confirmed in the Spearin Doctrine. This, and other design considerations and risks, can be managed by including in the design a requirement for a full scale field test of the construction technique foreseen. In this regard, Bruce (2023b) provides guidelines for Owners, Engineers and Contractors, both general and specialized. (One key take-away is that the full scale field test must be conducted, analyzed and approved by the Engineer *before* production works are permitted to begin. The delay

between these phases is typically anathema to an aggressive contractor, but it is an invaluable insurance against poor quality concepts and workmanship).

It is very important that the design is independently reviewed either by an internal specialist team, and/or by an external Independent Technical Reviewer, comprising either an individual or a panel. Such a review must not simply be a numerical check on calculations, quantities and dimensions, but must involve a review of the fundamentals of the design such as outlined above. The result of this process will be a design that is of high quality, is and will be subsequently defensible, and the background details of which can be shared with bidding contractors as part of the Contract Documents (although the contractual status of these details must be clearly stated).

4.2. Specific Recommendations

For anchors and micropiles, the preconstruction full scale field test, conducted on either “sacrificial” elements or on production elements which may, or may not be permitted to be incorporated into the permanent works depending on the test results, has relatively straightforward acceptance criteria. Thus, quantitative criteria are imposed on elastic and permanent movements, and on creep characteristics, typically over a quite short duration. As a consequence, the element (and its design assumption) is proved acceptable as is, or otherwise may require modification and further testing. Similarly, for a permeation grouting project, the most common acceptance criterion is proof that the residual permeability of the treated soil target has been met. For a compaction grouting project, the resultant soil density is typically the measure of success, although compaction grouting techniques and materials are often used to verify that voids or particularly loose/soft zones do not remain undetected in the ground: compaction grouting is equally an investigation as it is a treatment.

However, full scale field testing of jet grout columns often leads to uncertainty, dispute and project delay (Bruce, 2023b), and there are many reasons (and remedies) for this, including:

- (i) The Engineer should not permit the Contractor to proceed into full production until all parties agree on the outcome of the trial, despite the normal pressures of schedule (and hence cost), and the (typical) offer from the Contractor to proceed at his “own risk”, pending full analysis and acceptance of the trial.

- (ii) Inconclusive evidence is presented regarding actual in situ column diameter, full depth, as revealed by coring at 14 to 28 days. Column diameter, and hence the conclusion that the ground has been completely and uniformly treated by fully overlapping columns, is typically the most critical test consideration. Insufficient use is generally made of other techniques to verify column diameter or the homogeneity of the treated block, such as the use of an Optical or Acoustic Televiewer in cored holes, or (proprietary) geophysical tools.
- (iii) Over-reliance is placed on testing of “wet grab” or surface spoils samples, especially when these are used to provide lab permeability test data, as opposed to the use of cored samples, or preferably, in-situ values.
- (iv) The full scale field testing program should be well thought out and clearly defined in the bid documents. This should include the expectations as to what specific attributes the program is designed to target, how these will be evaluated, and what will be the gage for determining acceptability. It is very important that the time required for this program be included in the schedule.

Other aspects of testing are discussed below in relation to specification development.

5. Specifications and Their Development

5.1. General Comments

A specification of high quality is essential for the successful and non-confrontational execution of the work. Conversely, the reverse is also true: a poorly written specification, created by “cobbling together” sections from previous documents, internet searches, and unawareness of contemporary standards of practice, will inevitably lead to a product – of at best – adequate quality, and to contractual dispute. At that time, words, sentences and paragraphs will be poured over and interpreted by the aggrieved parties and their attorneys: a marginal decision will always go against the drafter of the specifications. The phrase “defective specifications” is the nightmare of Engineers and Owners, and a lifeline to contractors in a project which has turned “sour”.

Strong generic guidance on the types of specifications – prescriptive, performance, and open – is provided in PTI (2014). The pros and cons of each type of specification are also summarized therein. There are many factors which determine the type of specification, but an important theme and goal of a quality specification for a specialty geotechnical construction process is to permit and encourage the technical input and expertise of the specialty geotechnical contractor who will bid the project and build it, if successful. Innovation should be encouraged: innovation most typically comes from the specialty contractors.

Any specification will have a combination of prescription and performance elements, and the drafter must clearly define the respective responsibilities and therefore risks of each party. Especially when the specifications veer towards the prescriptive end of the spectrum (and the Owner is inclined/obliged to select the “Low Bid” offer), it is extremely important that the specifications detail the qualification and prequalification requirements of the prospective contractor. Weaver and Bruce (2007) addressed this issue as follows with particular regard to rock grouting projects:

“It is highly desirable to prequalify potential bidders before the solicitation for bids.

However, as noted by Houlsby (1990), “legal considerations prohibit some organizations from accepting any but the lowest tender. This can cause difficulties if the grouting contractor thus chosen is not competent”. Prequalified contractors are then named in the bid documents, and no additions or substitutions should be permitted after this point. The prequalification process should go well beyond identifying contractors who have had experience in drilling holes and injecting grout; a far more holistic basis of preapproval is necessary. It is common to find the following criteria used:

- corporate experience in similar projects in the preceding 10 years or so (backed by a list of owner references and their phone numbers);
- individual experience of key field and head office personnel who will be committed to the project (and the identification of these positions);
- lists of corporate equipment resources in terms of drilling, grouting, and ancillary equipment;
- at least three years of audited financial statements, in confirmation of financial stability and resources (including bonding);

- confirmation that corporate resources and current and anticipated workload will allow the project's foreseen schedule to be observed;
- proof of all necessary contractor's licenses applicable to the project location (especially if outside the United States);
- confirmation of an acceptable quality plan;
- confirmation of an acceptable safety record and that all statutory requirements regarding social, environmental, hiring and employment policies, and wage rate conditions are in place;
- the company's record and its reputation for claims and litigation; and if the invitation to prequalify contains sufficient detailed background data on the project, the contractors should be invited to demonstrate their understanding of the project in a brief review describing the project challenges and the concept of the proposed solution. Any alternative solution is invited (but must be kept confidential by the owner) to demonstrate the innovative potential of the bidder.

Overly elaborate proposals should be discouraged, although something more than a cobbled-together collection of catalog cuts and promotional literature is essential. "The balance must be struck between the need for the contractor to "show his colors" and the awareness that assembling this proposal should not pose a significant financial burden on the Contractor at this stage in the bidding process."

The necessity of the Contractor providing personnel of suitable experience, expertise and quality cannot be overstated. Recent attempts by certain contractors to have requirements relaxed – because they do not have suitable human resources – must be resisted, since inferior staffing will lead to inferior quality of construction.

It is recognized, however, that the specialty construction industry is challenged by a narrowing pool of highly experienced personnel capable of meeting these critical requirements. It may be conducive to all to cooperate in the effort to broaden the industry expertise. This may be accomplished by orchestrating a site team that collectively can satisfy the qualifications and

experience requirements that will fit the needs of the project. This would also serve to provide individuals with the opportunity to gain the experience in the areas for which they are lacking.

Quality in the contractor procurement process is addressed in Bruce (2023a), and although it is therefore not covered in this paper, its importance cannot be overstated.

5.2. Specific Recommendations

Current standards and recommendations provide a very sound foundation for the drafting of specifications for specialty geotechnical construction processes. The following are specific points which should be especially addressed in these specifications:

- (i) The concept of the progressive cyclic Performance Test procedure (PTI (2014)) should be extended to every anchor installed on a critical infrastructure project, such as a dam stabilization. The data which accrue from such testing are invaluable in verifying the proper functioning of the anchors and so their suitability to perform as intended in the long term. Progressive cyclic loading should also be conducted on test micropiles.
- (ii) In every anchor or micropile test, Performance or Proof, the load must be returned to Alignment Load after successful testing to Test Load. Thereafter, the load can be raised to Lift-Off Load. Only by returning to Alignment Load after reaching Test Load, can the total tendon extension be quantitatively partitioned into permanent and elastic components, thus permitting the latter to be used in calculation of apparent tendon debonding.
- (iii) This same approach should be used for micropile testing, for which a tensile test (as opposed to a compressive test) is an inherently more rigorous demonstration of the micropile's performance, as well as being a cheaper and easier test.
- (iv) For any grouting project, and especially in the full scale field tests referred to above, it is essential that the specifications clearly detail the acceptance criteria, and the method to be used to achieve the results. These criteria should emphasize the in-situ tests and measurements and de-emphasize the lab test data, especially where a permeability or homogeneity target is to be achieved.

- (v) It should not be overlooked that a full-scale field test is not only a demonstration of the finished product. It is equally a demonstration and verification of the means and methods used at each step of the construction process. This permits the Contractor to commission his equipment and optimize his processes and provides comfort to the Engineer/Owner that a replication of these means and methods will assure a satisfactory and consistent quality of the subsequent production works.
- (vi) Drilling methods should be based on the site-specific details of the project and clearly defined and stated as to those that are acceptable or prohibited within limiting factors. This will simplify the bidding process and help to create a level playing field.

6. Contractor Work Plans

6.1. General Comments

The requirements for these preconstruction submittals will have been included in the specifications. These submittals are vital for the implementation, supervision and verification of the work, and are an integral part of the project's documentation. However, one often gets the impression as reviewers of such work plans, that in effect the first time the contractor has really "thought through" the details of his work is when he is obliged to produce the Work Plan itself. A sure indication of this is when the submittal is very short on descriptive narrative and details, but very long in appendices comprising voluminous data sheets and catalogue extracts.

Bearing in mind that a basic metric of quality is the elimination of rework, a simple strategy is for a *Draft* submittal to be prepared and discussed, preferably in person, between all parties in a spirit of cooperation. Thereafter, the final version can be quickly developed and approved. This approach eliminates the tedious and often contentious process of successive rounds of submittals, rejections, resubmittals and so on, which can often end with the Engineer's disposition "No objection", since the project (and its personnel) have moved on (or would like to have moved on) in the meantime.

It is a matter of professional pride that submittals be presented by the Contractor on schedule and are reviewed by the Engineer/Owner as expeditiously as possible, regardless of the typical

“boiler-plate” granting the latter, say, 28 days for a review turn-around. Given that most work plans are required before construction begins, and that a mass of daily construction records have to be produced, analyzed and approved, by the Engineer, it is in the best interest of all parties to complete the preproduction submittals briskly, clearly and conclusively as early in the project as feasible. Of course, other submittals are invariably required during the currency of the project, but these can build sensibly on the quality of the original preconstruction submittals.

6.2. Specific Recommendations

These are largely covered by Section 6.1, above. However, it should be reiterated that the Work Plans must address the specific requirements of the specification and be sufficiently informative and detailed to act as a manual for the use of the construction monitoring personnel. A good quality Work Plan will not only be a pathway through the project, but will also be a firm basis for making changes should unexpected conditions or performances be encountered.

While the Draft Submittal can be helpful in expediting the process, caution needs to be exercised guarding against the formulation of a skeleton document or plan presented for review. This situation leads to the description of “Design by Comment”, which means that critical components of the plan have not been well formulated and rest on the reviewer responses to devise the plan, design of the work, or method of approach.

7. Contractor Construction Records

7.1 General Observations

The quality of these records is reflected in their completeness, accuracy, clarity and timeliness. Such records provide in almost real-time a platform for informing the Owner and the Engineer of the details of the progress of the work, and an opportunity for the Owner and the Engineer to concur, challenge or correct. These records also provide a basis for interim payment, but also justification for the acceptance or rejection of a contractual claim, such as for a Differing Site Condition: they are the fundamental briefing source for external “experts” and attorneys in such cases.

The details of the requisite construction records – their contents, format and deadlines – are to be defined in the Contract Documents. On very large projects, these records are generated and transmitted via a computerized Data Management System (DMS). The effort and resources required to set up and efficiently run the DMS should not be underestimated, but often are, meaning that the early days and weeks of the project may be classified, kindly, as a “quality learning curve”.

The DMS will also handle the Contractor’s QC records and test results, and the QA information provided by the Owner and his agent(s). This part of the process is under the direction of the Contractor’s Quality Control Manager, who on a large complex project operating double shifts, may be responsible for upwards of thirty individuals in the field and in the office. It is natural, therefore, that on the same project the Owner/Engineer’s Quality Assurance staff will be of similar number, and it is always helpful for the smooth and efficient operation of the process that the teams on each side have equivalent skills, experience and – as far as possible – personalities.

7.2. Specific Recommendations

A compliant and cooperative QA/QC operation is a major component of a high quality project. Bruce et al., (2020) listed the key components – “cornerstones” – of a successful QA/QC program, emphasizing from the onset the need for close collaboration between the respective parties and avoidance of confrontation. Most of these 10 points are touched upon in other sections of this paper, but are worth reiterating here:

- clear and complete specifications,
- appropriate organizational structures and qualified personnel,
- close communication,
- instrumentation monitoring plan and emergency action plan,
- input of Technical Advisory Boards,
- benefit of lab and full scale field tests,
- continuous instrumentation monitoring and observance of threshold and action levels,
- an efficient Data Management System,
- maintenance and validation of checklists for every construction process,
- regular QA/QC personnel meetings, both before each shift and at “cleanup” meetings,

- partnering meetings conducted at milestones or potentially contentious moments can aid in re-aligning the focus of the project and developing the path moving forward.

8. Performance Verification

8.1 General Observations

As noted previously, a fundamental pillar of TQM is that after a product is built, you cannot inspect quality into it, the corollary being that by using successive processes of high quality in the construction, a high quality product will result. However, there is a distinction between process improvement and product verification, and this is particularly important when dealing with underground, in-situ construction. Demonstration of verification is essential for all parties: comfort to the Owner that the work he has to pay for is “fit for purpose”, confirmation to the Engineer that his design has been constructed compliantly, and justification for the Contractor to submit his invoice.

8.2. Specific Recommendations

Obviously the nature and details of the verification process will depend on the type of work conducted, but the vision is common: provide a quality of verification that leaves no doubt as to the acceptability of the work. Hence, prestressed rock and soil anchors have an intrinsic advantage in that every installation is stressed and tested to beyond its Design Working Load, typically by a factor of at least 1.33, and subjected to a creep test, usually of short duration (10 to 60 minutes, but up to 5 hours in creep susceptible soils). Acceptable load transference is demonstrated by an initial lift-off test. Long term monitoring of residual load is conducted by installing load cells, or by ensuring access is provided to at least a representative proportion of the anchor heads in order that lift-off testing can be conducted. Three important points must be made:

- (i) The PTI Recommendations document (2014) is an elegant and definitive basis for all aspects of anchor technology, including stressing, testing and monitoring. This document has been developed over many decades and addresses changes and challenges which have occurred in North American practice, and incorporates the best

- elements of comparable foreign standards. The PTI Recommendations should be followed in every project, and neither inexperienced “internet experts” nor should opportunistic contractors be permitted to specify or propose other guidelines for the acceptance of anchor works.
- (ii) As noted in Section 5.2, above, a common feature of anchor standards worldwide is the concept of load testing either by “direct” loading to Test Load, or by progressive cyclic loading to Test Load. In PTI, the former is referred to as a Proof Test, and the latter is termed a Performance Test. Each type of test requires the same equipment and quality of record keeping. The Performance Test will typically take an hour or so longer, but will provide much more intense information on the load transfer mechanisms within the anchor. Given that the typical dam anchor project will nowadays have a relatively small number (say less than 100) of relatively high capacity anchors (say up to 1,000 tons), that extra hour or so of testing is an extremely low price to pay for the quality of the verification, bearing in mind that the large, heavy high capacity jacks typically take several hours to move, set up, and then remove from an anchor head after testing is complete.
 - (iii) In order to calculate the apparent bond length at Test Load, which is one of the major anchor acceptance criteria, it is essential that the Test Load be reduced to the Alignment Load, before raising it to the final Lock-Off Load. This vital step is often overlooked or ignored in the heat of battle. Only in this way can the *elastic* tendon extension be quantified, and so debonding calculations made. These first three recommendations apply equally to the load testing of micropiles and indeed are broadly consistent with the guidance of FHWA (2005).
 - (iv) The unique factor of a grouted cut-off is that by far the greatest volume of the grout curtain (for it is indeed a three-dimensional structure) is that the vast majority of its conceptual volume is the virgin rock, with only very small proportions being grout or ungroutable soil filled fissures or features. Verification must recognize the natural variation of a grout curtain, and so is only conducted when the most detailed evaluation of the drilling, water testing and grouting records indicates the curtain has likely been successful in reducing the residual permeability of the rock mass to achieve the residual permeability target , typically less than 5 Lugeons, but in special

circumstances to less than 3 Lugeons. The verification process should only be conducted when these detailed analyses confirm that no zone of high permeability has been left untreated, bearing in mind that Lugeon values should not be averaged across a curtain: the presence of untreated highly permeable zones may greatly reduce the effectiveness of a curtain even though 90% or more, say, of the stages have reached the target Lugeon value. Acceptance is judged ultimately by drilling and water testing “Verification Holes” strategically located between the upstream and downstream rows of production grout holes. Depending on the predominant joint pattern, these holes may be inclined. The water testing procedure features the “Houlsby Method” (1976), wherein the permeability is assessed in five successive pressure steps which will not only allow the residual permeability of the curtain to be accurately demonstrated, but also the characteristic of the curtain to be inferred, with the “Washout” signature of most significance for projecting the long term durability and effectiveness of the curtain. Excellent guidance on evaluating grout curtains may be found in USACE (2014).

Having verified the quality of the cut-off, the ultimate verification of its quality will be by the long-term evaluation of its impact on piezometric levels, seepage rates, and other “signs of distress” (Bruce, 2013, 2015).

It is prudent, at the completion of a grout curtain project, to re-assess the instrumentation program and replace damaged instruments or provide additional instruments in order to monitor the performance of the constructed seepage barrier.

9. Closing Remarks

The concept of “quality” in our industry is often misunderstood and marginalized: it is not just the implementation of a specified “Contractor Quality Control Plan” detailing the number of samples to be taken and the criteria they must satisfy upon testing during construction. Rather it is a philosophy that must permeate each and every successive process which will ultimately lead to the construction of a successful, compliant project that will satisfy the intent for which it was

designed. The definition of “successful” includes the standard tropes of “under budget”, and “within schedule”, but must also include consideration of the enjoyment and pride to be taken by the participants both during the project, and in retrospective moments.

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