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2021 Outstanding Project: Retention Systems for Hydroelectric Dam

Deep mixing with double axis machine to form treated soil buttresses (credit, Trevicos)

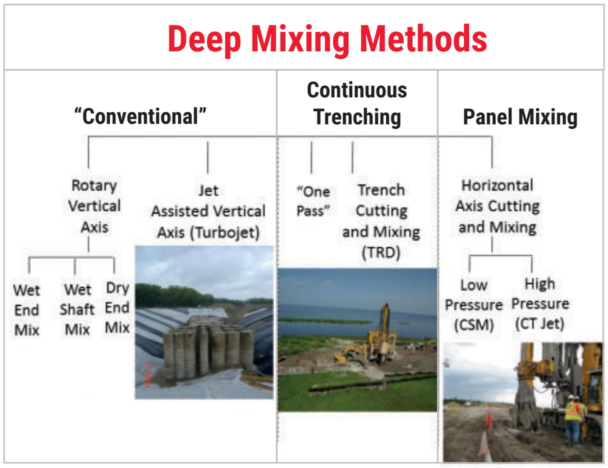
U.S. Deep Mixing Specifications and Quality Assessment

Deep Mixing Methods (DMM) have become widely used in the U.S. since their introduction by Japanese contractors in California in 1986. Deep Mixing treats and improves soils and fills by blending them in situ with a "binder," typically a cementitious grout, although some methods simply use a dry form. The many different DMM reflect their import from Japan and Europe, as well as domestically built systems, as shown in the figure.

The different methods basically follow three different mixing principles:

- Use of vertical single- or multi-axis machines in the "conventional" approach, in which the soil is blended with binder that is injected via ports in the mixing tool, creating single columns or overlapping groups of columns.
- Use of continuous trenching methods wherein the ground is cut and blended by large chainsaw-type tools, which are pulled slowly along at the ground surface.
- Use of panel mixing, in which two mixing wheels are mounted on horizontal axes; this approach is basically a derivative of the long-established hydromill, hydrofraise or cutter used for diaphragm wall construction.

The range of DMM applications is wide and much valued by practitioners in dam and levee repair; earth retention systems; port, harbor and highway construction; and environmental remediation, in particular. DMM popularity has been further enhanced by presentations at key international conferences — mainly run by DFI — such as in New Orleans (2003, 2012 and 2022), San Francisco (2015), Honolulu (2017), and an online conference in 2021, initially planned for Gdańsk,



Deep Mixing Series: *This article is the first in a series that covers keynotes from DFI's Deep Mixing Conference in June 2021. We hope you enjoy the Deep Foundations series, which will resume in 2022 magazine issues after this year's final, special issue about Smart Development.*

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Japanese engineers were keen to share DM knowledge during a 2004 Tokyo technical visit

Poland, in 2020. Conferences and workshops in Japan and Scandinavia have also been excellent opportunities to share experiences and learn from the original developers of the methods.

It is, however, timely to reevaluate certain aspects of the deep mixing industry, as the authors did recently with colleague David S. Yang, Ph.D., while presenting much of this paper as a keynote for DFI's online Deep Mixing Conference in June. In particular, the authors have developed strong views on deep mixing specifications and quality assessment based on recent experiences on major projects such as LPV111 in Louisiana, and Herbert Hoover Dike in Florida. In certain ways, these issues are magnified in myriad smaller projects located primarily on the Eastern and Western seaboards.

Standards And Specifications

It remains difficult to fully standardize design and acceptance criteria across the U.S. market, given its great geographical, technical and application diversity. Guide specifications are given in the *Federal Highway Administration Design Manual: Deep Mixing for Embankment and Foundation Support,* (FHWA-HRT-13-046, 2013) and at **www.geoinstitute.org/geotechtools/** (the recent login accessible home for the FHWA manual content that was at **www.geotechtools.org).** However, acceptance criteria should be project and purpose specific to meet individual project requirements and deep mixing quality goals.

We note however, that it is now typical for specified performance criteria to exceed the design demand; we speculate that this arises from misunderstanding the long-term performance goals of the final deep mixing product. DMM have been widely used worldwide for only about 50 years — barely the life expectancy of most projects, with little published research on the long-term durability of older DM installations. For example, the generally adopted criterion for maximum permeability ($1x10^{-6}$ cm/s) and minimum unconfined compressive strength of 100 psi (0.7 MPa) specified for seepage barrier walls should be justified as specific design requirements. These values are often used as default criteria, but are adopted from prior projects without sound technical reasons.

Quality Assessment

Depending on the DM application, and the specified acceptance criteria, some or all of the following factors are evaluated on each project:

- Compressive strength and permeability of the treated ground
- Verticality of individual elements
- Locations and dimensions of the elements
- Homogeneity of the treated soil material and continuity (overlap) of adjacent elements

Compressive Strength: As noted above, 100 psi (0.7 MPa) is commonly specified for the unconfined compressive strength (UCS) of deep mixing seepage barriers for dams and levees. Deep mixing elements used for foundation support or embankment reinforcement

Site of LVP111, the largest U.S. deep mixing levee project are designed to resist specific design loads and typically require higher strengths, up to 350 psi (2.4 MPa) or more. EuroSoilStab (2002) reports that the strength of in situ material can be 20 to 50% of that of laboratory-mixed specimens. To ensure compliance with 100 psi (0.7 MPa) as a minimum UCS, for example, contractors must target twice that value for wet grab tests and bench scale tests and adjust the binder content for the design mix accordingly. Since cement cost strongly influences the overall deep mixing installation cost, overconservatism in specifying strength can dramatically increase the final mixing cost.

The value of 100 psi (0.7 MPa) has some practical basis for seepage barriers in that acceptance criteria are often based on drilled core samples, and soft walls are inherently more difficult to core due to the expertise involved. A more rational approach might be to base strength compliance on post-production samples and use 200 psi (1.4 MPa) as the minimum acceptance criterion, with at least 90% of the samples passing. Verification borings and cores are used as the basis for compliance with specifications on homogeneity, continuity, and in situ permeability results.

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 damage borehole walls, leading to in situ permeability test values higher than those obtained from laboratory tests on pristine cast samples. In the authors' opinion, permeability should be judged using in situ testing as the most representative of a seepage barrier quality, delegating lab tests on samples (wet grab or core) to only serving as indicators of consistency.

Cutter soil mixing wheels in use (credit, Keller)

Criteria for judging the quality of a DMM structure should be rated as follows, listed by importance:

1. **Geometric Dimensions** (position, depth, width, verticality and overlap of panels) as determined by on-board electronic records and field measure.
2. **Drift,** with the FHWA Design Manual recommending a maximum drift of 1% in vertical alignment.
3. **Homogeneity** judged by visual inspection and percentage recovery of the cores and review of downhole video records (with no particle more than 3 in [76 mm] in any dimension).
4. **Continuity,** measured using angled cores spanning panel overlaps to confirm analyses of element verticality measurements and calculations.
5. **Permeability,** as measured by in situ falling head tests (if for a cutoff).
6. **Strength,** as measured from UCS testing of postproduction samples, with an appropriate reduction in measured values to represent in situ strength.

When deep mixing is used primarily to provide some form of strength, permeability is less of a design factor. Instead, strength testing would become second in importance in the above list. This is a generalization of a quality assistance/quality control (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 deep mixing product to undergo coring or grab sampling during construction, one must question the quality of the remaining 97%-99% of the deep mixing installation if repeated tests fail. The 2013 FHWA manual recommends that 2%-4% of deep mixing 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 QC/QA efforts be

A double axis machine conducts deep mixing for buttresses in an LVP111 foundation (credit, Trevicos)

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, eliminating the cost of the additional binder. It is often preferable to conservatively estimate 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.

The FHWA design manual recommends that the contractor 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 m^3 of treated soil, whichever produces the higher sampling frequency." FHWA's manual, which has been reshared at **www.geoinstitute.org/geotechtools,** expands this to require that "Sample locations shall be distributed uniformly both laterally and vertically within the deep mixed zone."

Many Lessons Learned

Published literature is replete with DMM project successes and innovative applications. Absent are criticisms and failures, likely for legal reasons. The following are a few authors' observations of shortcomings in U.S. design and construction of contemporary deep mixing projects:

Lesson 1: Designers often specify unjustified and sometimes unrealistic performance criteria, resulting later in unnecessary contractual issues due to noncompliance. For example, unless there is a valid 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. Rather than specifying an absolute maximum permeability limit, consideration should be given 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 noncompliant samples), but not a maximum strength (reflecting soil heterogeneity).

Lesson 2: DM specifications can become bloated by blind repetition of specifications from previous projects that are irrelevant and redundant. Such specifications often cross the line between performance and method specifications, further complicating issues.

Lesson 3: Designers can spend months and even years evaluating a project and preparing contract documents, drawings and specifications. However, a fraction of this time is made available for contractors to bid the job. This "back-end acceleration" hampers the contractor (who may lack the opportunity to fully understand project nuances), and the owner (who, for the same reasons, may receive an unbalanced, unrealistic bid that leads to a contractual/financial dispute). In addition to giving bidders more time, owners should ensure that they provide the Geotechnical Data Report, the Geotechnical Interpretative Report and the Design Basis Report (each prepared by the designer) to enhance bidders' understanding.

Lesson 4: Designers should provide field QA staff with a manual of engineering considerations, with a brief description of the project's purpose and goals. The manual should relate the relevance of each QA and QC item to the design intent, allowing field personnel to fully appreciate their individual tasks. Field personnel should also undergo training on the nuances of the DMM employed.

Lesson 5: 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 contractor submittals and prompt review of test results by the owner's representative.

Lesson 6: Contractors can be overconfident when assuming the adequacy of a binder design based on past experience, which can reduce preconstruction field investigation and laboratory testing for new projects. Preconstruction test programs should always be required to benefit the contractor and owner. The FHWA Design Manual recommends installing at least three test elements using different mixing parameters. These programs benefit both parties in that the deep mixing elements can be installed as designed. The 2013 manual recommends that any changes exceeding 10% of the previously approved mix design be revalidated through laboratory and field testing, which we fully support.

Lesson 7: Coring and wet grab sampling for the validation program should be held to the same standards as the production works.

Lesson 8: Fresh grout temperature is usually restricted in specifications to below 95˚F (35˚C) to minimize thermal stresses and cracking. But this requirement is 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 deep mixing installed using continuous trenching methods due to the monolithic nature of the installation. Some relaxation of this rule should be adopted, though, for these projects installed using a primary-secondary pattern of element construction since there is some time for heat to dissipate between these elements.

Lesson 9: Prehydration of bentonite is often specified for mixes containing bentonite. In some ground conditions and with high cement factors, it has been demonstrated that the compressive strength and permeability at 28-days' curing time are unaffected by adding nonhydrated bentonite. This relatively new development has not been proven to be universally applicable, so adoption of nonhydrated bentonite should be on a case-by-case basis, with approval demonstrated by comparative tests both in the laboratory and field (using site-specific soils and binders).

Lesson 10: To minimize core and borehole wall damage during drilling, verification borings should be conducted by experienced drillers using state-of-the-practice techniques and drilling rates not exceeding one ft/min. Generally, triple-tube, wire-lined coring produces the best results because the drilling tools are more stable and the core more insulated from drilling disturbances. 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 such requirements seemingly intrude on the contractor's means and methods, noncompliant test results for an otherwise acceptable deep mixing product soon become the owner's problem.

Lesson 11: Optical televiewer technology allows video inspection in great detail of the entire borehole length. This enhances confident evaluation of homogeneity, at least in the vertical direction. Linear consistency of compressive strength test results from postproduction "wet grab" samples adds to 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.

Lesson 12: It is difficult for some contractors to successfully core low-strength mixed soils without damaging the core, leading to a misrepresentation of the compressive strength of the in situ material. In such circumstances, more effective and representative measurements can be based on postproduction samples, but only after applying a correction factor of double the required design strength.

Lesson 13: In situ falling head tests should remain the acceptance criterion for the specified maximum permeability of a deep mixing seepage barrier. The only value of laboratory permeability tests on postproduction samples is added confirmation of consistency. Laboratory tests on core samples often lack accuracy and are misrepresentative due to sample microfissuring, especially if hard gravels are incorporated into the DM product.

Conclusion

By virtue of the many large and successful projects completed over three-plus decades, and the pro-active business development efforts undertaken by contractors and the various trade associations supporting them, DMM has 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 cash flow largely define market size and direction.

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