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DEEP MIXING GROWS UP

The Evolution of Deep-Mixing Technology in the U.S. Market over the Last Decade

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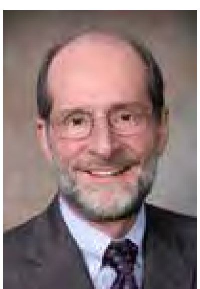

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Over the last decade, deep mixing in the U.S. market has grown from being something of a mystery into a reliable ground modification technology that can be designed rationally, implemented with capable equipment, and verified with a full suite of QC/QA measures. This article provides a brief overview of deep-mixing technologies, the evolution of the technology during the last decade, key resources, and deep-mixing issues that would benefit from further research and development.

Figure 1. Deep mixing by the dry method using single-shaft, vertical-axis equipment at Orleans Avenue Floodwall in New Orleans. (Photo courtesy of Hayward Baker, Inc.)

Brief Overview

Deep mixing blends cementitious binder with soil in situ to create soil-cement that is stronger and less compressible than the original soil for support applications and less permeable for seepage barrier applications. In U.S. practice, the binder is frequently Portland cement, ground granulated blast furnace slag, or a blend of the two. The binder can be introduced pneumatically in dry form, which is called the "dry" method of deep mixing, or pumped in slurry form, which is called the "wet" method. The dry method is applicable to soft soils with high water content, and the wet method can be applied to a wide range of soil types and conditions.

Many types of mixing machines have been developed, including:

- Single-shaft, vertical-axis machines with mixing blades near the bottom of the shaft to create soil-cement elements consisting of single columns at each set-up location (Figure 1).
- Multiple-shaft, vertical-axis machines with mixing blades near the bottom of the shafts to create soil-cement elements consisting of a set of 2-6 overlapping columns at each set-up location (Figures 2 through 4).
- Twin, horizontal-axis cutting and mixing wheels equipped with teeth to create soil-cement elements consisting of rectangular prisms (Figure 5).
- "Chain-saw" type machines in which a toothed chain circulates around a vertical post or an inclined blade that advances while mixing to create walls of soil-cement.
- A horizontal-axis rotating drum equipped with teeth and mounted on a stick attached to a backhoe boom to create continuous masses of treated ground.

Soil-cement elements can be installed in arrays of isolated elements or overlapped to produce walls, grids, or complete treatment of an area. Treatment depths in excess of 100 ft can

Figure 2. Deep mixing by the wet method using twin-shaft, vertical-axis equipment at earthen levee LPV 111 in New Orleans. Inset shows mixing blades in operation. (Photos courtesy of TREVIICOS.)

Figure 3. Deep mixing by the wet method using four-shaft, vertical-axis equipment at Perris Dam in California. (Photo courtesy of JAFEC USA Inc.)

be achieved with crane-mounted equipment, and treatment depths to about 30 ft can be achieved with the rotating drum attached to a backhoe.

Design values of unconfined compressive strengths for soil-cement produced by deep-mixing methods typically range from about 50 to 500 psi. The average strength and the strength uniformity depend on the soil type (particle size distribution, plasticity, water content, organic content, and organic type are all important), binder type and amount, added water amount, mixing energy, curing time, and curing conditions.

The term "mass mixing" is used for mixing that: achieves 100 percent or nearly 100 percent area coverage in plan view, is not more than about 30 ft deep, and typically has a strength at the low end of the 50 to 500 psi range. However, there is no precise dividing line between deep mixing and mass mixing. Large-diameter, single-axis machines and horizontal rotating drums are frequently used for mass mixing.

Evolution Over the Last Decade

Deep-mixing methods were developed in Japan and Sweden in the 1960s, with Japanese and Swedish technologies focusing on the wet and dry methods, respectively. Although several large and small projects were completed in the U.S. between the mid-1980s and the mid-2000s, the state of practice in the U.S. lagged behind that in Japan and Sweden. Misconceptions and real problems occurred on several projects regarding design, construction, and QC/QA. However, interest in deep mixing by the U.S. Army Corps of Engineers and the U.S. Federal Highway Administration led to research projects designed to learn about Japanese and Swedish use of deep mixing and to investigate how these technologies could be best utilized in engineering practice in the U.S. Simultaneously, improvements occurred in mixing equipment capabilities and construction QC monitoring. Two large, recently completed projects have been particularly significant in enabling deep mixing to fully emerge as a reliable ground modification technology in the U.S. market:

- *Lake Pontchartrain and Vicinity (LPV) 111 Levee Raise*. This deep-mixing project produced 1.7 million cy of soil-cement to support a 5.5-mile-long earthen levee over soft clays and peat in East New Orleans, LA. This is the largest, single, deep-mixing project completed in the Western Hemisphere to date. The deep mixing was done using twin-shaft, vertical-axis mixing machines with moderate pressure slurry injection or air-water emulsion slurry injection.
- *Herbert Hoover Dike Remediation*. To stabilize dikes around Lake Okeechobee, three technologies were used in each of three separate reaches (each reach was thousands of feet long) to construct a seepage barrier through the dike and underlying sand, weathered limestone, and limestone. Two

Figure 4. Excavation of test/demonstration section at Perris Dam. These elements were installed by the wet method using four-shaft, vertical-axis mixing equipment. (Photo courtesy of California Department of Water Resources.)

of the technologies selected were deep-mixing methods, and the other was an excavate-and-replace technology. One of the deep-mixing technologies used equipment with twin, horizontal-axis wheels with teeth, and the other technology used a vertical post and a "chain-saw" type mixer with cutting teeth.

Several publications, presentations, short courses, and entire conferences have been devoted to technology transfer in deep mixing. As a result of this aggregate activity in research, implementation, and technology transfer, several facets of U.S. deep-mixing practice have significantl improved y during the past 10 years. These improvements can generally be separated into the categories of mixing equipment and procedures, analysis and design methods, and QC/QA methods. Furthermore, the integration of the components has also improved.

Improved Mixing Equipment and Procedures

Equipment manufacturers and contractors continually strive to improve their mixing equipment and processes. Examples include:

- Widespread use of weight batching to produce consistently high-quality slurry
- Incorporating one or more stationary bars on a single-shaft vertical axis machine to enhance mixing
- More powerful equipment with more mixing blades
- Moderate pressure injection of slurry from multiple nozzles located along the full length of the bottom cutting and mixing blades to increase mixture homogeneity
- Addition of pressurized air to the slurry to create an emulsion that can increase the mixture's homogeneity

Marked improvements have also occurred in automated machine control with monitoring and feedback loops for penetration rates and slurry delivery rates, such that the slurry delivery rate per foot can be preprogrammed over multiple depth zones to permit treating a peat layer, for example, with more binder than overlying and underlying inorganic soils. Such control can now be achieved with constant or varying penetration rates of the mixing tools. Similarly, slurry batch plants with automated, feedback-control loops are available.

Analysis and Design Methods

In past U.S. practice, and unfortunately on some recent projects, ad hoc approaches without careful validation have been used for design of deep-mixing support systems. As a result, some projects have been substantially over-designed, and others have been under-designed and performed poorly.

Fortunately, reliable analysis and design procedures are now available to design deep-mixing systems for static capacity and settlement control, although there is room for additional progress in seismic design. Important factors for static and seismic applications include: (1) selecting appropriate soil-cement property values with consideration of variability, and (2) accounting for all ultimate and serviceability failure modes. Factors like these are important for all geotechnical design, and they are especially important for designing deep-mixing support systems. Depending on soil type, mixing equipment, and mixing parameters, soil-cement produced by the deep-mixing method can be more variable than naturally deposited clays, and this variability should be taken into account during design. Otherwise, use of ordinary values of factor of safety can produce lower reliability than desired or expected based on experience with other geotechnical systems.

Regarding multiple failure modes, deep-mixing support systems consisting of isolated elements may be subject to bending failure modes that are not easily captured in limit equilibrium slope stability analyses. If the potential for bending failure is ignored, the actual factor of safety against collapse can be much lower than calculated based on the composite shearing failure mode that is represented in limit equilibrium slope stability analyses. Depending on configuration and loading, other failure modes that should be checked include bearing capacity at the toe of the improved zone, crushing of the soil-cement at critical locations, overturning stability of the treated zone, vertical shearing at overlaps between potentially misaligned elements in shear walls, and extrusion of soft soil between parallel shear walls.

QC/QA

Parallel with improvements in automated control, monitoring of equipment operations using electronic data acquisition has also improved dramatically. Modern instrumentation and data acquisition systems are used to produce reports for every deep-mixed element installed on a project, including logs versus depth of mixing parameters such as penetration rate, withdrawal rate, rotation rate, slurry delivery rate, power expenditure, and verticality. Logs of post-processed combination parameters, such as blade rotation number, are also included in the reports. These reports can be reviewed by the contractor and the owner (or the owner's engineer) to identify questionable elements off a project. If questionable elements are produced, they can be investigated and/or remediated as necessary. Daily logs of slurry plant operation are also produced.

Figure 5. Deep mixing by the wet method using twin, horizontal-axis cutting and mixing wheels at BC Hydro substation in Burnaby, British Columbia. (Photo courtesy of Pacific Ground Engineering.)

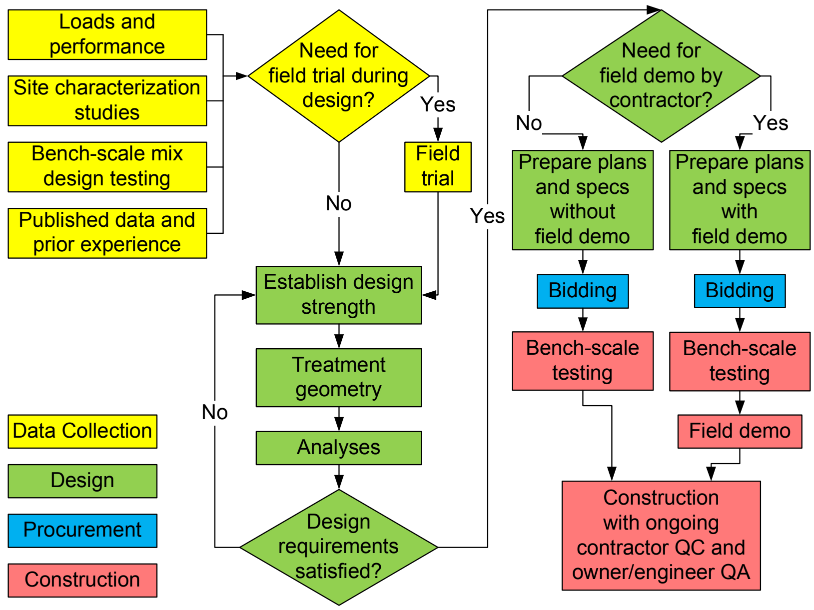

Figure 6. Flow chart for design and construction of deep-mixing projects.

Supplementing these QC operations and performance documentation, QA of deep-mixing projects includes: observation of materials, equipment, and processes; careful review of the contractor's QC records; sampling and laboratory testing; and, sometimes, in-situ testing. Coring and unconfined compression testing of core specimens has become standard for most deep-mixing projects. Contractors have developed coring techniques to obtain high recovery rates and good-quality samples of soil-cement for most deep-mixing applications. Triple-tube, wire-line coring tends to provide the greatest protection against core damage, and details of the core bit configuration, coring rate, and drilling fluid type and pressure are important. For some mixtures that are designed to be relatively weak and/or that contain coarse sand or gravel, coring can be difficult or impossible. In such circumstances, wet-grab sampling combined with high–resolution, optical televiewer images in bored holes can provide a viable alternative to testing core samples. Various types of continuous penetration tests are also possible in weak soil cement, but these are not widely used in U.S. practice, where relatively high mixture strengths are specified, particularly for mechanical support applications.

For seepage barrier projects, in-situ falling head permeability tests are often performed in cored holes. In some circumstances, however, even the best coring practices can produce vertical cracks that did not exist before the hole was drilled, as evidenced by vertical cracks in the core hole wall, but not in the recovered core from the same elevation. Such cracks frequently can be observed with an optical televiewer, and failing permeability tests in such holes should not count against the contractor's satisfaction of specification requirements. Backfilling cracked holes with grout made from micro-fine cement with a small portion of bentonite is a suitable remediation procedure. Countermeasures to reduce the potential for core-induced cracking of seepage barriers were applied at the Herbert Hoover Dike. The data from in-situ falling head permeability tests on uncracked holes should be reduced using an appropriate procedure that takes into account the three-dimensional nature of the test, and not using a procedure that assumes a bored hole has been formed in a homogenous material of great lateral extent.

Integration

The entire process of investigation, analysis, design, specifications, construction, QC, and QA should be fully integrated. Figure 6 shows a flow chart of key phases and steps in a deep-mixing project. When each step has been carefully followed, this process has produced successful outcomes on numerous deep-mixing projects. The project plans and specifications are essential to successful integration of project components. The specifications should allow as much flexibility as possible for the contractor in terms of means and methods, including element geometry, while still protecting the owner's interests. This occurs by requiring the necessary overall outcomes of system geometry and strength, and by accommodating the inherent variability of soil-cement properties produced by deep mixing.

The flow chart allows for field trials during design and field demonstrations early during construction. Field trials during design are expensive when the contractor is not already mobilized. Consequently, they are typically used only on large projects where prior experience in similar site conditions is deemed insufficient. On the other hand, field demonstration elements installed early during construction are very common. Demonstration elements allow the contractor to investigate and demonstrate suitable field-mixing parameters, and they permit all parties to exercise, demonstrate, and understand the methodology and effectiveness of QC/QA operations.

Full integration of project phases was achieved on the LPV 111 project by employing an early contractor involvement process. The contractor was part of the project team during the design phase. This involvement allowed for effective contractor input on material properties, design, plans, specifications, and QC/QA requirements, while the owner and the owner's engineer remained in control of the final requirements for outcomes necessary to achieve the project objectives.

Issues Worthy of Further R&D

Although great progress has been made in deep-mixing practice in the U.S. in the last decade, there will always be room for improvement in all aspects of the technology. The following issues would benefit from special attention to further enable optimizing deep-mixing design and construction:

- Stress-strain and strength characterization of deep-mixed soil-cement, including cyclic loading and large strain response, under various conditions of confinement and drainage
- Spatial correlation of soil-cement properties as mixed in situ with differing equipment and procedures in differing soil types
- Seismic design, including three-dimensional effects
- Specifications and QA methods for seepage barriers, including appropriate consideration of narrow cracks and cold joints on overall seepage barrier function. GS

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