



## **SPECIALTY GEOTECHNICAL CONSTRUCTION TECHNIQUES – QUALITY RULES**

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### **ABSTRACT**

The extent to which the success of any project can be achieved, regardless of the metric adopted, is a direct result of the quality of each of the successive processes followed from conception to completion. For projects involving specialty geotechnical construction techniques used for building or remediating dams and levees, these processes are long and intense, and will be conducted over several years. The processes range from site investigation and characterization to the in-situ demonstration of compliance and confirmation that the built product is ‘fit for purpose’.

Embracing some of the guiding and enduring principles of Total Quality Management (TQM), this paper provides guidelines as to the concepts and details pertaining to each of the successive processes, involved in the construction of cut-off walls using “Excavate and Replace” methods or “In-situ Mixing” (Category 1 and 2 methods respectively), grouting and prestressed anchors. It is intended to be of value to Owners, Regulators, Engineers and Contractors alike.

### **I.PERSPECTIVE**

For both new dam construction, and for dam remediations, many types of specialty geotechnical construction techniques play prominent roles. In this regard, drilling and grouting, cut-off walls, Deep Mixing and prestressed rock anchors have seen widespread application for many years, while, for certain types of challenges, such as the stabilization of elderly timber crib dams, micropiles have also been used.

There is no doubt that design and construction standards have improved over the years, largely reflecting the particular difficulties inherent in the remediation of large embankment dams on foundations comprising karstic limestone, or potentially liquefiable soils. However, there are signs that there is a creeping complacency in attitudes towards such projects, reflecting a “taken for granted” tendency among engineers and contractors who did not have the opportunity to participate personally in the landmark projects of the century to date. Further, the ability to quickly become an “internet expert” does not come with the experience and judgment to properly apply the results of the internet searches. Likewise, simply being a member of a committee of a trade association which publishes some type of “guideline”, usually obsolescent on arrival, should not automatically constitute an authoritative voice for defining best practices.

Quality is a widely used word, but often narrowly and lightly used. Webster’s dictionary (1986) provides many definitions of the word “quality”, but arguably the most apposite for our business are “a distinctive inherent feature”

and “a degree of excellence”. One of the fundamental precepts of the philosophy of Total Quality Management (TQM) was that “you cannot inspect quality into the finished article”. Indeed, its proponent and chronicler Philip B. Crosby reiterated in the dedication of his 1979 book “Quality is Free”, the opinion “Quality is not only right, it is free. And it is not only free, it is the most profitable product line we have.”<sup>1</sup>

Quality does not start – or – finish – with the implementation of the Contractor’s Quality Control/ Quality Assurance program on a given project. Rather it is a guiding light which must pervade each project at each step of its development, implementation, and verification. This paper highlights key areas where quality must be applied – and maintained – including:

- site investigation
- design development
- specification development
- contractor procurement process
- contractor work plans
- contractor construction records
- performance verification

For each of these successive stages in the evolution of a project, guidance is provided on particular aspects to be addressed in the most common specialty construction processes used in dam and levee construction and remediation. The goal of the paper is to provide a reminder to experienced engineers, and guidance to less experienced professionals, to ensure that the hard-won lessons of the last three decades are not lost, so leading to a decline in the quality of the constructed works.

## **II.SITE INVESTIGATION**

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 (service – and construction – 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”

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<sup>1</sup> For those interested in the development of TQM, beginning with Stewart in 1931, and accelerated by Deming and Juran from the late 1940’s, the textbook “Total Quality Management for Engineers” by Mohamed Zairi (1991) is highly recommended. He quotes Juran (1988) on the need for long term planning using the example of a manager surrounded by alligators: “He undertakes to slay alligators, one by one – a reptilian version of project by project improvement. But there will never be an end to it, because more and more alligators keep emerging from the swamp. The ultimate answer is to drain the swamp.” Sounds familiar?



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 needs of the construction technique to be employed. For example, if a prestressed rock anchor project is contemplated, it is essential to know the strength, permeability and lithological variability of the rock, as well as the geochemistry of the groundwater (insofar as it may constitute a chemically “aggressive” environment). Similarly, if a cut-off wall is considered a likely option, then the presence and distribution of cobbles and boulders in the overburden (and its density and granulometry) is essential, as is the presence of very soft and organic horizons. When such a cut-off is to be “toed” into bedrock, then the strength, structure and abrasiveness of the rock are vital to quantify.
- (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 really don’t have “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 at least, with clear statements regarding its quality and relative significance.
- (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.

### **III.DESIGN DEVELOPMENT AND DOCUMENTATION**

The key elements of a high quality design are well known, and must address:

- (i) consistency with the site conditions, above and below ground,
- (ii) consistency with the goals of the project,
- (iii) consistency with the most up-to-date relevant standards and guidelines,
- (iv) awareness 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 warranty 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 (2023a) provides guidelines for Owners, Engineers and Contractors, both general and specialized. (One key take away from that paper 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).

As alluded to in the following section, it is essential that a design is independently reviewed either by an internal specialist team, and/or by an external Independent Technical Reviewer, either an individual or a panel. Such a review must not simply be a numerical check on calculations, quantities and dimensions, but must comprise a review of the fundamentals of the design such as outlined at the beginning of this section. The result of this process is a design that is of high quality, is and will be defensible, and the background details of which can be shared with bidding contractors as part of the Contract Documents (although its contractual status must be clearly stated).

### **IV.SPECIFICATION DEVELOPMENT**

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 not reflecting contemporary states 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, and 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”.

Weaver and Bruce (2007) devoted an entire chapter to specifications and contracts, principally related to dam grouting projects. The two “book end” types of specifications are defined, and details are provided of the tasks and responsibilities to be allocated and of items to be addressed and defined in the technical specifications. In Chapter 3 of its “Recommendations for Rock and Soil Anchors” (2014), the Post Tensioning Institute provides an admirably succinct summary of specification types, responsibilities and submittal requirements:

#### **“3.1 – Specifications**

The three types of specifications most commonly used for rock and soil anchor work are as follows.

##### **3.1.1 – Prescriptive specifications**

The Owner describes specific procedures that must be followed. These may not necessarily fully define the objective of the work. When prescriptive specifications are used, the Owner is responsible for the satisfactory performance of the system. The Contractor is responsible for satisfying the detailed requirements of the specifications.

### 3.1.2 – Performance specifications

The Contractor assumes greater control over certain design, construction procedures, or both, but must demonstrate to the Owner through testing, certification, or both, that the final project meets the specified project performance criteria. This method allows and encourages the Contractor to provide a competitive/innovative anchor system design within the framework of the overall design requirements. The responsibilities for the work are shared between the Owner and the Contractor in well-defined categories. It is important when using this method to provide the information that the Contractor needs for design, or to allow sufficient time for the Contractor to obtain it. An example of this is data on corrosion potential of the ground.

### 3.1.3 – Open specifications

These leave the scope and design of the installation completely up to the anchor Contractor. This method is especially common for securing bids on temporary anchor work. The responsibility for design and performance is placed entirely on the Contractor. Open specifications are not recommended for permanent anchor applications. The corrosion protection requirements must always be specified by the Owner. This method allows the Contractor to select the most economical anchor system and keeps change orders to a minimum.

## 3.2 – Responsibilities

The contract documents must clearly describe the respective responsibilities of the Owner, Engineer and Contractor. Prior to commencing the work, the Contractor shall demonstrate to the satisfaction of the Owner that he has sufficient resources and experience, both organizationally and individually, to perform the work in accordance with the specifications. The allocation of responsibilities will depend on the type of specification and whether the work is temporary or permanent. The installation of anchors requires specialized equipment, knowledge, techniques, and expert workmanship. Not every detail of the work can be specified, and not every potential problem can be anticipated. Therefore, only Contractors who are thoroughly experienced in anchor work should be selected.”

A list of the major tasks to be performed on an anchor project is provided in the Recommendations. The party responsible for each task must be clearly identified and mutually agreed upon at the earliest point in the contracting process. The process of continuous communication between all the parties involved, regardless of the allocation of responsibilities and tasks, is essential to achieve a result of suitable quality. Clear communication and close cooperation are particularly important in the startup phase of a project. In addition, timely preparation and review of all submittals is always beneficial in any project.

In the earlier days of dam remediation, the specifications were heavily performance based. This reflected the relative inexperience of consultants, who therefore, logically relied on the input of the specialty contractors. This was especially evident in the cases of projects involving cut-offs (e.g., Wolf Creek, KY, Bruce, 2013), and prestressed anchors, where most of the technical input came from the suppliers of the prestressing materials and equipment, and not the contractors who were essentially site investigation drillers (Bruce et al., 2023)

In recent years, specifications have become more prescriptive, as consultants have gained experience, and the contractors have reached a high degree of parity in terms of technological innovation and quality of work. This is particularly the case with projects involving cut-off walls and/or grouting, and anchoring. However, innovation is frequently the key to overcoming particularly severe technical, logistical and scheduling challenges, such as are typically found in the remediation of existing dams and levees. Since technical innovation is most typically driven by the specialty contractors, it is logical to involve them in the development and design of a project, at the earliest practical stage. The ingredients of the newer contracting methods are described below.

Weaver and Bruce (2007) also provided as Figure 16-1 a simple illustration of the key elements of responsibility as related to specification type.

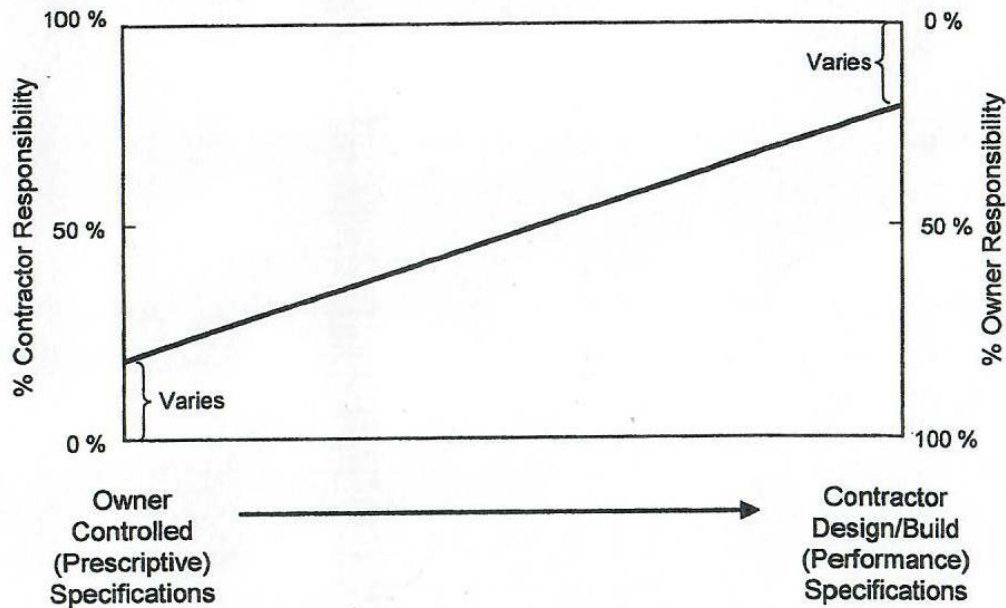


Figure 16-1. Allocation of responsibility depending on the type of specification method. (Weaver and Bruce, 2007).

They further discussed the qualification and prequalification requirements relating to the Contractor, as follows:

"It is highly desirable to prequalify potential bidders before the solicitation for bids. However, as noted by Housby (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 candidates – must be resisted, since inferior staffing will lead to inferior quality of construction.

A final point relating to the quality of the specifications is the advisability of engaging the services of an independent technical reviewer, either an individual or a team. “This is no slight to the Owner’s existing engineering team (internal or external)... Rather, this is a logical and often invaluable role, which can provide all parties with reassurance, confidence, perspective, discipline and knowledge in various proportions.” (Weaver and Bruce (2007). (It is typical for the Independent Technical Review Team to be retained during subsequent construction).

Although written with large complex dam grouting projects in mind, this guidance, mirrored in the views of PTI (2014), is applicable to the design and specification of any specialty construction technique.

## **V.THE CONTRACTOR PROCUREMENT PROCESS**

An early and vital process in any construction project is to determine the method by which the “right” contractor is selected, and the terms under which he then builds the project in concert with the other stakeholders. It may surprise some engineers that the word “contract” derives from the Latin verb “contrahere” meaning “to draw together”.

The concept of selecting a contractor based on his ability (or misfortune) to calculate a price lower than any of his competitors, dates from a time when the construction world was simpler, but undeniably more corrupt. Public openings of bids was a logical and transparent process adopted to negate the opportunity for less than honest officials in the public and private sectors to influence bid awards through bribery and corruption. The puritanical spirit of this concept even went so far as to invalidate bids from contractors who had the common sense (and temerity) to take exception to certain terms and conditions in the Contract Documents or, heaven forbid, to offer an alternative solution (even if it were better for the project). The apogee of this process occurred within the last 50 years in large federally-sponsored dam grouting projects, where the successful (i.e., low) bidder became, in effect, merely a purveyor of labor, equipment and materials, subject to intimate technical direction by the Owner’s inspectors in the field. It is now generally recognized that the stagnation in dam grouting practices in the U.S. between the 1920’s and the 1980’s was directly due to this suppression of inventiveness (Weaver and Bruce, 2007).

Significant changes have occurred in our industry over the last few decades which have forced procurement practices to be re-evaluated, and strong and far reaching attempts have been made to stamp out unlawful practices in contractor procurement and payment processes. More significant from the viewpoint of the vast majority of owners, engineers and contractors alike is the fact that the technical demands placed on the construction industry have changed. Industry no longer focuses on building highways in greenfield sites between centers of population: it is now building arteries through and under such cities. New dams on “good” geology are now relatively few and far between in terms of numbers under construction: the remediation of existing structures on problematic geologies is now the focus.

The reaction by “contracts and procurement specialists” over the last few decades has been varied. On the one hand, many continue to favor the low bid system which is not unreasonable or inappropriate for works of a relatively simple nature, mainly above-ground, and therefore visible and inspectable at every phase of construction. However, many have chosen or have been obliged by the nature and complexity of the project, to adopt other methods of contractor procurement. The onus with such works is on “best value”, as opposed to “low bid” although

many times the two become one and the same. Thus, various contractual flexibilities such as Pre-bid or Post-Bid Alternates and Value Engineering were introduced and indeed, despite their various well-known deficiencies, are still in vogue. Partnering has become an excellent addition in the last 30 years or so, although it must be recalled that Partnering is a post-award process. (AGC of America, 1991). However, when properly implemented, it provides a robust platform for creating “best for project” principles of decision-making and conflict resolution.

In the 1980’s, some large Federal agencies introduced for especially challenging dam remediation projects a “two-step” process. In this, the favored bidder is identified on the basis of a detailed Technical Proposal (quantitatively analyzed and graded). Provided he is within the project’s pre-established “responsive price range”, then he is invited for contract award negotiations. A slight variation on this theme is where the bidders submit separate Technical and Price proposals for the same project. Each proposal has a certain numerical “weighting”, e.g., 70% Technical and 30% Price, and each proposal is evaluated by a separate panel of specialists. The bidder with the highest aggregate score is then invited for final negotiations, or indeed may be awarded the project outright on the basis of these quantitative analyses.

In the private sector, it is increasingly common, given the growing sophistication and engineering capabilities of the better resourced specialty contractors, to find “Design-Build” structures. These are described (as “Contractor Controlled” projects) in the Micropile Implementation Manual (2005).

Despite all these good ideas and noble intentions, the North American construction industry remains a highly litigious and adversarial environment, even though the capacity of its participants to collaborate to find technical solutions continues to astonish observers, both at home and overseas. When faced with challenges, technical and contractual, of enormous complexity, the North Sea oil and gas industry responded by creating the “Project Alliance” concept. Following its initial success in the late 1990’s at assuring project delivery on schedule and under budget, it has spread to other major infrastructure industries in Europe and Australasia, with similar success. Variants of this concept have been creeping into U.S. practice in recent years, but it is by no means common at this time. (Carter and Bruce, 2005).

Closer to home, the concept of “Early Contractor Involvement” (ECI) has been more widely employed to the advantage of all shareholders on a number of high profile and complex projects. The concept is self-explanatory: a contractor is selected to work beside the Engineer-of-Record to help develop the initial plans and specifications which he will be governed by during the subsequent construction phase. This approach ensures project quality while at the same time allowing project costs to be closely managed. The paper by Rounds et al., (2022) is an excellent recent case history.

Each method has its own merits and place, but the underlying question should be – “How does each approach best serve the needs of a very complex and challenging project requiring the engagement of the “right” contractor?”

Methods to procure contractors – and especially specialty contractors usually acting as subcontractors – have evolved over the years. This evolution has had several drivers many of which have had primarily commercial and contractual roots. However – and again in the specialty construction arena – projects have become more technically challenging at the same time that the variety of means and methods has greatly expanded as the result of domestic ingenuity and foreign developments. The goals of all project stakeholders should be common, and must be aligned to ensure a mutually successful outcome. This harmony is typically not fostered by the low bid method wherein the combined skills and experiences of the stakeholders are little shared, and usually not at all in the preconstruction stages.

More details on these newer, alternative procurement methods may be found in Bruce (2023b).

## **VI.CONTRACTOR WORK PLANS**

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 a reviewer 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 submittal itself. A sure indication of this is when the submittal is very short on descriptive narrative and details, but is 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 disposition "No objection", since the project (and its personnel) have moved on (or would like to move 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, generating 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.

The efficient implementation of the Work Plan process will be a major step towards satisfying one of the prime goals of Total Quality Management, namely the elimination of rework: "do it right the first time!"

## **VII.CONTRACTOR CONSTRUCTION RECORDS**

The quality of these records is reflected in their completeness, accuracy, clarity and timeliness. These records provide in almost real time a platform for informing the Owner and his Engineer of the details of the progress of the work, and an opportunity for the Owner and his 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.

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 onsite

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 well 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.
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## VIII. PERFORMANCE VERIFICATION

Another 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 improvement and verification, and this is particularly important when dealing with products constructed underground, in-situ. 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.

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 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 opportunistic contractors must be permitted to specify or propose other guidelines for anchor works.
- (ii) 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. For all these reasons, it is strongly recommended that all dam anchors are subject to a Performance Test.
- (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.

The construction of a concrete cut-off wall, either by using clamshell and hydromill, or by secant pile methods, involves an intricate series of processes to assure a compliant, high quality project in the ground. Given that the construction parameters are continuously recorded and displayed, that the individual excavated elements must be measured for deviation and dimension (by at least two different methods), and that tight controls are exercised during the concrete placement phase, the construction of a single wall element can involve the generation of hundreds of pieces of information, and the signing-off of dozens of “hold points”. However, final demonstration of acceptability is still required, with particular attention paid to the inter-element joints. (In this regard, clear guidelines must be provided in the specifications as to what will constitute an acceptable joint (e.g., good “mating” between adjacent elements) or what will need remediated (e.g., the presence of substantial thickness of continuous slurry trapped between adjacent elements). It should be noted, however, that joints are rarely perfect and a pragmatic and reasonable level of acceptance must be established in advance. One must be wary of the “Swiss watch” syndrome.

Samples of concrete are taken during its placement to demonstrate adequate rheology and stability when fluid, and rate of gain of strength when set. Testing such samples for permeability in the lab is of dubious value. The typical standard of care nowadays involves coring through the joints, by either vertical or inclined drilling. Retrieved samples are logged for core recovery, and homogeneity before being sent for strength testing. The frequency of the coring is considerably higher in the Preproduction Test (or Demonstration) Section. Thereafter, each hole is best subjected to an Optical and/or Acoustic Televue survey – to confirm that the core samples are in fact acceptably representative of the in situ conditions. These holes are then permeability tested, either with the constant head method, or the falling head method. The former is used in conventional concrete structures which can resist some excess pressure without cracking, while the latter is common and safer in “soft” walls. Examples of comprehensive descriptions and methods may be found in Valagussa et al., (2013) and Ginther et al., (2022), for diaphragm walls, and Schmutzler et al., (2012), and Bruce et al., (2020) for deep mixed cut-offs.

The unique factor of a grouted cut-off is that by far the greatest volume of a 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 is therefore a different animal from that in cut-off walls, given 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 the target residual permeability target, typically less than 5 Lugeons, but in special circumstances to less than 3 Lugeons. Acceptance is judged ultimately by drilling and water testing “Verification” holes 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, whether installed by concrete cut-off, Deep Mixing or grouting, 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, 2015).

## **IX.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. The definition of a “successful” project 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.

Both English and Metric units are preferred for use in ASDSO publications, with Metric units listed as secondary (in parentheses). The use of the International System of Units (SI Units) is recommended.

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