CONSTRUCTION CHALLENGES WITH CUTTER SOIL MIXING IN POROUS LIMESTONE AT THE PORT OF MIAMI TUNNEL

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Port of Miami Tunnel Background

The Port of Miami (Port) is an island seaport located on Dodge Island in Miami, Florida. The Port of Miami is recognized as the cruise ship gateway to the Caribbean and the "Cargo Gateway of the Americas" (Ref. 1). As the "Cargo Gateway of the Americas", the port primarily handles containerized cargo.

The Port of Miami is an important contributor to the local south Florida and state economies. This combination of cruise and cargo activities supports approximately 176,000 jobs, and has a total economic impact of over $17 billion. Port revenues in 2011 totaled more than $101 million (Ref. 1).

In 2009 approximately 16,000 vehicles travelled to and from the Port each day (Parsons Brinkerhoff, 2009). Currently this traffic is routed over a four lane bridge into downtown Miami. Traffic is anticipated to increase to 70,000 vehicles per day by 2033 (Parsons Brinkerhoff, 2009). In the late 1980s the Florida Department of Transportation began studying ways to alleviate this anticipated congestion.

The idea to link the Port of Miami to the nearby interstate system (I-395) and alleviate commercial traffic congestion in downtown Miami was developed in the early 1990's. In 2009 the Florida Department of Transportation (FDOT) contracted with the Miami Access Tunnel (MAT) concessionaire group to construct two 42-feet (12.8m) outside diameter, 4,000-foot (1,220m) long tunnels with two lanes of traffic each way under the Government Cut channel between Watson and Dodge Islands (Figure 1). The Port of Miami Tunnel (POMT) project is a public-private partnership (PPP) that is responsible for the design, build, finance, operate and maintenance of the tunnels.

Figure 1

Regional Geology of South Florida / Miami

Miami lies within the Coastal Plain Physiographic Province, on the Atlantic Coast on the east side of the Everglades (Fenneman, 1938; Hunt, 1967). This coastal plain incorporates the entire project construction area. The Florida peninsula is the emergent of a large extension of the North American continent that is known as the Florida Plateau. Ancient, deep lying igneous and metamorphic rocks form the basement upon which the Florida Peninsula has been formed. The Florida peninsula is composed of sedimentary rocks that have been deposited over the basement rocks. In Miami-Dade County, the upper few hundred feet of these sediments are mainly carbonates such as limestone, dolomites, marls, and shell beds.
Site Geology

The installation of the CSM panels intersected through the silty sand overburden and the limestone-based Miami, Fort Thompson, Key Largo and Tamiami Formations. Each layer presented unique challenges during the construction of the panels.

Construction rubble and other obstructions were deposited with approximately 15 feet of fine silty sand during construction of the man-made islands. During construction of CSM panels on the Watson Island SOE a 2 to 3-foot layer of peat and organic silts were discovered in portions of the native fine sands and silts that lie above the top of the Miami Formation.

The top of the first limestone layer encountered, the Miami Formation, lies approximately 20 feet below the ground surface. Approximately 7 feet thick in the SOE areas, The Miami Formation consists of an oolitic limestone of relatively consistent hardness and permeability. Unconfined compressive strength results on core samples ranged from 1,000 to 2,500 psi. Although generally less permeable and porous than the underlying limestone layers, the hydraulic conductivity as measured by borehole packer tests ranged from $1 \times 10^{-3}$ to $8 \times 10^{-2}$ cm/sec.

Below the relatively hard and competent Miami Formation, a highly variable transition layer of limestone with fingers of interbedded silty sand lies between the Miami and Fort Thompson Formations. Blow counts in this layer ranged from weight of hammer (WOH) to over 50 blows per foot.

The top of the Fort Thompson Formation is observed at approximately 35 feet below the ground surface. The Fort Thompson formation consists of layers of sand, limestone, cemented sands. CSM panels installed for the Watson and Dodge Island SOEs keyed a minimum of 5 feet into a relatively hard 10 to 15-foot thick layer of limestone in the Fort Thompson Formation. Unconfined compressive strengths results on core samples collected from this layer ranged from 1,000 to over 4,000 psi.

The approximately 30-foot thick coralline Key Largo Formation begins approximately 85 feet below the ground surface. It consists of stacked coral heads with relatively little fine material. Sonic cores taken in this layer indicated a porosity ranging from 35 to over 50 percent. Sufficient water could not injected into this layer during borehole packer testing to accurately measure its hydraulic conductivity. Since the tunnel excavation under the channel is primarily in this formation, three 7-foot diameter observation excavations were completed to the bottom of this formation to better understand its lithology. Video taken after completion of the excavations revealed relatively large horizontal crevices in the transition zone between the Fort Thompson and Key Largo Formation. The remainder of the Key Largo Formation was observed to have relatively large voids between the coral heads ranging from a few inches to over a foot in size.

The top of the Tamiami Formation was encountered during construction of CSM panels on Dodge Island. Composed of interbedded limestone and marl, it is relatively consistent with hard lenses and relatively low porosity.

Cutter Soil Mix (CSM) Technology

Cutter Soil Mixing (CSM) is a type of wet soil mixing (WSM) which is defined as the mechanical blending of soil material with a slurred material designed to modify the properties of the in-situ soils. Typically the strength is increased and the permeability of the mixed soil decreased through the addition of cementitious material or bentonite. However, other materials such as oxidizers can be blended into the soil for environmental remediation work.

Generally WSM tools are generally comprised of a set of horizontal paddles or nozzles rotating on a vertical axis to produce spherical elements.
CSM utilizes two sets of rotating, horizontally mounted, cutter mixing wheels (see Figure 2) to produce rectangular elements. The CSM tool reduces energy losses by generating energy directly at the cutting head with a hydraulic motor rather than at the top of a Kelly bar with a rotary. The combination of power and aggressive cutting wheels allow the CSM to penetrate through difficult soils including cemented sands and limestone with compressive strengths in excess of 4,000 psi. The rectangular final product can be employed multiple configurations as dictated by the design.

CSM panels can be used in a variety of applications including Support of Excavation (SOE), barrettes, block ground improvement, seismic liquefaction cells, groundwater cutoff walls, mass treatment and treatment windows.

**CSM Installation Techniques**

CSM panels are installed using either a single or dual phase technique in an alternating primary/secondary installation sequence. Both techniques require the liquefaction of the in-situ material during the penetration of the CSM tool to reduce friction and permit withdrawal of the tool. Mixing is completed with both techniques during the withdrawal of the tool.

The single phase technique uses cementitious slurry during penetration and withdrawal of the CSM tool. Approximately two thirds of the planned total amount of slurry is typically required during the penetration phase to liquefy the soil. The remaining slurry is injected into the soil during the withdrawal of the tool.

The dual phase technique injects different slurries during the penetration and withdrawal of the tool. Typically bentonite slurry is injected during the penetration to liquefy the soil. Cement slurry is injected into the liquefied soil during the extraction of the CSM tool.

The single phase technique is preferred when penetration is sufficiently rapid to complete the panel installation prior to the setting of the soil-cement material. The single phase technique eliminates several logistical complications with
respect to commissioning and plumbing of the slurry batching plant. Its use allows the possibility for a slightly quicker withdrawal rate since the soil is already premixed with the majority of the planned slurry amount. The dual phase technique is preferred when the penetration rate is slower and the possibility of the setting of the soil-slurry mix exists.

**CSM Applications on the Port of Miami Tunnel**

CSM panels were originally intended to be used for SOE and barrettes on the Port of Miami Tunnel project. Due to the demonstrated ability of the CSM tool to successfully cut and mix the porous limestone, additional ground improvement applications including groundwater cutoff and mass treatment blocks were implemented during the project to address various design and constructability issues with the tunnel and ancillary features.

A plan view sketch is included as Figure 4, showing the general alignment and locations of the various scopes of work related to the successful launching and receiving of the TBM.

![Figure 4](image)

**Figure 4**

**CSM Support of Excavation**

Launching and receiving of the 42-foot diameter by 457-foot long Tunnel Boring Machine (TBM) requires an approximately 110-foot wide by 400-foot long ramp on Watson and Dodge Islands. The excavation bottom of the ramp steps down 15 feet for the last 150 feet to a depth of 45 feet below grade to allow for erection of the cutting head assembly. CSM panels with embedded soldier piles were selected as the method for construction of the SOE perimeter walls. The 9.2-foot wide CSM panels offered far fewer construction joints than a secant pile wall, and the rectangular dimensions of a CSM panel minimized the potential for leakage at the tremie seal interface.

Lateral support for the SOE walls is provided by W36 wide flanged soldier piles installed on 4-foot spacing. The soldier piles are restrained laterally at the top of the wall with a single row of 6-inch diameter post-tensioned rock anchors installed just above the groundwater table.

While the soldier piles and anchors provide lateral support, the CSM panels serve as low permeability lagging between soldier piles. An unconfined compressive strength of greater than 250 psi is required to provide arching between the soldier piles. An in-situ permeability of less than $1 \times 10^{-5}$ cm/sec is specified along with a maximum leakage rate of 3 gallons per 1,000 square feet of exposed wall.

Support of Excavation at the TBM Break-In and Break-Out Plug requires a more unique approach as the TBM is not capable of mining through the soldier piles used for the SOE perimeter walls. CSM panels were constructed in an overlapping lattice pattern to form square boxes. A 12-ft diameter in-fill drilled shaft was installed in each box in a bi-directional secant pile pattern. The CSM panels prevent the vertical migration of water between the in-fill shafts thus creating an unreinforced 114-ft wide by 60-foot long by 50-foot minimum depth low permeability block of improved and replaced soil. The block was used to facilitate both the support of excavation at the face of the tunnels and accommodate substantial shear forces related to launching and receiving of the TBM.

**CSM Barrettes at Tunnel Portals**

Ground improvement of the overburden material was required to prevent unwanted mining of surficial loose cohesionless material until the crown of the TBM passes below the Miami
Formation. Wet Soil Mixing utilizing a 9-ft diameter single-axis soil mixing tool was employed to strengthen the overburden soil. CSM panels were used as barrettes between the closely spaced tunnels near the portals to act as columns and provide arch support for the improved overburden soil and to prevent potential soil loss around the first tunnel during the mining of the second tunnel. Although the CSM barrettes have no permeability requirement, a minimum strength of 435 psi was required.

**CSM Groundwater Cutoff at Maintenance Shed**

The abrasiveness of the quartz-based sand as well as the limestone requires that the cutting teeth and rollers on the TBM be changed prior to its passage underneath the channel separating Watson and Dodge Island. In order to provide a safe harbor for the workers, a maintenance shed that would allow compressed air to evacuate the groundwater in the cutter head chamber is required.

Based on the successful implementation of CSM as a low permeability groundwater barrier on the SOE, a maintenance shed of consisting of 35-foot by 60-foot rectangular box of CSM panels to a depth of 103 feet below grade along with 15-foot thick lid of 100 percent overlapping WSM columns at the surface was used to contain the compressed air and allow the evacuation of the water in the cutting chamber.

**CSM Mass Ground Improvement at Cross Passages**

As part of the fire safety plan for the tunnels, five “cross passages” are required between the larger vehicle traffic tunnels for pedestrian access between the portals. The invert of the cross passages range between 65 to 96 feet below working ground surface (approx. El. +10).

Construction of the cross passages requires excavation between the finished tunnel tubes.

Various means and methods were contemplated to construct the cross passages, including ground freezing, low mobility grouting, chemical or micro-fine grouting with tube-a-machete, jet grouting, secant pile compression rings, and cutter soil mixing. The various options posed their own unique design and construction challenges, particularly in the complicated soil profile consisting of hard, porous limestone and also loose sand. A permeability of less than $1 \times 10^{-5}$ cm/sec and a minimum UCS of 435 psi are required for the construction of the cross passages.

Based on the successful implementation of CSM to provide structural support and a low permeability groundwater barrier on the SOE, CSM was selected as mass ground improvement at three of the five 14-foot wide by 10-foot high emergency access cross passages between the tunnels (see Figure 5).

![Figure 5](image)

The cross passage plugs were designed as mass ground treatment with continuous overlapping panels in two directions to create two 35-foot by 30-foot by 40-ft and one 35-foot by 60-foot by 40-foot solid blocks of low permeability, strengthened cement-soil material. The designed requires mass ground improvement from approximately 5 feet above the top elevation of the cross passage and to 5 feet below the invert of the excavation. The blocks effectively retard the inflow of water,
while at the same time creating a cemented soil zone through which to safely mine. Once the main 42-ft diameter traffic tunnels are bored, the improved ground between the twin tubes will be conventionally excavated to construct the cross passages.

**CSM Mass Ground Improvement at Maintenance Sheds**

The continued successful employment of CSM led to additional applications as a mass ground improvement. Higher than expected wear on the cutter head teeth and rollers in the initial 600 feet of tunneling led to the need for maintenance on the cutter head prior to the planned maintenance at the crossing under the channel. Overlapping CSM panels are used to construct a maintenance shed consisting of 10-foot by 48-foot by 30-foot mass ground improved block. Compressed air was used to evacuate the groundwater and provide a safe harbor. The successful use of the maintenance shed on Watson Island led to an additional six maintenance sheds along the alignment of the TBM to permit safe sheltering while performing maintenance to the cutter head assembly.

**CSM Construction Challenges and Solutions**

While the obstructions in the overburden proved to cause minimal difficulty with the installation of CSM panels, the inconsistent nature and hardness and porosity of the Miami, Fort Thompson and Key Largo Formations provided harder challenges and required more mitigation measures to be taken.

An extensive quality control program was implemented to ensure that quality of the CSM panels remained consistent even in highly variable soil conditions. The quality control program included evaluation of daily equipment reports from the CSM and slurry plant equipment, field measurements, laboratory and field analysis of wet grab bulk samples and verification cores.

A correlation between UCS and permeability and the specific gravity of the wet mix had been observed on previous CSM projects. Specific gravity measurements from wet grab samples taken at various depths from freshly mixed panels were the primary indicator that the strength or permeability requirements would be met. The relative water-cement ratio for a given amount of cementitious material is a function of the specific gravity.

Once the soil-cement mix is collected, it is screened to pass only ¾-inch minus material while all larger aggregate is cast aside. The larger aggregate is acknowledged to only create irregularities in the cylinders and generate false fracture planes, unrepresentative of the actual in-situ unconfined compressive strength of the constructed CSM panel. The screened soil-cement material is then poured into 3-inch x 6-inch cylinders, tamped to remove air bubbles, and cured in a water bath. These cylinders are tested for unconfined compressive strength and permeability.

**Hard Limestone Construction Challenge - SOE and Barrettes**

The design requirements for the SOE walls and TBM Break In/Break Out Plugs on Watson and Dodge Island required the CSM panels to be constructed through the overburden and Miami Formation and keyed into the relatively hard limestone layer in the Fort Thompson Formation described previously. The hard Fort Thompson limestone layer provided temporary lateral support at the bottom of the wall until the tremie seal was poured.

While the overburden was able to be mixed with a single-axis 9-foot diameter tool, the Miami and Fort Thompson limestone is not suitable for most conventional types of soil mixing. Although the CSM is able to eventually crush and penetrate limestone, production rates while
mixing competent rock are greatly reduced in comparison to production rates through loose or weak soil. In addition, significant wear and maintenance issues are compounded while the CSM tool is advanced through hard, abrasive material.

Several pre-production and production phase tests were employed to evaluate the effectiveness of predrilling and its value of performing the additional work in the site specific geology. It was determined that, on average, panels without predrilling took three times as long as panels with predrilling when advancing through the cemented limestone formation.

In order to increase production rates and reduce wear on the tool, a predrilling program was conducted in advance of the CSM panel installation. A Bauer BG-50 hydraulic top-drive fixed mast drill rig with a 4-foot diameter continuous flight auger (CFA) was used to predrill the cemented limestone formations along the alignment of proposed CSM panels. The predrilling was accomplished by advancing the CFA auger down to proposed tip elevation of the panel and then counter-rotating the auger out of the drilled hole. This counter-rotation leaves the fractured in-situ soils and rock in the drilled hole and eliminates the generation of spoil material during predrilling.

Additional testing and observation resulted in the optimal predrill pattern for overlapping CSM panels, where the predrilled holes are centered at the overlaps of each panel. This reduced the amount of predrilling necessary for completion of the wall and had no adverse effect on production. The critical area of resistance with respect to advancing the CSM tool appears to be the outside edges of the CSM tool, rather than the center of the unit between the cutting wheels. It was determined that the center of the CSM tool will cut soil and rock more effectively due to the counter rotating action between the wheels. The two predrill patterns tested are shown in Figure 6.

Figure 6

The process of crushing the voids in the limestone required that approximately 25 to 30 percent of the volume of each predrill had to be added back into each predrill hole in the form of a fine sand material during the withdrawal of the auger.

Even with predrilling, advancement of the CSM tool through the limestone formations was significantly slower than typical production rates in soil. Panel installation time ranged from 2 hours to over 5 hours. Because of the time required to penetrate through the various limestone layers, a dual phase technique using bentonite slurry during the penetration of the tool was selected.

The combination of the dual phase technique and the predrilling allowed for the successful installation of CSM panels for SOE and barrettes.

Loss of Material Construction Challenge and Solutions

Prior to commencement of the CSM work there was concern with loss of cement slurry during construction of the panels because of the highly porous nature of the Miami, Fort Thompson and Key Largo Formations. Grout overruns of 200 percent of neat line are commonly observed during installation of CFA piles in Miami. Additionally, the volume of additional backfill required to fill the predrill holes confirmed the porous nature of the limestone.
The selection of the dual phase technique greatly mitigated the potential for loss of cement slurry during the withdrawal of the tool. The liquefied soil-bentonite filled the adjacent voids during the penetration phase and provided containment of the cement-slurry within the limits of the panel during withdrawal of the tool.

**Lack of Fines Construction Challenge - Maintenance Sheds and Cross Passages**

The use of CSM for the deeper maintenance shed and cross passages proved to be a harder challenge. Panel installation time for these applications ranged from 8 hours to over 18 hours. The time required to penetrate through the Miami, Fort Thompson and Key Largo Formation proved to be problematic even with the use of the dual phase technique.

It was observed during preliminary laboratory testing that the strength and permeability of the soil-cement material is dependent on its water-cement ratio. Furthermore, unconfined compressive strength and permeability testing on core samples have shown that the in-situ water-cement ratio may be different than laboratory measurements on cylinders cast from wet grab samples due to pressure filtration effects on the in-situ soil-cement material.

UCS results and field observations indicate that the porosity of the in-situ soil is a determining factor in the water-cement ratio of the mixed material (see Figure 7). Soil material that lacks fines has a higher porosity and thus a greater percentage of water in the saturated conditions below the water table. The fines injected during the CSM installation process reduce the porosity and water-cement ratio. However, if there is a lack of fines in the soil prior to installation of the CSM panels, it can be expected that the water-cement ratio will be higher and strengths lower than if fine soil material were present.

Two contributors to a lack of fine soil material in the material prior to the injection of cementitious material were observed. The natural lack of fines and high porosity of the limestone formations were one contributor. In particular, the Key Largo Formation was noted to have little fines and a relatively high porosity.

However, the lack of fines in these formations was further exacerbated due to the hardness of the limestone. Even though the flow rate of bentonite was minimized a minimum flow rate was required to prevent clogging of the nozzle. When penetration of the several feet hard to very hard limestone occurred during installation of panels for the maintenance sheds and cross passages, relatively large quantities of bentonite slurry were injected during the penetration phase even at low flow rates. Grab samples of the material collected at various depths during the penetration phase revealed that the specific gravity of the soil-bentonite mix was consistent at varying depths, but decreased over time with the amount of bentonite injected during penetration. The fine sands were “floated” out of the panel with the bentonite and removed as spoils.

The combined effect of a lack of natural fines and removal of the available fines during penetration resulted in a higher water-cement ratio.
ratio and low unconfined compressive strengths. After completion of the first cross passage, five core samples were completed and tested for UCS as well as density. Density of the test cylinders correlated well with the unconfined compressive strength. It was observed in the core samples that the aggregate settled to the bottom of the panels through the relatively thin soil-bentonite material. This left a significant zone of CSM panel with a high water-cement ratio and low UCS above the aggregate zone.

It was determined that a cost-effective solution to lower the water-cement of the soil cement CSM panel was required. A quality control program on deeper CSM barrettes on Dodge Island proved that adjustments would be required in the procedure to achieve the required performance criteria when performing cutter soil mixing through several feet of limestone.

One potential solution is to decrease the water-cement ratio is to increase the cementitious content. Another solution is to reduce the porosity of the material by adding fines to the panel after penetration was completed. Initially both solutions were implemented in order to ensure that the required UCS and permeability results were achieved. The cementitious dosage was increased by 15 percent. The installation procedure was amended such that the CSM tool would be advanced to tip elevation and then removed from the soil-bentonite material. After withdrawal, approximately 2500 liters of sand was added to each panel with a skid steer bucket loader. The CSM tool is then reinserted into the already cut Bentonite slurry trench and advanced with the sand fill placed at surface to distribute and disperse the sand down to the tip elevation. The panel is then completed as normal by injecting cement slurry into the panel.

The QC program was amended to include collection of wet grab samples on every panel to check the specific gravity of the panel while it was still fluid. It was determined from correlations between specific gravity and UCS that samples with specific gravities less than 1.60 may result in below average strength results. This procedure allowed for an immediate check on performance of the panels. Any panel that did not meet the required strength criteria would be remixed with additional cement slurry, added sand fill, and re-sampled.

It was determined after additional sampling that the added cementitious material could be removed. Adding sand was sufficient to lower the water-cement ratio and meet the UCS and permeability requirement.

Construction Challenges – Heat of Hydration in Mass Treatment

An exceptionally interesting, and potentially problematic, resultant of mass treatment was the heat generation of the mass treatment block of curing soil-cement material. The effect of the heat of hydration with respect to soil mix strength has not yet been evaluated. However, it can be noted that 3 months after initial mixing, the soil-cement material was found to have an internal temperature of 131° Fahrenheit.

In one specific occurrence, a mass treatment was required to be performed immediately in front of the TBM. The TBM was advanced into the mass treatment and pressurized to allow safe inspection and maintenance on the massive cutting head of the tunnel boring machine. At the time, the curing CSM mass was only 24 – 72 hours in age, and generated an ambient temperature within the chamber of the TBM on the order of 149° Fahrenheit. The initial intensity of the heat, and the slow dissipation of heat over time, may be a consideration for any designer or contractor who considers similar type work. Mass effect is well documented with respect to mass concrete pours (i.e. Hoover Dam case studies) but rarely considered or documented in consideration of ground improvement techniques.
Conclusions

Predrilling with a continuous flight auger that is the diameter of the constructed CSM panel is necessary in limestone to remain economical and productive with the technology.

However, by pretreating the soils, CSM was able to produce a superior product, even despite the competent cemented rock layers.

The success of soil mixing, with respect to constructability and achieving the performance criteria, is heavily dependent on the soil types that are being mixed. The geologic profile at the Port of Miami Tunnel, consisting generically of silty sands over vuggy limestone, proved to be an effective medium to soil mix with appropriate provisions. Most of the CSM panels for the SOE Walls had a bottom elevation that was only a few feet into the underlying Fort Thompson limestone formation. These panels exhibited great performance with high strength and low permeability, without requiring any additional measures aside from the predrilling and dual-phase grouting method described above.

Of more than 500 CSM panels completed in the base contract scope of work, less than one percent failed to meet the unconfined compressive strength performance criteria. These panels were completed to an average depth of approximately 59 feet. At a depth of 59 feet, the majority of the CSM panel is constructed in sand and only a few feet into the hard Fort Thompson Formation.

The unconfined compressive strength is directly proportional to the water-cement ratio and specific gravity of the material. The most economical means to increase the specific gravity and lower the water-cement ratio was found to be the addition of fines and re-stroking the panel with the CSM tool.

At the writing of this paper, less than five percent on panels constructed required remixing thanks to the revised installation procedures. This construction method dramatically increased strength results for deep CSM panels through the Key Largo limestone formation. Samples taken before adding additional fines through increased binder and sand fill averaged an unconfined compressive strength of 618 psi. After the program was changed as discussed, the average unconfined compressive strength of panels increased to 887 psi, with no CSM panels falling below the specified strength criteria.

Cutter Soil Mixing produces a product of exceptional quality. Due mainly to the quality of the product, designers can consider the application of this technique in an endless array of ground improvement, cut-off wall, and excavation support applications.
References:

