

THE APPLICATION OF THE DEEP MIXING METHOD TO DAM AND LEVEE REMEDIATION IN THE UNITED STATES

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ABSTRACT

The paper provides historical construction data on the 84,000 dams and 100,000 miles of levee in the U.S. This is an aging portfolio of structures and it is increasingly vulnerable due to deficiencies in design, construction and maintenance, as well as threats from natural sources such as earthquakes, floods, and unstable geology. The three major groups of DM technologies are reviewed, namely conventional, vertical multi-axis DM; continuous trenching (e.g., TRD) and horizontal axis mixing (e.g., CSM). The four groups of applications of the DMM to dam and levee remediation are described and illustrated with reference to major case histories. The paper concludes that although the remedial market is fundamentally driven by the outcome of risk-based analyses, its rate of growth and volume is a reflection of the comprehensive design guidelines, high quality construction techniques, and intense QA/QC and Verification programs now granted to the dam and levee engineering community by DM specialists.

SCOPE, CHALLENGES AND APPLICATIONS

The Congress of the United States of America authorized the U.S. Army Corps of Engineers (USACE) to conduct an inventory of dams in the U.S. through the National Dam Inspection Act of 1972. The resultant National Inventory of Dams (NID) was first published in 1975 and updates have been made in the succeeding years, in accordance with the Water Resources Development Act of 1986. The most recent Dam Safety Act (2006) reauthorized the maintenance and update of the NID.

The USACE's NID website covers dams meeting at least one of the following criteria (Ragon, 2011):

- 1) High hazard classification - loss of one human life is likely if the dam fails,
- 2) Significant hazard classification - possible loss of human life and likely significant property or environmental destruction,
- 3) Low hazard classification – no probable loss of human life and low economic and/or environmental losses, but the dam:
 - Equals or exceeds 8 m in height and exceed 15 acre-feet in storage,
 - Equals or exceeds 50 acre-feet storage and exceeds 2 m in height.

Based on the input from many sources and, in coordination of the Federal Emergency Management Agency (FEMA), more than 100,000 dams have now been reported, although only about 84,000 of these meet the NID criteria. Almost 14,000 are classified as "High Hazard." Almost 6,200 dams are at least 15 m high, with over 1,600 being in excess of 30 m, while about 50 percent of the dams are less than 8 m high. The dams have the following ownership distribution:

• Private	68%
• Local Government	20%
• State Government	5%
• Federal Government	4%
• Public Utilities	2%
• Unknown	1%

The Federal Government total of 3,075 dams includes those owned and/or operated by the USACE, the Bureau of Reclamation, Forest Service, Bureau of Indian Affairs, Bureau of Land Management,

Fish and Wildlife Service, National Park Service, International Boundary and Water Commission, and the Tennessee Valley Authority. These agencies only began building dams in the early 1900's. Before then, private funding prevailed and design and construction methodologies were uneven and unregulated.

Over 87% of the total dams are primarily classified as earth embankments of some form, while no other category (including arch, buttress, concrete, gravity, masonry, multiarch, rockfills and timber cribs) exceeds 3% of the total.

Figure 1 summarizes the dam population by primary purpose: more than one-third are for recreation, while less than 3% are primarily for power generation. Many of the dams are multipurpose. Figure 2 categorizes them by completion date: about 50 percent of the nation's dams were completed between 1950 and 1979, while the median age in the year 2020 is sixty-nine years.

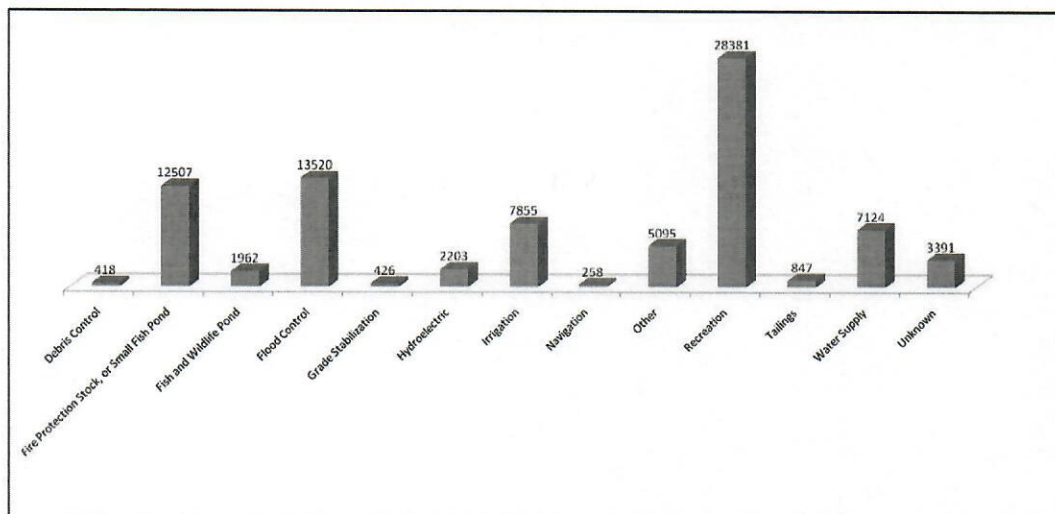


Fig. 1. Dams by primary purpose. (From National Inventory of Dams, *CorpsMap*, <http://nid.usace.army.mil>, 2010)

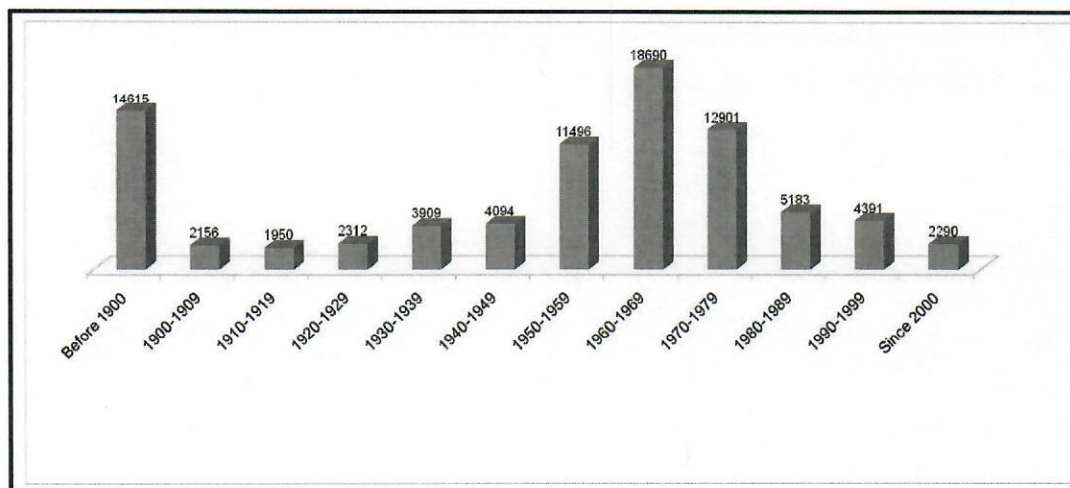


Fig. 2. Dams by completion date. (From National Inventory of Dams, *CorpsMap*, <http://nid.usace.army.mil>, 2010)

Whereas one can calculate that all the dams in the U.S., if placed end to end, would form a structure about 17,000 miles long, *preliminary* estimates put the total length of levees as over 100,000 miles. [“The total number of levees across the nation is still unknown (USACE 2009)]. It is important to note the distinction between a dam and a levee. FEMA (1998) defined a levee as “a manmade structure, usually an earthen embankment, designed and constructed...to *contain, control, or divert* the flow of water, so as to provide protection from temporary flooding.” According to Halpin (2010), there are levees in all 50 states, and in addition to the uncertainty regarding their number and extent, there is equal ignorance about their current condition and the threat they pose to the population and property they protect. It is clear, however, that tens of millions of people live and work in close proximity to levee systems: originally constructed to protect property, they have often inadvertently increased flood risks by attracting greater development to the flood plain.

Until the 1930’s, levee construction was sporadic and unsophisticated without the benefit of systematic engineering or scientific expertise. Levees were considered “simple” structures and so not designed or built to contemporary dam standards. After great devastation and loss of life from the floods in the Mississippi and Ohio River valleys and in Florida, the USACE was directed, at full federal expense, to take a more active role in levee design and construction, resulting in the 14,000 miles or so of “robust” levee systems now in place. Many of these levees, which make up the backbone of the nation’s levee system, are now therefore well over sixty years old and, even when regularly maintained, may not have been brought up to the most recent engineering standards. The balance of the inventory includes municipal, local and agricultural structures.

The situation was described in chilling terms by Halpin (2010): “The potential consequences of levee failure can be devastating. The situation is the result of more than 100 years of inattention to, and in some cases neglect of, levee infrastructure combined with a growing population living behind levees and an economy and social fabric that are in a particularly vulnerable state. The current levee safety reality for the United States is stark — uncertainty of location, performance and condition of levees, and a lack of oversight, technical standards, and effective communication of risk.”

Dam or levee failure can arise from one or a combination of factors relating to design, construction or maintenance shortcomings on the one hand, and fundamental geological and geotechnical controls on the other hand. In this regard, while few structures are actually founded on evaporites, such materials associated with other (less soluble) lithologies such as limestones and dolomites underly 35 to 40 percent of the forty-eight contiguous United States (Martinez et al., 1998). Further [Figure 3](#) is the U.S. earthquake hazard map for 2 percent probability of ground motion exceedance in fifty years, i.e., a 2,500 return period. It shows regions of extreme seismicity in the Mississippi/Tennessee area, centered around the New Madrid fault system, South Carolina, and of course along the West Coast and in the eastern Rockies. Many damaging earthquakes have been recorded in New England, but one must take into consideration the longer and more intense human habitation of the area and so the high sensitivity and precision of the historical database.

To these challenges must be added those transients posed by extreme weather events, causing flooding and overtopping, while the problem in the New Orleans area is exacerbated by the ongoing regional settlement of the delta, estimated at 2 – 12 mm per year.

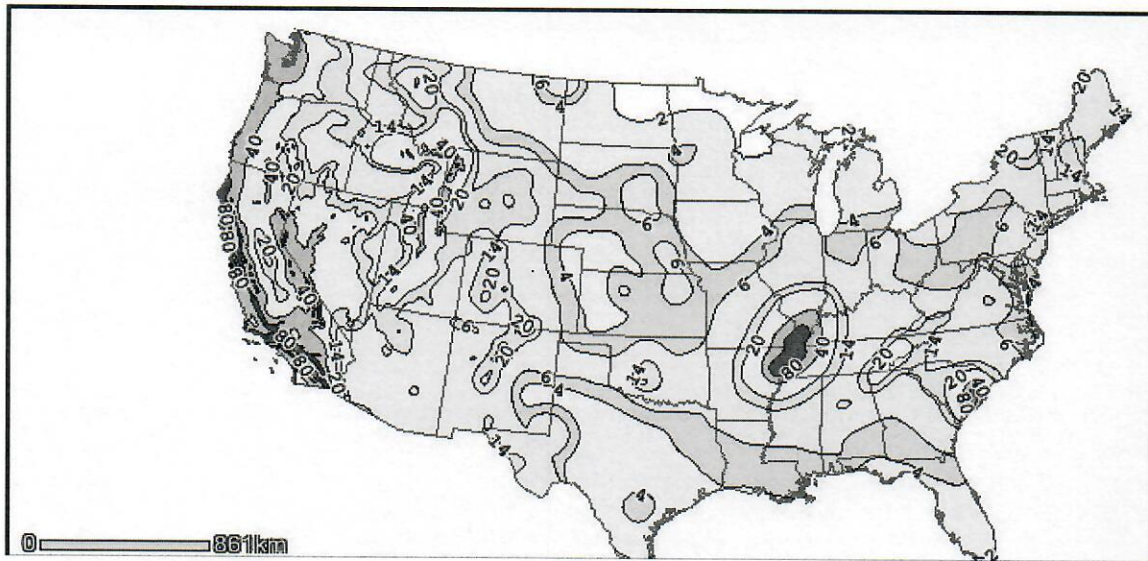


Fig. 3. Peak horizontal acceleration with 2 percent probability of exceedance in 50 years.
Note: The contour values represent peak ground accelerations in percent g (From U.S. Geological Survey, *National Seismic Hazard Maps of Conterminous U.S.*, <http://earthquake.usgs.gov/hazards/apps/>, 2008.)

Faced with these threats to their aging and potentially vulnerable infrastructure, Owners now systematically evaluate their portfolios of dams and levees, using risk-based analyses. For each structure, a Potential Failure Modes Analysis is rigorously conducted to identify the likely weaknesses and so determine the need for, and type of, remediation. This process is applied to the structure as-is, but also to the vulnerability of the structure during remediation. Such threats may be of the straightforward technical type (e.g., will the remediation temporarily destabilize the embankment?) but may also arise from the environmental corner (e.g., is raising-and hence widening of a levee in a Wildlife Refuge Area – a feasible, permissible option?).

For over 30 years now in the United States, the various DM Methods have been used both in existing structures, and to improve the foundations of new/replacement structures. The three major groups of traditional applications are for:

- seepage cutoff
- seismic remediation
- new/replacement foundation strengthening

Most recently a fourth group – DMM for cutoff and support buttressing for new/replacement dams – has been developed.

Each of these applications is illustrated in the four case histories described below.

DM METHODOLOGIES

A classification of the DM Methods used in the U.S. is provided in Figure 4.

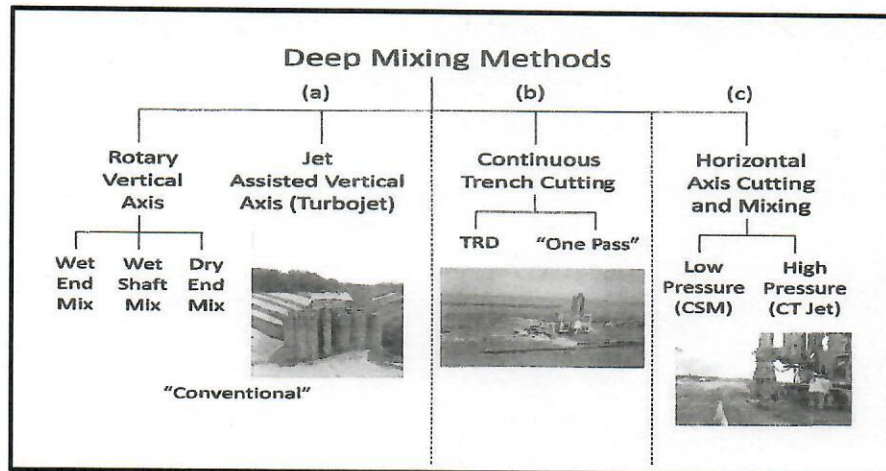


Fig. 4. A classification of the DM methods used in the U.S.

Based on observations of the dam and levee market since the first application of DM in 1987, Table 1 provides a simple perspective. Although the dry DM method was used on several smaller projects in the New Orleans area in the period 2006 – 2010, all other DM techniques used for dam and levee remediation have used wet methods (Bruce et al., 2012). A common thread in all these major dam and levee remediations is the very intense levels of QA/QC and Verification which are applied. These include the value of the onboard instrumentation which contemporary models of DM equipment of all types carry. Thus, there is precise control over the location, depth, width and continuity of the DM elements, as well as their material properties, in situ.

Table 1. Summary of DMM Usage for dams and levee remediation

APPLICATION	CONVENTIONAL VERTICAL AXIS	CONTINUOUS TRENCHING	HORIZONTAL AXIS
Seepage cutoff	Originally used : now less common	Very attractive on big projects	Very popular
Seismic remediation	Very common	Not applicable	Common
Foundation strengthening	Very common	Not applicable	Common
Cutoff and buttress	Can be used	Can be used	Can be used

ILLUSTRATIVE CASE HISTORIES

Seepage Cutoffs

As indicated in Table 1, conventional vertical multi-axis DM was the original method of choice, from Jackson Lake Dam, Wyoming (1987) onwards. However, with the issues inherent in such cutoffs (e.g. restrictions on depth, continuity of the cutoff, productivity) and the introduction of CSM and TRD (and similar types) in 2005 – 2006, the use of conventional vertical axis DM has subsided in favor of the other methods. This is not, however, to denigrate the older work done after Jackson Lake, (Ryan and Jasperse, 1989), for example at Cushman Dam Washington, (Yang and Takeshima, 1994), Lockington Dam Ohio, (Walker, 1994), or on the Sacramento, Idaho, and New Orleans Levees, (Yang, 2013). However, the work done, and still underway at Herbert Hoover Dike, Florida, provides an excellent showcase for the more modern methods, and so is featured below.

Lake Okeechobee in southeastern Florida is surrounded by a very heterogeneous levee known as the Herbert Hoover Dike, on which early construction by locals first began around 1915 utilizing mostly sand and topsoil (Garbin, et al., 2009). Portions of the original embankments were overtopped by hurricane-induced surges in 1926 and 1928, resulting in the loss of over 2,500 lives. As a result, about 120 km of levee were reconstructed by the USACE between 1932 and 1938. A major hurricane in

1947 illuminated the need for additional flood protection, and the current dike system for Lake Okeechobee was completed in the late 1960s. The dike system now consists of about 220 km of levee with nineteen culverts, hurricane gates and other water control structures. Lake Okeechobee has become the third largest freshwater lake in the continental United States, draining to the ocean through the Everglades. The levee crest is typically at around elevation + 11 m, and the lake is normally at EL + 3 to 4 m. However as constructed, sections of the levee are prone to instability due to water seepage and piping, in particular when lake levels increase beyond certain elevations due to surge caused by severe weather (hurricanes). Therefore, the USACE designed a seepage cutoff wall constructed progressively in prioritized “reaches” each several miles long to mitigate piping concerns and ensure dike stability during extreme weather events, Figure 5.

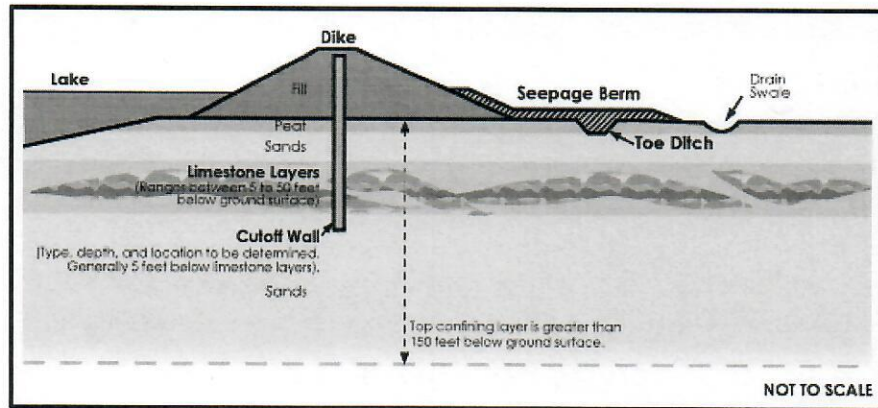


Fig. 5. Schematic of cutoff wall and seepage berm concept, Herbert Hoover Dike, Florida (U.S. Army Corps of Engineers, <http://www.saj.usace.army.mil/Divisions/Everglades/Branches/HHDProject/HHD.htm>, 2007.)

Given the scale of the project (Phase 1 was over 32 km long, and Phase 2, currently underway, is over 48 km long) and the urgency of the remediation, the USACE managed the four major risk elements as follows:

1. **Technology Risk:** Prequalification of 3 different cutoff wall methods (out of 8 proposed), each with very detailed statements of prior experience.
2. **Schedule Risk:** Breaking down the whole project into numerous smaller reaches so permitting simultaneous work in several sections.
3. **Project-Specific Risk:** Each section was predicated by a 150 m-long Demonstration Section. Production was only permitted after USACE had accepted the Demonstration Section Report. USACE also employed an external consulting group as continuity/oversight over all individual contracts. For in-situ homogeneity, extensive reliance was placed on the use of the Optical Televiewer (Robertson Geologger).
4. **Performance Risk:** Use of Performance Based Specification, but featuring very clear QA/QC and Verification criteria defining:
 - Continuity, homogeneity, verticality;
 - 45 to 90 cm;
 - In-situ permeability $\leq 1 \times 10^{-6}$ cm/s (in coreholes at 60 m centers);
 - UCS 0.7 to 3.5 MPa from cores, at 28 days;
 - Chemical compatibility with groundwater and soil.

Approximately 70 percent of Phase 1 was conducted using TRD and CSM, the balance being a Self Hardening Slurry Cutoff constructed by traditional cutoff wall methods i.e., grab and hydromill. The QA/QC program was very intense with core data were supplemented by testing of shallow “bulk” samples and deeper “wet grab” samples, (Garbin et al., 2009). Both contractors elected to use grouts

with a high slag content, in addition to bentonite and other admixtures to extend workability as required. Samples continued to gain strength even beyond 200 days age. It was common to take special measures, such as chilling the mixing water, to combat the very high ambient temperatures over the summer months.

Bearing in mind the considerable heterogeneity of the conditions to be mixed, the cutoff was found to be extremely homogeneous in appearance and engineering properties. In the case of the CSM sections, this was aided by the contractor's decision to predrill and remove substantial thicknesses of peat and replace them with controlled quality granular backfill.

Seismic Remediation

Details of the design and construction of the seismic remediation projects undertaken at Sunset North Basin Dam, California, Clemson Upper and Lower Diversion Dams, South Carolina, and San Pablo Dam, California, were provided by Yang (2013). Since then, a similar, massive project has been conducted at Perris Dam, California, (Chen et al., 2015). In each case, multiaxis conventional DM was used to create "cells" to intercept potentially liquefiable layers at various depths. Details of the design layout of course vary between the projects, but the scheme adopted for Clemson Dam is typical (Figure 6). The transverse shear walls of the cells provide the necessary resistance to lateral forces induced by an earthquake whereas the connecting longitudinal wall prevents liquefied sediments from squeezing or flowing between the transverse walls. DMM is usually selected as the preferred option when the construction of a major excavation at the downstream toe of a dam (to remove and replace liquefiable materials) would cause unacceptable dam safety conditions.

Foundation Strengthening

Throughout the world, one of the most common applications of Deep Mixing is to improve foundation conditions under new (or replacement) embankments and levees. Settlements are thereby reduced, and the bearing capacity of the foundation materials improved. Design procedures have been formalized by many famous authors especially in the Nordic Countries, Western Europe, Japan and the U.S. (Filz and Templeton, 2009), and so the procedures are well established and well known. In the U.S., the most prominent example to date is the works at LPV111, in New Orleans. This project has been the subject of many papers in the 2012 Grouting and Deep Mixing Conference, amongst other venues.

As part of the Lake Pontchartrain and Vicinity Hurricane Protection System, the levee enlargement project identified as LPV-111 presented challenges that required innovative approaches in design, contracting, and construction. LPV-11 extends 9 km along the north bank of the Gulf Intracoastal Waterway (GIWW), bordered on both sides by the Bayou Sauvage National Wildlife refuge. This constricted levee construction to the existing right-of-way, making DMM an effective means for reducing cost and schedule.

Subsurface conditions consist of clayey levee fill over soft clays, peat, and organic clays to a depth of about 21.3 m below the crest of the existing levee. Underlying the soft clays are stiff Pleistocene age clays and medium dense sands.

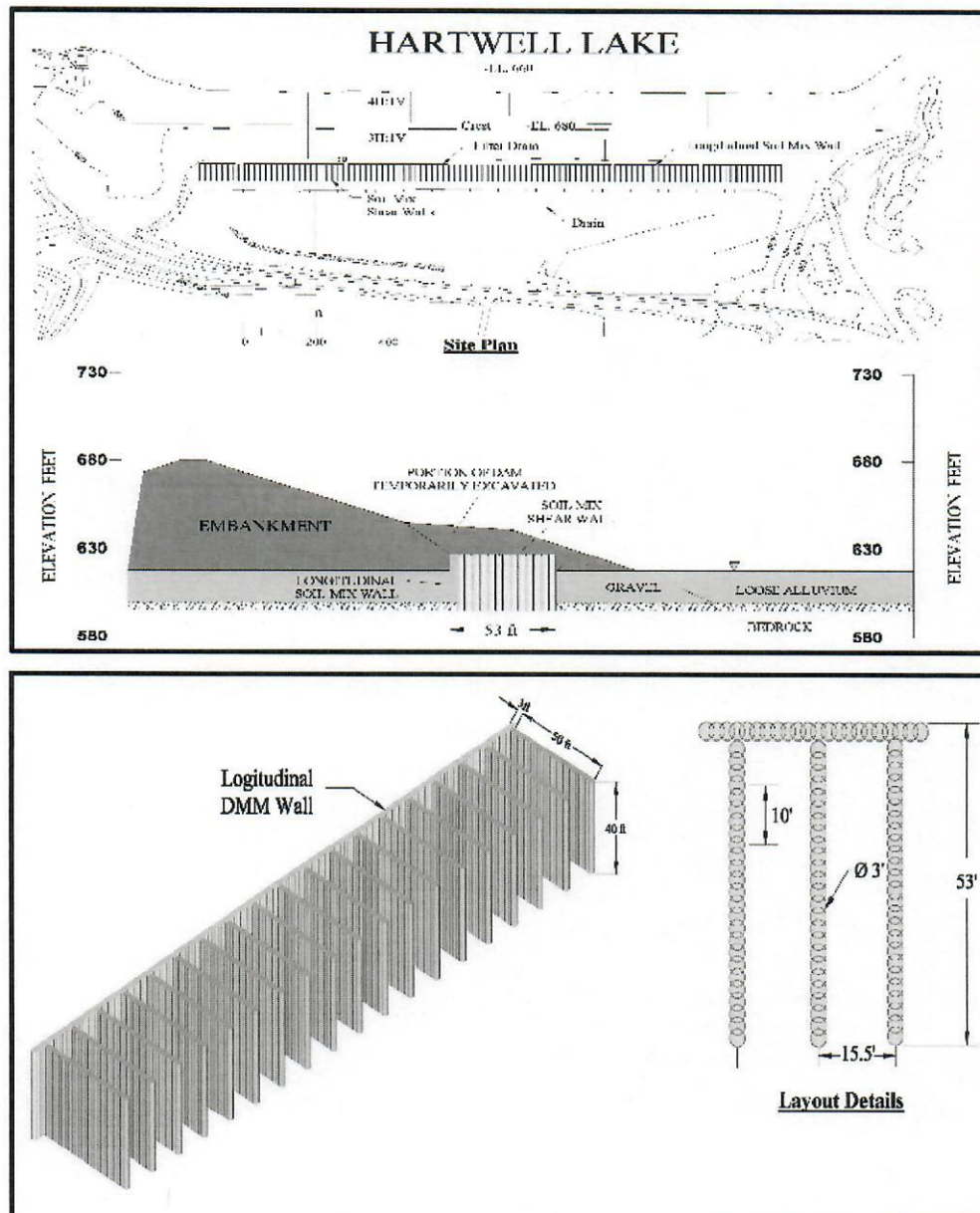


Fig. 6. DMM layout at Clemson Dam, South Carolina. (After Wooten, R.L., and B. Foreman, Proceedings of the 25th Annual United States Society on Dams Conference, 2005; Courtesy of USSD.)

To enlarge the existing levee by 3.3 m, and meet the more stringent design standards of the Hurricane and Storm Damage Risk Reduction System (HSRRS), DMM panels were used to buttress the levee against shear failure and to reduce settlement to a negligible level. Overlapping columns were installed 20.3 m through a level working platform and into the foundation, as shown in Figure 7. Excess return material, which was a blend of binder and foundation soil, generally fat clay of medium consistency, was used to construct the levee core. The return material, termed Recycled Embankment material (REM), proved to be highly competent levee fill, having properties similar to the columns. Using REM proved to be an excellent business decision that saved construction time and cost. This was another first for flood protection barriers. Design methodology and use of Early Contractor Involvement (ECI) as the acquisition plan for contract award to accelerate construction are described

in Cali et al. (2012). The result was project completion on time, within budget, and to the highest industry standards.

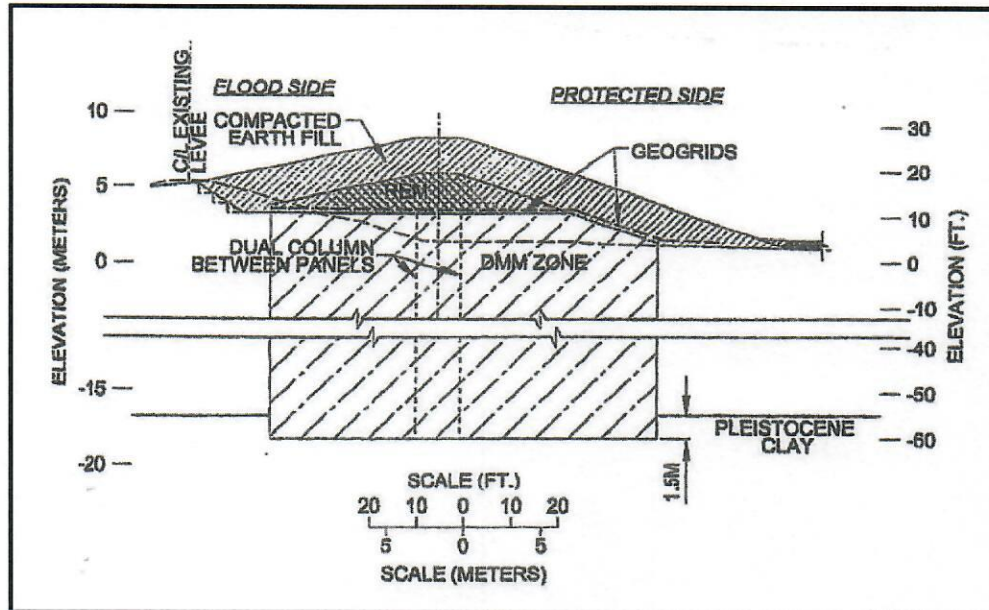


Fig. 7. Final levee design section, Reach 12B (Cooling et al., 2012)

The material used for the project consisted of binder, consisting of 25 percent type I/II Portland Cement and 75 percent slag cement, and potable (city) water. For the entire project, over 417,000 tonnes of binder was used at a rate of over 2,000 tonnes per day. Over 454,000 cubic meters of water was used.

Two different technologies were applied to treat over 1.4 million cubic meters of foundation soil: 1) TREVI Turbo Mix (TTM), single and double axis, and 2) FUDO Contrivance Innovation Cement Mixing Columns (CI-CMC) to create about 18,000 columns having diameters of 1.6-m, as detailed in Schmutzler et al., (2012). An intense QA/QC program involving the coring of about 3 percent of the 18000 individual DM elements not only verified the in-situ quality, but allowed binder ratios to be safely reduced as the work progressed.

Cutoff and Buttress for Replacement Dam

Buckeye Lake, Ohio, was formerly known as Licking Summit Reservoir, and was originally a “feeder” reservoir for the Ohio and Lake Erie Canal System. Upgrading of a natural lake by construction of 6.5 km of new clay and shale embankments on the glacial soils lasted from 1825 to 1830. The unfaced upstream slope of the embankment failed in 1832 due to wave action, flooding areas outside the reservoir boundaries. In response, a masonry wall was constructed on the upstream face. By the early 1900’s, the canal system was in disarray, and lots on the dam were sold or leased to the public: 370 cabins and cottages were built into the downstream toe of the embankments. Throughout the ensuing century, tourism became ever more popular, and major population centers arose around and downstream of the embankments. A series of studies between 1968 and 2015 concluded that interim risk reduction measures be immediately implemented given the deterioration of the embankment, including seepage and internal erosion episodes. The first phase of these measures included the placement of an embankment stability berm outboard of the existing dam and a 12 m deep DM wall as a seepage cutoff (Figure 8). This was conducted by both conventional DMM and by the “One Pass” trenching method and involved 75,000 cubic meters of treatment. Phase 2 (Figure 9) involved the construction, by similar DM methods, of a 3 m wide stability buttress,

supported by the Phase 1 cutoff and by a deeper row of DM elements. Four thousand passive anchors were installed through the buttress, and into the cutoff to provide better structural continuity. The treated volume of the buttress was about 110,000 cubic meters.

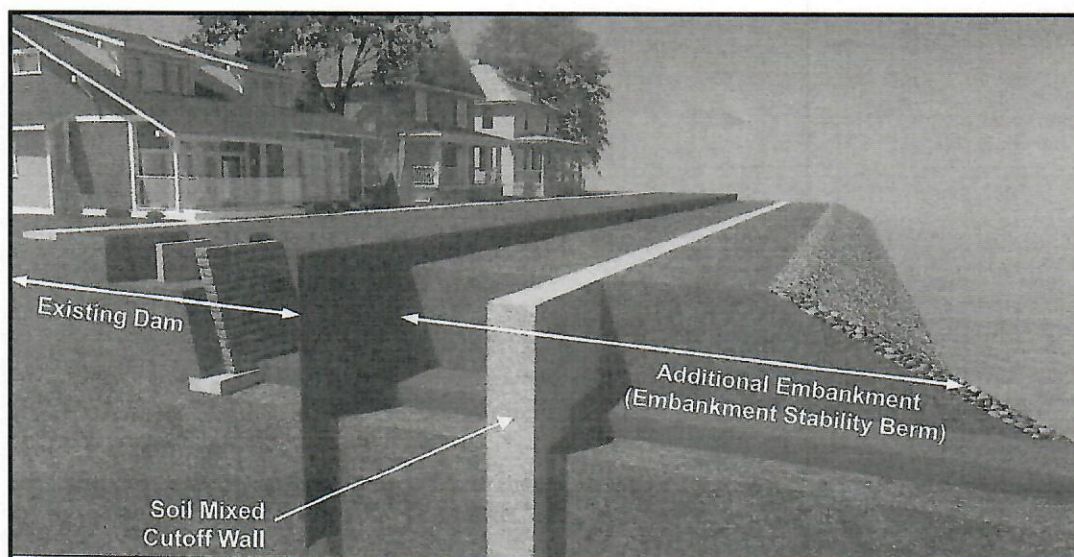


Fig. 8. Phase 1, Buckeye Lake Dam Remediation showing the stability berm and the DM cutoff wall

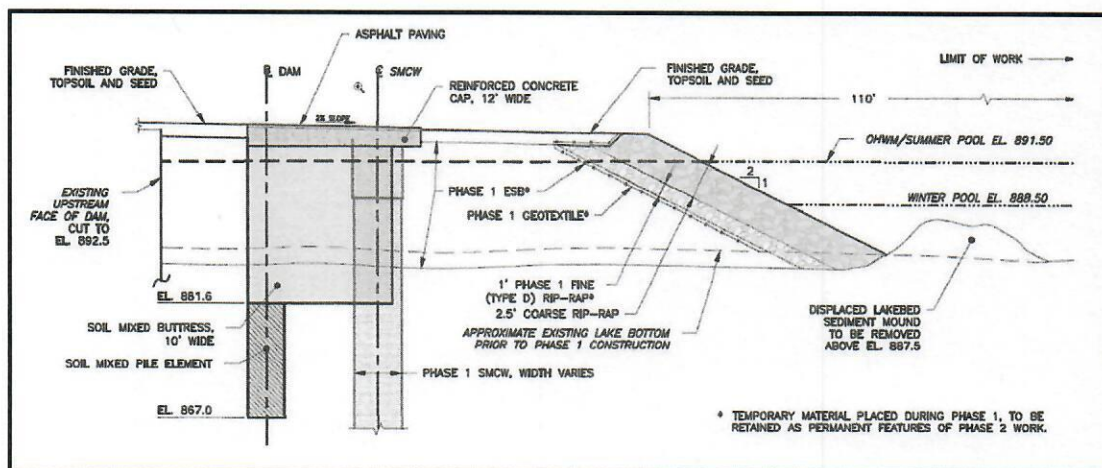


Fig. 9. Phase 2, Buckeye Lake Dam Remediation showing the DM buttress.

This innovative design has secured the safety of the embankment against several Potential Failure Modes, and has done so while minimizing disruption to existing home owners, and the natural environment. Tourist and recreation amenities have been enhanced while the roadway located above the buttress allows easy access for inspection and maintenance. A similar remediation has recently been implemented at Portage Lakes Dam, Ohio, also under the purview of the Ohio Department of Natural Resources.

CLOSURE

The vast and aging portfolio of dams and levees in the United States is increasingly vulnerable to the consequences of inadequacies in design, construction and maintenance, as well as to the threats posed by natural phenomena such as aging, seismicity, floods, and unreliable foundation materials. That

there is a market for DM technologies to provide remedial solutions for the various risks these issues have imposed on the dams and levees is unsurprising. However, what is surprising is the size of the market and the rate at which it is developing. This is due to a combination of factors, including the development of comprehensive design guidelines, the availability of well resourced specialty contractors offering a wide range of innovative and reliable construction techniques, and the imposition of intense QA/QC and Verification programs. There seem to be no major obstacles in the path of further expansion of DM projects in the dam and levee remediation market in the US.

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