

PRACTICAL ASPECTS OF QA/QC AND VERIFICATION FOR DEEP MIXED CUT-OFF WALLS

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ABSTRACT

The Deep Mixing Methods (DMM) are popular for constructing seepage cut-offs through and under existing dams and levees. A major reason for this is the development of reliable QA/QC and verification methodologies. This paper begins by highlighting the cornerstones of a successful QA/QC program, starting with the quality of the project Specifications themselves, and goes on to place heavy emphasis on the qualifications, efficiency and cooperation of the personnel of all parties involved. Wall geometry relates to position, depth, width, verticality and continuity, and guidance is provided for each of these aspects. Homogeneity is also discussed. Sampling and testing procedures are reviewed, relating to the strength, deformability, unit weight and permeability of samples taken from the wall both during installation, and after it has hardened. The paper reminds that the DMM methods produce an inherently heterogeneous material in place, and so that a pragmatic approach to dealing with test results is warranted. Further, the authors acknowledge that what may be preferable on large, high profile projects, may not always be commercially viable on relatively small projects in very competitive markets.

INTRODUCTION

In the U.S. the current nationwide program to remediate existing dams and levees includes, among other measures, the construction of cut-off walls to prevent failure modes related to seepage and internal erosion. 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, 2013):

- Category 1 walls, in which the in-situ material is excavated under supporting slurry with long-reach excavator, clamshell, or hydromill equipment and replaced by an engineered material of controlled properties (e.g., concretes, self-hardening slurry, soil-cement-bentonite and soil-bentonite). Secant pile cutoff walls are also included in this category.
- Category 2 walls, which entail the mixing of the in-situ material with a fluid grout 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). These are the subject of this paper.

Cut-off walls will be effective only if they have been properly designed and constructed. Appropriate construction Quality Control (QC) and quality assurance (QA) programs are essential to verify that the cut-off wall has been constructed as designed. QC/QA programs should be developed with a thorough understanding of the design intent for the cut-off wall and its method of construction. Inappropriate specification requirements for QC/QA activities can result in inadequate verification of cut-off wall construction and/or in unnecessary costs and/or contract disputes.

Procedures and concepts of QA/QC and Verification have evolved quickly over the last decade in particular in response to issues which have arisen in the field, and as a reflection of input provided by

Owners, Engineers and Contractors alike, and from many excellent Conferences such as those held in 2012 (New Orleans), 2015 (San Francisco), and 2017 (Honolulu).

It is of course the case that Quality Control refers to measures implemented by the Contractor during the execution of his work. Quality Assurance refers to measures taken by the Owner, or his Agent 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 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 by the particular type of construction method adopted, while projects of smaller extent in particularly competitive markets may not be able to sustain the optimum suite of tests desired.

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 have to pass before the performance 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 inject quality. Instead one has to manage the construction *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 SUCCESSFUL QUALITY CONTROL AND QUALITY ASSURANCE PROGRAMS

The most effective and efficient programs are based on close collaboration between the parties responsible for Controlling and Assuring the Quality. There may well be two (or more) parties on-site measuring, recording, testing and observing, but their efforts should be collaborative, not confrontational.

Based on the authors' recent experiences with major U.S. Government projects, the following key elements are fundamental to creating a quality QC/QA environment and process.

- Clear and complete specifications. Without clearly written specifications, the Contractor will not be able to determine what QC activities and submittals are required. Similarly, the specifications must be complete because it is unfair to expect the parties to perform QC/QA activities that are not identified in the specifications. In addition, it is equally important that the specifications establish requirements that are based on the design objectives of the cut-off wall and consistent with the construction technologies that the specifications allow. If unnecessary requirements are specified, the construction cost will be unnecessarily increased. Specifications for QC/QA programs should be tailored to the unique objectives, subsurface conditions, and construction technologies permitted for each individual project.
- Appropriate organizational structures and qualified personnel. For both the Owner/Engineer and the Contractor, project teams generally include home office personnel, field personnel, and laboratory personnel. All personnel involved should have the necessary training and experience. On virtually all cut-off wall projects, the Contractor must employ a full-time Quality Manager, while on medium to large projects, there should also be a dedicated CADD/GIS/IT specialist to

manage the data. Additional materials specialists, engineers, geologists, and technicians may be necessary, depending on the size and complexity of the project.

- Communication. As introduced above, there must be close collaboration between the Contractor's QC personnel and the Owner/Engineer's QA personnel, including rapid and complete sharing of observations and data. Early identification of problems enables quick corrective actions to be taken in the least expensive time to make corrections and avoid building substantial sections of cut-off wall with ineffective parameters. The frequent interactions between the Contractor's and Owner's personnel should be collaborative rather than confrontational, since all team members must surely share the common goal of completing the project to achieve the specified end result. Communication flows should be open and rapid, not only horizontally, but also vertically, such that managers, home office personnel, and review boards have easy access to essential information.
- Instrumentation monitoring plan and emergency action plan. Depending on the type of project, hydraulic loading conditions which change during construction, as well as the effects of the construction itself, can trigger the need for emergency action responses. Potentially adverse conditions should be anticipated, appropriate instrumentation installed with redundancy, an instrumentation monitoring plan developed, action levels established, and emergency action plans developed.
- Advisory Boards. It is common for Owners to appoint a Board of Consultants/Expert Panel to advise, and 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 Support Team, formed from senior personnel from Head Office. Such groups, especially when a Joint Venture is in play, have the potential to 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 collectively 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 typically will 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 pre-production 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 sections can be, and should be, within the location of the "production" wall. This benefits several issues, 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 dam or levee 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. 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 is 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 maintained, initiated by the QC representative, but validated by the QA representative in real time. Such checklists

are typically generated by the Contractor, based on approved procedures, and each will have multiple 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 construction personnel) prior to each shift to 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, incidents or non-compliances which could have prejudiced the quality of the work as built.

OBSERVATIONS, MEASUREMENTS, AND TESTS

Geometry

- **Position.** For Category 1 cut-offs, reinforced concrete guide walls are typically prepared on a firm working platform. This assures that the various elements comprising the cut-off are precisely located with respect to their planned position. For Category 2 walls, however, the challenge historically has been more difficult since Deep Mixing technologies do not require a pre-surveyed, confining, guide trench. In recent years, however, GPS has condemned this issue to a practical irrelevance, 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, such as the crest of the dam or levee they are remediating. Positioning can be specified and controlled within an accuracy of 75 mm using contemporary techniques. In short, there is no sustainable 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 DMM 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 operational characteristics. These data are generated 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 calibration of this system. 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 involve second-guessing. Following construction, the depth of the wall can be further verified by full-depth coring and from the depth information provided from high resolution down-the-hole logging cameras.
- **Width.** Cut-off wall width is determined by the equipment dimensions, which can be easily measured while the mixing tools are at the ground surface. This assumes there is no interruption to the injection of the binder during construction, and that there is no inappropriate mix behavior or extraordinary hydrogeological conditions which would impact the soil cement mix before it hardens. For cutoffs constructed in panels by the "conventional" multiaxis or CSM Methods, the two parameters to be defined are thickness and overlap. The effective wall thickness in the shortest path for water to pass through a wall, as shown in Fig 1. Conversely overlap is a reflection of wall continuity and it represents how much one panel overcuts its adjacent panel, as shown in Fig. 2. Compliant thickness and overlap have to be established at all elevations in a wall, although it is typical for cutoffs of depths down to 40m or more to have these measurements made at the top, middle and bottom only. These measurements are then recorded on the as built cutoff wall drawings. Misalignment can affect the average wall width, but it can also have more serious consequences, such as creating a defect in the cutoff wall. Consequently, controlling positioning and verticality of adjacent columns is especially

important when cut-off walls are constructed from overlapping elements. The ability to satisfy the minimum width criterion (and other requirements), is best illustrated in a Test or Demonstration Section.

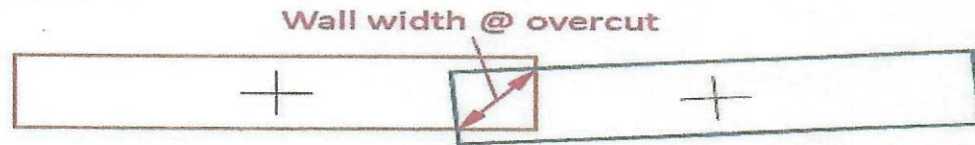


Fig. 1. Panel width at the overcut.

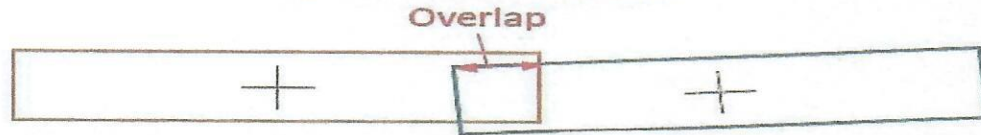


Fig. 2. Panel overlap at the overcut.

- **Verticality.** Although a high degree of accuracy is not generally necessary for the overall verticality of a cut-off wall, accurate control of verticality is important when overlapping elements are used to construct a cut-off wall with the most important factor being that adjacent elements are constructed at the same inclination to maintain the design overlap over the full depth of the cut-off wall. Generally, this is accomplished by specifying a fine tolerance for deviation from vertical for each individual element, e.g., now within 0.3% of plumb. Verticality can and should be continuously monitored by inclinometers mounted on the construction equipment. Verticality is less important than continuity. For walls constructed using a continuous construction technique, such as backhoe slurry trenches and TRD, fine tolerances on verticality are not generally necessary. Any requirement for a maximum wall thickness is redundant.
- **Continuity.** Cut-offs constructed with “conventional” vertical-axis DMM and CSM methods have inherent lateral discontinuity as they have joints between adjacent elements. This is mitigated by the use of “Fresh in fresh” as opposed to Primary-Secondary work sequences. Cut-offs formed with TRD or similar “one pass” methods do not have this problem due to the practice of significant “back-cutting” following a non-productive period. Any continuity acceptance criterion should address the quality of interelement joints and must realistically address what can reasonably be expected in the field. Coring of DM material of UCS over 0.5 MPa is feasible using appropriate coring means and methods, and permits physical examination of samples, as well as providing access for acoustic or optical cameras. “Perfect” joints (i.e., where the joint is intact and practically undetectable to the naked eye) are of course desirable. Even when “imperfect” (i.e., the core separates when handled, and the joint is clearly visible), they are most likely acceptable and fit for purpose, unless proved otherwise by the results of an in-situ permeability test, as described below. “Defective” joints feature measurable and continuous thicknesses of unmixed, soft material and would, instinctively be regarded as unacceptable. Even then, however, the Engineer may have to demonstrate that such a defect could somehow maintain or create a Potential Failure Mode at that location, given the presence of embankment material either side, the hydraulic gradient and the thickness and composition of the defect. Joint quality is a direct reflection of construction technique and is a factor which can be managed to acceptable, pragmatic standards by choosing appropriate means, methods, and sequencing on the part of the Contractor.

Homogeneity

It must be borne in mind that DMM cut-offs will comprise a composite material containing up to 70% of the native soil (with all its attendant variability). Hence, a realistic definition of homogeneity must be specified. By way of illustration, a wall penetrating a plastic clay stratum may have large (>150

mm) pockets of unmixed clay, but subject to “blow out” analyses, may still be fit for purpose, especially given that the hydraulic gradients imposed by levees or low embankments will not be high. However, in common practice, it is typical to find a criterion requiring no defects (i.e., unmixed pockets) more than 75 mm in maximum dimension.

For materials stronger than 0.5 MPa, coring is the standard method of in-situ evaluation of homogeneity with holes typically drilled at a spacing of 30-60 m along the wall. Cores should be inspected and logged by a certified 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 stronger walls, whereas 85% may be a more realistic criterion in softer 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 ($\geq 80\%$) should be set. Core should be not less than 60 mm in diameter and retrieved in runs not more than 3 m long. Alignment checks need to be conducted to verify that hole deviation is within acceptable limits (e.g., within a drill depth of 30 m, 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 an optical or acoustic camera run at a relatively modest rate (say not more than 1 m per minute) also demonstrates material homogeneity.

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

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 or for cut-offs in highly seismic terrains. For DMM 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). The soil-slurry mixture can then be sampled, when still fluid, by various methods:
 - Spoils can be retrieved at the surface (“bulk samples”).
 - A “wet grab sampler” can be pushed into the soil-cement mix prior to its 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, as a result of wet sample preparation involving sieving, and the potential for damage to samples during coring. Alternatively, for mixes which are susceptible to pressure filtration into adjacent sandy soils, there is a progressive consolidation prior to stiffening. This will result in core samples at depth having higher strengths than shallow core samples, or indeed wet grab samples, assuming similar geotechnical conditions at these elevations.
 - A double concentric plastic or steel tube with an open end can be pushed into the newly installed soil-cement mix. The small annulus between the inner and outer tube is filled with grease to prevent the 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

cured 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 sample retrieved in the inner tube, which is cut into convenient lengths (typically 1.5-3 m) 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 or from deficiencies in the curing, handling and preparation of samples. It is also important to seek out trends and, in this regard, a running 10-point average is a responsive way to proceed.

- Permeability (hydraulic conductivity). Cut-off walls are built to arrest seepage and the potential for internal erosion. 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 cure (Jefferis, 2012). Samples taken of the backfill before placement, during placement or after placement can indeed be tested — most accurately in a triaxial cell (flexible wall permeameter). Such tests give uniformly low values (10^{-6} to 10^{-8} cm/s) which, of course, simply reflect the grout-like nature of the backfill material, and are therefore of marginal value unless there are gross errors in the batching or the in-situ mixing process — issues which should be flagged-up by visual observation of the test samples as they are taken in the field.

However, laboratory 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 causing fracturing and hence a false condition. Also, bentonite should not be used as a drilling fluid during coring 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 a downhole camera 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, which is very susceptible to coring- or testing-induced cracking. In such cases, special directionally-controlled drilling systems may be necessary.

The determination of permeability from rising or falling head tests in boreholes in cut-off walls requires consideration of the cut-off wall geometry in relation to the borehole diameter. For example, flow to or from a 15 cm diameter borehole in a 60 cm wide cut-off wall will be markedly faster than that to/from the same borehole in cut-off material of infinite extent. The intake factors in equations such as those by Hvorslev (1951) and Bouwer and Rice (1976) do not take into account the complexities created by the cut-off boundary conditions. The authors would therefore advocate the use of numerical methods such as those developed by Britton et al. (2002) to determine intake factors. Failure to use cut-off wall specific intake factors may lead to an overestimation of the permeability of a cut-off wall, typically by a factor of about three. The actual factor will of course depend on the geometry of the wall and the test.

The authors are not aware of any validated analytical procedure for the determination of permeability from tests where the section of a borehole which is under test is wholly or significantly above the adjacent groundwater level.

A typical acceptance criterion for a “joint core” hole is 10^{-6} cm/s.

For walls which are too weak to be cored without creating artificially-induced permeabilities, in-situ permeability can be assessed 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, its elimination of suspended sediments or from induced changes in seepage water chemistry in the seepage outlets. Effectiveness can be verified by large-scale pumping tests on discrete stretches, or "cells," although these must be conducted with high 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, for example, by a significant rise in reservoir level. 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. The precision and clarity of these methods are admirable, and they allow us to detect variations and defects which have heretofore gone unnoticed. However, 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 imperfections may be present. The authors recognize that QA/QC and Verification methodologies can be seen as expensive, and appropriate only to major projects. However, owners who fail to specify sufficient QA/QC may learn of defects only later when the cut-off fails to perform in service.

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