

BEST DMM PRACTICES AND LESSONS LEARNED: U.S. REPORT

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ABSTRACT

This paper presents an overview of the state of best practices in DMM in the United States. To provide historical context, the evolution of the DMM market is described, since its introduction to California in 1986, highlighting the impact of Japanese and European contractors and manufacturers. The functioning of the market is reviewed, together with the main application, significant examples of which are detailed. Applicable guidance standards, which lead to specifications governing construction, QA/QC and contractual compliance are reviewed. Contemporary construction methods are described, illustrating significant developments in “conventional” vertical axis mixing, as well as newer DMM techniques such as TRD and CSM. The final section is devoted to “Lessons Learned”, and contains recommendations particularly addressed to designers and specifiers of DMM projects.

1. INTRODUCTION

Various types of Deep Mixing Methods (DMM) have been used in the United States since 1986 in California and in that period have become widely accepted as reliable and cost effective soil treatment techniques. The market has owed much to the early and strong influence of Japanese specialty companies providing wet DMM equipment and expertise, while in recent decades, European contractors and equipment manufacturers have become prominent, thus creating a very competitive, technically adept DMM environment. Reflecting the major groups of applications (i.e., seismic retrofits, seepage cutoffs, and deep excavations in particular), by far the greater portion of the DMM market (estimated as around 200 million US dollars annually) is conducted with wet DMM techniques, principally “conventional” vertical axis methods, CSM (Cutter Soil Mixing) and TRD (Trench Remixing Deep) as opposed to the Nordic dry DM Methods which were first introduced in the mid 1990’s. There are around 10 specialty contractors active in the U.S. market.

Many aspects of the U.S. market are common to other regional markets, and are doubtless already well known to specialists outside North America. In addition, experiences have been shared in a number of international conferences, including those in New Orleans (2012), San Francisco (2015) and Honolulu (2017), and remain to be shared during this current conference in Gdansk (2020). For these reasons, the authors have attempted in this paper to highlight only specific subjects which we trust will be of particular interest or will be most informative. We therefore focus on recent developments in design, construction, QA/QC and Verification, while also addressing “Lessons Learned” – often at great cost – from U.S. practices and projects.

2. THE CHARACTER OF THE U.S. MARKET

2.1. Evolution

The first major application of the contemporary DMM method in the United States was the foundation improvement for the reconstruction of Jackson Lake Dam in Wyoming in 1987 for the U.S. Bureau of Reclamation by an alliance of SMW Seiko and GeoCon (now Geo Solutions). The ground improvement scheme consisted of a series of honeycomb shaped DMM structures to reinforce the liquefiable foundation, and a cutoff wall along the upstream toe of the embankment to reduce seepage. For the soil-cement cells and wall to function adequately, the specification required that the neighboring columns should be in contact for their whole depth. Multiple shaft mixing tools were proposed and accepted on a Value Engineering basis to install the soil-cement cells and wall in lieu of the foreseen jet grouting method. Although

this application generated great interest in the engineering community, major applications of DMM after this project were scarce since U.S. engineers were sensitive to the potential liability of exceeding the so-called generally accepted engineering practice. However, in 1992, DMM was used for the Central Artery/Tunnel in Boston, MA. The Bird Island Flats Project alone included a 910 m long cut and cover tunnel project requiring a maximum excavation depth of 24 m. Approximately 40,000 square meters of DMM wall and about 3,000 pre-stressed anchors were used to complete the temporary shoring system for tunnel construction. The ensuing, larger Fort Point Channel Project (FPC) required the installation of 430,000 cubic meters of soil-cement buttress walls to stabilize the soft ground for excavation and construction of tunnels. The maximum depth of DM buttress wall was 43 m (O'Rourke and McGinn, 2006). The DMM was therefore a key technology for the Boston CA/T that provided for the stabilization of basal clays at the BIF excavation and the improvement of weak organics and marine clay deposits in a region of complex construction at FPC. Consequently, DMM was recognized as a reliable and versatile ground treatment technique in the United States resulting in the expansion of both number and scale of DMM work from the late 1990's onwards.

As has been widely reported (Bruce and Cali, 2020), the aftermath of Hurricanes Katrina and Rita in 2005 led to a huge increase in the DMM market in the New Orleans area, while at the same time projects for seismic stabilization and deep excavations continued to increase especially in the San Francisco Bay area, and on embankment dams nationwide.

The apogee of the New Orleans work was the LPV (Lake Pontchartrain and Vicinity) 111 Contract in 2009-2011, which, with over 1.3 million cubic meters of ground treated, remains by far the single biggest DM project in North America, and one of the largest outside Asia.

Activity continues at a brisk pace, the trend being for numerous projects of medium – large scale (say less than 10 million dollars) rather than a small number of huge “flagship” projects.

2.2. Functioning of the Market

Not surprisingly, innovation and technology is brought to the market by the specialty contractors, most of whom have direct Japanese or European roots and support. Most of these companies operate equipment designed and built by themselves, although some supplement their own resources and systems with equipment manufactured by others. An example is the growing popularity of CSM, manufactured by Bauer in Germany, and which has been found to be comparatively easy and economical to operate, in the right hands, or course.

The specialty contractors will operate both as prime-, and as sub-contractors, depending on the application and the scale of the project. For example, for DMM used for support of deep excavations for new high rise buildings, the DMM contractor is invariably a subcontractor to the prime, or to the Construction Manager. In contrast, in dam or levee remediation, where the ground treatment is the major construction activity and cost, the DMM contractor is often the prime, or is in joint venture with a general contractor, who will provide support services.

Each project has a design engineer, who is officially the Engineer-of-Record and is engaged separately by the Owner. Many consulting companies now have inhouse inspection of DM projects, more recently relying on Federal guidelines, as described below. Even then, it is common for these companies especially on larger and/or more complex projects, to engage the services of an independent DM specialist to provide internal peer review services. Further, it is typical on major dam and tunnel projects in particular, that the Owner convenes a Board of Consultants, independent and experienced professionals who provide high level oversight and guidance to the project as a whole. Such Boards meet regularly and issue progress reports, containing recommendations for future work: recommendations which the Owner and his Engineer-of-Record ignore at their professional peril.

The contribution of academia is limited to the consulting activities of senior, well networked professors at a small number of universities, principally Virginia Tech, Cornell, and Bucknell. Fundamental academic research into a full scale construction technique like DMM is always expensive, and difficult for universities to conduct on their own. Added to this is the absence

of ground treatment topics from the vast majority of teaching course curricula: practitioners “learn on the job” after graduation, upon joining the specialty contractors or consultants, and not in the classroom.

The Federal Government, in the form of FHWA and NHI, has been active in promoting DMM since the late 1990’s via its sponsorship of reports (e.g., FHWA 2000, 2001, 2001a) and short courses for state employed engineers. It also arranged a collaborative research project, funded by several states, but the outcome provided by academia at one particular university without historical background in DMM has had no discernible impact on the market.

While professional societies have made practically no contribution, trade associations (and in particular the Deep Foundations Institute) have been very active in promoting DMM via active committees, frequent short courses, and their organization of conferences.

Readers of this section will therefore notice major differences between other major DMM centers of excellence such as Japan and the Nordic countries, where research and development into DMM has been massively backed by Government funds and agencies, research facilities, and consortia of DMM contractors and materials suppliers. There are no DMM Associations in the United States.

2.3. Major Applications and Typical Projects

Table 1 summarizes the major types of applications, and the typical Ownership categories. It will be noted that Ownership category varies greatly, from the Federal Government, through State Organizations and industrial clients, to private developers.

Table 1. Application of DMM for Ground Treatment in the U.S.

Project Category	Type of application	Typical Organizations/Owners
Dams and Levees	Seepage control, slope 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, MN, Virginia; SC. Valley Transit, and other private owners.
Port and Shoreline	Port and shoreline stabilization; seismic stability	Port of Oakland, Port of Long Beach.
Industrial Facilities	Bearing capacity, settlement control and seismic stability	Petroleum and chemical plant owners, nationwide.
Deep Excavations	Support of excavation	Private developers.

Dams and Levees – Applications of DMM for dams and levees include seepage control and stabilization of embankment foundations. Seepage control is accomplished through the use of a single row of soil-cement elements to reduce the volume of seepage through permeable embankments and foundations. This is the major application of DMM for flood control in Sacramento, California for example. Application of DMM for the stabilization of embankment foundation is versatile. For static lateral force, a series of soil-cement shear walls perpendicular to the longitudinal alignment of the embankment is used to reinforce the embankment and provide additional lateral resistance during high flood condition. This is the major application of DMM for hurricane protection in Louisiana. Another important application of DMM is for seismic upgrade. In the 1980’s the Jackson Lake design concept was to use DMM cells to increase the shear strength of the foundation. In its 2004 technical memo, the Government stated “.... the SMW (DMM) structure designed to prevent liquefaction of soils both the

upstream and downstream outer shells of the embankment is in place.” The DMM ground treatment concept involves increasing the composite shear strength to prevent liquefaction. Following the Jackson Lake Dam project, four dam projects in California have used DMM cells for seismic mitigation. Although the main purpose for seismic mitigation was to prevent the liquefaction induced embankment failure during and after the earthquake, the design approach remains as ground reinforcement to resist lateral seismic force since there is no manual or guideline developed to provide a generally accepted procedure for the analysis and design of DMM cells for liquefaction prevention. Understanding is developing that DMM cells can increase the rigidity of the treated ground and reduce the strain of the liquefiable soils during the earthquake. This consequently reduces the generation of excess pore pressure and liquefaction potential. For seismic mitigation, the treatment ratio and strength of DMM cells are still designed with the assumption that the liquefiable soil would partially or fully lose its shear strength due to the increase of excessive pore water pressure during and after the seismic induced ground shaking. In fact, since the ground is reinforced with DMM cells, the generation of excessive pore water pressure is suppressed to the level that the assumption of low or no shear strength in the liquefiable soil becomes over-conservative and provides addition safety margin in the seismic mitigation design. An example of DMM cells for seismic mitigation designed by California Department of Water Resources is shown in [Figure 1](#). The soilcrete unconfined compressive strength used for seismic mitigations ranges from 2.1 to 3.4 MPa, which of course is higher than the strength of soil-cement produced in soft ground with high clay content and water content. These high strengths were feasible due to the high sand content and low water content of the potentially liquefiable soils at the dam sites.

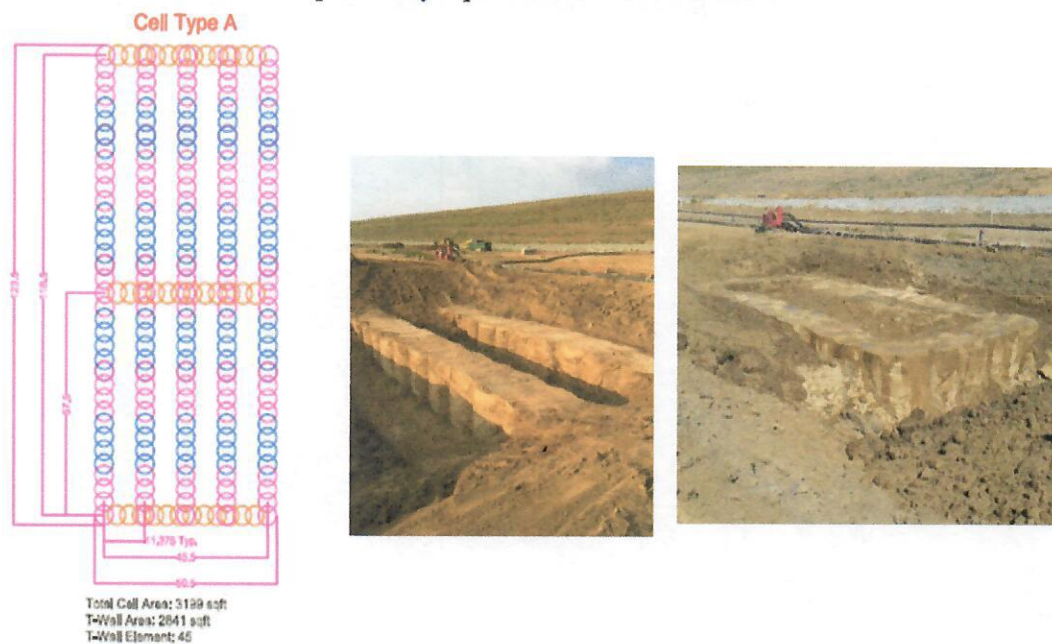


Figure 1. DMM layout design, test wall and test cell, Perris Dam Seismic Remediation, CA

Figure 2 shows the DMM column layout for the (static) foundation remediation at LPV111, LA. This is typical of such designs, following the guidance established by FHWA (2013)

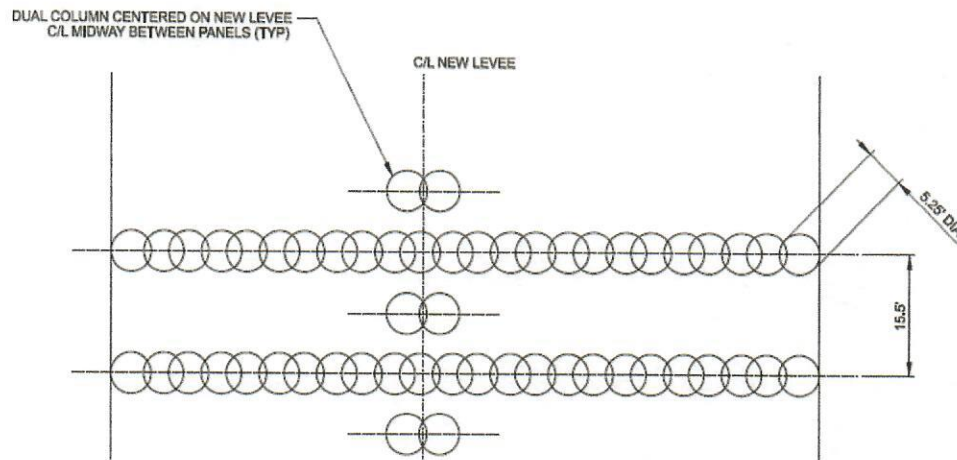


Figure 2. Layout of DM panels, LPV111, LA (Bruce and Cali, 2020)

A novel application, recently introduced into two 19th century dams in Ohio, is illustrated in Figure 3. The solution provides a strengthened foundation block, to support the new embankment built above and upstream of the existing dam, and a seepage cutoff. The design and implementation of this scheme has won professional recognition from the dam safety community. Further details are provided by Bruce (2020).



Figure 3. DM for dam rebuilding, OH (Rendering courtesy of Gannett Fleming, Inc.)

Transportation Infrastructure - Applications of DMM for transportation infrastructure include excavation shoring, bearing capacity and settlement control. DMM shoring systems

consist of a single row of DMM improvement elements reinforced by steel beams to resist bending movement of the excavation and to control the horizontal flow of ground water toward the excavated area. Anchors or internal bracing generally are needed to resist the lateral forces caused by the excavation. A major application of DMM shoring systems is for the construction of grade separation structures and cut-and-cover tunnels. Conventional DMM shoring walls are used for temporary excavation support during construction. In some cases, DMM walls are extended significantly deeper than the embedment required to maintain toe stability. This unreinforced deeper section of DMM walls serves as a cutoff wall for groundwater control during the construction of underpasses and continues to function as a cutoff wall to control the long-term seepage and to minimize the water to be pumped out of the underpass roadway. A recent development in the application of DMM shoring wall is to utilize the steel reinforcement inside the DMM shoring wall as part of the permanent concrete retaining structure. Headed steel studs are welded onto the exposed flange of the steel H-piles of the shoring wall and cast with the concrete wall to form a composite structure for use as the long-term retaining structure of the underpass or bridge abutment. An example of the composite retaining structure is shown in Figure 4.

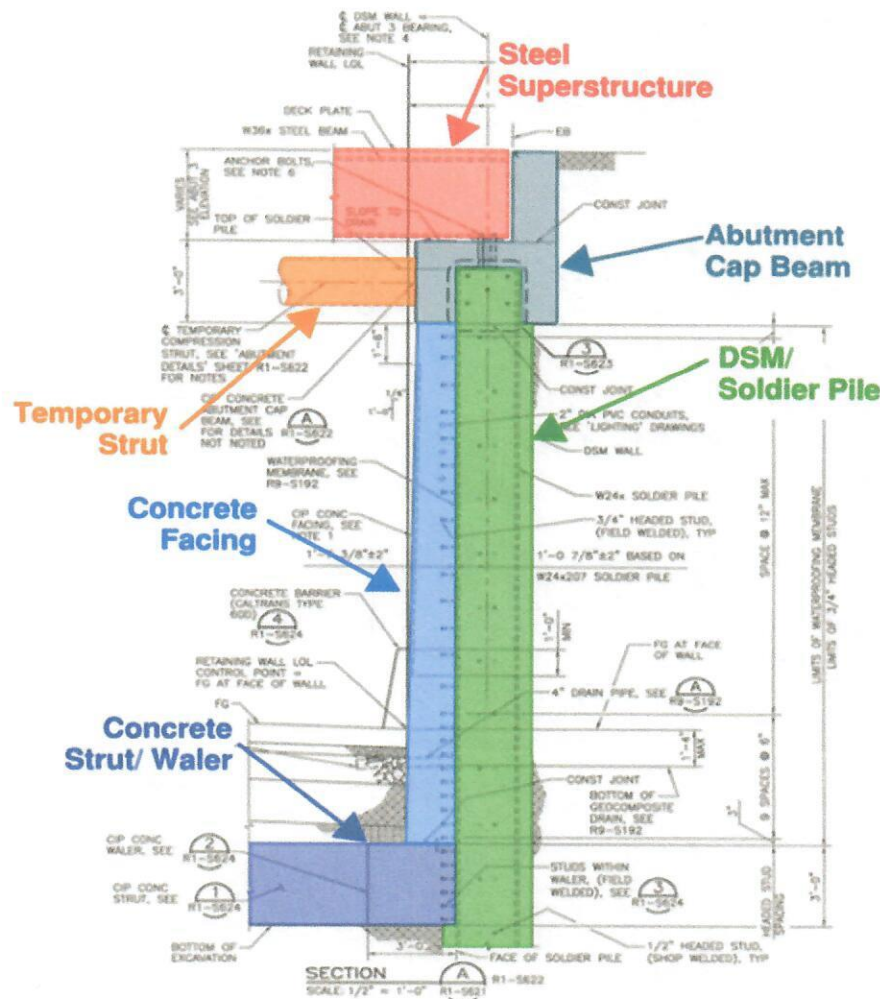


Figure 4 Composite structure of DMM and concrete walls, CA (Yang et. al., 2015)

For ground improvement, columns of DMM treatment are used under the portion of embankments with limited bearing capacity and settlement for transportation infrastructures. Shear walls with DMM are used under embankment slopes, MSE walls or abutment walls to

provide the bearing capacity and settlement control, and maintain stability. An example DMM layout for the construction of a grade separation structure is shown in Figure 5.

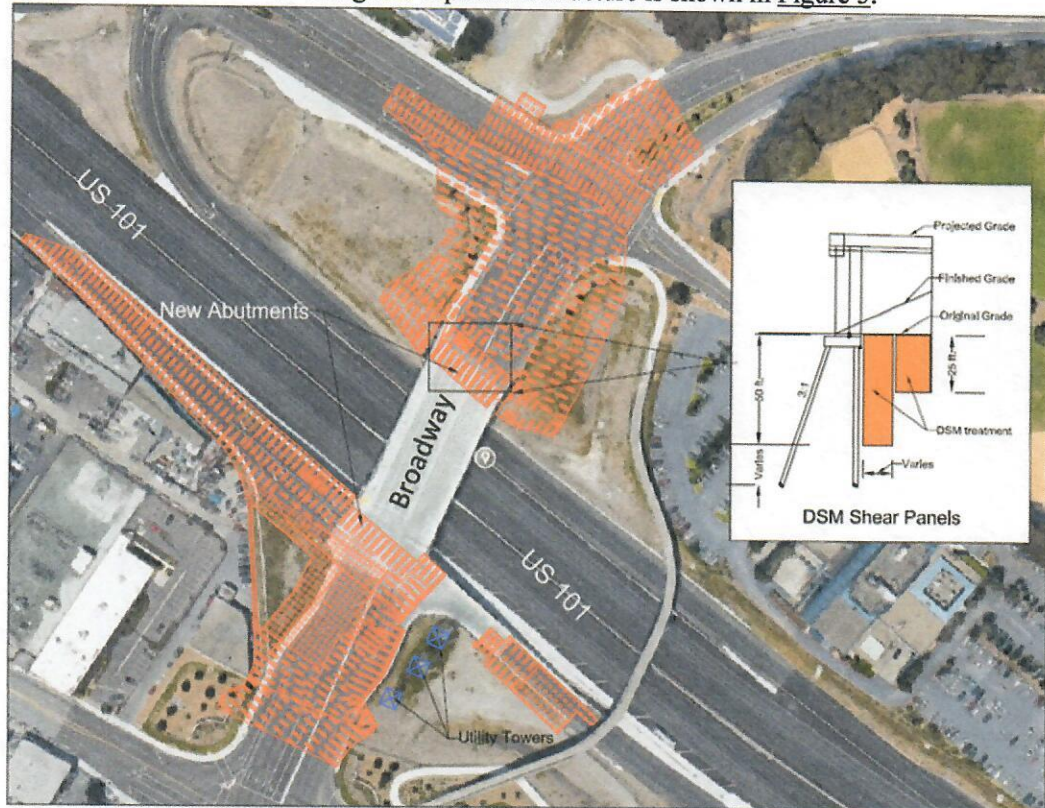


Figure 5 DMM layout for US 101 / Broadway Grade Separation Project, California (Shrestha, et. al., 2020)

Port and Shoreline – DMM is used to improve the foundations of slopes at waterfronts to maintain berth stability and provide shoreline protection. DMM buttress structures are typically cellular layouts consisting of transverse walls and longitudinal walls. Similar to the DMM cell for seismic mitigation, the transverse walls of the DMM buttress are designed to resist the main seismic lateral force perpendicular to the longitudinal alignment of the berth. The longitudinal walls are designed to resist the minor seismic lateral force in the longitudinal direction and maintain the integrity of the transverse walls. The effect of DMM cells for reducing the generation of excessive pore water pressure and liquefaction potential are not considered in the design. Two examples of DMM buttress for berth stabilization are shown Figure 6.

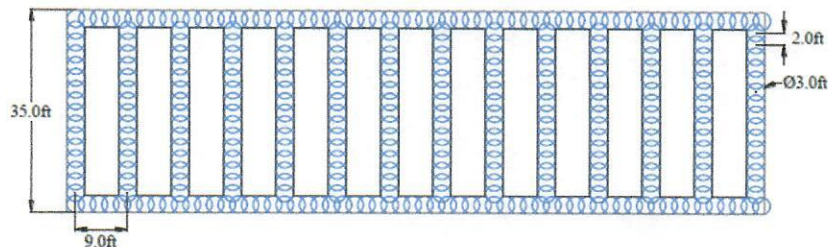


Figure 6a. DMM buttress, Port of Oakland, CA (Yang, 2010)

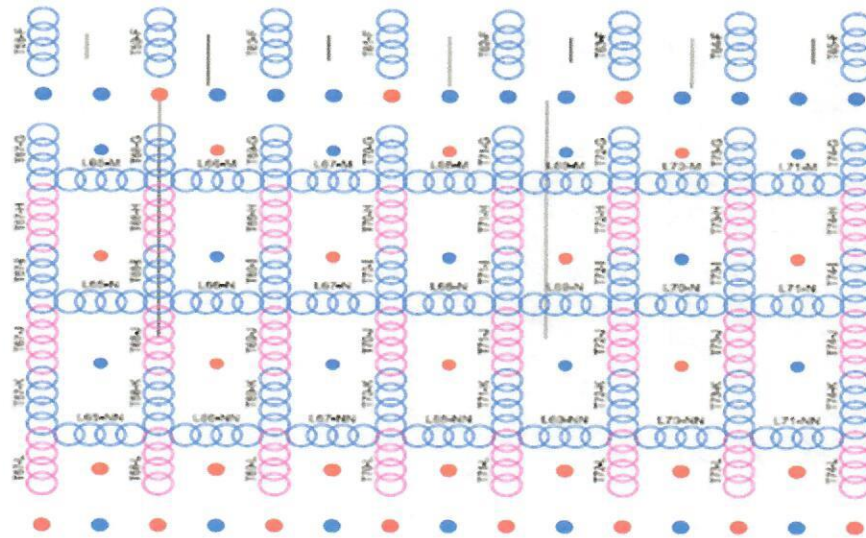
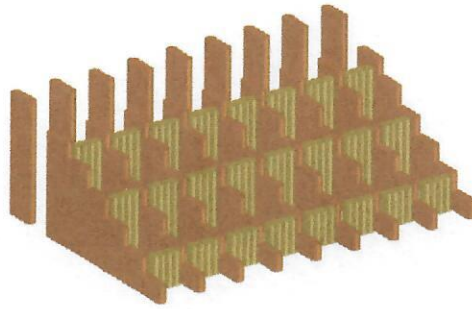


Figure 6b DMM Buttress under berth, Moin, Costa Rica 1 ft. $\equiv$ 0.3048 m)

DMM shear panels with a longitudinal headwall at the waterfront are used for shoreline stabilization. The shear walls are designed to resist the main seismic lateral force acting perpendicular to the shoreline and the longitudinal wall is designed to retain the liquefiable soil from flowing toward the open water and also to perform as a retaining structure if the unimproved waterside slope slides during the earthquake. An example of the DMM shoreline protect system is shown in [Figure 7](#).

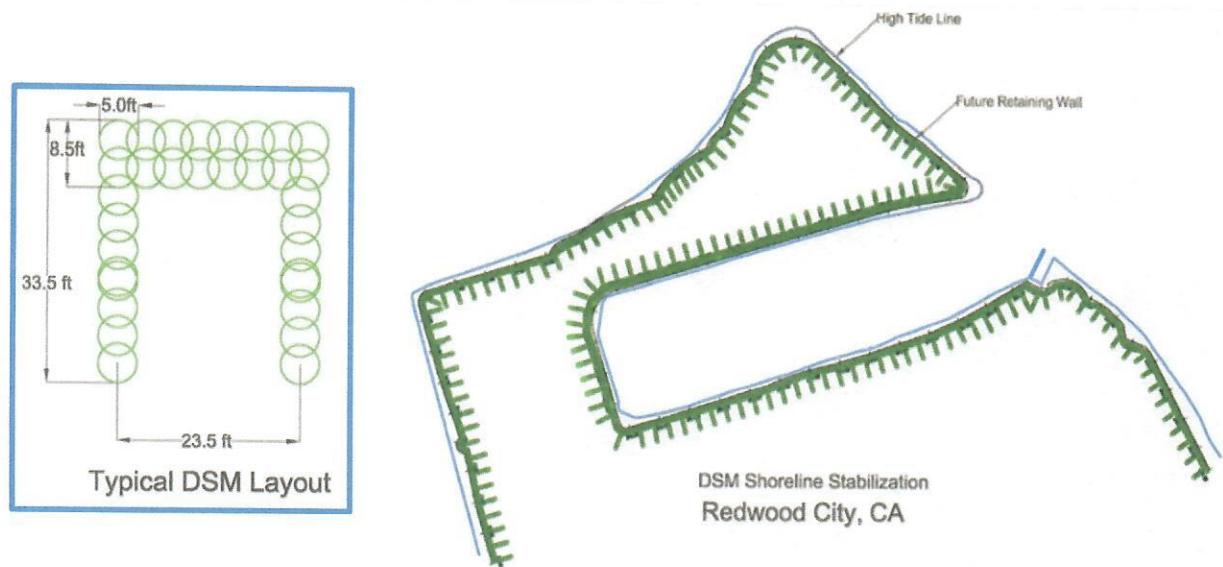


Figure 7. DMM shear wall for shoreline stabilization, California

Industrial facilities - Applications of DMM for industrial facilities mainly are to provide bearing capacity and settlement control for the development of industrial sites underlain by soft ground. DMM in a cellular layout is preferred due to the structural sensitivity of, for example, a petroleum chemical plant to total and differential settlements. The DMM foundation transfers the structural loads from the equipment mat to competent underlying soil layers therefore controlling settlements within tolerable limits. Cellular DMM foundations consisting of inter-connected DMM columns provide an effective load transfer mechanism that minimizes both differential settlement and structural demands on the foundation mats required for the support of various facilities of industrial plants.

3. STANDARDS, SPECIFICATIONS AND COMPLIANCE

3.1. Status of Current Standards

It remains difficult to fully standardize design and acceptance criteria across the U.S. market, given its great geographical and technical diversity. Guide specifications are given however in the Federal Highway Administration Design Manual: Deep Mixing for Embankment and Foundation Support, (2013) and can be found at the <http://www.geotechtools.org>, website. Because acceptance criteria are project and purpose specific, they must be tailored to meet the project requirements and DM quality.

3.2. Parameters Measured for Quality Assessment

- Compressive Strength
 - UCS on core samples (preferable on most projects)
 - UCS on post-production (wet grab) samples (in lieu of core samples in gravelly soils). Such samples tend to have a higher binder content on account of the aggregate screening process involved during preparation, and so give relatively high strengths
- Permeability
 - In situ falling or rising head tests
 - Laboratory tests on core samples (useful only as an indication of homogeneity)

- Verticality (on-board equipment instrumentation during element installation)
- Geometric Dimensions (length, width, and depth)
 - Physical or on-board electronic measurement
- Continuity and Homogeneity
 - Visual inspection of cores
 - Downhole video imagery
 - Monitoring of consistency in batching and installation operations

Particular guidance on each of these follows:

Compressive Strength

Commonly 0.7 MPa is specified for the unconfined compressive strength of DM seepage barriers for dams and levees. DM elements used for foundation support or embankment reinforcement are designed to resist specific design loads and typically require higher strengths (up to 2.4 MPa or more). EuroSoilStab (2002) reports that the strength of in situ material can be 20 to 50 percent of the strength of laboratory-mixed specimens. To ensure compliance with 0.7 MPa as a minimum UCS, for example, Contractors must target 1.4 MPa for wet grab tests and bench scale tests and adjust the binder content for the design mix accordingly. Since the cost of cement is a major component of the overall DM installation cost, over conservatism in specifying strength can dramatically increase the final DM cost.

A standard minimum 0.7 MPa UCS has some practical basis for seepage barriers in that acceptance criteria are often based on samples taken from drilled cores, and soft walls are inherently more difficult to core since the results are closely linked to the drillers' expertise. A more rational approach might be to base strength compliance on post production samples and use 1.4 MPa as the minimum acceptance criterion. Specifications often require at least 90% of the samples pass the acceptance criterion. Verification borings and cores are used as the basis for compliance with specifications on homogeneity, continuity, and in situ permeability tests.

Permeability

Compliance with the specified maximum permeability for seepage barriers is best judged from the results of in situ falling or rising head tests. Verification boreholes drilled with less than careful methods can create damage in the borehole walls, leading to in situ permeability test values higher than those obtained from laboratory tests on pristine laboratory-cast samples. In the opinion of the authors, permeability should be judged using in situ testing as the most representative of a seepage barrier quality. Tests should be evaluated using the method proposed by Britton et al. (2002, 2005), which accounts for the 3D geometry of a single-well test in a barrier wall surrounded by relatively permeable soil.

Criteria for judging the quality of a DM seepage barrier should be rated as follows, in order of importance:

1. **Geometric Dimensions** (position, depth, width, verticality, and overlap of panels) as determined by on-board electronic records and field measurements. The FHWA Manual recommends a maximum drift of 1% in vertical alignment.
2. **Homogeneity** judged by visual inspection of the cores and review of downhole video records. (No particle more than 76 mm in any dimension)
3. **Continuity** measured using angled cores spanning panel overlaps to confirm analyses of element verticality measurements and calculations..
4. **Permeability** as measured by in situ falling head tests.

5. **Strength** as measured from UCS testing of post-production samples, with an appropriate reduction in measured values to represent in situ strength.

For applications where DM is used primarily to provide some form of strength, permeability is not a concern. For such applications, strength testing would be moved up to second in importance in the above list. This is a generalization of a QA/QC program that would, of course, have to be tailored to the specific application.

However, considering that many specifications require 1-3% of the DM product 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 recommends that 2-4% of DM elements be cored, with the larger percentage applying to more important projects and to smaller projects.

A combination of 100% QC coverage and a relatively small amount of verification coring and testing can provide relatively high reliability that the mixing is of good quality, provided that QC and QA work is done well, with high frequency observations of all QC/QA activities by the owner/engineer. It is imperative 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 drilled at 28-days age during the field validation program and 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.

In the FHWA Manual (2013), it is recommended that the contractor should propose locations for wet grab sampling while considering input from the owner/engineer, 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 for every 500 m³ of treated soil, whichever produces the higher sampling frequency." This recommendation was expanded in 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.

Further views on QAQC and Verification are provided by Bruce et al. (2020)

3.3. **Specifications**

Efforts have been and are nevertheless being made to standardize specifications (and acceptance criteria.) Planning, design, and construction quality control guidance are offered in the yet unpublished United States Army Corps of Engineers Engineering Manual for Cutoff Walls (Draft), October 2012; United States Federal Highway Administration Design Manual: Deep Mixing for Embankment and Foundation Support, October 2013; and www.GeoTechTools.org.

We note that, most often, specified performance criteria generally exceed the 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 (0.7 MPa) specified for seepage barrier walls should be justified as specific design requirements. These values are often used as default criteria, adopted from previous projects without sound technical reasons.

4. CONSTRUCTION TRENDS

Twenty years ago, the Deep Mixing Methods employed worldwide – and including those then used in the U.S. – were classified by FHWA (2000). As shown in [Figure 8](#), these were all what we now refer to as “conventional” DM Methods, using one or multiple vertical axis mixing tools. Their main points of differentiation were the binder type (i.e., wet or dry), the slurry injection pressure (i.e., low or high – as in Geojet), and the location of the mixing action (i.e., all along the shaft(s) or just at their ends.). In the interim, some of these conventional techniques have survived and evolved, others have become defunct (e.g., MecTool), new methods/companies have been introduced or developed, while some (e.g., lime-cement and columns) have dropped from favor in the U.S.

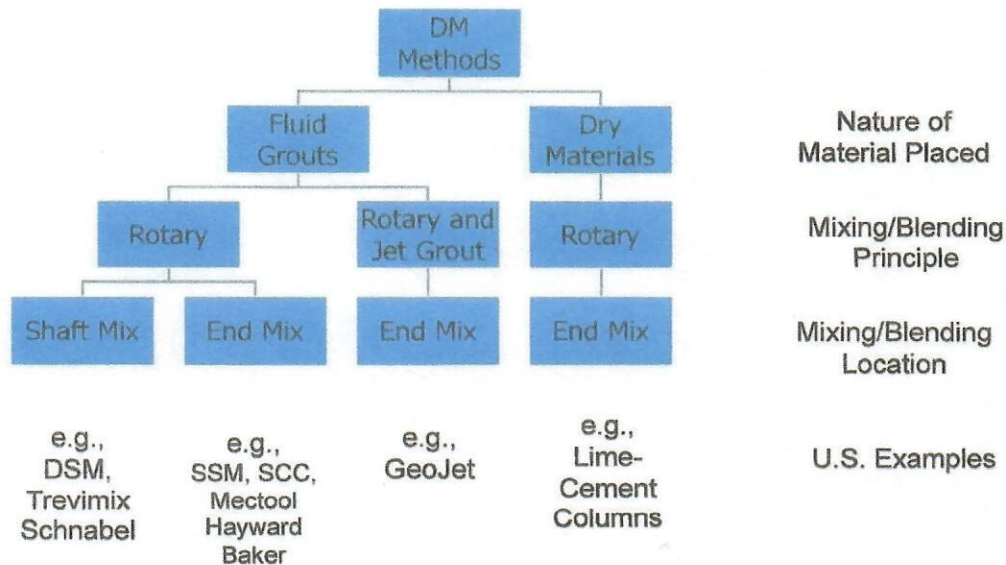


Figure 8. Original Classification of Deep Mixing Methods (FHWA, 2000)

Reflecting these changes, an updated classification was introduced by Bruce (2010). As shown in [Figure 9](#), there are now essentially three basic types of DMM processes used in the U.S., namely:

- (i) “Conventional” Vertical Axis Mixing
- (ii) Continuous Wall Cutting and Mixing
- (iii) Horizontal Axis Cutter Wheel Mixing

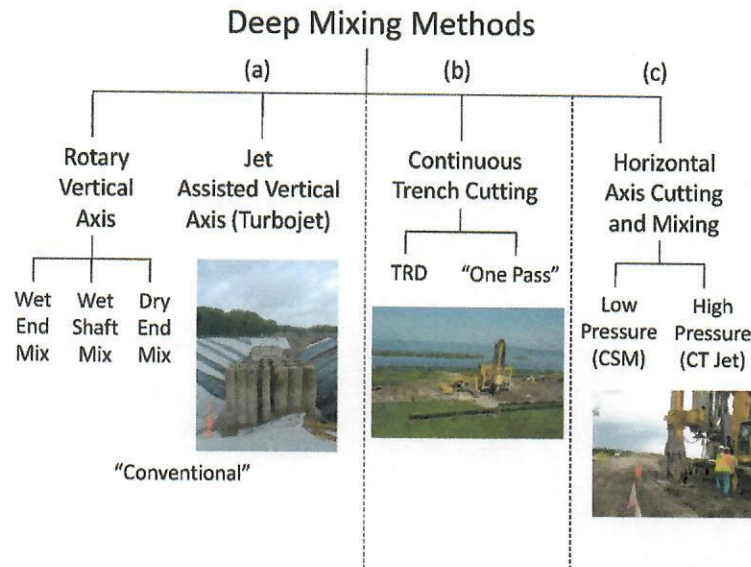


Figure 9. Classification of DMM used in the United States (Bruce, 2010)

(i) "Conventional" Vertical Axis Mixing

Variants with up to six axes on each rig are common, and collectively probably account for well over 50% of the market (outside Herbert Hoover Dike, FL, as discussed below). Different contractors use different combinations of installation parameters and some regularly use compressed air (e.g., JAFEC) in the slurry to improve penetration and mixing efficiency. Others (e.g., TreviCOS) use a hybrid system where the mechanical mixing action of the blades is supplemented by high pressure grout injection – in effect a refinement of the venerable Geojet system. Most applications feature the use of high slag content mixes (up to 90% of the cementitious fraction), although mixes for support of excavation projects still rely primarily on Portland cement.

(ii) Continuous Wall Cutting and Mixing

The TRD method was introduced into the U.S. from Japan by the Keller Group in 2005. It proved an excellent choice for building miles of cutoff wall at Herbert Hoover Dike, FL through extremely heterogeneous fills and foundations from 2008 to 2011. (Photograph 1) The method is described in Bruce (2013). Since then, and reflecting the method's preference for long "runs" without sharp changes of direction, applications have been somewhat fewer. However, the method retains the profession's fascination, and it remains a most viable DMM in projects of appropriate scale, soils, and geometry.



Photograph 1. TRD in use at Herbert Hoover Dike, FL (Courtesy of the Keller Group)

More recently, an independent U.S. company – DeWind – has enjoyed success with its “One-Pass” system . (Photograph 2). This has been used in many small – medium sized projects especially in dam remediation and environmental applications.

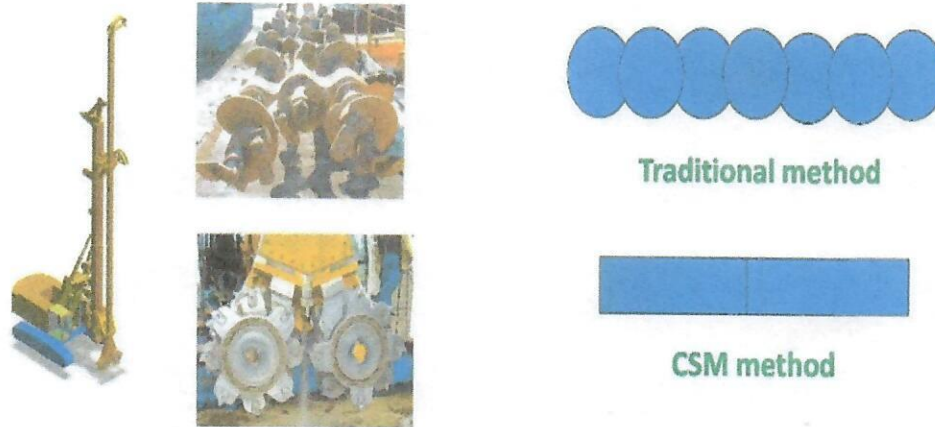


Photograph 2. “One Pass” Trenching equipment (Courtesy of DeWind)

(iii) Horizontal Axis Cutter Wheel Mixing

This Cutter Soil Mix (CSM) method was developed jointly by the Bachy Soletanche Group, and Bauer Maschinen, in 2004 and is a blend of hydromill and deep mixing technology (Photograph 3). The equipment has been made available for purchase by the Bauer manufacturing arm, and has proved attractive to a number of specialty contractors wishing to access the DMM market. Many large projects have been carried out with CSM in the U.S. and in Canada. Predrilling, and replacement of unsuitable materials (such as organics, boulders, or ice), is a common precursor to the mixing itself. A similar technique (with high pressure binder injection) has been developed by Trevi, under the name CT Jet. As with TRD, the CSM method has been used extensively at Herbert Hoover Dike, FL: both methods gave

excellent homogeneity and productivity and proved to be a viable alternative to the “excavate and replace with Self Hardening Slurry” method equally successfully used for many miles of the cutoff, constructed by Trevi ICOS.



Photograph 3. CSM method (Courtesy of Bauer Maschinen)

Despite the differences in the various DM techniques used in the U.S., there are some clear commonalities:

1. In general, the DMM projects have been, and are being, conducted with high levels of skill, performance and quality. This is a direct reflection of the experience of the contractors and their employees at all levels, and the reliability and capability of the specialty mixing equipment they employ.
2. Each DMM technique features a high and sophisticated level of real time installation monitoring instrumentation. This gives invaluable information to DMM operators in the field, and a high level of confidence and comfort to those parties responsible for assessing the work – and paying for it!
3. As noted in Section 3 of this paper, there is a growing consensus in the DMM community as to acceptable DM performance criteria. While this has long been the case in Japan and the Nordic Countries, the more fragmented nature of the U.S. market has allowed regional or corporate preferences to govern, so giving rise to different measures of compliance across the country. Even so, there is still active but healthy debate about first tier issues like the acceptability and appropriateness of coring (relatively weak) soilcrete as opposed to extracting wet grab samples, and less critical issues such as the real value of conducting laboratory permeability tests or (cored or wet grabbed) samples. There is consensus, but it is not yet unanimous.
4. There is however, unchallenged agreement that the logical sequential path of lab (bench scale) testing, full scale field demonstration testing, and very closely instrumented monitored and verified production works, is really a very good idea indeed.

5. LESSONS LEARNED

The published literature on DMM is replete with project successes and innovative applications. Conspicuously absent are criticisms and failures which of course, for legal reasons often cannot be

published. Noted below are a few of the authors' observations of shortcomings in design and construction of contemporary DM projects in the U.S.:

- 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 permeability, (typically 1×10^{-6} cm/s) consideration 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 DMM applications involving structural support, it is appropriate to specify a minimum UCS or shear strength (with limits on the number and distribution of non-compliant samples) but not appropriate to specify a maximum strength (reflecting soil heterogeneity).
- Specifications for deep mixing have become bloated by blind repetition of specifications from previous projects without culling irrelevant, redundant contractor submittal requirements that are perhaps unnecessary to quality. Such specifications often cross the line between performance and method specifications.
- Designers typically spend months and even years 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 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. Field personnel should undergo training on the nuances of the DM method being employed.
- 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 still, sometimes, overconfident and assume the adequacy of a design mix based on past experience to then 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 DM 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 approved mix design be subjected to revalidation through laboratory and field testing. This is fully supported by the authors.

- Coring and wet grab sampling for the validation program should be held to the same standards as production works.
- Fresh grout temperature is usually restricted in specifications to below 35°C 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 climates without extraordinary measures. The 35°C rule should always be applied to DM installed using continuous trenching methods due to the monolithic nature of the installation. Some relaxation of this 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 these elements.
- Pre-hydration of bentonite is often specified for mixes that contain bentonite. In some ground conditions and with high cement factors, it has now been demonstrated that the compressive strength and permeability at 28-days curing time are unaffected by adding 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 drilling rates 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 insulated from disturbance by drilling. Specifications should detail the handling, storage and transport of core samples selected for acceptance testing if the test results of core samples 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 the borehole. This enhances a confident evaluation of homogeneity, at least in the vertical direction. 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 demonstrate 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).
- 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 homogeneity. Such tests on core samples often do not provide accurate and representative results due to microfissuring of such samples, especially if hard gravels are incorporated in the DM product.

6. CLOSURE

By virtue of the weight of many large and successful projects completed over three decades and more, and the aggressive business development efforts undertaken by the contractors and

the various trade associations they support, DMM has now reached a “mature” status in the eyes of U.S. ground engineers. The DMM market is vigorous and competitive and its flexibility is illustrated by its ability to very quickly satisfy “emergency” requests in an economical manner while still providing a high quality product. The specialty contractors drive innovation and development, but Mother Nature and national wealth largely define market size and direction.

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