

QC/QA AND VERIFICATION FOR DEEP MIXED STRUCTURES: SOME FUNDAMENTAL OBSERVATIONS AND RECOMMENDATIONS

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ABSTRACT

It is well known that the Deep Mixing Method (DMM) has been widely used in North America in many applications since 1986. During that period, there have been many extremely positive developments in design and construction which have contributed greatly to the efficiency, quality, and competitiveness of the technique.

Despite the availability of numerous guideline documents, the authors – who collectively and individually, typically serve in high level review capacities for individual projects – still find that approaches to QC, QA and Verification are not as well aligned as in other aspects of Deep Mixing (DM) such as design principles and construction techniques. In this paper, they present some fundamental observations and recommendations as a contribution towards the development of consistent and relevant practices. In particular, the advantages and disadvantages of testing laboratory samples as opposed to testing the in-situ properties of the DM structure are discussed, as are the advantages and challenges of verification drilling and sampling.

This paper is presented at a time when the DMM is becoming progressively more popular and accessible to a new generation of designers and contractors who may be tempted to “reinvent the wheel” from a lack of awareness of the previous decades of old arguments and hard-earned lessons.

Keywords: Deep Mixing, QC/QA, Verification, Specifications

1. INTRODUCTION

The Deep Mixing market in the United States is dispersed and multifaceted, given its great geographical and geotechnical diversity, and the wide range of applications. As detailed by Bruce et al., (2020), the major groups of applications are as listed in Table 1.

Table 1. Applications of DMM for Ground Treatment in the US

PROJECT CATEGORY	TYPE OF APPLICATION	TYPICAL ORGANIZATIONS/OWNERS
Dams and Levees	Seepage control , embankment stability and seismic mitigation.	US Army Corps of Engineers, Bureau of Reclamation, California Department of Water Resources, major utilities.
Transportation Infrastructure	Shoring, bearing, capacity, settlement control, maintaining stability.	Departments of Transportation in MA, CA, WA, MN, VA; Valley Transit, and other private owners.
Port and shoreline	Port and shoreline stabilization, seismic stability.	Port of Oakland, Port of Long Beach.

PROJECT CATEGORY	TYPE OF APPLICATION	TYPICAL ORGANIZATIONS/OWNERS
Industrial Facilities	Bearing capacity, settlement control and seismic stability.	Petroleum and chemical plant owners, nationwide.
Deep Excavations	Support of excavation	Private developers and their general contractors in urban areas.
Environmental Remediation	Containment and fixation of contaminated soils.	Certain Federal Agencies, but primarily industrial plant owners.

The same authors also describe the numerous types of DM methods being employed, including “Conventional” Single or Multiple Vertical Axis (Wet and Dry), Cutter Soil Mix, and continuous trenching such as TRD or “One Pass” (Fig. 1).

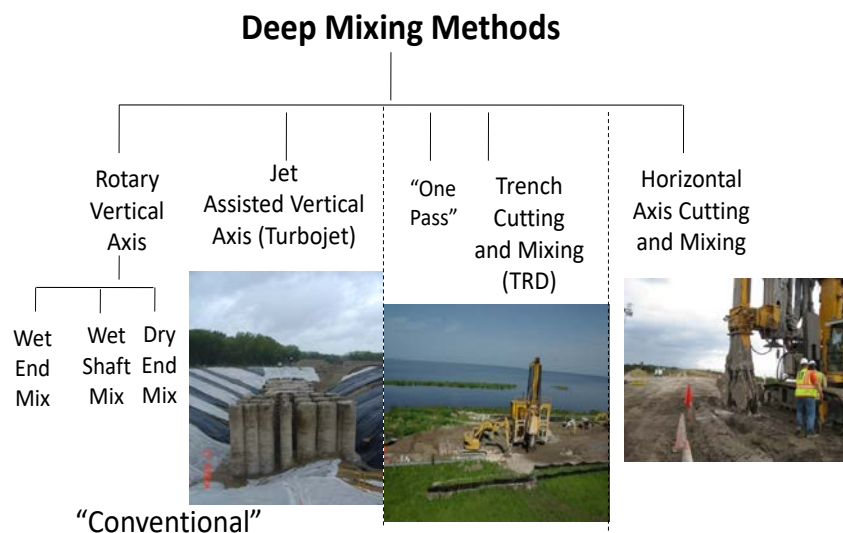


Figure 1. Classification of DMM used in the United States (Bruce, 2013)

The path to the success of any DM project begins with the quality of the site investigation, the design and the specifications. Inherent in this statement is the fact that appropriate construction Quality Control (QC) Quality Assurance (QA) , and Verification programs must be developed, implemented, and evaluated to confirm that the project in question can be built to a standard of care which will ensure that it will satisfy the design intent in service.

Inadequate and/or inappropriate QC/QA programs will lead to uncertainty and dissatisfaction with the finished product, and even to the expensive and time-consuming distractions of contractual disputes. In this regard, alternative contracting methods such as Early Contractor Involvement or Design Build should anticipate potential quality concerns prior to construction. There should always be a focus on assuring the quality of the processes, not just the status of the installed as-built product.

Procedures and concepts of QA/QC and Verification have evolved quickly over the last decade both 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 International Conferences such as those held most recently in 2012 (New Orleans), 2015 (San Francisco), 2017 (Honolulu), and 2020 (Virtually, in Gdansk).

2. CORNERSTONES OF SUCCESSFUL QUALITY CONTROL AND QUALITY ASSURANCE PROGRAMS FOR DEEP MIXING PROJECTS

The most effective and efficient programs are based on close collaborations between parties responsible for Controlling and Assuring the Quality. There may be two (or more) parties on-site observing, measuring, recording, and testing, but their efforts should be collaborative, and complementary. The following components are fundamental for 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 actually required. Similarly, the specifications must be comprehensive 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 objective of the DM 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 the construction technologies permitted for each individual project. Further guidance is provided in Cali and Filz (2015).

Appropriate organizational structures and qualified personnel: For both the Owner/Engineer and the Contractor, project teams generally include home office staff, field personnel, and laboratory specialists. All members involved should have the necessary training and experience. On most projects, the Contractor should employ a full-time Quality Manager, while on medium to large projects, there should also be a dedicated CADD/GIS/IT specialist to manage and help interpret the data. Additional materials specialists, engineers, geologists, and technicians may be necessary, depending on the size and complexity of the project. Advice on providing proper field laboratory facilities is provided in Jefferis and Ouyang (2020).

Communication: As introduced above, there must be close collaboration between the Contractor's QC personnel and the Owner's QA personnel, including rapid and complete sharing of observations and data. Early identification of problems enables quick corrective actions to be taken, and it is the least expensive time to make corrections and avoid building substantial sections of the project 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 within the contract period. Communication flows should be open and rapid, not only horizontally, but also vertically, such that managers, home office staff, and advisory boards have easy access to essential information.

Instrumentation monitoring plan and emergency action plan: Depending on the type of project, 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. The benefits of an automated instrumentation monitoring program have become particularly obvious for construction in recent years since site inspections and manual monitoring opportunities have been restricted due to the pandemic.

Advisory Boards: It is common for Owners to appoint a Board of Consultants/Expert Panel to advise, and provide a further level of project oversight and input. More recently, Contractors on larger projects have started to create and use similar groups of external advisors to contribute to their internal processes, 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 is made available for the 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 will be found unique in at least one aspect.

Full-Scale Field Tests: Laboratory (bench scale) tests are vital to providing index properties for the mixes contemplated for a project. Such tests typically will have been based 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” treatment. All such tests should be thoroughly planned, reported, and reviewed as a prelude to allowing production to commence. Depending on the outcome of such tests, the Contractor’s Construction Method Statement may have to be modified, while the QC/QA plans of the respective sides may also have to be adjusted. It can be truthfully said that the field test program is a trial of the Contractor’s means and methods and is as beneficial to the Contractor as to the Owner.

Continuous Instrumentation Monitoring: On a typical dam or levee undergoing a major foundation rehabilitation for example, there may be scores of 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 continuously on a major project. These data must be collected accurately and shared efficiently so that QC/QA personnel can review 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 process 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, any comments or commentary which may be germane to the final quality of each process.

Meetings: The Contractor will usually hold an in-house meeting (involving construction personnel) prior to each shift to explain the QC implementations of the work contemplated. In addition, it is most useful for the QC and QA personnel to meet regularly (not less frequently 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.

3. STANDARDS AND SPECIFICATIONS

It remains difficult to fully standardize design and acceptance criteria across the USA given the diversities noted above. Guide specifications are given, however, in the Federal Highway Administration Design Manual: Deep Mixing for Embankment and Foundation Support (2013) which can be found at the website, <http://www.geotechtools.org>,. Guidance on planning, design, and construction quality control are offered in the yet unpublished US Army Corps of Engineers Engineering Manual for Cut-off Walls (Draft) October 2012, and the US Bureau of Reclamation Design Standards No 13 Embankment Dams

(Chapter 16 Cut-off Walls), July 2014. Acceptance criteria are project and purpose specific, and they must be tailored to meet the project requirements.

The authors note that, most often, specified acceptance criteria generally exceed the actual design demand. It is speculated that this arises from a lack of understanding of the long-term performance of the final DM product. The DM Methods have been widely used worldwide for only about 50 years – barely the life expectancy of most projects, and little research has been published into long-term durability of older DM installations. For example, the generally adopted criterion for maximum permeability (1×10^{-6} cm/s) and minimum unconfined compressive strength (100 psi) specified for seepage barrier walls should be justified as specific design requirements. These values are basically default criteria, adopted from previous projects without sound technical reasons which should include consideration of the actual required barrier function and the durability of the barrier which may be influenced by the volume and velocity of water permeating through it.

4. OBSERVATIONS, MEASUREMENTS AND TESTS

QA/QC and Verification programs for DM projects must address many aspects of the construction, ranging from those dealing with the geometry and continuity of the structure, through tests on material samples (taken both during and after construction), to considerations of the in-situ status of the structure.

4.1. Geometry

Position: It is obvious that the elements must be installed in the correct position both laterally and along the axis of the works in order to assure that the specified area replacement ratio is uniformly provided, and that adjacent elements overlap adequately: this is particularly the case where the purpose of the DM is to provide a hydraulic or environmental barrier, and where that diaphragm is to be built by discrete elements as opposed to continuous trenching.

Occasionally a challenge in former years, this issue has been removed from concern by the accuracy and sensitivity of contemporary GPS technology. However, spot checks in the form of conventional site surveying, tied logically into prominent site features such as the crest of a dam, or the face of an adjacent building is still strongly recommended. Today, a setting-out error should simply not occur, and locating an element within 3 inches of its design position should reflect a normal standard of care.

Depth: Every DM structure 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 is characterized by on-board instrumentation which provides the machine operator (and connected remote observers) with a real-time display of the depth of the excavation tool below ground surface as well as other information on verticality and operational characteristics. These data are generated from a sensor which records the movement of a steel cable attached to the excavation tool or the drill head (corrected for distance above ground level), or a sensor reading the hoist drum revolutions. The QA/QC program should 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 stem and verified by all parties in advance of construction as being accurate. This is a simple and compelling measurement which does not need overelaboration or involve second-guessing. Following construction, the depth of the mixing can be further verified by full-depth coring complete with depth information provided from high resolution down-the-hole-logging cameras.

Width: This is a consideration for projects involving DM to create a seepage barrier or cut-off. One could assume that the width will be closely approximated by the dimensions of the mixing tools, which of

course can be easily measured while these tools are above ground. However, 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 walls constructed in panels by the “conventional” multi-axis or CSM methods, the two parameters to be defined are thickness and overlap. The effective wall thickness is the shortest path for water to pass through a wall, as shown in [Figure 2](#) which shows a rectangular panel shape for simplicity. Conversely, overlap is a reflection of wall continuity and it represents how much one panel overcuts its adjacent panel, as shown in [Figure 3](#). Compliant thickness and overlap have to be established at all elevations in a wall, although it is typical for cutoffs of depths down to 100 feet or more to have these measurements made at the, top middle, and bottom only. These measurements are then recorded on the as-built cut-off wall drawings. Misalignment can affect wall width, but it can also have more serious consequences, such as creating a defect or “window”. Consequently, controlling positioning and verticality of adjacent elements is especially important when 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.

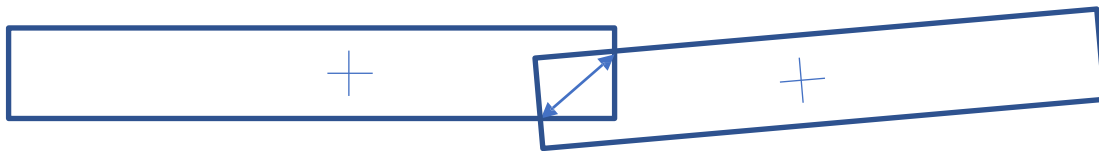


Figure 2. Panel width at the undercut

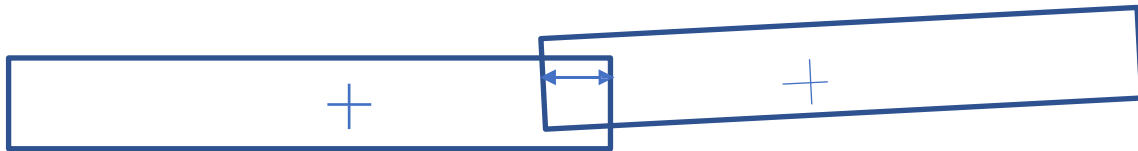


Figure 3. Panel overlap at the undercut

Verticality: It is important that the minimum overlap is maintained over the full depth of the DM element. For deep walls this will require tight verticality tolerances. For example, if two adjacent panels are 100 feet deep with 0.5% vertical deviation but in opposite directions, their centerlines will be offset by 1 foot from each other at depth.

4.2. **Homogeneity**

It must be borne in mind that DM structures comprise a composite material often 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 structure penetrating a plastic clay stratum may have large (greater than 6 inch) pockets of unmixed clay, but subject to engineering analyses, may still be fit for purpose. However, in common practice, it is typical to find a criterion requiring no defects (i.e., unmixed pockets) more than 3 inches maximum dimension.

For mixed materials stronger than about 100 psi, coring is the standard method of in-situ evaluation of homogeneity. Cores should be inspected and logged by a certified professional, and the drilling parameters of each hole (penetration rate, drillability, recovery, flush returns, etc.) carefully logged. Recovery targets should be pragmatically set – 95% or more is not unreasonable to specify in stronger DM, whereas 85% may be a more realistic criterion in softer structures, provided always that the lost 15%

can be rationalized as not resulting from a void or major soft inclusion. Likewise, high RQD (or rather SQD) targets ($\geq 80\%$) should be set. Core should be not less than 2.5 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 vertical 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 3 feet per minute) also demonstrates material homogeneity. For very soft DM structures, 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.

4.3. Material Properties

Strength, Deformability, and Unit Weight. Strength, per se, is not necessarily a fundamental design property for all DM structures. For example, the structural stresses induced in a cutoff are not significant. However, strength is linked to durability and to the resistance of a 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, deformability must be compatible with the design concept, especially when the DM has been installed as part of a “composite” structure, functioning with the natural soil, or as a cut-off in a seismic area.

The slurry injected during mixing 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 be sampled, while still fluid, by various methods:

- From spoils returned 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 elevations. 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 empty outer tube is then backfilled with an appropriate stable grout. The sample retrieved in the inner tube, which is cut into convenient lengths (typically 5 to 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 or the presence of coarse particles in the mixed material, 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.

Samples taken by the double tube method should not be sub-cored for laboratory testing (i.e., small diameter cores should not be drilled from a larger diameter sample), as this would cause damage as with field coring.

Note that Euro Soil Stab (2002) reports that the strength of in-situ material can be 20-50% that of samples prepared in the laboratory. Contractors must therefore adjust their binder factors accordingly prior to moving into Full-Scale Field Tests to achieve design results. However, since the cost of binder is a major factor in overall DM construction costs, over-conservatism in specifying strength can dramatically increase the final DM cost.

Contrary to the paradigms of unexperienced drillers, high core recoveries – a figure of 90% is typically specified – can indeed be achieved in DM material of UCS as low as 100 psi using appropriate means and methods. However, zones of poor recovery often are associated with hard, large soil particles, and acceptability will have to be proved by in-situ viewing of the DM element with an Optical or Acoustic Televiewer. As noted above, due to the inevitable, disturbance to core samples imparted by the drilling, retrieval, and handling processes, strengths are typically lower than strengths obtained from samples taken of the fresh soilcrete prior to its setting. Nevertheless, coring of verification holes is often the prime basis of DM compliance with regard to requirements for strength, homogeneity, and continuity. Perhaps the most comprehensive evaluation of factors affecting strength, homogeneity, and continuity are described in the four papers published on the LPV-111 project from 2009-2011, which can be found in the Proceedings of the 4th International Conference on Grouting and Deep Mixing, held in New Orleans, LA during February 2012.

Considering that many specifications require 1-3% of the DM elements to undergo coring or grab sampling during construction, one must question the quality of the remaining 97- 99% of the DM installation if repeated tests fail. The FHWA Manual (2013) recommends that 2-4% of DM elements be cored with the larger percentage applying to more important and to smaller scale projects.

A combination of 100% QC coverage and a relatively small amount of verification coring and testing can provide high reliability that the mixed soil is overall of good quality, provided that the QC and QA work is done well, with high frequency observations of all QC/QA activities by the Owner. It is imperative that QA/QC efforts be augmented by expert review of the daily DM installation records. In this way, data obtained from testing can be extrapolated to represent the entire DM works.

Test specimens taken from cores at 28-days age during the field test program and in production can be preserved for longer durations to demonstrate that a 56-day or even 90-day design strength specification has been achieved. This would allow the cost-conscious designer to specify a lower 28-day strength, saving the project the cost of the additional binder. It is often preferable to apply a conservative estimate of strength gain with time during design and to establish the specified strength in terms of the 28-day strength instead of the 56-day strength because this can facilitate the Contractor's staging operations. However, if it is known that the service load would not be imposed until months after construction and the construction schedule would not be delayed by DM acceptance after two months, then a 56-day curing strength could be specified as the target strength.

In the FHWA Manual (2013), it is recommended that the Contractor should propose locations for wet grab sampling while considering input from the Owner, and that the frequency be guided by the following: "One wet grab sample (one selected depth at one location) should be retrieved

every two production days or from every 600 cubic yards/day of treated soil, whichever produces the higher sampling frequency.” This recommendation was expanded in the document on FHWA’s website, <http://www.geotechtools.org>, to require that, “Sample locations shall be distributed uniformly both laterally and vertically within the deep mixed zone.”

The test results for cored samples and wet grab samples should represent the means and methods of the DM installation. Where soil conditions are uniform and the Contractor’s means and methods are duplicated, the data can be extrapolated as representative of duplicate DM elements. Conversely, when DM procedures or soil conditions are changed, corresponding changes in test results should be expected.

Permeability (hydraulic conductivity). A common application for the DMM is to arrest seepage and reduce the potential for internal erosion occurring through the native soils. Therefore, achieving the target permeability of the cut-off 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 soilcrete during or after placement can indeed be tested – most accurately in a triaxial cell (flexible wall permeameter). However, such tests give uniformly and predictably low values (10^{-6} to 10^{-8} cm/s) which, of course, simply reflect the grout-like nature of the DM 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.

Laboratory tests will not reflect any potentially disruptive effects created by the construction and placement methods on the permeability of the cut-off wall as a structure and so have value only as an index of homogeneity. So, the most representative test is to conduct an in-situ borehole permeability test, by rising head or falling head methods, so as not to over pressurize 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 in subsequent testing. It must be noted, however, that the results of such testing must be viewed with care and understanding, for several reasons, including:

In the case of low DM 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 soilcrete 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 6-inch diameter borehole in a 24-inch-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 intake factors derived from numerical analyses such as those developed by Britton et al. (2002, 2005). Typically, the use of the intake factors from Hvorslev (1951) will lead to an overestimation of the permeability of a cut-off wall by a factor of around 3. The actual factor will of course depend on the thickness of the wall, the borehole diameter, and the

length of the test section. In this respect it should be noted that the Hvorslev factors are themselves developed from a number of assumptions and are not strict analytically derived numbers. It is important that the procedure to be used for the determination of intake factors is set out in the specification.

- 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.
- For structures which are too weak to be cored without creating artificially induced high 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. If used, the testing must be continued for long enough that steady state conditions can be achieved. 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.
- Test cells are an excellent idea but even for damaged walls, the measured effective permeabilities may be low. Some years ago, the authors built two cells against a slurry trench cut-off wall, one 7 x 33 feet, and the other 16 x 20 feet. Pumping from a central well produced practically zero flow from either well. A further problem is that after any initial drawdown, water may slowly drain down from now partially saturated soil above so that even with a perfect wall, there may be a rise in the internal water level after the initial pumping. It was estimated that to prove the presence of a 10^{-7} cm/s wall, one would need to pump for at least a month.

5. LESSONS LEARNED AND GENERAL RECOMMENDATIONS

- Designers often specify unjustified and sometimes unrealistic performance criteria, resulting in unnecessary contractual issues due to non-compliance. For example, unless there is a design or quality assurance need for a specific compressive strength of a seepage barrier, the requirement should be eliminated, de-emphasized, or given a wide range as an acceptance criterion in the specifications. Rather than specifying an absolute maximum acceptable permeability, considerations should be given by the Designer to adopting the probabilistic approach for strength specification advocated by Filz and Navin (2010), particularly if and when permeability is measured on a large number of specimens recovered from core samples. For DM applications involving structural support, it is appropriate to specify a minimum UCS or shear strength (with limits on the number and distribution on non-compliant samples) but not appropriate to specify a maximum strength (reflecting soil heterogeneity).
- Cutoff wall designers should consider specifying transmissivity rather than permeability since transmissivity is the true design parameter for a cutoff wall. This would also allow Contractors to match permeability and wall width to their equipment to meet the design requirement.
- Specifications for DM have become bloated by blind repetition of specifications from previous projects without culling irrelevant, redundant Contractor submittal requirements that are unrelated to quality. Such specifications often cross the line between performance and method specifications.

- Designers typically spend long periods studying and evaluating a project and preparing the contract documents, drawings, and specifications. However, the amount of time made available for Contractors to bid the job is typically a fraction of this period. This “back-end acceleration” benefits neither the Contractor (who may have not had the opportunity to fully understand the nuances of the project), or the Owner, who, for the same reasons may receive an unbalanced and unrealistic bid which may eventually lead to a contractual/financial dispute. In addition to giving bidders more time, Owners should ensure that the Geotechnical Data Report, the Geotechnical Interpretative Report and the Design Basis Report (all previously prepared for him by the Designer) should all be shared to enhance the understanding of the bidders.
- Designers should provide to the field QA staff a manual of engineering considerations. In it, the designer should give a brief description of the project’s purpose and goals. It should relate the relevance of each QA and QC item to the design intent, so that field personnel have an appreciation of the importance of their individual tasks and be provided with appropriate site laboratory facilities and equipment for site QA/QC testing. Field personnel should undergo training on the nuances of the DM method being employed and be provided with appropriate site laboratory facilities and equipment for the on-site QA/QC testing.
- Whereas QC is the Contractor’s responsibility, as-built quality problems rapidly become the Owner’s problems through construction claims, delays, and remediation of defects. Specifications written to ensure quality throughout construction must be emphasized by demanding timely submittals by the Contractor and prompt review of test results by the Owner’s representative.
- Contractors are sometimes overconfident when they assume the adequacy of a design mix based on past experience and so reduce their pre-construction field investigation and laboratory testing. Pre-construction test programs benefit the Contractor and the Owner and should always be required as part of the contract. The FHWA Manual (2013) recommends installing at least three test elements using different mixing parameters. These programs are as much for the Contractor’s benefit as for the Owner’s confidence that the DM elements can be installed as designed. FHWA (2013) recommends that any changes exceeding 10% of the previously trialed mix designs be subjected to revalidation through laboratory and field testing. This is fully supported by the authors.
- Coring and wet grab sampling for the production works should be held to the same standards as for field Trial programs.
- Fresh grout temperature is usually restricted in specifications to below 95 °F to minimize thermal stresses and cracking – but this is a requirement taken from specifications for concrete placement. Temperature control is difficult to sustain in hot environments without special measures. The 95 °F rule should always be applied while using continuous trenching methods due to the monolithic nature of the installation. Some relaxation of the rule should be adopted for DM projects installed using a primary-secondary pattern of element construction since there is some time for heat to dissipate between the construction of these adjacent elements.
- Pre-hydration of bentonite is often specified for mixes. In some ground conditions and with high cement contents, it has now been demonstrated that the compressive strength and permeability at 28-days curing time are unaffected by incorporating bentonite that was not pre-hydrated. This is a relatively new development and has not been proven to be universally applicable, so adoption of non-hydrated bentonite should be on a case-by-case basis with approval demonstrated by comparative tests both in the laboratory and in the field, using site specific soils and binder slurries.
- To minimize damage to the core and the borehole walls during drilling, verification borings should be conducted by experienced drillers using state-of-the-practice techniques and controlled drilling rates typically not exceeding one foot per minute. Generally, triple-tube, wire-line coring produces the best results because the drilling tools are more stable, and the core is more protected

from disturbance by drilling. Specifications should detail the handling, storage, and transport of core samples that are to be used for acceptance. This particularly applies to samples from remote locations, tested offsite. Although these specifications seemingly intrude on the Contractor's means and methods, non-compliant test results for an otherwise acceptable DM product soon become the Owner's problem as well.

- Optical Televiwer technology allows video inspection in great detail of the entire length of a borehole. This allows a confident evaluation of homogeneity. Linear consistency of compressive strength test results from post-production "wet grab" samples adds to the level of confidence. Careful and systematic review of the daily production logs and real-time construction information by trained construction inspectors can discern consistency in means and methods that lead to homogeneity and continuity in the final product.
- It is difficult for some contractors to successfully core low strength mixed soils without damaging the core and so misrepresenting the compressive strength of the core test samples. In such circumstances, more effective and representative measurements could be based on post-production samples but only after applying a correction factor of double the required design strength (which would in turn improve core results). This could be particularly beneficial when the required 28 days curing period would sequentially impact construction completion.
- In-situ falling head tests should remain as the acceptance measurement for the specified maximum permeability of a seepage barrier wall. The only value of laboratory permeability tests on post-production samples is as an additional confirmation of consistency. Such tests on core samples often do not provide accurate and representative results due to microfissuring, especially if gravel particles are incorporated in the DM product.
- We must all recall that the DM methods produce an in-situ material which is inherently heterogeneous. A pragmatic and understanding approach to interpreting test data – and especially their variability – is essential. Further, the authors acknowledge that what may be preferable or larger high-profile projects may not necessarily be commercially viable on relatively small projects in particularly competitive regional markets. In such circumstances, the risks of not specifying a robust QA/QC and Verification program must be most carefully weighed by the Owner and his Designer.

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