

THE NEW ORLEANS LESSON: DEVELOPMENT OF A DMM MARKET

Dr. Donald A. Bruce, President, Geosystems, L.P., Venetia, PA USA, 724-942-0570,
dabruce@geosystemsbruce.com

Dr. Peter R. Cali, President Sea Level Engineering, LLC, Metairie, LA USA, 504-258-4280,
prcali@cox.net

ABSTRACT

This paper addresses the generic steps involved in the development of a DMM market in a new geographic area. It uses the case of the activities in New Orleans, Louisiana, between 2001 and 2011. The following stages in the development are identified:

- Stage 1: Education of the engineering community and full scale demonstration of the technique.
- Stage 2: Routine use of DMM on a number of small – medium scale projects.
- Stage 3: The confidence to use DMM on the first “mega project” and the consolidation of the market thereafter.

While acknowledging the huge impact of a sudden cause for DMM demand – in the case of New Orleans it was the disastrous hurricanes of 2005 – the authors argue that the market would have developed anyway given the immense challenges of heavy construction in soft deltaic sediments, albeit at a somewhat more relaxed pace.

INTRODUCTION

There is an old truism: “necessity is the mother of invention”. Equally valid is the expression “if the only tool you have is a hammer, every problem looks like a nail”. Geotechnical construction is inherently a conservative business in the sense that developments tend to be slow to evolve, that is, until some “great leap” Bruce (2015) occurs in response to a clear and present requirement. In this context, one can cite the use of high capacity micropiles for bridge retrofit in California following the Loma Prieta Earthquake of 1989, the “composite wall” concept for building diaphragm walls through and under existing embankment dams founded on karstic limestone (Bruce, et al., 2012) and the development of compensation grouting techniques to safeguard historical urban structures located above the advance of large diameter transportation tunnels in soft ground (Kettle, 2012).

The soils in the Mississippi Delta region of the United States are in many ways similar to the extremely soft natural deposits of the Nordic countries, and similar emplaced materials in Japan: the birthplaces of the Deep Mixing Method (DMM) technologies. However, deep foundation construction in the Delta, and especially in the city of New Orleans, was historically well served by “tried and proven” techniques. These had proved to be well suited to the demands imposed by the local soil conditions, and the related design and construction details were expertly and consistently implemented by the local practitioners

Prior to 2005, the design standard for the Lake Pontchartrain and Vicinity (LPV) Hurricane Protection System was a Category 3 hurricane utilizing the Saffir-Simpson Scale, which is based on wind speed, not storm surge. After-Action Reports have shown that this level of protection was adequate to resist only a storm having a one in fifty year (2%) probability of occurrence. Protecting low-lying coastal cities from hurricane and river-related flooding is a growing concern due to the increased threat of world-wide sea level rise. Since Hurricane Katrina swallowed New Orleans on August 29, 2005, the risk of storm-related flooding in the Greater New Orleans, Louisiana, area has been reduced by raising the elevation of the flood protection system to withstand a storm having a probability of one chance in one hundred of striking the area in any given year. Many believe that this probability should now be reduced to one in five hundred or even one thousand years by raising the height of the levees and floodwalls to this higher level, often given the misnomer of Category 5. The practicality of raising the height of the protection system to such a level on marginally competent foundations poses a design and

construction challenge that would no doubt include the widespread implementation of the best ground improvement technologies such as DMM.

The disastrous floods associated with Hurricanes Katrina and Rita in August 2005 prompted an emergency construction effort unparalleled in the US for its scope and urgency, given the need to have the levee system repaired and fortified to withstand the potential challenges of the next year's hurricane season. DMM was elected as an integral part of that effort, named "Task Force Guardian (TFG)" by the governing Federal Agency, the US Army Corps of Engineers (USACE). Thereafter and building on the experiences of those works, the USACE, via its Hurricane Protection Office (HPO), has successfully implemented several other huge DMM projects, the largest of which was the LPV 111 (Lake Pontchartrain and Vicinity) contract of 2009 – 2011, at that time the largest DMM project constructed outside Japan. (Bruce, et al., 2012). Amongst the key drivers in the selection of DMM for LPV111 were the environmental challenges, and the logistical considerations of raising 9km of levee in a National Wildlife Refuge. (Bertero, et al., 2012; Cali, et al., 2012; Cooling et al., 2012; and Schmutzler, et al., 2012).

Within the local geotechnical engineering community DMM was viewed as experimental prior to 2005. Resistance to most innovative construction methods stemmed from general conservatism in design and lack of experience with DMM and other new technologies. Before DMM would be accepted by the project owners (USACE) and designers to become an integral part of the flood protection system that protected the lives and property of hundreds of thousands of people, it had to be proven to be safe, effective, and economical.

STAGE 1: EDUCATION AND DEMONSTRATION (CONVINCING THE OWNERS, REGULATORS AND DESIGNERS)

In the United States, innovation in specialty geotechnical construction is mostly driven by the specialty geotechnical contractors. For "business development", or "marketing" motives, representatives of such companies give seminars and workshops, publish numerous case histories, and are sponsors and activists at national and regional conferences. Potential owners then realise what a new technique – like DMM – can do for them, while consultants begin to appreciate that there will be a demand for their services if owners decide to require the new technique in their particular project. The initial strategy is therefore to "educate" potential owners and consultants, and the key to this is for engineers from such groups to be given time, encouragement and resources to attend national and regional conference and seminars given by contractors and specialty consultants. The seeds are then sown.

The catalyst for developments in New Orleans then arrived in 2001 the form of a major full scale test program funded by the USACE at a cost of over \$1 million. This was the backdrop to its possible use during replacement of an obsolete lock structure at the Inner Harbour Navigation Channel, (Cali et al., 2005). The immediate goal of the test was to better understand the mechanics of using DMM to improve the slope stability of earthen levees, with the ultimate goal of raising the levees without substantially widening the existing right of way.

To satisfy design requirements, the shear strength of the upper 8 m of native soil had to be increased from the original 350 psf to 2,000 psf. Calculations showed that this could be accomplished with columns of average shear strength 6,060 psf at a replacement ratio of 30%. A test section was a prerequisite since this type of construction had not been used by the USACE before.

The specific goals of the test section were to:

- optimize design (and cost estimating) procedures;
- demonstrate the ability of DMM to satisfy the design intent;
- obtain better understanding of column-soil interaction in a slope stability application; and
- establish QA/QC procedures.

The area comprised fill and recent Holocene soils consisting of swamp/marsh deposits, deltaic plain deposits, beach ridge sand deposits, and near shore Gulf deposits to depths equivalent to EL -20 m. Test details are provided in Table 1 and are illustrated in Figure 1.

The test program was planned for three phases: a bench scale test and a full-scale test section in two phases, the specific objectives of which were:

- 1) Bench Scale Test and Phase I Test – To obtain comparative data regarding the in-situ relationship between column shear strength and column design parameters, such as mix design, loading rate and mixing energy.
- 2) Bench Scale Test and Phase I Test – From full-scale column data, adjust the initial design for the Phase II test section so that loading to failure could be achieved.
- 3) Phase II Load Test – To verify column/soil interaction assumptions made for infinite levee slope stability analyses upon which the actual flood protection levee design would be based.
- 4) Phases I and II Test – To study the construction methods, quality test methods, and intangible aspects of construction using lime-cement columns.

The bench scale test (a dry DMM method was anticipated) featured four different soil types and five different mixtures and dosages of binders, and led to the use of mainly cement, but also lime-cement-columns in the 11 m-long, 800 mm diameter test columns themselves. In addition to the suite of tests shown in Table 1, the upper 5 m of four of these columns were excavated, sealed, inspected, tested in mass, and further cored, to determine the properties obtained. Many Phase I lessons were learned, not all positive or encouraging given the “learning curve” difficulties of the mixing process, and the variability of the native materials.

Table 1. As-Built Phase I Columns and Testing

	MIX COMPOSITION	CEMENT FACTOR (kg/m ³)	MIX METHOD	TESTING TYPE
1	100% C	150	1	RCPT
2	100% C	150	1	PM
3	100% C	150	1	EXP
4	100% C	150	1	RCPT
5	25% L / 75% C	150	1	PM
6	100% C	134	1	RCPT
7	100% C	200	1	RCPT
8	100% C	130	1	PM
9	100% C	200	1	EXP
10	100% C	139	1	PM
11	25% L / 75% C	200	1	PM
12	100% C	136	1	RCPT
13	100% C	200	1	RCPT
14	100% C	130	2	PM
15	100% C	150	1	EXP
16	100% C	144	1	PM
17	25% L / 75% C	150	2	PM
18	100% C	153	1	RCPT
19	100% C	200	1	RCPT
20	100% C	200	2	PM
21	100% C	200	1	EXP
22	100% C	154	1	PM
23	25% L / 75% C	200	2	PM
24	100% C	150	1	CPT

RCPT = Reverse Column Penetration Test

PM = Pressuremeter

EXP = Exposed for 6' Coring and UU Testing

Columns 2, 5, 8, 11, 14, 17, 20 and 23 were also bored using 3" sampler and UU testing

Mix Method 1 – Injection of binder during both penetration and withdrawal

Mix Method 2 – Same as Mix Method 1 with a remix in Organic layer

Two “test cells,” with 12% and 20% replacement ratios, respectively, were built (Figure 1) with the overlapping columns arranged in panels. All columns were installed with 100% cement binder. Each cell was instrumented to measure load distribution between the soil and columns, pore pressure increase in the soil, and depth and inclination of the failure surface, in real time. An untreated reference cell was also loaded to failure using the same steel ingots as a baseline condition.

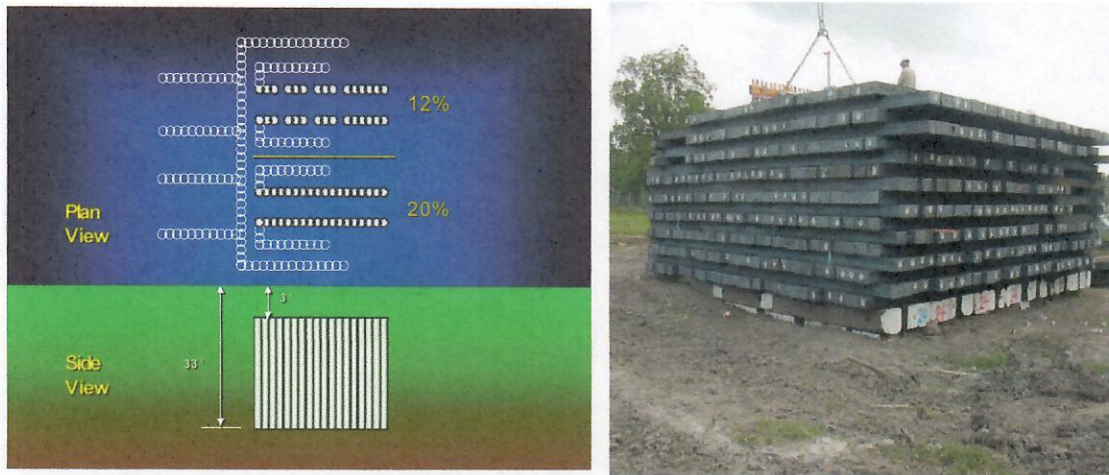


Figure 1. (Left) As-built cell configuration with 12% and 20% replacement ratios. (Right) Cell A fully loaded with 1 million kilograms of steel (177 kN/m²).

Invaluable information was obtained during this program. In short, while the applicability of (Dry) Deep Mixing had been clearly demonstrated, there were sufficient doubts (and, arguably, misunderstandings) about its technical capabilities and its comparative cost effectiveness that it was decided to keep the technique “on ice.” Successful execution of the test section paved the way for acceptance among the USACE of DMM as a viable tool that could be used to solve difficult levee stability problems. Details of the test section were presented at Deep Mixing '05 in Stockholm (Cali, et al., 2005) – nearly four years after completion of the test section and three months before Hurricane Katrina tragically demanded the introduction of a DMM market into New Orleans. After the first use of DMM in the New Orleans area, designers could appreciate the benefits of DMM as a construction technology perfectly suited for soft foundation soils.

STAGE 2. POST KATRINA USE OF DMM ON SMALL-MEDIUM SCALE PROJECTS

Initial efforts after the hurricane passed were dedicated to rescue, clean-up, and re-establishment of order in the city. Restoration and fortification of the severely damaged levee and floodwall system were assigned to the USACE TFG, who had the daunting mission of rebuilding the flood protection system to its pre-Katrina condition, an emergency construction effort unparalleled in the US for its scope and urgency, before the beginning of the following hurricane season, which began on June 1, 2006 - only nine months after the storm passed. Because of the emergency of the mission, normal federal budgetary, regulatory and bureaucratic roadblocks to expedited construction were bypassed, and the mission was successfully completed. However, it was quite obvious that the pre-Katrina condition of the flood protection system was woefully inadequate to resist such powerful hurricanes, leading to adoption of a plan to raise the protection level to one in one hundred year probability of occurrence. This 1% plan would lead to the formation of the USACE Hurricane Protection Office (HPO).

HPO's mission was to raise the elevation of the flood protection to the 1% probability level while increasing the Resiliency, Redundancy, and Reliability of the system by increasing the slope stability factor of safety and armouring the earthen embankments against erosion due to overtopping. The term "Hurricane Protection System" was changed to "Hurricane and Storm Damage Risk Reduction System" (HSDRRS) to more accurately describe the probability of overtopping of the 1% system and to communicate to the public the inevitable risk of any flood protection system.

Conventionally, to raise the height of a levee and maintain the authorized levee factor of safety, earthen stability berms were constructed to counterbalance the increase in driving force behind the slope instability. The limited right-of-way available in a congested urban environment precluded the construction of stability berms in most cases, shifting the design of the levee enlargement from an all-earth solution to a combination levee and floodwall solution. However, most of the failures that occurred as a result of the hurricanes were due to water load on the floodwalls, so floodwalls (I-Walls) were justifiably discouraged as a first design alternative. Instead, to simultaneously raise the height and increase the stability factor of safety of the new HSDRRS, extraordinary measures would be needed to improve the foundation. It is said that DMM is the tool in the toolbox that is used only when needed but, when needed, it is the best tool for the job.

As noted above, the requirements placed on Task Force Guardian were such that time was far more of the essence than money, while technical doubts could be compensated by conservatism in design. From early 2006 to mid-2009, there were numerous small- to medium-sized DMM projects which had now attracted the wet methods (Ratio, Inc.) as well as the dry methods, as practiced by Hayward Baker, Inc. In the majority of projects, the beautiful path was followed in exemplary fashion: bench scale testing, followed by a full-scale field, demonstration test, in turn followed by a closely instrumented and monitored production phase, with later verification of in-situ DMM properties, typically by coring. Each of these projects generated site-specific data on the relationships between the existing soils, the contractors' means, methods and materials, and the resultant treated soil properties. All were conducted for the New Orleans District, USACE, which therefore, via its internal resources, and through the offices of its specialty consultants and advisors, developed an extremely pertinent and potent database of experience regarding the use of DMM in the New Orleans area. Of course, not all the experience was good, but it is fair to say that all experiences were instructive.

During the period of 2006-2009, the New Orleans area experienced the highest intensity of deep mixing projects in North America, with the possible exception of California, and the Port of Oakland in particular, and all technical — and commercial — eyes in the deep mixing community in the U.S. were firmly focused on New Orleans. This focus was sharpened further by the decision of the USACE to hold "industry days" to brief potential participants about the nature, scale and timing of the anticipated upcoming works. These "works in planning" were of a scale and intensity not heretofore seen in North America and — amongst other natural reactions — attracted growing international interest.

STAGE 3: THE MEGAPROJECT AND BEYOND (LAKE PONTCHARTRAIN AND VICINITY HURRICANE PROTECTION, LPV-111)

Thereafter and building on the experiences of those works, USACE, via its Hurricane Protection Office (HPO), has successfully implemented several other huge DMM projects, the largest of which was the LPV 111 contract of 2009 – 2011, at that time the largest DMM project constructed outside Japan (Bruce, et al., 2012). LPV-111 presented challenges that required innovative approaches in design, contracting, and construction. The levee extended 9 km along the north bank of the Gulf Intracoastal Waterway (GIWW), bordered on both sides by the Bayou Sauvage National Wildlife Refuge ([Photograph1](#)). This constricted levee construction to the existing right-of-way, making DMM an effective means for reducing cost and schedule.

Subsurface conditions, fully described in Cooling et al. (2012), 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.



Photograph 1. LPV 111 within Bayou Sauvage National Wildlife Refuge

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 (HSDRRS), 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 2](#). 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. 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) and Cooling et al. (2012). ECI allowed design and construction to partner for the betterment of both. The result was project completion on time, within budget, and to the highest industry standards.

As detailed by Bertero et al. (2012), the binder material used for the project consisted of 25% type I/II Portland Cement and 75% slag cement, and potable (city) water. For the entire project, over 417,000 tonnes of binder was used, and 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).

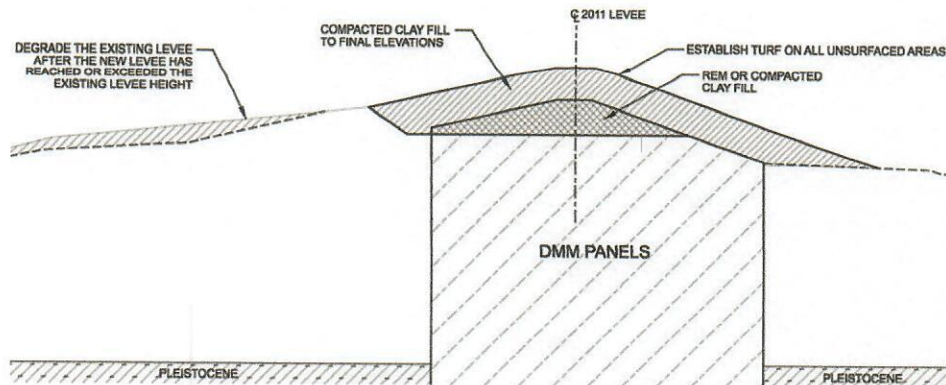


Figure 2. Typical LPV 111 Levee Cross Section (Bertero et al., 2012).

Of all the challenges overcome by the LPV-111 design and construction teams, two benchmark accomplishments stood out as pathways to future acceptance of DMM as a “conventional” construction method by the USACE. First was the preparation of a unified and peer-reviewed design method by Filz et al. (2011). Rather than individual analyses for each potential failure mode, the unified method addressed all design considerations and potential failure modes within a single analysis. The second was use of Early Contractor Involvement (ECI) to involve the DMM Contractor in the design. When the contractual rules under which the owner is governed permit consultation with the DM contractor during the design phase, the construction process will be smoother, the outcome will almost certainly be better, and the overall cost will generally be lower. This is not possible with the conventional “design-bid-build” contracting vehicle, where award is made via “lowest bid” or “set aside” contract awards to general contractors for whom the DM is performed by a subcontractor. With the Early Contractor Involvement (ECI) contracting method, a contractor is hired at an early stage of design, perhaps the 30% milestone. This gives the designer and the contractor time to “fine-tune” the design for efficiency and construction ease. Modifying the design slightly by adjusting column or panel width, barrette length, shear strength, or permeability to fit his equipment and methods while still achieving the design intent saves time and cost. Imbedding the contractor with the owner’s design team creates a seamless transition from design to construction. It builds the trust necessary to share risk, such as incorporating the probabilistic approach to meeting key design parameters for the DM, such as shear strength and permeability. The great success of the LPV-111 DMM project was the product of the ECI arrangement between the USACE Hurricane Protection Office, the joint venture of Archer Western/Alberici as the general contractor, and the joint venture of Treviicos/FUDO as the DM subcontractor. A similar method of innovative contracting procedure is the Construction Management at Risk, whereby the Contractor is selected based on qualifications during an early stage of design. The Contractor agrees to construct the project at a guarantee maximum price (within limitations) and then works with the design team to reduce construction cost and schedule. This contracting vehicle is being used for the Mid-Barataria Sediment Diversion Structure in Plaquemines Parish, Louisiana – another major construction project that will include DMM.

OVERVIEW

DMM has been used to great advantage in New Orleans for the enlargement of levees and reinforcement of floodwalls in the aftermath of Hurricane Katrina in 2005. In deciding whether DMM is the right solution for levee enlargement, one must consider the elimination of consolidation settlement in the foundation and the savings potential of eliminating future enlargements. In addition, the beneficial use of mixing spoil, which provides a very suitable construction material, should be considered in the economic analysis.

Many levee enlargement projects slated for construction by the USACE for which DMM can be a valuable tool are yet to be designed. Notably, levee enlargements and sediment diversion projects along the Mississippi River in Plaquemines Parish, new levee projects in St. Charles and Jefferson Parishes, and the 100 km long Morganza to the Gulf Hurricane Protection Levee, which has been stalled due to federal budgetary constraints. The eventual goal of the USACE is to raise the hurricane protection levee and floodwall system to the higher 2057 hydraulic grade, accounting for sea level rise and regional subsidence. For some areas, environmental concerns and right-of-way constraints alone will dictate the use of DMM reinforced levees or conversion of levees to floodwalls.

Only the Morganza to the Gulf project has potential to rival the LPV 111 levee in scale of DMM effort, but still much work remains. Given the current national sentiment in the U.S. to reduce federal spending on all levels, no doubt spending on infrastructure, including flood protection, will suffer. But this will likely result in increased use of ground improvement methods such as DMM that produce overall savings in cost and schedule.

Such an attractive state of affairs for Deep Mixing specialists in the Mississippi Delta region would have been unthinkable 15 years ago, or arguably 19 years ago when the first Demonstration Program was conducted. However, in retrospect, the development of the DMM market in the region has followed a classic path of awareness, demonstration, and implementation in growing scale and intensity, which is greatly to the credit and foresight of all concerned. And what of the impact of the disaster of 2005? Given the combined phenomena of rising sea levels, and the regional settlement of the Delta region, the massive levee rebuilding program was inevitable, bringing with it the need for DMM. We are of the opinion that the events of 2005 merely accelerated the development schedule by providing the need for a hitherto unused tool for deep foundation construction.

REFERENCES

- Bertero, A., Leoni, F.M, Filz, G., Nozu M and Druss D., (2012). "Bench-scale testing and quality control/quality assurance testing for deep mixing at levee LPV 111," Fourth International Conference on Grouting and Deep Mixing, Organized by International Conference Organization for Grouting, Managed by Deep Foundations Institute, February 15-18, New Orleans, LA.
- Bruce, D.A., Cali, P.R., and Woodward, M.L. (2012). "Composite cut-off walls for dams: theory and practice," Deep Foundation Institute, 4th International Conference on Grouting and Deep Mixing, New Orleans, LA, February 15-18, pages 640-660
- Bruce, D.A. (2015). "The Evolution of Specialty Geotechnical Construction Techniques: The 'Great Leap' Theory," The Terzaghi Lecture, International Foundations Congress and Equipment Expo (IFCEE), March 17- 21, San Antonio, TX, 89 slides.
- Bruce, D.A, Dreese T.L., Harris M.C., and Heenan D.M., (2012). "Composite cut-off walls for dams: theory and practice," Deep Foundation Institute, 4th International Conference on Grouting and Deep Mixing, New Orleans, LA, February 15-18 pages 1248-1264.
- Cali, P., Woodward, M.L., Bruce, D.A., and Forte, E., (2005). "Levee stability application for deep mixing (1) – design for full scale test section using dry mixed soil cement columns". Deep Mixing 05, Stockholm.
- Cali, P.R., Lelong B., Bruce D.A., Valagussa S., Beckerle J., Gardner J., and Filz G., (2012). "Overview of deep mixing at levee LPV 111, New Orleans, LA," Fourth International Conference on Grouting and Deep Mixing, Organized by International Conference Organization for Grouting, Managed by Deep Foundations Institute, February 15-18, New Orleans, LA., pages 661-671.
- Coastal Development Institute of Technology, Japan, (2002). The Deep Mixing Method: Principle, Design and Construction.

Cooling, T., Boeckmann A., Filz G., Cali, P., Evans J., and Leoni F, (2012). "Deep mixing design for raising levee section, LPV 111, New Orleans, LA," Fourth International Conference on Grouting and Deep Mixing, Organized by International Conference Organization for Grouting, Managed by Deep Foundations Institute, February 15-18, New Orleans, LA, pages 672-681.

Filz, G., Templeton, A.E. and Burns Cooley Dennis, Inc. (2011). 'Design Guide for Levee and Floodwall Stability Using Deep-Mixed Shear Walls, Final Report for New Orleans District and Hurricane Protection Office of the U.S. Army Corps of Engineers.

Kettle, C.T., (2012). Compensation Grouting – Evolution, Field of Application, and Current State of the art in UK practice, Deep Foundation Institute, 4th International Conference on Grouting and Deep Mixing, New Orleans, LA, February 15-18 pages 134-199.

Schmutzler, W., Leoni F.M., Bertero A., Leoni F., Nicholson P., Druss D. and Beckerle, J, (2012). Construction operations and quality control of deep mixing at levee LPV 111 in New Orleans," Fourth International Conference on Grouting and Deep Mixing, Organized by International Conference Organization for Grouting, Managed by Deep Foundations Institute, February 15-18, New Orleans, LA, pages 682-693.

Thompson, J.E., 2008. (Email communication, "Mix Design Summary 14-day". February 19. Coastal Development Institute of Technology, Japan, 2002. The Deep Mixing Method: Principle, Design and Construction.