QUALITY CONTROL AND QUALITY ASSURANCE IN CUT-OFF WALLS

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ABSTRACT

There is an unprecedented level of activity in the construction of cut-off walls for existing dams and levees. Such cut-off walls range in type from Category 1 walls (i.e., excavated soil and total replacement with an engineered "backfill") to Category 2 walls (i.e., some form of Deep Mixing). This paper provides, for each wall type, a description of the various tests and assessments which are used to quantify the various parameters upon which acceptance is typically based. These are principally homogeneity, strength and permeability. It highlights how certain tests may not be wholly appropriate for different types of walls ─ an issue which is often at the source of contractual disputes.

INTRODUCTION

The current nationwide program of remediation of existing dams and levees includes, among other measures, the construction of cut-off walls. The construction methods vary widely, depending on the depth of the cut-off wall, its required properties, the nature of the foundation material and the available technologies. These technologies can be grouped in two categories (Bruce and Sills, 2009):

- Category 1 walls, in which the in-situ material is excavated under slurry with long-reach excavator, clamshell, or hydromill equipment and replaced by an engineered material of controlled properties (e.g., concretes, self-hardening slurries, soil-cement-bentonite and soil-bentonite). Secant pile walls are also included in this category, although they are excavated with water (Amos et al., 2008) or air as the evacuation medium (Bruce and Dugnani, 1995).

- Category 2 walls, which entail the mixing of the in-situ material with a fluid grout by utilizing deep mixing equipment (e.g., vertical axis Deep Mixing Method (DMM), the Trench cutting and Re-mixing Deep wall (TRD) method, and the Cutter Soil Mix (CSM) method).

  The control measures and the testing procedures used to demonstrate that the cut-off wall is installed in accordance with the requirements of the specifications and/or the design intent of the project, also vary significantly from project to project. In general, the following performance requirements need to be demonstrated for a cut-off wall:

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- Geometry
  - Position
  - Depth
  - Width
  - Length
  - Verticality

- Homogeneity/Integrity

- Material Properties
  - Strength, deformability, unit weight
  - Permeability

It is, of course, the case that Quality Control (QC) refers to measures implemented by the Contractor during the execution of his work. Equally, Quality Assurance (QA) refers to measures taken by the Owner, or his Agent (either directly or via a third party) during and/or after the work is installed. The exact scope of each respective quality program is defined on a project-specific basis. This paper simply identifies the various tests and measurements. It does not dictate which test or measurement must be conducted by each party, although it is natural that some are conducted by both parties, within a relatively short time frame, and often simultaneously. Further, additional or alternative tests or controls may be dictated in response to particular type of construction method adopted.

In contrast, the verification of the effectiveness of the cut-off, as a durable seepage barrier, is normally a longer-term project being conducted or reaching fruition long after the construction has been completed and the Contractor has demobilized from the site: many climatic seasons or hydraulic cycles may be necessary before the intended contribution of the cut-off can be challenged and evaluated within the framework of its intended purpose.

Another basic precept of QA/QC is that, to the extent practical, possible and reasonable, each parameter should be capable of being verified by at least two independent means and methods and further, that all data and results, whether measured or recorded by Contractor or Owner, should be shared to the maximum extent contractually permissible for the overall benefit of the project.

Some readers will remember the days when Total Quality Management (TQM) was — justifiably — king. One of its fundamental precepts was that after a *product* is built, it is too late to build in quality. Instead one has to manage the *processes* in real time to ensure that the final product meets expectations and specifications. Nothing really changes — the king is dead and long live the king!

CORNERSTONES OF A SUCCESSFUL QUALITY CONTROL AND QUALITY ASSURANCE PROGRAM

It is assumed that the Specifications are clear in their (minimum) requirements in this regard and that the Contractor has satisfied these requirements regarding Preconstruction Submittals and Plans.

Thereafter, the most effective and efficient programs feature close collaboration between the parties responsible for Controlling and Assuring the Quality. This is a very simple, but oft-overlooked, fact. There may well be two (or more) parties on-site measuring, recording, testing and observing, but they should be complimentary and confirmatory, not adversarial and contradictory.

Based on the author's recent experiences with major Federal projects, the following key elements are fundamental to creating a quality QC/QA environment and process.

- Human Resources: There will be numerous positions to be filled with properly qualified and trained personnel, and the command structure should be similar for both parties. Even projects of moderate scale or duration will require multiple positions to be filled, including materials specialists, geologists, engineers and at least one CADD/GIS Data Manager. In addition, of course, there must be a dedicated full-time Quality Manager, reporting directly to the most senior on-site project executive on each side. Depending on the project, this Manager can also be the Technical Manager, and the Health, Safety and Environment responsibilities may also lie in this Department.

- Emergency Action Planning: Commonalities, across all types and sizes of projects, include the development of Emergency Action Plans, Joint Instrumentation Monitoring Plans (i.e., who reads which instrument, how frequently and how everyone is to react to the data), and dam/levee safety exercises. In addition, there are project-specific plans such as — for a Category 1 wall — slurry loss plans, and the associated slurry loss drills.

- Vertical-Horizontal Teaming: The Owner will have continuous involvement via his site team, but the clear, open and frequent involvement and participation of Head Office staff (e.g., District personnel, if the project belongs to the Corps of Engineers) is absolutely essential. This can be achieved by remote viewing of automated construction, quality and instrumentation data, as well as via routine regular internal Technical Meetings. In addition, the Owner's Agency may well have a more distant oversight body (e.g., a Risk Management Center) which will have a strong mandate and a powerful influence to satisfy.

  It is common for Owners to appoint a Board of Consultants/Expert Panel to provide a further level of oversight and influence. More recently, Contractors on larger projects have started to create and use similar groups of external advisors to contribute to their internal affairs, particularly regarding quality aspects. This provides an excellent platform for the respective groups of "experts" to discuss non-contractual matters with their peers and it assures that independent insight from the highest technical levels are made available for the benefit of the project.

  Similarly, the Contractor will often have the services of an Internal Technical Team, formed of senior personnel from the Head Office. Such groups, especially when a Joint Venture is in play, have the potential to greatly enhance so many aspects of site quality, given their knowledge and experience of the particular construction techniques being used or contemplated. There are typically few problems or difficulties that such a group have not experienced before, although every project is unique in at least one aspect.

- Full-Scale Tests: Laboratory (bench scale) tests are vital to providing index properties for the mixes contemplated for a project. Such tests will, typically — and hopefully — have been predicated on the outcome of desk (literature) studies of particular relevance. However, there is absolutely no doubt that the execution of full-scale field tests is vital to confirming that quality goals can be measured and achieved, as well as providing an opportunity to optimize construction means and methods. Test locations can be, and should be, in the line of the "production" wall. This satisfies several concerns, including cost, sequencing, and relevance. All such tests should be thoroughly planned, reported and discussed as a prelude to allowing "production" to commence. Depending on the outcome of such tests, the Contractor's Method Statement may have to be modified, while the QC/QA plans of the respective sides may also have to be adjusted.

- Continuous Monitoring: On a typical embankment dam undergoing a major foundation rehabilitation, there may be several hundred instruments to be monitored and interpreted, round the clock. Action level thresholds have to be set, responsibilities allocated, and actions implemented and justified. The embankment or levee must be inspected and evaluated, as related to specific construction activities or locations. Continuous monitoring is linked both directly and reciprocally to QC/QA activities since it drives the evolution of the design and the requirements placed on controlling and assuring the quality of the construction: a QC/QA Plan is indeed a "living document."

- Data Management: A huge amount of data are generated constantly on a major project. These data must be collected accurately and shared efficiently so that QC/QA personnel can absorb and react accordingly. This applies to site staff as well as others in remote locations. This is a major responsibility, underlining the critical position occupied by the CADD/GIS personnel in the respective QC/QA organizations.

- Checklists: For every construction process, a detailed checklist should be developed, initiated by the QC representative, but validated (or not!) by the QA representative in real time. Such checklists are generated by the Contractor, based on approved procedures, and each will typically have many (i.e., more than 10) specific checkpoints. Sufficient physical space must be allowed on each checklist to record, comprehensively, any comments or commentary which may be germane to the final quality of the process.

- Meetings: The Contractor typically will hold a QC meeting (involving Production personnel) prior to each shift to understand and/or explain the QC implications of the work contemplated. In addition, it is most useful for the QC and QA personnel to meet regularly (not less than weekly) to discuss all relevant activities, and especially to review any breaches of protocol or incidents which could have prejudiced the quality of the work as built.

CUT-OFF WALL GEOMETRY

Position

The position of certain types of Category 1 walls can be well controlled, via the use of guide walls. These are typically reinforced concrete structures, firmly and accurately pre-positioned in the working platform so that the starting position of the successive elements of the cut-off are known with great certitude. The traditional "land surveyor" techniques of former years have been complimented in more recent years with the use of GPS technologies which have become increasingly refined and accurate: even where walls are being installed with the backhoe method, the GPS potential, allied with good and standard field controls, should assure that the cut-off wall is being built in the correct location.

For Category 2 walls, the challenge historically has been more difficult since these technologies do not require a pre-surveyed, confining, guide trench. In recent years, however, GPS has condemned this issue to a practical irrelevance, particularly since standards of site inspection have improved, and awareness levels for non-compliance have increased. There is also the fact that remedial cut-offs lend themselves especially well to accurate physical location based on known existing structures, i.e., the dam or levee they are protecting.

In short, there is no reasonable contemporary argument that a cut-off wall should not be built in the correct location to acceptable and anticipated tolerances.

Depth

Every cut-off wall must reach the minimum depth specified and, depending on the nature of the construction technique and the Contractor's proposal, may have to extend some finite distance lower, to ensure that the design intent is met.

Contemporary excavation equipment of most types of Category 1 and 2 walls is characterized by on-board instrumentation which provides the machine operator (and remote observers) with a real-time display of the depth of the excavation tool below ground surface as well as other information on tool verticality and other mechanical characteristics. These data are generated, very simply, from a sensor which records the movement of a steel cord attached to the excavation tool or the drill head (corrected for distance above ground level), or a sensor reading the drum revolutions. A good QA/QC program will allow for frequent, periodic calibration of this system.

Following the excavation phase, the depth of the excavated element in Category 1 walls can be measured manually with a weighted tape, or some other simple mechanical device. Certain instruments used in Category 1 excavations to measure the shape or verticality of an element, e.g., the Koden ultrasonic sensor, also have very accurate depth recording capability.

For Category 2 walls, depth is further assured by reference to the actual penetration depth measured by welded marks placed on the drill mast, and verified by all parties in advance of construction as having been accurate. This is a simple and compelling measurement which does not need over-elaboration or which should merit second-guessing.

However, if required, following construction the depth of Category 1 and 2 walls can be further verified by full-depth coring and from the depth information provided from down-the-hole logging devices such as the Optical Televiewer.

Width

Cut-off width is dictated by the width of the individual elements, and by their overlap. Category 2 walls have a lateral dimension equivalent to the diameter or width of the mixing tool: provided there is no interruption to the injection of the grout during construction, or there are no extraordinary hydrogeological conditions, then there is no real possibility that the thickness of the as-built elements can be doubted. Even then, a test or measurement is often specified at no more than 100-foot centers, and at 10-foot vertical intervals.

Category 1 walls may occasionally be suspected of having a final in-situ width smaller than their excavated width, as a result of trench instability. Firstly, the real potential for such instability must be evaluated: this is, in fact, a very remote occurrence. The simplest way for element width to be proved is to demonstrate the free movement of the excavation tool for the entire depth and length of each element so constructed. Further assurance may be provided once the excavation tool is extracted:

- An ultrasonic scanner (e.g., Koden Ultrasonic Drilling Monitor) can be introduced.
- A sonic caliper can be introduced.
- The volume of backfill can be carefully logged against the rise in the backfill level in the trench, so allowing calculation of "overbreak" (typically 10-20%), and confirmation of no excavation collapse.

For the geophysical methods in particular, the slurry in these Category 1 trenches must have a low unit weight (e.g., ≤ 75 pcf) and a small amount of suspended solids (e.g., ≤ 5%) for accurate and effective results. Regarding the issue of overlap of adjacent elements, recent advances in on-board instrumentation for the excavation tools afford the Contractor a surprisingly high degree of verticality measurement and control. As a consequence, the as-built geometry and location of each element — panel or pile — is provided in real time by inclinometers in the hydromill, clamshell or rotary rig. Such data are then double-checked by one or more of three post-excavation methods outlined above. Further processing with CAD can then be done to illustrate the inter-element overlap at any depth, and thus proving that the minimum wall thickness has been assured at joints.

Inclinometers on DMM, TRD and CSM equipment provide a similar profile of verticality and, where required, a calculation of interpanel overlap.

It is now not unusual for wall verticality to be measured to an accuracy of 0.10% depth, although the key issue is wall continuity.

From a pragmatic viewpoint, any requirement for a maximum wall thickness is redundant. The ability to satisfy the minimum thickness criterion (and other requirements) is best illustrated in a Test or Demonstration Section.

Structural Continuity

Most Category 1 walls, and certainly those deeper than 100 feet, are constructed in discrete elements, such as panels or large diameter piles. They therefore have inherent discontinuities (i.e., joints) at regular intervals. Category 2 walls installed with vertical axis DMM or CSM are also formed in panels and have inherent lateral discontinuity, unless the "fresh-in-fresh" method is utilized. The backhoe excavation and TRD construction require a number of joints that is significantly reduced because of the characteristics of these methods.

A continuity acceptance criterion should address the quality of inter-element joints, and assure that they are properly constructed, with full contact and without defects such as entrapped slurry or unmixed material, open seams or open cracks. The key to creating good joints is of course appropriate quality control measures such as proper forming and cleaning of joints, thorough desanding of the slurry, adequate "bite in" and overlap between adjacent elements, and rigorous control over the quality and placement of the backfill material.

In general, walls with an unconfined compressive strength of 60 psi or more can be cored, provided the appropriate coring equipment and methods are used: there is no question that the coring of these walls is a specialized form of drilling, and is one wherein penetration rate must be sacrificed for recovery and verticality. Otherwise there is the potential for core recovery to be poor, and for borehole walls to be cracked. Special standards of care must be imposed during the selection of an acceptably qualified driller. Cores can be taken of the interior of the element itself (vertical), of inter-element joints (vertical, but difficult due to hole deviation tendencies), or both (i.e., by holes inclined across joints, in the longitudinal plane of the wall). Whereas it is not atypical to find minor smearing of joints in Category 1 walls formed with high-strength concrete, it is equally common to find excellent contact in "softer" walls, or in plastic concrete walls. Permeability tests (falling head or constant low head or rising head) can be a run on such joints to further demonstrate continuity, as can Optical Televiewer surveys.

CUT-OFF WALL HOMOGENEITY

The definition of homogeneity varies from project to project and is different for Category 1 and Category 2 walls. The former are to be composed of a backfill material batched on the surface and placed into a previously excavated element, whereas the latter may incorporate up to 70% of the native soil in a blend with slurry grout introduced during excavation.

It is not unreasonable to expect Category 1 walls — with the exception of deeper backhoe walls — to comprise backfill with no foreign debris inclusions, and minimal bleed or segregation. In other words, the in-situ material should not be sensibly different in uniformity, composition and appearance and other properties from the material as batched on the surface (e.g., plastic concrete walls). Due to their relatively simple method of construction, backhoe walls can equally reasonably be anticipated to be somewhat less homogeneous, while still remaining fit for purpose.

Category 2 walls must have a more pragmatic definition of homogeneity applied, in line with the type of construction, the nature of the soils and the purpose of the wall. By way of illustration, a mass DMM treatment of a plastic clay stratum to improve the ground for structural bearing purposes may have unmixed pockets of 6 inches in dimension or more, and still be acceptable. However, the same size of inclusions in a TRD or CSM cut-off wall subject to high differential head in service may permit piping to develop and so would not be acceptable in the long term. In general, a reasonable criterion would be to assert that homogeneity is inconsistent with the presence of defects or inclusions greater than 3 inches in any dimension.

For walls stronger than 60 psi, coring is the standard method of in-situ evaluation of homogeneity and are typically installed at a spacing of 100-200 feet. Cores should be inspected and logged by a professional and the drilling parameters of each hole (penetration rate, drillability, flush returns, etc.) carefully logged. Recovery targets should be pragmatically set — 95% or more is not unreasonable to specify in "hard" walls, whereas 85% may be a more realistic criterion in soft and/or Category 2 walls, provided always that the lost 15% can be rationalized as not being truly representative of a void or major soft inclusion. Likewise, high RQD (or rather SQD) targets (≥ 80%) should be set. Core should be not less than 2¼ inches in diameter and retrieved in runs not more than 10 feet long. Alignment checks need to be conducted to verify that hole deviation is within acceptable limits (e.g., within a drill depth of 100 feet, a maximum deviation of the order of 0.5% can be achieved with adequate care and technique).

In-hole testing (e.g., permeability) or logging with the Optical Televiewer run at a relatively modest rate, say not more than 3 feet per minute, also illustrates material homogeneity.

For "soft" walls coring may not be viable or representative, and so other methods are used, more akin to soil investigations, such as cone penetrometer test with piezocone, dilatometer or shear vane. In some cases a piston sampler can be used.

MATERIAL PROPERTIES

Strength, Deformability and Unit Weight

Strength, per se, is not a fundamental design property of a cut-off wall since structural stresses induced in service are not significant. However, strength is linked to durability and to the resistance of the wall to piping-induced erosion under service conditions. Statistical methods for analyzing strength data from QC/QA programs have been developed (Filz and Navin, 2010). These methods can properly allow for consideration of the inherent variability of strength measurements

Conceptually, a cut-off's deformability characteristic should be compatible with that of the surrounding embankment material at the time of the installation. This of course is a critical consideration when constructing a cut-off wall through deep alluvium under a new dam. This drove the recent decision to install a plastic concrete diaphragm at, for example, Papadia Dam in Greece wherein the ultimate strength had to be restricted to 100 psi to assure a correspondingly low degree of stiffness.

For Category 1 walls, such tests are routinely conducted from samples of the backfill materials as delivered to the excavation, in addition to measurement of slump and bleed. For Category 2 walls, the slurry to be injected during mixing with the soil is typically and routinely sampled to confirm both fluid properties (specific gravity, apparent viscosity and bleed) and hardened properties (strength, deformability and unit weight).

In-situ sampling of Category1 walls is commonly conducted by coring, except in "soft" walls where some other type of sampling (e.g., piston sampler) is used, if indeed any in-situ sampling is requested. Samples are subject to the broad battery of tests, usually at 28 days of curing, although there is great benefit from conducting similar tests at 7, 14, 56 and 112 days (and more).

This same range of sampling and testing is also applied to Category 2 walls which, however, lend themselves to other forms of sampling in addition to coring:

- Spoils can be sampled at the surface ("bulk samples").

- A "wet grab sampler" can be pushed into the soil-cement mix prior to initial set, to retrieve samples from discrete intervals. Such samples are best located near to where coring is to subsequently occur, so as to allow the impact of in-situ curing and the rigors of coring to be established. It is not unusual for bulk and wet grab samples to have average strengths up to 20% higher than corresponding samples from cores.

- A double concentric plastic or steel tube with an open end can be pushed into the wet soil-cement mix. The small annulus between the inner and outer tube is filled with grease to prevent soil-cement mix from entering it during insertion into the trench. When the soil-cement mix has reached initial set — or at any time thereafter — the inner tube, filled with soil-cement mix, is then pulled out leaving the outer tube in place. The void inside the outer tube is then backfilled with an appropriate, stable grout. The soil-cement mix retrieved in the inner tube, which is cut into convenient lengths (typically 5-10 feet) during withdrawal, is then available for curing and testing as required.

  When assessing the results of such tests, it is important to closely rationalize exceptional or unexpected data, e.g., anomalously low strength can result from drill-damaged cores, or from the presence of relatively large inclusions. It is also important to seek out trends and, in this regard, a running 10-point average is a responsive way to proceed.

Permeability

Cut-off walls are built to arrest seepage. Therefore, the assessment of permeability is of prime importance. Permeability is typically measured at 28 days after placement, and it does tend to decrease with age as the backfill continues to chemically hydrate. Samples taken of the backfill before placement, during placement or after placement can indeed be tested — most accurately via a triaxial cell. Such tests invariably give uniformly low values (10^{-6} to 10^{-8} cm/s) which, of course, reflect the concrete- or grout-like nature of the backfill material.

However, such tests will not reflect any potentially disruptive effects created by the construction and placement methods on the permeability of the cut-off as a structure. So, when the wall can be cored, the most representative test is to conduct an in-situ borehole permeability test, typically by rising head or falling head methods so as not to overpressurize the wall and cause fracturing. Also, bentonite should not be used as a drilling fluid and completed holes should be flushed to ensure that the actual in-situ permeability is not being masked. It must be noted, however, that the results of such testing must be viewed with care and understanding, for several reasons:

- In the case of lower strength materials, coring may damage the wall, causing or triggering fissures to develop which would artificially increase the measured permeability. It is in such cases that borehole logging with the Optical Televiewer is so useful, combined with a close examination of the cores themselves.

- Especially in the case of deeper walls, natural tendencies for boreholes to deviate can lead to perforation of the side of the cut-off, or the phenomenon of having only a very thin "skin" of backfill on one side of the hole, and so very susceptible to coring- or testing-induced cracking. In such cases, special directionally-controlled drilling systems may be necessary.

- The interpretation of the actual field test data is not always straightforward because of the cut-off wall geometry in relation to the borehole diameter: simplified equations (e.g., Hvorslev, 1951) to calculate in-situ permeability do not take into account the complexities created by boundary conditions. The authors would therefore advocate the use of more rigorous numerical methods instead to calculate more accurately borehole permeability results.

For walls which are too weak to be cored without creating artificially-induced permeabilities, in-situ permeability can be verified with other types of testing such as a piezocone.

On the large scale, the hydraulic effectiveness of a cut-off is most accurately and responsively demonstrated by its effect on piezometric levels upstream and downstream of it, its effect on seepage volumes, and its elimination of suspended sediments or dissolved minerals in the seepage outlets. Effectiveness can be verified by large-scale pumping tests on discrete stretches, or "cells," although these must be conducted with extraordinary levels of engineering common sense (but frequently are not), and tend to be very costly. Alternatively, one must wait for the cut-off to be naturally tested, by a significant amount of reservoir raising. The benefit and accuracy of such testing is directly proportional to the extent of the historical "baseline" information which is available.

FINAL REMARKS

The authors fully support the concept and practice of providing the highest practical standards of Quality Control and Quality Assurance during cut-off projects. Equally, the authors acknowledge the "bottom line" value of large-scale hydraulic loading events, both artificial (e.g., pump tests) and natural (e.g., reservoir or river rises). However, a call for pragmatism must be made. In recent years there have been truly significant developments made in the accuracy and resolution of the instrumentation used to monitor the construction of cut-offs, both during and after installation. While the precision and clarity of these methods are admirable, they do allow us to detect variations and defects which have heretofore gone unnoticed. In any event, an engineering evaluation should always be made to judge if the cut-off is still fit for purpose and if it will likely satisfy the design intent, even though flaws may be present.

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