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Northeast Boundary Tunnel: Applied lessons learned from the Anacostia River Tunnel Project, Washington, USA

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ABSTRACT: The Northeast Boundary Tunnel (NEBT), the largest component of the Clean Rivers Project, is a deep, large sewer tunnel that will increase the capacity of the existing sewer system in the Washington DC area, significantly mitigating sewer flooding during large storm events and improving the water quality of the Anacostia River. The construction of this last portion of the project was awarded to Salini Impregilo Healy JV (Lane), already successfully leading the completion of the previous Anacostia River Tunnel (ART) project in 2018. The Salini Impregilo Healy JV is currently (Dec. 2018) excavating the new tunnel using the same ART machine after full refurbishment, recertification and size adjustment. This will operate in the same Potomac formation but under larger overburden and water head, thus introducing additional design and construction challenges. The NEBT project is benefiting from the lessons learned from ART in terms of fine tuning the TBM equipment, soil conditioning strategy, EPB pressure definition, segmental lining design and adits connections with shafts performed through soil improved areas.

1 INTRODUCTION

The DC Water and Sewer Authority's long term CSO control plan includes a system of tunnels to control combined sewer overflows.

The discharge of these tunnels will be into the Anacostia River, Rock Creek, and the Potomac River after the transport of those captured flows to the Blue Plains Advanced Wastewater Treatment Plant. The Anacostia River Tunnel is one component of this long-term control plan. The project was completed in 2018 and has contributed to an increased capacity of the District's sewer system, significantly mitigating the frequency, magnitude, and duration of sewer flooding. It is also helping to improve the water quality of the Anacostia River.

The Northeast Boundary Tunnel is the largest component of DC Water's Clean Rivers Project and it will be a large, deep sewer tunnel that will increase the capacity of the District's sewer system. The tunnel will be 16 to 53 feet below ground and run 8,9km from just south of Robert F. Kennedy Stadium to the intersection of Rhode Island Avenue NW and 6th Street NW. It will be aligned to intersect with the existing chronic flood areas along Rhode Island Avenue NW. With the completion of the NEBT Project in 2022—two years ahead of the Consent Decree schedule—the CSO Overflow Volume to Anacostia River will reduce by 98 percent from the 1996 Baseline.

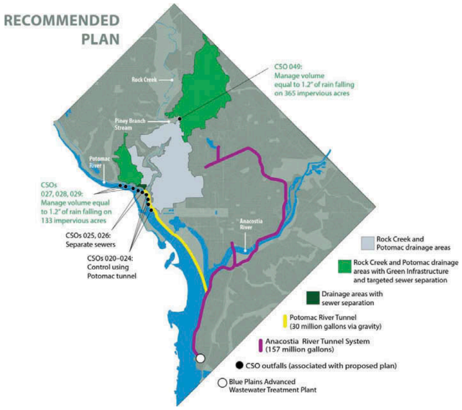


Figure 1. View of DC Water's Clean River Plan.

2 THE GEOLOGICAL CONTEXT

2.1 *Potomac formation*

The project area is located at the western edge of the Atlantic Coastal Plain Physiographic Province, with the Piedmont Physiographic Province lying to the west, separated by the Fall Line. Starting at the Fall Line and thickening eastward, a wedge of Coastal Plain sedimentary deposits overlie older Piedmont residual soils and crystalline bedrock.

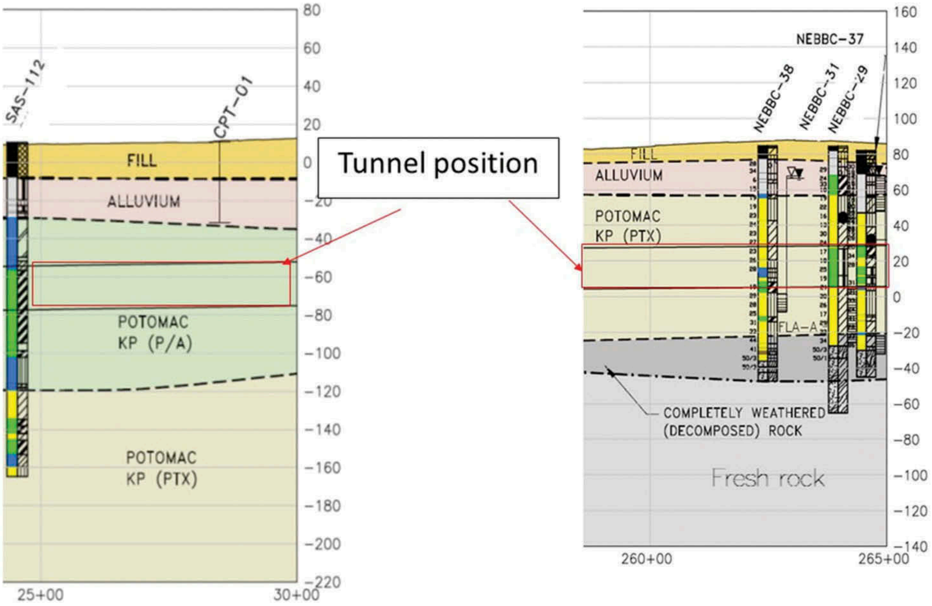
Thus, the geological history of the site is characterized by successive periods of sedimentary deposition and erosion over millions of years. Figure 2 shows two typical stratigraphies located between ART and NEBT and at the intersection area between (Rhode Island Avenue/ 6th street).

A brief description of the soil is provided hereafter:

- Fill comprised of fine-grained to coarse-grained soils containing fragments of construction debris;
- Alluvium deposits consisting of soft clay, loose silt and fine sand, with varying amounts of organic material. Gravel deposits including cobbles and boulders are also present.
- The Cretaceous soils belonging to Potomac formation consist of hard and over-consolidated fine-grained cohesive soils and dense to very dense coarse-grained soils with variable amounts of fine-grained soils. The Potomac soil deposits can be divided into two sub formations: Patapsco/Arundel Formation (P/A) which has predominance of silt and clay and Patuxent Formation (PTX) which has predominance of sands and coarse material.
- Underlying the Potomac Group soils, the Pre-Cretaceous crystalline bedrock is present, formed by metamorphic rocks (predominantly amphibolite with schists and gneiss).

Table 1. Description of the geotechnical units.

Groups	Description
G1	High plasticity, sticky clays with high swelling potential. Slickensided/fissured over-consolidated clays will behave in low-strength blocky manner; may slide or fall as slow to fast raveling ground. Fast raveling behavior when dewatered
G2	Lower plasticity, medium to high stickiness, with medium to high swell potential.
G3	Slow to fast raveling to flowing behavior when saturated depending on amount and plasticity of fines; running behavior when dewatered
G4	Below groundwater table, mixture of soil and water flows into the tunnel from all exposed surfaces; running behavior expected when dewatered



(a) (b)

Figure 2. Typical stratigraphy along Anacostia River System; (a) representative of ART and first portion of NEBT, (b) representative of second half of NEBT.

From the geotechnical point of view, the P/A sub-formation is characterized by G1 and G2 groups while PTX sub-formation by G3 and G4 groups which are described in Table 1.

2.2 *The alignment and profile for the two tunnels*

Although ART and NEBT are excavated in the same Potomac formation there are some pronounced differences mainly because of the distance of each alignment from Anacostia river (see Figure 1). The alignment of ART runs close to the river (under-passed once) with a relatively shallow overburden due to lower ground elevation in this area. The alignment of NEBT has a portion close to the river, but then it deviates away from the river, where ground elevation increases and thus increasing the thickness of the overburden. In this latter stretch, the P/A sub-formation (G1 and G2) becomes shallower and thinner. The P/A sub-formation is missing at locations, where the tunnel is excavated into the PTX sub-formation through the end of the alignment where the bedrock becomes closer to invert. At shallower overburden (almost all ART and southern portion of NEBT close to river) there is an alternation of the two sub-formations, while in the remaining portion of NEBT the presence of PTX is predominant.

3 FACE STABILITY CONTROL

Face stability is maintained by two main components while tunneling using an EPB machine: application of the correct face pressure and proper conditioning of the excavated material in the plenum.

3.1 *Face pressure calculation*

Among different methods to define the face pressure to be applied at the face to control the face stability while tunneling with and EPB machine, the method of Anagnostou & Kovári

(1996) was selected. Using this method, it was possible to better calculate the face stability in the two very different tunneling conditions where the alignment is always located under water table; the cohesive P/A sub-formation and the cohesionless PTX sub-formation.

The key-point has been to optimize as much as possible the applied face pressure to reduce cutterhead wear, to preserve the TBM components and to speed up the excavation process.

This criterion was successfully applied to the ART tunnel excavation and has been used again to define the face pressure for the NEBT tunnel underway between 2018 and 2020. The face pressure is calculated according to the following formulas

$$ST = s' + hf \tag{1}$$

$$s' = F_0\gamma' D - F_1 c + F_2\gamma'\Delta h - F_3 c'\Delta h / D \tag{2}$$

Where *ST* is the face pressure; *s'* is the effective component of ST that resists the ground load and filtration forces; F_0, F_1, F_2 and F_3 are dimensionless coefficients given by nomograms as a function of the friction angle and *D, H* and h_0 ratios; γ' is the submerged unit weight [kN/m3]; *D* is the diameter of the excavation [m]; *H* is the overburden height; *c* is the effective cohesion [kPa] and Δh is the piezometric difference between the fully hydrostatic head (h_0) and the piezometric height in the excavation chamber (h_F). Figure 3 shows the geometry and the main variables used in Equation (1).

In case of cohesionless material the second and fourth terms of the equation (2) are zero, while the third term become zero if no filtration of water through the face is allowed and the full water head is applied at the face.

On the other hand, in cohesive material the second term is not zero and the third and fourth are not zero as well if filtration is allowed.

Therefore, the key-point is thus the filtration, which is namely a function of the third term except in cohesive soil where a reduction is applied as reflected by the fourth term.

According to this principle, and with the aim to reduce as much as reasonable the pressure at the face to make more efficient and economical the excavation process, in soil groups G1 and G2 the calculated and required pressure at face could be set below the hydrostatic head, while in soil groups G3 and G4 the required and applied pressure should be closer or higher than the hydrostatic water head. This principle has been successfully implemented at ART tunnel as shown in Figure 4 where the applied pressure is plotted with the overburden and the water head.

The overall average face loss recorded in ART using topographic survey was 0.27% in the P/A and 0.18% in the PTX, which is the evidence of success of this kind of approach.

Salini Impregilo Healy is proposing the same Anagnostou & Kovári (1996) method for calculating face pressures for the NEBT Project. As of the submittal of this paper (Sept. 2018), the full EPB calculations and report are under reviewed by the Owner.

3.2 *Soil conditioning*

Given the geotechnical groups and behavior as described in Table 1, different strategies were implemented in ART to manage the different soil groups and proposed for NEBT:

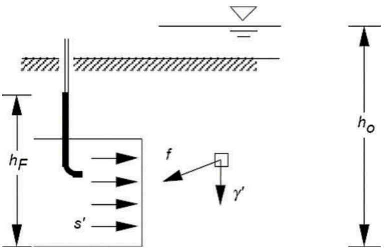


Figure 3. The geometry of the face stability problem from Anagnostou & Kovári (1996).

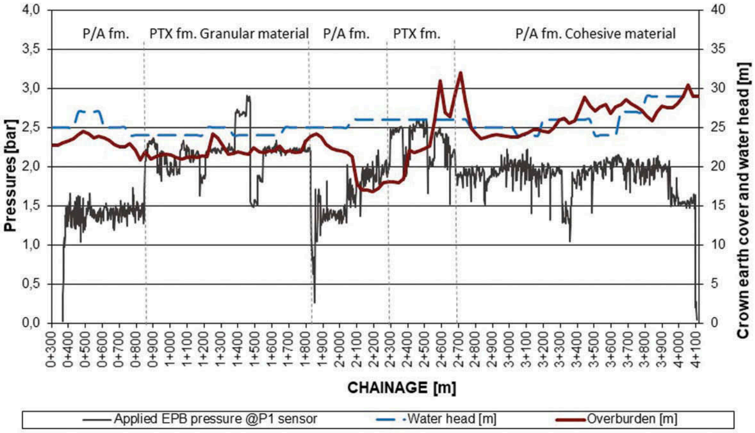


Figure 4. Record of applied pressure for ART.

- Group G1 exhibits high plasticity and high potential for clogging
- Group G2 is similar to G1 but with less potential for clogging and thus results in an ideal material for EPB tunneling
- Group G3A has more sandy behavior with some fine which is good material for EPB tunneling
- Group G4 is a fine to coarse sand material which could create problems due to water inflow and EPB control

Each of the soil groups described above has different conditioning requirements.

Group G1 requires (1) significant amount of conditioning agent with a Foam Injection Ratio (FIR) of 60% or more obtained with a foam concentration (Cf) greater than 2%; (2) Foam Expansion Ratio (FER) of 1:6-1.7 and (3) Water Injection Ration (WIR) of 10-15% introduced directly in the excavation chamber in order flush out the clay from the excavation chamber and therefore reduce clogging.

G2 and G3A require (1) less FIR of 50-55% (Cf 1.6%); (2) FER of 1:6-1:7 and (3) almost no water due to the presence of groundwater.

G4 requires (1) FIR of 50-55% with Cf=1.6 but (2) a FER up to 1:10 to dry out the material with (3) adding of polymers and bentonite to control the EPB along the screw.

4 THE SEGMENTAL LINING

Both tunnels are designed using a fiber reinforced universal ring with a typical 6+1 configuration of bolted and gasketed 1828mm average length segments as shown in Figure 5.

The relevant difference is related to the thickness of the ring itself which changed from 30.48cm (12”) of ART to 35.56cm (14”) of NEBT.

The change is caused by the increase of the overburden, long-term maximum water head and finally the required TBM thrust related to this new condition.

The NEBT segmental lining is expected to support higher loads because of the reduced relaxation effect during excavation in the Potomac deposits which, in turns, leads to a higher load on the liner. In other words, the Potomac deposits do not exhibit as much arching compared to other formations thus increasing in the overburden loading on the liner in addition to the higher possible ground water load.

Moreover, most of the tunnel to shaft adit connections are in an urban area, far from the river where the PTX sub-formation is more present. The sandy deposits are characterized by a lower value of the at rest coefficient (ratio of horizontal to vertical effective in-situ stress)

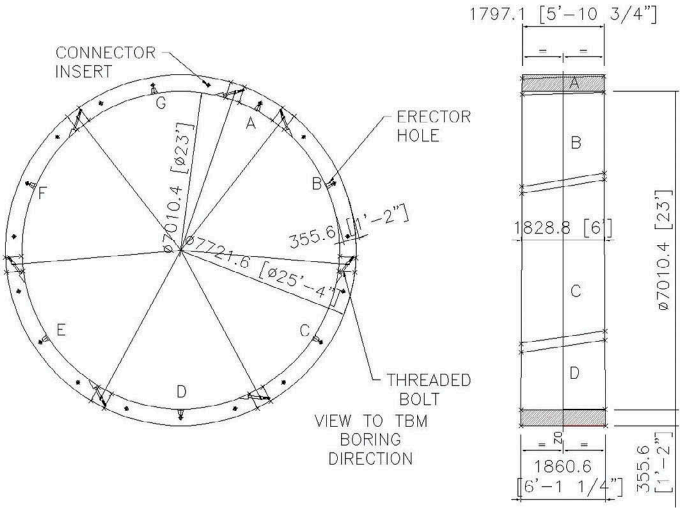


Figure 5. Segmental lining for NEBT.

resulting in higher differential pressure, thus inducing higher flexural loading on the liner. This effect becomes more pronounced at the openings where connections are created, thus requiring a special arrangement for the rings at and near the opening such as conventional rebar reinforcement.

5 UNDERPASS OF RELEVANT PRE-EXISTING STRUCTURES

To mitigate the impact from the TBM tunnel excavation underneath sensitive structures, a compensation grouting campaign was implemented in the ART Project. The crossing of the fragile and essential 108 inches force main located in Anacostia Park was of major concern for DC Water, as the force main is currently servicing a wide area of the District.

The TBM tunneling underneath the 108 inches force main was performed continuously within the area where the TBM area of influence could potentially impact the main. The ground underneath the utility was pre-grouted by means of Tube-A-Manchettes (TAM) ahead of the TBM arrival, followed up by the actual compensation grouting during the TBM crossing. Extensometers, Utility Monitoring Points and arrays of optical targets were continuously read and available to the Engineers and TBM crew during the TBM undercrossing.

Figure 7 shows in section the location of the TAM valves and grouting area, with reference to the ART tunnel and the force main: the targeted area is the ground immediately below the 108" foundation piles. The plan view of the same figure is presented in the same Figure 7 that shows the extension of the grouted area on each side of the TBM tunnel to the extent of the zone of influence.

A series of multi-base extensometers were installed in the same area, with 3 sensors at different elevations, the first one directly above the grouted area, the remaining 2 below the grouted zone and therefore between the grouting and the crown of the tunnel. Figure 7a shows Extensometer arrangement. The data from the instrument sensor located immediately above the new tunnel shows that the pre-grouting operation slightly heaved the ground at S1 sensor located above the grouted zone (Figure 7b), while downward displacement was observed at the other 2 sensors located within grouted zone.

The Utility Monitoring Point UMP-21 shown in Figure 8 was attached directly to the crown of the 108 inches force main, and optically surveyed in real time as the TBM was progressing. This point did not show any significant movement neither during the pre-grouting or during the TBM crossing.

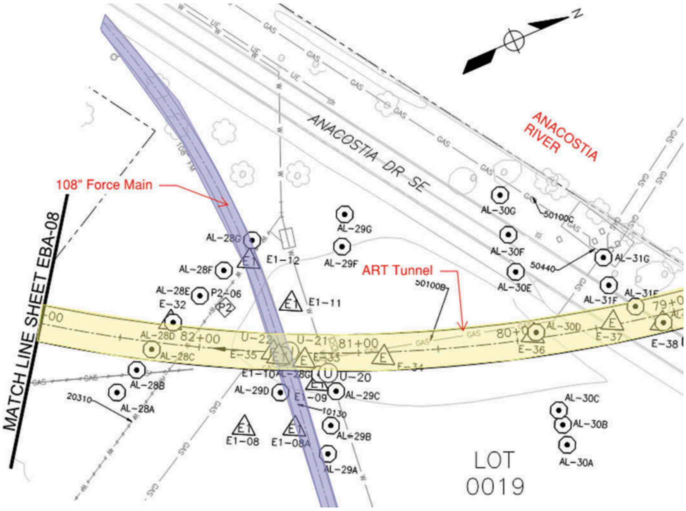
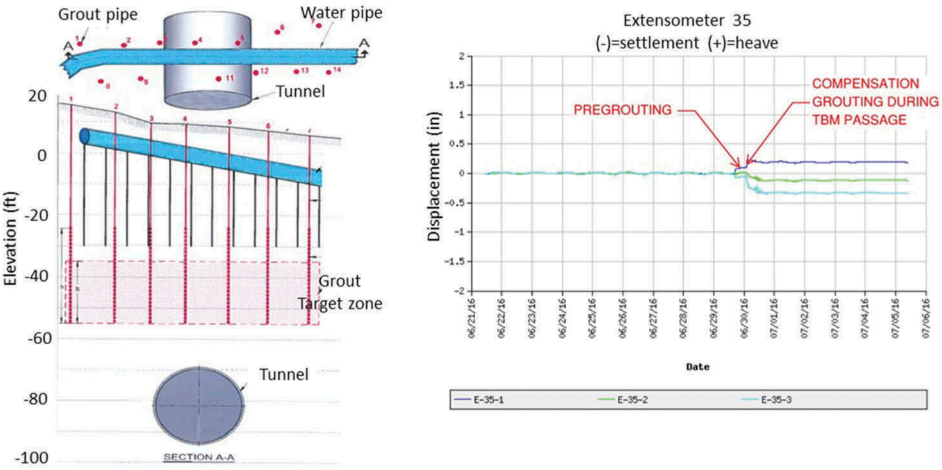


Figure 6. TBM Crossing 108 inches Force Main where (U) = Utility Monitoring Points (E) = Extensometers (o) = Ground Monitoring Points.



(a) (b)

Figure 7. (a) Plan view and section of the TBM Crossing 108 inches Force Main with TAM locations. The red area represented the grouted zone (b) extensometers readings.

Overall, a total of 2437 liters of a cement-bentonite grout was pumped during the preconditioning phase, and a total of 6703 liters during the production phase. A total of 9140 liters were injected in the ground to prevent any settlement during the TBM passage.

Even though the compensation grouting or other means of ground improvement are effective methods to prevent or mitigate settlements, it should be recognized that the best way of controlling ground loss and possible impact on existing structures is through the optimization of the TBM excavation process.

Figures 9 to 11 show the TBM data recorded during the crossing of the 108 inches force main. The following main factors contributed to the success of the operation:

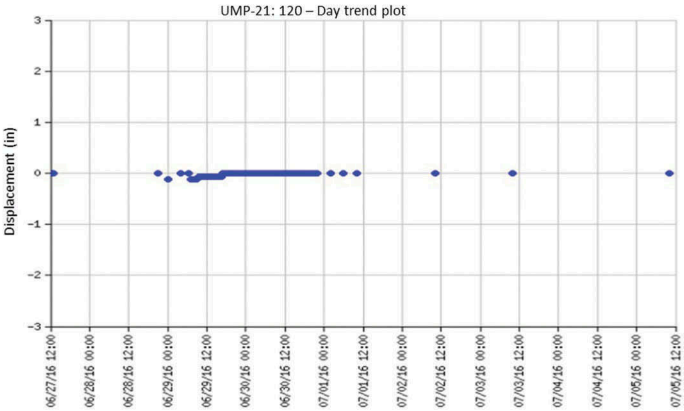


Figure 8. Vertical movement of the 108 inches Force Main at crown.

Table 2. Amount of grout injected.

Grout Pipe location	No. of Ports	Volume (gals)	No. of Ports	Volume (gals)	Total Program Volume (gals)
CMP 01	0	0	15	240	240
CMP 02	3	48	4	64	112
CMP 03	7	112	4	64	176
CMP 04	7	112	16	256	368
CMP 05	1	16	8	128	144
CMP 06	1	16	2	32	48
CMP 07	1	14	9	137	151
CMP 08	0	0	7	112	112
CMP 09	7	112	8	128	240
CMP 10	2	32	6	86	118
CMP 11	1	15	4	64	79
CMP 12	2	32	13	204	236
CMP 13	5	75	8	128	203
CMP 14	4	60	8	128	188
TOTALS	37	644	112	1771	2415

- Performing planned maintenance, add stoppage for precautionary maintenance before entering the zone of influence to the main (conveyor belt extension, cutterhead inspection, other).
- Making sure that all consumable materials are available at the construction site, including emergency stock, to secure continuity of the excavation operation.
- Ensuring that communication is well defined between all key personnel involved in the operation and defining the roles and responsibilities clearly for the crew and reviewing the procedures with each shift and making sure that each one of the key personnel has a backup.
- Review TBM parameters and fine-tune it based on feedback from surveying and instrumentation. This is not always possible as ground condition can change, or surface conditions may not allow. In this case, Impregilo Healy Parsons had a short tunnel length between the Anacostia shore and the 108 inches force main where the information from the optical points arrays was used to tweak TBM parameters such as EPB pressures, conditioning, apparent density and grout pressures.

- Focusing on few key indicators of TBM performance. Until Artificial Intelligence will be widely and commonly used with TBM, the flow of information and data can be overwhelming to inexperienced engineers and operators. Engineering judgement and experience are the key success factors for TBM excavation. Specifically, for this operation key parameters include: apparent density and EPB, grouting volumes and pressures, spoil balance and ground conditioning.
- Have a backup plan and detailed Emergency Response Plan in the event of failure of the 108” force main. These emergency procedures were identified well ahead of time in conjunction with the Owner of the utility DC Water.

The following figures shown the TBM recorded data during the crossing of the 108 inches force main. The figures are indicative of how the excavation proceeded uninterrupted and following rigorous control of key TBM parameters such as EPB, spoil weights, backfill grout volumes and pressures and others.

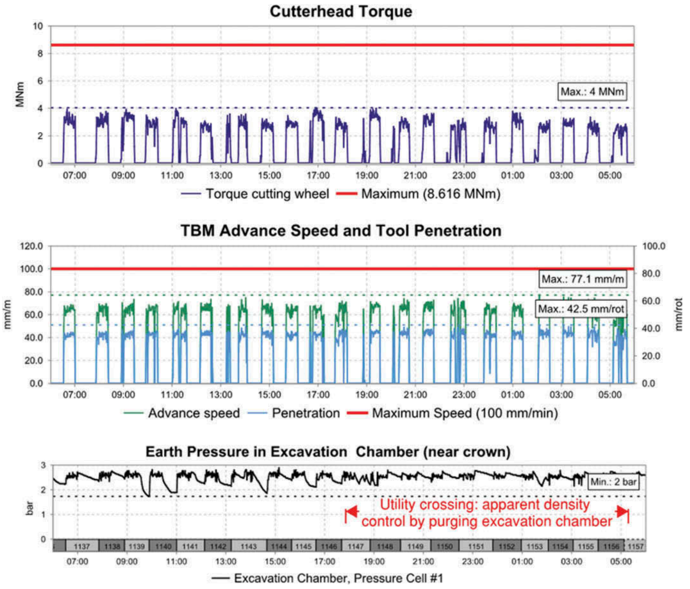


Figure 9. Cutterhead and main parameters.

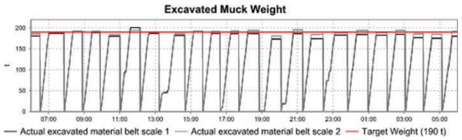


Figure 10. Control of the amount of extracted material.

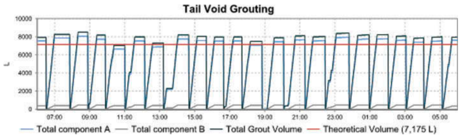


Figure 11. Control of the tail void grouting volumes.

Under the above circumstances, with the TBM operations regularly performed, the grouting may not be deemed necessary but it was injected as an additional measure of protection to minimize the risk of settlement for fragile and essential 108 inches force main. This was a contractual requirement included in the Contract Specifications.

6 CONCLUSIONS

This paper presented the lesson learned by the construction of Anacostia River Tunnel in Washington DC. The design of the Northeast Boundary tunnel, which is the last portion of the Anacostia River Tunnel System and part of the DC Clean River Project, greatly benefitted from these lessons learned both in terms of segmental lining design and TBM operations.

This was possible as both Anacostia River Tunnel and NEBT are excavated within the Potomac formation despite some differences that were well identified in relation to overburden and ground water load.

The varying geological formation has been managed by applying a range of face pressures based on the methodology developed by Anagnostou & Kovári (1996), allowing filtration of water through the face whenever possible to reduce value of applied face pressure and by the smart application of soil conditioning technique with a wide range of FER-FIR and WIR. This guaranteed the success (based on settlements readings) of the ART excavation, where good productions were achieved with minimum impact on existing structures and utilities and is now applied for the NEBT Excavation.

Moreover, during the TBM tunnel excavation, Salini Impregilo Healy Joint Venture will have the opportunity to further take advantage of the knowledge of the ground and the already trained personnel, to further minimize the risk of potential impact on existing structures. In fact, as the experience of the crossing of the 108 inches force main has once again shown, ground improvement techniques associated with good knowledge of the ground, well-engineered TBM processes and controls are key factors for TBM excavation in urban areas.

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