Levee Foundation Remediation Using the Deep Mix Method

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ABSTRACT

Hurricane Katrina was responsible for hundreds of deaths, billions of dollars of damage, and left the levee system in New Orleans in a state of disrepair. Many levees that make up the Flood Protection system for New Orleans were overtopped and sustained considerable damage.

This case history will look at one section of levee in New Orleans East designated LPV (Lake Pontchartrain and Vicinity) -111 that is 5.3 miles in length. LPV-111 was overtopped and breeches occurred adjacent to structures. The United States Army Corps of Engineers (USACE) was tasked to not only repair the levee, but also to raise the effective height to provide the One Hundred Year level of protection by increasing the levee crown from Elevation 17' to Elevation 28'.

A conventional levee with stability berms was quickly ruled out due to the limited right-of-way that existed due to the close proximity of the Bayou Sauvage Wildlife Refuge. In order to stabilize the weak soils underlying the existing levee, the USACE decided to improve the characteristics of the soils by utilizing the Deep Mixing Method (DMM). The DMM would create a stable foundation on which the height of the levee could be increased while also controlling overall settlement and provide lateral stability to resist future storm surges.

The project consisted of stabilizing more than 1.6 million cubic yards of soil to depths up to approximately 70' while using over 460,000 tons of binder consisting of both Ordinary Portland Cement and Blast Furnace Slag. Eight deep mixing rigs were used to successfully complete the project while working around the clock for a total of 14 months. The project was an outstanding technical success and is the largest deep mixing project in the world, outside of Japan.

Introduction

During hurricane Katrina, as well as a substantial percentage of New Orleans East Levee System, LPV111 failed, see Fig. 1. The Hurricane Protection Office of the US Army Corps of Engineers attributed the failure of the system to overtopping, erosion, and subsequent breaching of levees along the Gulf Intracoastal Waterway (GIWW).

Fig. 1. Hurricane Damage at LPV-111

Reach LPV-111 is a part of a levee system designed to protect the city of New Orleans and the surrounding areas (New Orleans East) from the storm surge resulting from a 100 year hurricane event. This reach specifically protects the Bayou Savage National Wildlife Refuge, which is the largest urban wildlife refuge in the United States and home to several threatened or endangered species of birds as well as many reptiles, amphibians and small mammals.

Scope Of Work

Due to the sensitivity of the protected marshlands, deep soil mixing technologies were utilized to limit the footprint of the raised levee. The increase in the load bearing capacity of the treated soil allows for a significant decrease in the footprint necessary to attain the required height increase.

The USACE established the Task Force Hope Program to upgrade the levees, floodwalls, floodgates, surge barriers, and pump stations that make up the Greater New Orleans Hurricane and Storm Damage Risk Reduction System. A critical component of the risk reduction system was to raise and reinforce the LPV 111 levee while limiting its width to the pre-Katrina levee right-of-way (See Fig. 2).

Fig. 2. LPV-111 Overview

To add height (+17 feet to +28 feet) and maintain the levee stability while keeping the footprint within the existing right of way and soil conditions, USACE needed to strengthen the levee foundation. After evaluating several methods, the Corps and its engineering team determined that the deep-soil mixing method (DMM) was the best of several alternatives for this project.

As part of a $300 million LPV 111 contract (including pre-construction services), the joint venture team of Archer Western and Alberici (AWA) selected specialty subcontractor TREVIICOS South to reinforce the levee by creating a row of buttresses, running perpendicular to the levee centerline using deep soil mixing methods. The contract specified early contractor involvement that involved both AWA as the prime contractor and TREVIICOS as the deep mixing subcontractor.

The scope of work consisted of improving the soil beneath the existing levee in order to increase the height of the levee within a limited footprint. The levee to be improved was 5.3 miles in length. Deep Mixing was performed to a maximum depth of 67 feet (Fig. 3) and it was designed to increase the bearing capacity of the existing soils, limit future settlement, and to resist lateral loads imposed by storm surges on the levee.

The 5.25 foot diameter DMM elements were overlapped to form a double element which then was arranged in buttresses perpendicular to the levee alignment. Buttresses were then installed at a maximum center to center spacing of 15.5 feet. One additional double auger DMM element was placed midway between consecutive buttresses at the centerline of the levee to further help prevent settlement (Fig. 4).

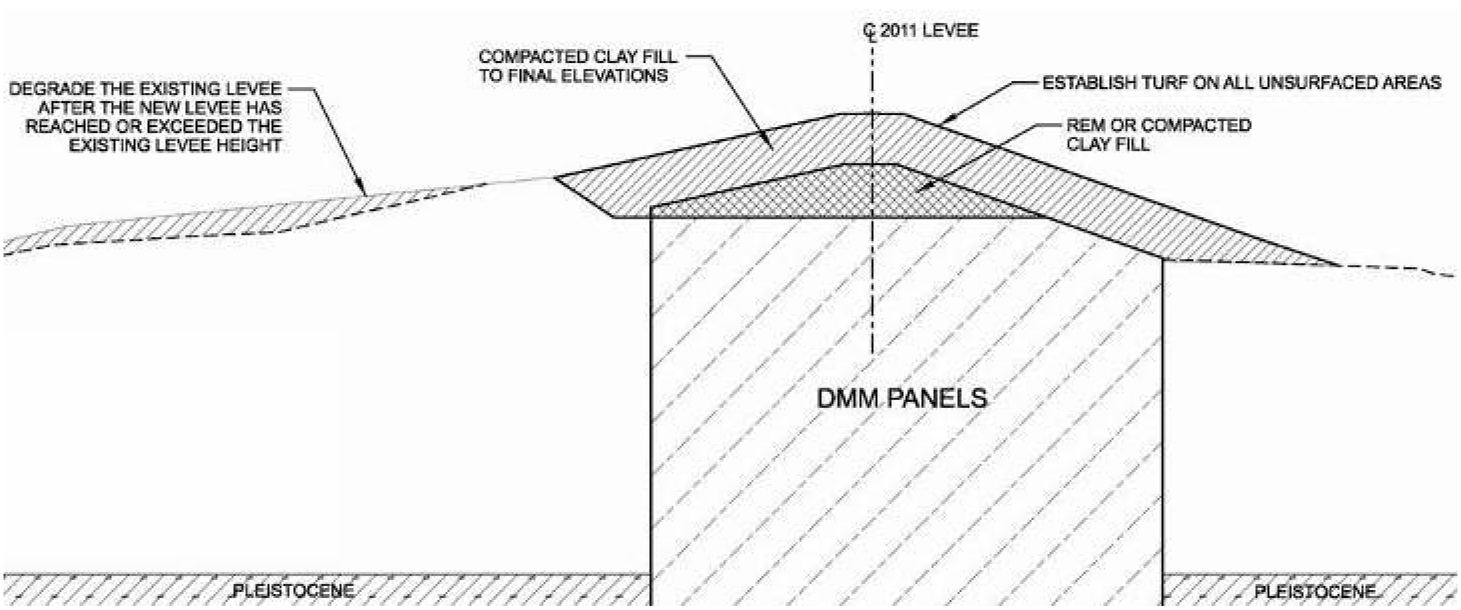

Fig.3. Typical Cross Section (REM: Recycled Embankment Material which is the cement/soil spoil from the Deep Mixing)

Over 18,000 elements were installed to complete the project. Most elements were formed by using double auger rigs. Each auger was 5.25 feet in diameter and had an overlap of 12 inches. Some areas of the site had limited access and single auger TTM rigs were utilized in these areas. The wet method of DMM was utilized. At LPV-111 two different technologies were applied: 1) Trevi Turbo Mix (TTM), single and double, and 2) Contrivance Innovation Cement Mixing Columns (CI-CMC). Both technologies are considered "wet systems" due to the fact that the binder is injected in the form of liquid grout slurry through outlets positioned near the end of the hollow stems of the rigs. The grout is injected in advance of the stirring tool, which is properly configured to fine-cut the soil and to mix it with the grout to create a homogeneous mixture. Both the TMM and the CI-CMC employed multiple sets of blades or paddles located at the bottom end of the drilling rods to enhance the cutting and mixing effect of the rotation applied to the rod string. The combination of vertical penetration/withdrawal rates, rotational speed and tool configuration, along with the injection parameters and the properties of the grout, are fundamental for the success of the soil treatment.

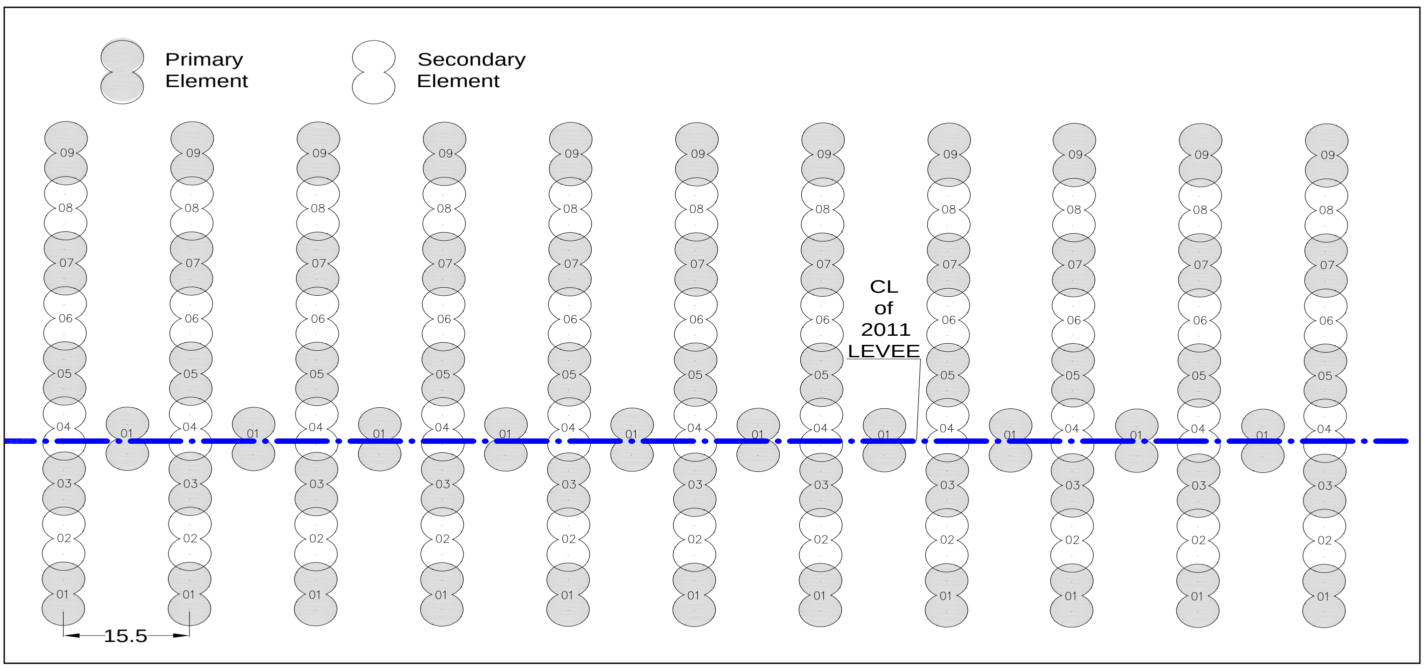

Fig.4. Typical layout of DMM improvement

Pre-Construction Testing

Early Contractor Involvement (ECI).

ECI, or preconstruction services was utilized on this contract by the USACE to expedite the design and construction. When the contract was awarded the construction documents were at the 35% design stage. The ECI process allowed the USACE and URS (Designer of Record) to refine the design by allowing input by AWA and TREVIICOS. Meetings were held on a daily basis to discuss scheduling, logistics, equipment, tooling configuration, and the availability of the 460,000 tons of binder required for the DMM portion of the project. Scheduling was a prime factor for this project as the LPV-111 levee section had to be completed by the start of hurricane season in 2011.

Bench Scale test program.

A deep soil mixing field and laboratory testing program was designed and developed to determine the parameters able to meet the requirements of the deep soil mix design related to shear strengths required for stability. This program included soil sampling (Fig. 5), evaluation of soil types, soil characteristics and laboratory testing of soil types to determine the mixing parameters that were required to meet the specified shear strengths. Field testing (Validation) was completed in the field based on the Bench Scale test program information to ensure the required deep soil mixing characteristics could be achieved in the field. All testing was to conform to applicable standards. The testing program was developed and submitted to the USACE for approval.

The Bench Scale Testing (BST) program included four phases. Phases 1, 2, and 3 used soils from different sections of the levee. A smaller Phase 4 was undertaken to supplement previous investigations of binder type. Samples for the BST were obtained from borings drilled at a spacing of approximately 1000 ft along the levee alignment. In addition to providing material for the BST, the borings also served to disclose variations in stratigraphy by supplementing the borings that were completed for levee design.

Fig. 5. Soil Sampling

Index property testing including natural water content, Atterberg limits, particle size, unit weight, organic content, specific gravity of solids, pH, sodium content, and sulfate content were performed on selected soil samples. However, the main objective of the BST was to investigate the impacts of binder type, binder amount, and water-to-binder ratio on the unconfined compressive strength of mixtures from the various types of soil that would be treated during production mixing.

Based on visual classifications and results of the index property testing, soil samples from the borings were generally grouped into the following categories, from the ground surface downwards: existing levee fill, soft clay, marsh/peat deposits, fat clay, and Pleistocene soils.

Mixing, curing, testing, and data reduction and presentation were performed in general conformance with the procedures described by Hodges et al. (2008).

Two binder types were incorporated in the BST program: Ordinary Portland cement (OPC), and Portland blast furnace slag cement (PBFC). Four binder ratios were tested: 100% PC - 0% PBFC, 75% PC - 25% PBFC, 50% PC - 50% PBFC, and 25% PC - 75% PBFC. Binder factors ranging from 180 to 550 kg/m^3 were employed in the test program, where the binder factor is the dry weight of binder divided by the volume of soil to be treated. Water-to-binder ratios varied from 0.8 to 1.25. The general pattern for each batch was to prepare enough 50-mm by 100-mm (diameter x height) specimens that two specimens could be tested each at 7, 14, 28, and 56 days, and also allow some extra specimens to account for damage during handling and for additional testing in case of anomalies. Altogether, 86 batches were prepared and 688 unconfined compression tests were performed. Although this was a large test program, it was appropriate for being able to optimize mixture proportions on a project of this size with several soil types that varied along the levee alignment.

For each batch, the unconfined compression strength test results were plotted versus curing time. Additional insights into the influences of mixture components on mixture strength were obtained by plotting the results for each soil type and binder type versus binder factor (defined above), binder factor in-place (weight of dry binder divided by the volume of the mixture), and total water-to-cement ratio of the mixture (dry weight of binder divided by the weight of soil water plus the slurry water). These terms are defined and their use is illustrated by Filz et al. (2005).

<u>Validation.</u>

It is known that many factors influence the results of the DMM, including: soil composition, groundwater chemistry, types of dissolved salts, concentration of organic material, characteristics of the binders utilized, equipment configuration, etc. DMM results cannot be accurately predicted based only on past experience. In addition to a well targeted laboratory test program, a field test program should usually be performed prior to actual production mixing is started. The field tests should follow a comprehensive but flexible approach, allowing adjustments and modifications to the parameters initially foreseen as the operations proceed and new or more detailed information is acquired.

At the LPV111 project, the field test program was conceived to achieve the following objectives: 1) verify and refine the binder type and content, preliminarily determined through the bench scale testing, to attain the target mechanical characteristics of the treated soil; 2) determine the most appropriate DMM operating parameters and equipment configuration; and 3) develop QC/QA procedures for the DMM production stages.

Five field campaigns, called Validation Tests (VT), were planned at five different locations (Fig. 6) along the levee, characterized by diverse underground conditions, to verify the responses of the soils to various ranges of installation parameters.

At each VT location, both technologies were tested and verified for compliance with the project specifications and the desired quality of the product. The installation of the elements was accomplished by applying different combinations of binder content, water-cement ratio (W/C), and construction parameters, such as: penetration and withdrawal speeds; rotational speed (rpm); grout delivery rates; grout pressure; air pressure and flow rate (only for CI-CMC); grout and cement quantities; and mixing tool configuration. This approach allowed the development of relationships between the construction parameters and the final result in terms of continuity, homogeneity, and mechanical characteristics of the improved soil. Overall, 75 elements (TTM single, TTM double, and CI-CMC double) were installed for the five VT locations and additional test installations performed.

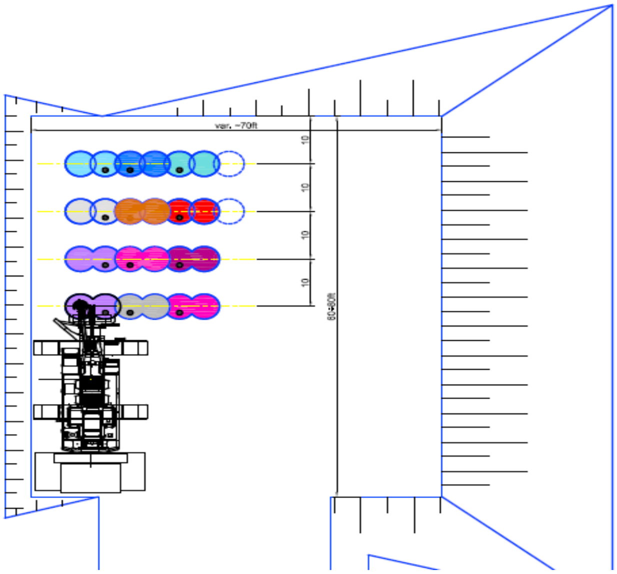

Fig. 6. Validation Area 1 layout

Equipment

A total of eight DMM drill rigs were utilized. Three double and two single axis using TREVI Turbo Mix (TTM) and three double axis rigs were supplied by FUDO Construction using CI-CMC.

The 5 Soilmec TTM rigs (Fig. 7); 3 SR-90s, 1 SR-80 and 1 SR-70 were all equipped with the Drilling Mate System (DMS) software to insure the quality of the elements. The TTM rigs are equipped with pass through rotaries. The grout was mixed at localized grout plants and sent to the drilling rig where it was injected at pressures between 100 and 200 bar through strategically placed nozzles to provide homogeneous soil mixing throughout.

The 3 FUDO rigs (Fig. 8) were supplied with top drive rotaries and a parameter recording system. These rigs utilized air pressure supplied at 15 bar simultaneously with low pressure grout.

In order to meet the demanding schedule on LPV-111, batch plant (Fig. 9) placement, rig sequencing, and site support was critical to the successful completion of the project. Grout for the rigs was supplied by eight batch plants spaced at approximately 1,500 foot intervals along the protected side of the levee. Each plant consisted of one high speed mixer, one agitator, one high pressure pump for each deep soil mixing auger, two vertical cement silos, one horizontal cement pig and a 20,000 gallon water tank.

Fig. 7. Twin Auger TTM Rig

Fig. 8. Twin Auger Ci-CMC Rig

Fig. 9. Grout Batch Plant

During peak production, each plant required up to 22 trucks of binder every 24 hour period. To optimize the binder consumption and account for the variable soil conditions, crews drilled additional soil borings to more precisely define the organic layers and the fat clay layers. The production parameters for the elements were changed as the soil conditions warranted, minimizing production times.

Each cement truck would carry about 23 short tons of a blend of 25 percent type I/II Portland cement and 75 percent blast furnace slag cement. The total amount of binder used for the project was over 460,000 short tons.

During many 24 hour periods, over 120 trucks were needed to supply all the active batch plants. In conjunction with the binder, over 136,000,000 gallons of water was used in the grout mix. Over 500,000 hours were worked on the project and the production was completed in 14 months.

<u>Batch Plant Quality Control</u>

Quality control of the batch plants was a crucial component in the process to verify that the grout supplied to the DMM rigs met the specifications. The mixing equipment was calibrated using test weights periodically to insure proper proportioning. Tests performed on the fresh grout included apparent viscosity, using a Marsh Funnel, and density, using a calibrated mud balance. Cylinders of the fresh grout were taken daily from each plant and checked for unconfined compressive strength.

<u>DMM Rig Quality Control</u>

All of the DMM rigs were equipped with a GPS system to facilitate the accurate layout of the elements. The rig GPS was validated at least once per shift by a hand-held GPS to verify element location.

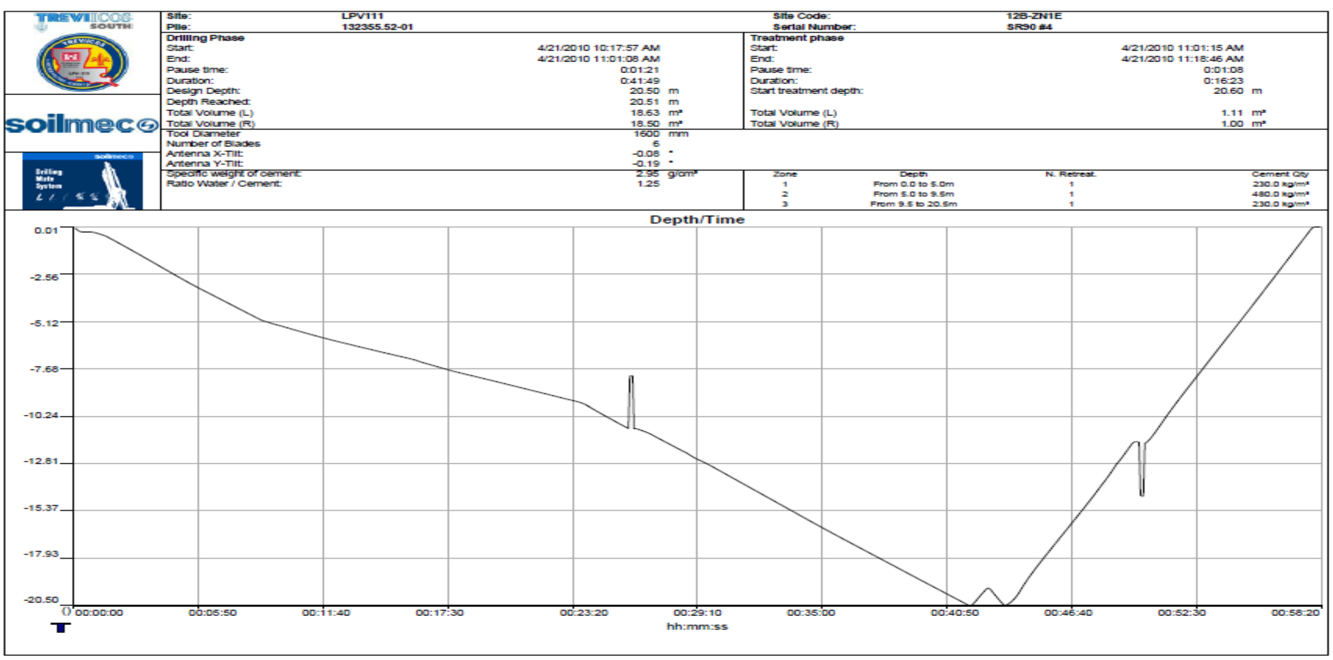

Fig. 10. Typical DMS Output

The SOILMEC drill rigs were equipped with the Drill Mate System (DMS) installed to control, record, and transmit installation parameters and rig performance data. The DMS was also capable of controlling the drill rig to preset parameters for up to 4 different soil types. The DMS instrument allows both the operator and the jobsite personnel to interact in real-time with the rigs sensors, safety devices, and engine operations to facilitate defined drilling parameters. It includes a full color, jobsite-ready touch-screen as well as a diesel engine electronic control unit and machine parameters interface. Data collected (Fig 10) during an operation can be used to run jobsite reports, analyze production and processing and plan machine maintenance.

Using the DMS Manager tool, operators can monitor and control the rig operations remotely using radio, GSM/GPRS, Wi-Fi or satellite. The remote staff can visualize the entire operation and machine parameters, map positions and even perform certain operations from the remote site. On the New Orleans levee project, DMS provided an inside look at the deep-soil mixing process as it happened. Throughout the deep-soil mixing operation, the SOILMEC DMS software electronically guided the installation of the soil-mixed elements and automatically adjusted the penetration speed in the different soil layers based on the pre-established cement quantities. The DMS is capable of controlling the drill rig to preset parameters for up to four different soil types. At the same time, TREVIICOS South's field personnel were able to monitor all the installation parameters remotely to ensure that the construction design was met and intervene to correct a problem in a timely manner if issues occurred.

Once each element was completed, the DMS was programmed to e-mail a comprehensive report to the engineering staff on site for review. If staff noted any problems, they could immediately stop operations and reinstall the element correctly. The same outputs were compiled at the end of the day and included in a Daily Progress Report that was submitted to AWA.

The full data stream from all rigs on the jobsite was also monitored at Soilmec headquarters in Italy. Soilmec monitors rigs worldwide on a real-time basis in order to provide each customer with the added assurance that mechanical issues that could affect the long-term performance of the machines can be preempted.

The DMM rigs supplied by FUDO were equipped with a system capable of monitoring and recording the installation parameters.

Quality Control Coring

In order to confirm that the DMM met design assumptions, the specifications called for 3% of the elements to be cored to their full depth. To keep up with the production, three coring rigs were used working six days per week. The acceptance criterion for the DMM was:

- Recovery ≥ 80%
- No total inclusions > 12 inch
- 90% of UCS ≥ 100 PSI at 28 days
- 10 UCS specimens per core
- Proof that design bottom elevation was achieved

As can be seen in Fig. 11 only 1.31% of the UCS samples fell below the requirement. The overall core recovery was over 99% with no core failing the requirements. The core drill samples were typically retrieved after the columns had set for approximately 26 days. Subsequently, on the 28th day after element installation, these samples were trimmed and Unconfined Compressive Strength Testing was performed.

TOTAL N	AVG UCS PSI	<100 N	%	STDEV PSI	COV	MEDIAN PSI
5029	292	66	1.31%	126	0.433	275

Fig. 11. Summary of the results of QC test on cored samples

Conclusion

This paper gives a brief overview of the equipment and methods used in the largest DMM project performed to date in the United States, and one of the largest land projects ever performed anywhere. It also provides an overview of the challenging logistics required to move and place massive quantities of binder in a short period of time. Other facets of this world-class project can be found in papers presented at the 4th International Conference on Grouting and Deep Mixing
The challenges presented on the LPV-111 project were daunting, but with the assistance of all the parties, the DMM portion of the project was completed ahead of schedule with exceptional quality.

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SR-90
TREVI
LPV111 PROJECT - 09/2009 TO 03/2011
FUDO
18,022 DMM ELEMENTS - 1,681,000 CUBIC YARDS TREATED