

## Building a Box in a Sponge: Excavation Support for a Tunnel



**Aerial of Watson Island SOE** (Smith Aerial Photography)

The Florida Department of Transportation (FDOT) has a unique transportation project with a concessionaire group, the Miami Access Tunnel, to alleviate commercial traffic congestion in downtown Miami. The Port of Miami Tunnel project is a public-private partnership responsible for the design-build-finance-operate-and-maintenance of the tunnels. Bouygues Civil Works Florida, a minority partner in the concessionaire group, is the design-builder. The \$630 million project includes two cut-and-cover tunnels with two lanes of traffic each between Watson and Dodge Islands. A highly challenging part of the project was a temporary excavation support system in difficult geotechnical conditions. This system was essential to the bored tunneling operations and the subsequent permanent work.

The sedimentary geologic/geotechnical conditions included highly permeable subsurface materials and high static ground-

water levels. Fill material with rubble overlies the native sand, underneath which are several layers of very porous, vuggy limestone that serve as the bearing layer. Loss of material into the permeable lower limestone layers was a primary concern during design and construction.

The design team chose an excavation support system consisting of a Cutter-Soil-Mix (CSM) wall with embedded soldier piles that serves as a lateral structural support of excavation (SOE) and groundwater cut-off. Additional lateral support at the top of the wall was provided via pre-stressed, 5 to 9 strand, 6 in (152 mm) diameter tiebacks structurally connected to the face of the CSM panels through a system of double channel walers. A bottom groundwater cut-off consisted of tremie concrete seals anchored with a combination of H-pile reinforced 36 in (914 mm) diameter cast-in-drilled-hole



**SOE plan view** (Smith Aerial Photography)

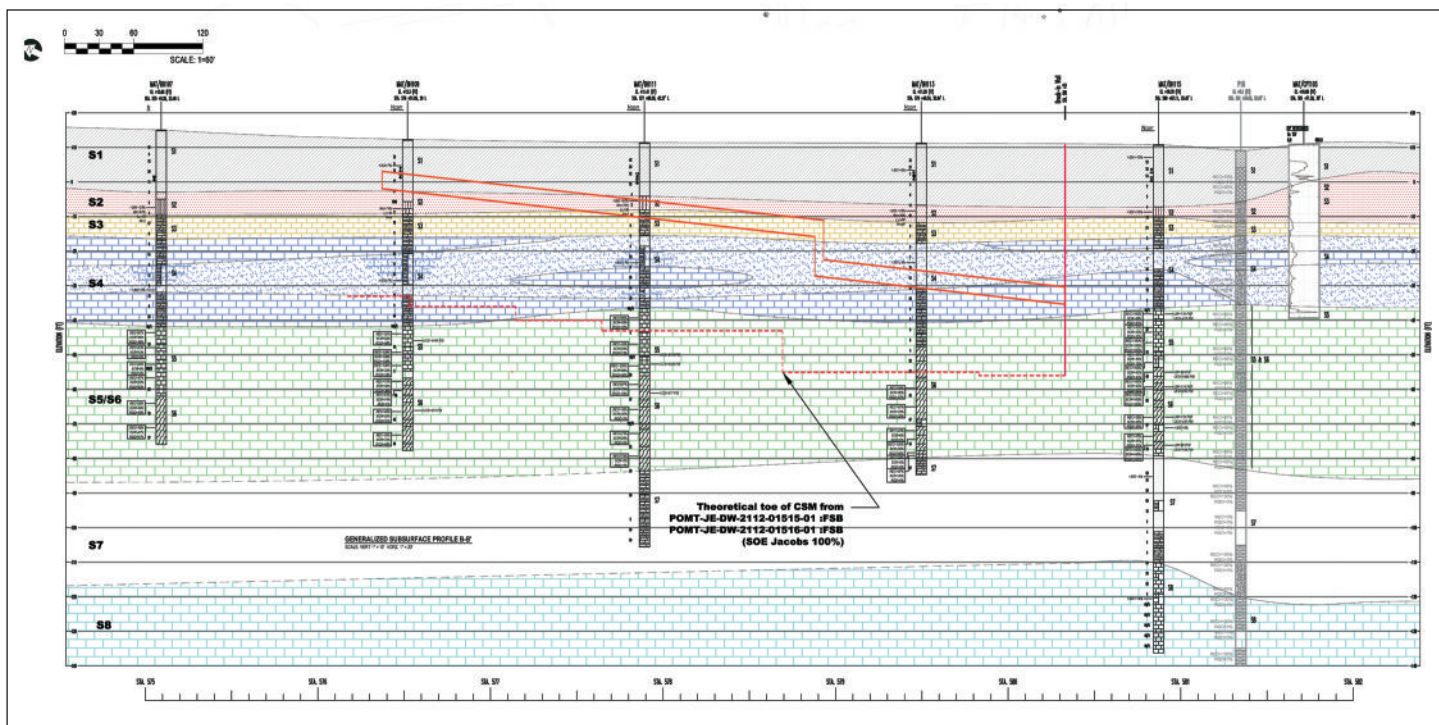
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**Soil profile** (Bouygues Civil Works Florida)

(CIDH) elements and 8.5 in (216 mm) diameter micropiles, reinforced with 3 in (76 mm) diameter high-strength threaded bars. The combination also provided lateral support to the SOE walls at the base of the excavation and uplift resistance in the temporary condition. At the break-in/break-out location for the tunnel boring machine (TBM), the contractors constructed the plug immediately adjacent to the SOE system, the CSM panels and 12 ft (3.66 m) diameter unreinforced secant piles configured in an overlapping pattern.

## Installation Sequence

The project's tight schedule required that several SOE elements be installed concurrently. Work on the north side of the SOE west wall was started in the approximately 39 ft (12 m) wide median of MacArthur Causeway in September 2010, following the test program for the CSM and CIDH elements and early testing of micropiles. The narrow median necessitated close coordination between the general contractor and the specialty foundation subcontractor. They had to remove and relocate existing utilities and to relocate the eastbound lanes of the causeway while work progressed on the SOE west wall, CIDH tie-down elements and the TBM plug. The team installed the

SOE east wall after the relocation at the causeway. Similarly at the west side, the CIDH tie-down elements followed immediately after the SOE east wall was installed as it progressed southward towards the TBM plug. Work on the plug recommenced after completion of the SOE east wall.

Next, a dry excavation to Elev. 3 ft (0.9 m) allowed the workers to install the tie-back anchors. Following completion of the TBM plug, they made a wet excavation to the bottom of the 5 ft (1.5 m) thick tremie seal slab. The top portion of the wet excavation was ramped at an approximately 5.2 percent grade from the bottom of tremie seal at Elev. -1 ft (-0.3 m) to Elev. 16.1 ft (-4.9 m). To allow space for the TBM erection, they excavated an 11.4 ft (3.5 m) step prior to resuming the 5.2 percent grade to the excavation bottom at Elev. -35.4 ft (-10.8 m). Micropile tie-downs were placed from a sectional barge platform after the excavation was completed. The contractors then poured the tremie seal slab after cleaning the SOE walls and the excavation floor. After the seal cured, the excavation was dewatered.

**Cutter-Soil-Mix Wall.** The SOE walls along the east and west sides of the excavation were originally designed as a combination of sheet pile in the shallow

excavation and secant piles in the deeper section. The designers revised this plan and chose a CSM wall that reduced the number of joints and provided a smoother surface for the tremie seal, which minimized the potential for water infiltration. They used several software programs to design the CSM SOE wall, including Shoring Suite, FLAC and L-Pile. The design allowed for a movement on the order of 4 in (10 mm).



Wide flanged W36 (914 mm) soldier piles placed every 4 ft (1.2 m) in the freshly mixed soil serve as the lateral support while the cement-soil mix serves as low permeability lagging between them. The performance criteria for the CSM wall required a permeability of less than  $1 \times 10^{-5}$  cm per second, no more than 3 gal of seepage per 1,000 sq ft ( $0.12 \text{ L/m}^2$ ) of exposed wall and no flowing water. A minimum strength of 250 psi (1.72 MPa) for the cement-soil was required to provide arching between the soldier piles.

The contractors used a 4 ft (1.2 m) continuous flight auger to process the overburden and underlying limestone layers to increase production and help maintain CSM panel verticality. The auger also confirmed the relative hardness and elevation of the limestone layer used as the primary lateral restraint. Preconstruction borings indicated that the top of the limestone layer along the SOE east wall might have a dip in a portion of the wall, so the planned tips were extended deeper. The design team used automatic monitoring equipment data from the drill rig to document the relative resistance of the soil and rock and confirm that the limestone layer did not dip in the deep section of the SOE wall. They were able to respond quickly and reduce the depth of the CSM panels, saving time and cost of construction.

Because of the expected time to penetrate through the limestone and its high permeability, the team used a two phase technique for the CSM panels. This included low-concentration bentonite slurry to lubricate the cutter wheels during penetration. The bentonite slurry in combination with the soil cuttings effectively plugged small voids and provided excavation stability. This soil-mixed system assured the cement slurry did not migrate away from the panel during injection and withdrawal of the CSM unit. The quantity of cement per cubic meter of mixed soil and volume of cement slurry were based on both laboratory mix design and field trials.

**Tieback Anchors.** The tieback design was based on resisting an unfactored anchor load of 30 to 60 kips per lf (438 to 876 kN/m) of wall. We spaced the tiebacks between soldier piles from 4 to 8 ft (1.2 to

2.4 m) on center. The tiebacks have free stress lengths on the order of 100 ft (30.5 m) through the upper four soil strata and a bonded length within the lower limestone rock layers for tieback anchorage. The design of the tieback bonded length was based on results of initial sacrificial load test, the maximum allowable shear resistance of 8.5 ksf ( $4.15 \text{ kg/cm}^2$ ) in the limestone layer. All performance and proof testing accorded with FDOT specifications. The placement of the anchor heads above the water table at Elev. 4 (1.2 m) made construction easier while maximizing tieback performance. Walers connected to the tiebacks transferred the load to the CSM wall soldier piles to provide lateral restraint for its top.

After excavating a 30 ft (9.1 m) wide bench at Elev. 3 ft (0.9 m) on each side of the SOE, the contractor installed 122 No. 6 in (152 mm) diameter, 5 to 9 strand, tiebacks with lengths of 110 ft (33.5 m) to 140 ft (42.7 m) using a dual rotary drill rig. We used a down-the-hole-hammer (DHH) to remove the drill cuttings while twisting the casing into place with the lower rotary unit. Even though geotextile socks and a thixotropic grout additive were used to minimize the amount of grout that would migrate into the highly porous limestone, grout overage averaged 400% over theoretical volume.

#### **Tie-Down Elements.**

Two types of tension elements resist the hydrostatic uplift on the tremie seal and provide axial support of the TBM during assembly. The shallow tremie seal was anchored by a combination of fifty-two 36 in (914 mm) diameter cast-in-drilled-hole (CIDH) elements reinforced with HP14 x 102 (HP360 x 152) sections and the lower tremie seal was anchored with 8.5 in (216 mm) diameter micropiles reinforced with 3 in (76 mm) diameter high-strength threaded bars. The larger diameter CIDH elements were selectively used in the permanent structure to provide resistance to uplift for the permanent U-Wall and cut-

and-cover tunnel sections. The engineers determined the tension element embedment length based on the side shear resistance of the limestone rock of the individual element capacity as well as for group effects; the most stringent resulting embedment governed the design. Two sacrificial load tests were required for each type of element. A test load of 820 kips (3,648 kN) and 1,200 kips (5,338 kN) was specified for the minipile and CIDH, respectively, and a maximum vertical movement set at 1.25 in (32 mm) under the design load. The load test performed satisfied the criteria.

Prior to excavating the tieback bench, workers installed CIDH tension elements with the top of concrete and bearing plates ranging from 15 to 25 ft (4.6 to 7.6 m) below grade. Temporary 48 in (1,220 mm) casing was initially installed and excavated to approximately 4 ft (1.2 m) below the



**CSM wall with tieback anchors** (photo by Mike Butler and Dan Riebe)

planned concrete cut-off to provide SOE after removing an inner 39 in (990 mm) sectional casing that extended to the top of the limestone bearing layer. Workers cleaned the concrete surface and removed excess concrete to the cutoff elevation. We placed the H-pile bearing plate at the proper elevation using a multi-positional follower beam of the same size as the pile reinforcement with a connection plate with drilled holes to match the bearing plate of the production pile. Styrofoam block outs placed at the top of the H-pile kept a clean bonding surface for the subsequent tremie seal.



The contractors installed micropiles from sectional barges using a dual-rotary drill rig after excavation to the tremie slab subgrade level to minimize any damage to these elements during excavation. A DHH was used to remove drill cuttings within the casing while it was twisted into place with the lower rotary unit. A 3 in (76 mm) diameter Grade 150 (1,034 MPa) high-strength threaded bar was placed in the cased excavation prior to tremie placement of grout. The micropiles extended through competent limestone into more porous

connection on the top of the threaded bar prior to pouring the tremie seal.

The TBM plug provides a water tight entry point for the start of the tunneling process. After the TBM penetrates approximately 36 ft (11 m) into the plug, the pre-cast 2 ft (600 mm) thick concrete segments, the tail void grout and the tunnel shield are in place to prevent water seepage. The plug also supports the excavation along this face and acts as a self-supporting retaining structure capable of resisting all super-imposed lateral loads.



**Tunnel boring machine at the entry plug** (photo by Mike Butler and Dan Riebe)

zones. The test pile installation confirmed suspicions that the grout overage would be excessive even with the use of geotextile socks, due to the porous and permeable subsurface materials. The original specification required that grout be visible at the top of the casing, 40 ft (12 m) above top of pile. After discussion, the design team decided to install three levels of thermocouples within the pile profile to confirm the presence of grout as the casing was withdrawn; the grout could be confirmed at the top of pile and pile integrity maintained. A high-strength ballistic-cloth grout sock minimized grout overage. Divers later attached the shear plate

Lateral resistance was achieved from side and base shear as well as shear keys, as required to provide an adequate factor of safety against sliding and overturning. The plug is cast integrally and in direct contact with the tremie and CSM system walls.

The TBM plug was originally designed as a mass excavation supported by sheet piles. During the pre-construction phase, the specialty subcontractor re-designed this portion using a 114 ft (35 m) wide by 59 ft (18 m) long by 50 ft (15.2 m) deep TBM plug as a cost-saving measure. The design team quickly confirmed its feasibility and provided construction drawings. The plug is comprised of a

square lattice of overlapping CSM panels with an inside face-to-face of approximately 7 ft (2.1 m). After completion of the panels, the unmixed soil within the lattice was excavated in a secant pile pattern in both directions and replaced with a minimum 750 psi (5 MPa) controlled density fill. The lattice work of CSM panels supported the excavation for the 12 ft (3.65 m) diameter secant piles and served as low permeable material in the unexcavated material between the secant piles.

## SOE Wall

The SOE wall is fully instrumented for performance monitoring including inclinometers, tieback load cells, piezometers, deformation monitoring points and survey target points. To date, no reading has exceeded the project threshold values. Six verification boreholes with rising head permeability tests as well as laboratory permeability test values confirmed the maximum permeability of  $1 \times 10^{-5}$  cm/sec requirement was met. No flowing water through the CSM wall has been observed since SOE dewatering was completed in July 2011, and there has been no appreciable vertical movement observed in the tremie seal. All test results indicated that the 250 psi (1.72 MPa) design strength was achieved. In addition, a down-hole camera was used to inspect the cores through the CSM wall.

## Conclusions

To our knowledge, the Watson Island SOE is the deepest and largest excavation in South Florida. The CSM/soldier pile system performed remarkably well in very challenging ground conditions. Wall movements and water infiltration were well within limiting values of the design criteria. Laboratory results and field observations have validated CSM as an effective water-resistant barrier. The anchored tremie seal has also been proven an effective water-resistant barrier including the construction joint between the CSM wall and the tremie seal.

### Acknowledgements

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