Innovative Tunneling in the Norris Cut Channel

Bernard THERON,
BESSAC, St Jory, France
Bernard CATALANO,
BESSAC Inc, Canonsburg, PA, USA
Eloy RAMOS,
NICHOLSON, Canonsburg, PA, USA

1. ABSTRACT

In early 2014, Nicholson Construction Company was awarded, together with its tunneling sister company Bessac, the Norris Cut Miami Tunnel Project. The 2.5-meter-diameter segmental-lined tunnel, of 1,600 meters in length, replaced the existing 54-inch force main tunnel, connecting the waste water treatment plant on Virginia Key to Fisher Island.

To overcome the highly permeable limestone of the Fort Thomson Karstic Formation (one of the most permeable formations in the world), the project team developed state-of-the-art solutions:

- The TBM was launched using a pipe-jacking technique for the first 70 meters, and then converted to segment erection mode. This allowed substantial schedule savings and drastically reduced the size of the circular launching shaft.
- The TBM, jointly designed and manufactured by Bessac and Herrenknecht, can convert from slurry to EPB mode within a few minutes.
- The cutters can be replaced by wet divers thanks to an innovative application in the TBM industry.

Dans les premiers mois de 2014, Nicholson Construction Company a été attribuée, la construction du projet Norris Cut Tunnel en partenariat avec Bessac, entreprise spécialiste de constructions souterraines faisant partie du même groupe. Ce tunnel de 1600 mètres de long à voussoirs de 2.5 mètres de diamètre intérieur, vise à remplacer une conduite forcée existante de 54'' de diamètre allant de la station d'épuration des eaux usées de Virginia Key à l'ile Fisher.

Pour surmonter la couche calcaire Karstique Fort Thompson, hautement perméable (dans les plus perméables au monde), l'équipe du projet a du développé des solutions innovantes et de hautes technicités :

- Le tunnelier a été lancé en mode fonçage sur les 70 premiers mètres, puis converti en mode pose d'anneau universel. Ceci a permis un gain substantiel sur l'échéancier et a réduit considérablement la taille du puits circulaire de départ
- Le tunnelier, conjointement dimensionnée et fabriquée par Bessac et Herrenknecht, peut opérer en mode pression boue et mode pression de terre grâce à un changement de mode en quelques minutes seulement.
- Les outils de coupe peuvent être remplaces par des scaphandriers sous eau, grâce à une solution innovante.

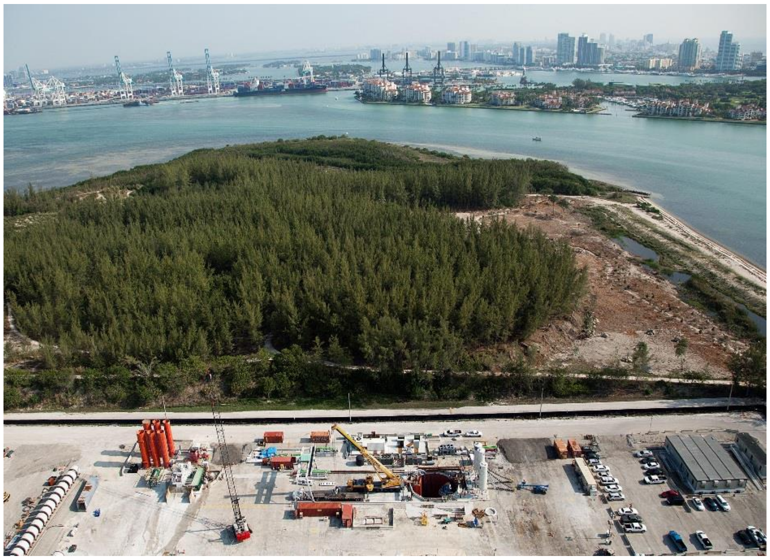


Figure 1. View of the Project

2. INTRODUCTION

The aim of the Norris Cut Miami Tunnel Project was to install a 60” FRPM pipeline as a replacement of the existing 54-inch force main pipeline, which currently transfers all sewage collected from Miami Beach, Surfside, Bal Harbor, Bay Harbor, North Bay Village and Fisher Island, to the Central District Wastewater Treatment Plant (CDWWTP). The existing pipeline is comprised of pre-stressed concrete-cylinder pipe, which is in poor condition in a number of locations and could be subject to sudden failure.

An adjacent portion of this existing force main under the Government Cut (North Fisher Island) has already been replaced as part of a previous design-build contract and involved the installation of a 60-inch diameter fiberglass-reinforced mortar pipe installed inside a micro-tunneled casing.

The Norris Cut Project involves the construction of (Figure 2):

1. Approximately 5,300 linear feet (1,615m) of pre-cast concrete segmentally lined tunnel that commences from a launch shaft located in Virginia Key (CDWWTP) and terminates at a retrieval shaft located in Fisher Island. The 8.2’ (2.5m) internal diameter (ID) tunnel is mined using a dual mode hybrid tunnel boring machine (TBM) for alternating between slurry and earth pressure balance. The excavation is performed at a depth of 65 to 90ft (20 to 28m).

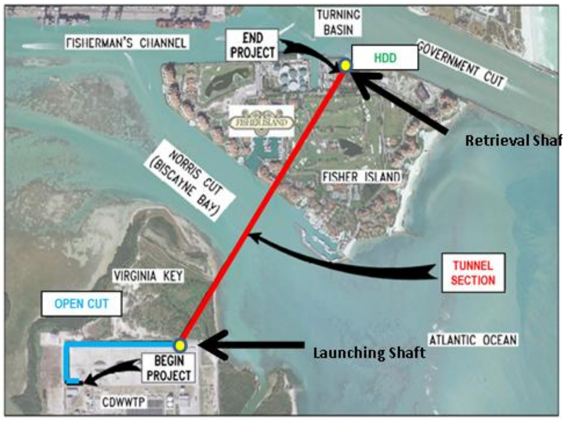


Figure 2. Overall View of the Project

2. A launching shaft built using secant piles in Virginia Key with a diameter of 42ft (12.8m) and a depth of 100ft (33m).
3. A retrieval shaft built using the deep soil mixing technique with a diameter of 29ft (8.8m) and a depth of 85ft (26m).
4. After tunneling completion, installation of a 60-inch diameter FRPM pipe inside the tunnel and then injection of annular void cellular grout from inside the FRPM .
5. Approximately 2,700 linear feet (820m) of 60-inch ID pipe installation at the CDWWTP that extends from the tunnel shaft to the grit chamber facility using open-cut construction methods.
6. Approximately 900 linear feet (275m) of 8-inch ID horizontal directional drilled (HDD) sewage force main on Fisher Island that extends from pump station to the retrieval shaft.

This scope of work is not only challenging because of the varying soil conditions, but also because it includes numerous technical construction methods such as secant piles, deep soil mixing, tunneling works, and HDD, but also ground freezing and underwater tremie slab. In addition to the access challenge to reach Fisher Island, several world firsts associated with the tunneling works were developed specifically for this Project by Nicholson and Bessac to overcome Miami’s adverse ground conditions.

3. TUNNELING CHALLENGES

3.1. Geological conditions

Most of the challenges on this project are related to the ground conditions. Indeed, as evidenced by the very small number of underground structures in Miami, ground conditions are not favorable for tunneling. Only a few tunnels have been built in Florida. Due to its large diameter, the Port of Miami Tunnel was one of the first and was mined in a partially improved ground (tailor-made light cementitious, low mobility grout injected on one third of the drive). The Norris Cut Tunnel runs fully within the Fort Thompson (FT) formation, which consists of limestone and loose interbedded sand (FT-1 and FT-5, respectively).

This limestone is porous and karstic and therefore extremely permeable. The Fort Thompson formation in Dade County is in a major part of one of the most permeable aquifers (Biscayne Aquifer) ever investigated by the U.S. Geological Survey (Parker 1955).

For about 40% of the alignment, the project team was working with a mixed front configuration (Figure 3).

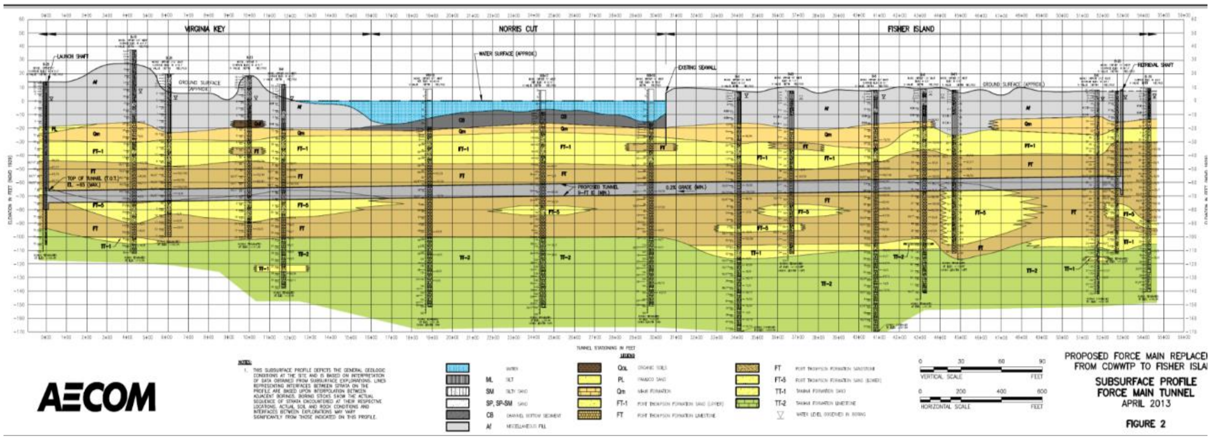


Figure 3. Project Geological Profile

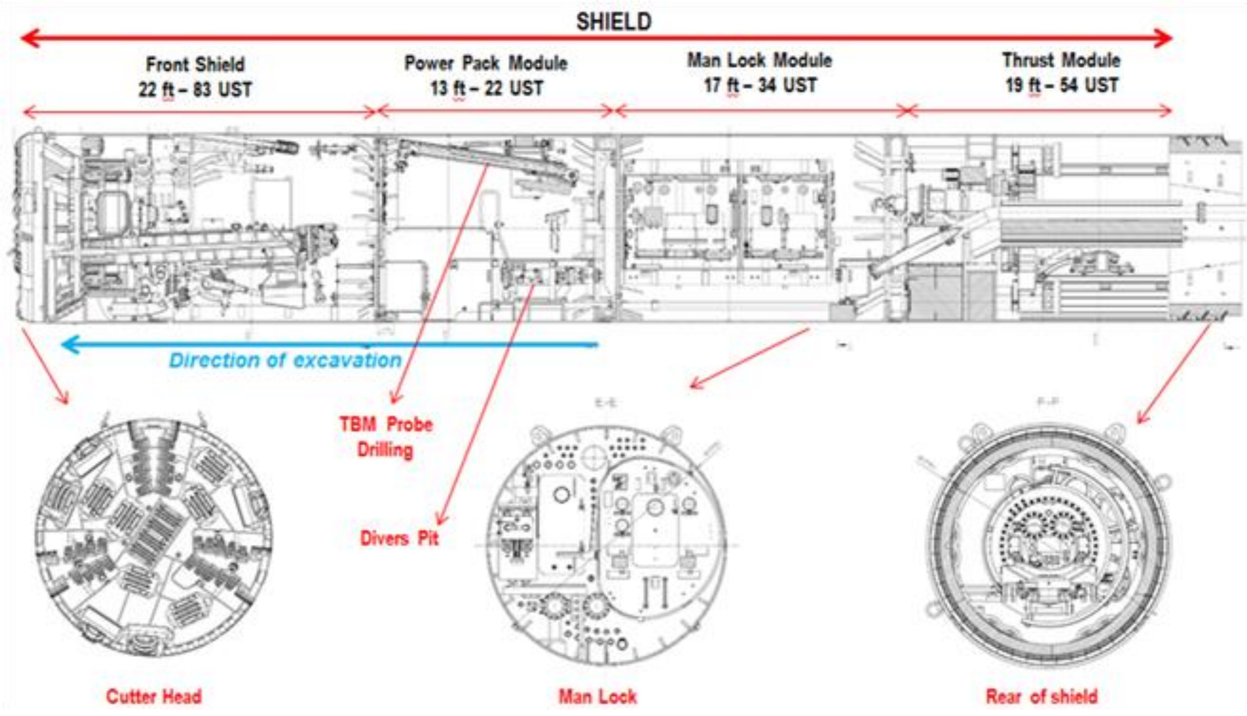
The main challenges associated with the geological conditions consisted of:

- Mixed-face conditions in FT rock with very loose inclusions and layers of sand randomly located within harder rock-like material.
- Mixed-face conditions in FT-5 sand with competent zones of bedrock (acting as “boulders”) embedded in softer materials.
- Loose to very loose sand encountered below the advancing TBM cutterhead, with potential for soil bearing capacity failure and adverse conditions for TBM steering.
- The potential for sudden and large-scale slurry fluid losses into karst features.
- Rock mass with frequently changing rock strength.

3.2. A tailor-made, dual mode TBM

A new 10.2ft Herrenknecht/Bessac TBM was manufactured to bore the tunnel. It is a dual-mode, hybrid TBM, capable of converting from slurry mode to EPB within the tunnel and within a short time.

Figure 4. TBM sections



This type of machine is quite unusual, especially in this diameter range. Only a few have ever been operated worldwide. In general, the machine consists of an earth pressure balance machine with a slurry box connected to the screw conveyor gate. For example, the Herrenknecht TBM used in the Port of Miami Tunnel (POMT) project was a convertible machine. It was selected because the tunnel crossed all subsurface layers, from ground elevation to the deepest layer. Moreover, a 12m diameter machine allows for easy installation of all the equipment required for a convertible solution, such as the screw conveyor and the slurry system. The situation is quite different from the small TBM required for this project. Consequently, Bessac and Herrenknecht had to innovate in the design of the machine in order to fit all the equipment (pumps, transformers, erector, etc.) in the tight space demanded by this small diameter.

The change from slurry mode to EPB mode (using a screw conveyor with slurry box) can be done in a short time by actuating several valves.

The shield is divided into four modules (Figure 4), and designed for ground water pressure up to three bars:

- The first module is the articulated shield. The cutting wheel is a closed-face type, equipped with disc cutters and scrapers and buckets. There are 15 x 14” discs, 20 scrapers and six buckets. The cutting discs are made using tungsten carbide inserts to reduce the wear and enhance the lifetime of the cutting wheel. The face access for cutter inspection / change is possible through a door of 18” x 18”:
  - In slurry mode, the TBM excavates like a standard micro tunneling machine.
  - In EPB mode, the excavated material goes through the screw conveyor, passes through the discharge gate, and is then transported by the slurry circuit. A reverse water flushing system cleans the suction port of the cutting chamber.
- The second module includes the power pack, the probe drilling rig and the divers’ pit to allow for wet cutter changes.

Figure 5. Diver pit for cutter change in the wet

- The TBM operator control cabin and the integrated air lock are located in module 3. They are configured to provide a 2-chamber / 3-door system by pressurizing the machine, which permits manned entry/exit whilst maintaining pressurized conditions.
- The last module is the thrust/segment erection system. The erector is a remote-controlled, center-free, rotary-arm type mounted on the tunnel axis with a vacuum segment-gripping system.

3.3. Cutting Tools Replacement

Working with ground that contains many voids makes front intervention in the TBM cutter head chamber very challenging. Indeed, replacing cutting tools usually requires replacing the slurry in the cutter head chamber by air in order to perform a dry hyperbaric intervention. The air pressure is chosen so as to counterbalance the ground water pressure and thus prevents water ingress into the chamber. But the Fort Thompson formation contains so many voids that it is impossible to seal this porosity in order to prevent the compressed air from flowing into the voids: Traditional hyperbaric works cannot be carried out to perform cutting tool replacement operations.

Anticipating this risk, Nicholson and Bessac developed a specific diver pit (Figure 5) built into the TBM allowing for wet interventions at the front of the machine in the event that dry interventions were not possible.

A specific decision-making process, based on the slurry intake to guarantee the proper seal of the FT formation, was put in place to select the most appropriate hyperbaric mode on a case-by-case basis, comparing cost, risk and time, for the most effective operation.

3.4. TBM Launching Sequence

Launching a TBM from a shaft is always a challenge. The smaller the diameter of the shield, the longer the shield length becomes. Enlarging the shaft just for one launch is very expensive, especially in such a porous formation.

Nicholson and Bessac designed and implemented a world first launching sequence, which improved safety, saved time, drastically reduced the size of the circular launching shaft required, and prevented complex and risky additional underground structures. The sequence consisted of the use of jacking pipes for the construction of the first 70 meters of tunnel, during the launching step of the TBM. This technique also avoids lowering the backup unit gantries one by one.

But since this was a world first, the project team had to thoroughly lay out the requirements to overcome the various challenges with all the associated contingencies (process adjustments, mechanical issues, structural adaptations, safety, etc.) and make it a success.

3.5. Other challenges

3.5.1. TBM jointly designed and manufactured by Bessac and Herrenknecht

The shield was built by Herrenknecht, whereas the back-up gantries were manufactured by Bessac. Both companies worked in close collaboration in order to build the machine and the machine's backup, ensuring design compatibility for each, and to increase efficiency. By sharing their vision, their methods, their experience and their specialties around this very specific machine, both companies improved their TBM manufacturer knowledge.

Finally, beyond the design and the manufacturing of this machine, the works performed inside by the crews were another big challenge since "everything is harder in a tight space—even changing a bolt can become a nightmare".

3.5.2. TBM Dismantling

Most tunnel boring machines are removed entirely from the ground after they break out. On the Norris Cut Tunnel project, only the front part of the shield was removed; the skins of the three remaining modules stayed in the ground, forming the final meters of the tunnel lining. However, all the noble equipment inside the three modules and the back-up gantries have been dismantled and removed. This operation was a challenge in terms of process (complex handling) and mechanics (sophisticated material) as well as safety (hot works in a tight space).

The break-through took place in February 2016.

3.5.3. Brackish Water

Most of the works performed on this project had to deal with brackish water due to the proximity of the sea. This specific environment had to be considered in numerous aspects of the project:

- Concrete mix for pre-cast segments, jacking pipes and secant piles
- Cement grout mix for deep soil mixing and tunnel annular void grouting
- Slurry mix and its stability
- Tail void grout
- Gasket design for pre-cast segments and jacking pipes
- Sealing resins for sealing injections, for instance injections during retrieval phase

4. SHAFT CONSTRUCTION

4.1. Launching Shaft

Due to the variability in rock strength, high permeability and reported water losses, slurry support for a diaphragm wall could have led to sudden slurry loss leading to ground support instability. Therefore, the secant pile method was chosen as the most prudent method for stability in a karstic setting.

The launch shaft was designed and built to accommodate the TBM and the installation of the 60-inch carried pipe. The launch shaft was built with a 42-ft interior diameter to provide sufficient room to install each section of the TBM including thrust frame and jacking cylinders.

4.2. Secant piles

39.4-inch (1m) diameter secant piles were installed on a 25.5-inch (0.65m) center-to-center spacing. They were built using a 5,000 psi (35 MPa) compressive strength normal weight concrete mix with admixtures to limit crack growth and permeability.

The secant piles were constructed using a conventional bored cast in-situ technique using a fixed mast Bauer BG 39 drill rig with full depth casing.

The shafts were designed to resist lateral soil and water pressure from hoop stress due to the circular shape. The secant piles therefore did not need to be reinforced, except for secondary piles on both sides of the opening for the TBM, which needed to resist the circumferential hoop stress and span between the top and bottom of the opening. In the break-in envelope, at the base of the shaft, fiberglass reinforcement cages were installed to maintain the integrity of the piles above and below the opening.

4.3. Excavation and Tremie Slab

Particular attention was paid to waterproofing details in order to allow the shaft to be dewatered without leaks after the installation of the tremie slab, and to perform the tunnel break-in without flooding the shaft or causing ground settlement.

Figure 6. Excavation of the secant pile launch shaft "in the wet"

The shaft bottom seal was built using a reinforced tremie slab.

Prior to shaft excavation, the overburden and limestone layer located within the footprint of the shaft were pre-drilled with the Bauer BG 39 using a CFA (continuous flight auger) attachment. Pre-drilling aided with "in the wet" excavation efficiency.

The rig loosened the ground through the advancement of the auger to shaft bottom. The auger was withdrawn by reversing direction so as to not remove material.

After the completion of the pre-drill operation, an excavator, a crane and a mechanical grab were mobilized to the site to begin the mass excavation (figure 6). The excavator removed as much material as possible from the top of the shaft based on its reach capacity. Once the excavator was not able to advance any further, a crane and a mechanical grab were employed to advance the remaining excavation. The mechanical grab was supposed to operate under its own weight and excavate the material "in the wet". However, some hard limestone layers required the use of a vibrator hammer assembled on a crawler crane to break the rock.

At the completion of the excavation, a tremie slab was poured. Dowels were drilled and epoxied into the wall to transfer the uplift on the slab to the piles. Flexible grout tubes with ports were secured to the secant piles near the top of the slab to act as a secondary measure of water tightness. A circular steel-reinforced cage was lowered to the bottom of the excavation and secured in place. Concrete was then pumped to achieve the proper slab thickness (around 6ft).

After the tremie slab had reached the required compressive strength, the inside of the shaft was dewatered using high capacity pumps.

4.4. Break-in

To maintain water tightness for the tunnel break-in, eight (8) additional secant piles were installed along the tunnel alignment in front of the main secant pile shaft. These additional piles aided in reducing the water ingress during tunnel launch. They were constructed with a low strength concrete.

The project team decided to complete the break-in block shown in Figure 7 with ground improvement using the ground freezing method for the following reasons:

1. To be able to inspect the cutter discs of the TBM at atmospheric pressure after crossing the secant pile wall
2. To stabilize the ground above the TBM during the launching phase and particularly while crossing the piles
3. To allow the demolition of the secant pile wall in order to install the entrance seal without having the risk of a big inflow.

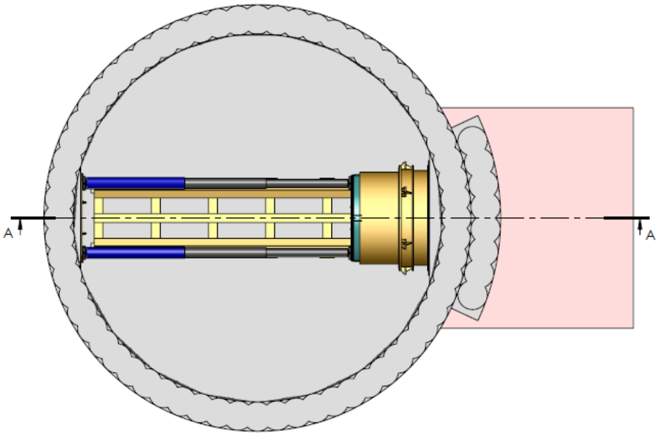


Figure 7: Plan view of the break-in – ground freezing block shown in pink

The dimension of the frozen block was 25ft wide, by 25ft high and 18ft long along the centerline. The frozen block was installed before the launch of the TBM and maintained during the first excavated meters.

The soil freezing technology converts water into ice by the continuous circulation of a brine fluid within a system of small-diameter, closed-end pipes. They were installed in a pattern consistent with the shape of the area to be treated. The team drilled and grouted holes to reduce the flow of groundwater into the break-in block using a rotary hydraulic drill rig.

4.5. Retrieval Shaft

The project team decided to use a deep soil mixing method to build the retrieval shaft.

Deep soil mixing is a soil improvement technique that is used to construct in-situ soil structures without excavation or dewatering. Soil mixing requires the insertion of a large diameter auger into the ground while grout is injected through ports in the tooling. The injected grout is mixed using paddles on the auger that mix the ground and grout as it progresses down a column. Soil-mixed columns may be overlapped to form foundation elements such as a retrieval shaft.

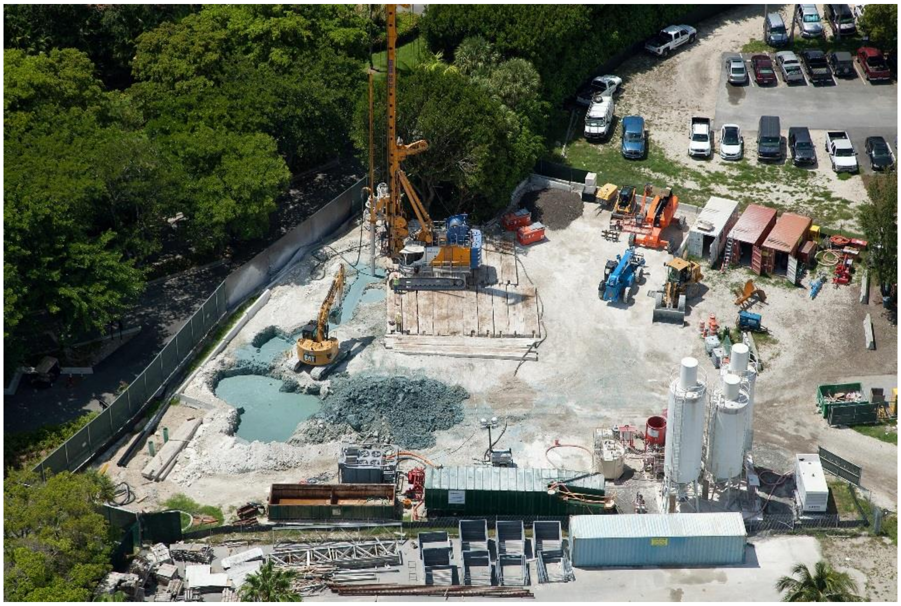


Figure 8. Deep Soil Mixing on Fisher Island

The soil-mixing retrieval shaft consisted of installing 75 overlapping columns to form a 42’ outer diameter, and 28’ inner diameter shaft for the removal of the TBM.

A 7-ft-diameter mixing auger was used (figure 8) with bullet teeth to provide extra wear protection. Injection nozzles in the stem and beneath the cutting blade pushed grout out as the tooling advanced to depth. The three paddles above the cutting blades help to mix the grout and soils together as it passes through the areas where grout was injected.

This tool and the complete system were installed on the same Bauer BG 39 drill rig used to install the secant piles at the launch pit.

The shaft was then excavated using an excavator with mill attachment up to 10ft above the crown of the tunnel alignment so that the TBM could break-out through the deep soil mix plug. Afterwards, it was backfilled with sand so as to counterbalance any water or slurry leakage coming from the break-out.

When the TBM reached the final station—meaning at the correct position to be removed—the backfill and the remaining plug were excavated in order to unearth the machine.

Finally, after installing and grouting a 60-inch ID carrier pipe, both shafts were backfilled at the end of the works.

5. CONCLUSION

The Norris Cut sewer was handed over and commissioned at the end of 2016.

Despite the challenging conditions, the project team, working closely with the owner and the designer, found cutting-edge solutions that had been rarely, if ever, implemented in the region, to overcome those challenges.

The tailor-made, dual-mode TBM is proving to be very well suited to these very specific ground conditions.

Figure 7. The construction team