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Baltimore Red Line Project: An Overview of the Cooks Lane Tunnel

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BALTIMORE RED LINE PROJECT
AN OVERVIEW OF THE COOKS LANE TUNNEL

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ABSTRACT

The Maryland Transit Administration's Baltimore Red Line is a proposed 14.1-mile east-west Light Rail Transit (LRT) line connecting the areas of Woodlawn, Edmondson Village, West Baltimore, downtown Baltimore, Inner Harbour East, Fells Point, Canton and the Johns Hopkins Bayview Medical Centre Campus.

Red Line has two tunnel segments namely, the Downtown and the Cooks Lane Tunnels. The Cooks Lane Tunnel (CLT) is the shorter of the two tunnels and will connect the proposed at-grade LRT segment running alongside I-70 with the at-grade LRT segment along Edmondson Avenue. The western CLT portal will be west of the intersection of North Forest Park Avenue and Cooks Lane and the eastern portal will be in the median of Edmondson Avenue close to the intersection with Cooks Lane. The length of the CLT is approximately 7,100 feet inclusive of the cut-and-cover and retained cut sections at both ends. The proposed CLT will be excavated below water table and in a variety of ground conditions ranging from soft ground to competent rock. Variable geotechnical conditions, mixed-face tunnel excavation, tunneling adjacent to the existing buildings and utilities, and cut-and-cover construction in urban environment characterize the design challenges of the CLT.

This paper presents the design approach for the Preliminary Engineering of the CLT and describes the current proposed design and construction methodology. Different alternatives for the CLT including double-track large-diameter TBM-bored tunnel, single-track twin TBM-bored tunnels, and mined (NATM) tunnel are discussed in this paper. The paper also discusses ground water control during construction, tunnel muck removal, and brief description on numerical modeling and tunnel structural design.

1. INTRODUCTION

The Baltimore Red Line LRT Project is a fourteen mile long east-west Light Rail Transit (LRT) line. The Red Line LRT System has two tunnel sections; the Cooks Lane Tunnel and the Downtown Tunnel. The Cooks Lane Tunnel (CLT) segment roughly 7,100 feet long, commences at a west portal located at the highway ramp for I-70 (to be removed) and terminates at the east portal which is the intersection of Edmondson Avenue (US Route 40) and Glen Allen Drive. This segment of project consists of the following construction components: approximately 4,786 feet of tunnels, 495 feet of cut and cover tunnel, and 1,830 feet of retained cut boat section. The approximate horizontal alignment for the RL LRT Project is shown in Figure 1.

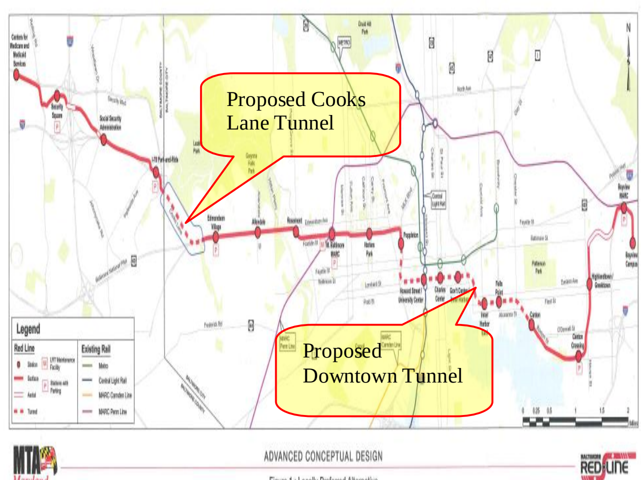

Fig 1. Redline LRT Horizontal Alignment

2. COOKS LANE TUNNEL

The Cooks Lane Tunnel will be excavated beneath the groundwater level, and in a range of ground conditions that are described as high strength and highly abrasive rock, classified as Ground Class I, II, and III in addition to mixed face of rock overlain by Transition Group classified as Ground Class IV and V, and three fault zones, each with distinct properties. The ground geological condition is classified based on the International Society of Rock Mechanics (ISRM, 1982) system of grading as;

GC	**Description (**ISRM Weathering Grades)
V	Completely weathered rock where all material is decomposed and disintegrated to soil but with original rock mass structure remains intact; disintegrates when agitated in water.
IV	Highly weathered rock where more than half is weathered to soil, does not disintegrate when agitated in water.
III	Fair to poor quality, closely to very closely fractured, slightly to moderately weathered rock
II	Good quality, moderately fractured, fresh to moderately weathered rock
I	Excellent quality, widely fractured, fresh to slightly weathered rock

The first 800-ft of the tunnel adjacent to the cut and cover sections at the portal on the West end of the tunnel and the last 400-ft just before the East portal, the tunnel profile will traverse through class IV and V material which is completely weathered and highly permeable. The remaining tunnel path is through competent rock as well as various combinations of ground types that create challenging mixed-face excavation conditions. A mixed face is usually defined as simultaneous occurrence at excavation face of two or more sufficient areas of ground with significantly different properties. The mixed face excavation conditions, in this case, refer to the conditions consisting of varying degrees of weathered and completely decomposed rock overlain by transition group (soil-like material) within 1/2 diameter of the tunnel crown or less. Such conditions are concentrated near the two ends of the tunnel, adjacent to the cut and cover structures (Fig. 2).

3. GROUNDWATER CONDITION

The groundwater levels along the proposed Cooks Lane Tunnel alignment are generally near the top of the Transition Zone, within about 30 feet of the ground surface. Overburden permeability is likely to be low (10^{-7} to 10^{-5} cm/sec) in the clay-rich residual soils but higher in the localized sandy zones. Permeability in the transition zone is expected to be generally low to moderate (10^{-5} to 10^{-3} cm/sec) but much higher locally (10^{-2} to 10^{-3} cm/sec) at open relict fractures, which could produce significant inflows.

Water-bearing properties of rock along the alignment are generally defined by fracture flow, with low permeability of intact rock. Rock mass permeability is expected to be highest in the fractured rock associated with fault zones. Results of packer permeability tests confirm that permeability in the rock mass is generally low (10^{-7} to 10^{-5} cm/sec), with higher permeability (10^{-4} to 10^{-3} cm/sec) in localized zones of closely spaced interconnected fractures or faulting.

Preliminary information suggests that the blanket of clay-rich soils along the proposed Cooks Lane Tunnel alignment is acting as a confining layer, allowing artesian conditions to develop in deeper fractured rock at either ends of the alignment. Recharge would occur through steeply dipping fractures at higher elevations near the central portion of the alignment. Excess pressure heads at depth were about 9 feet above water table levels during drilling. Due to the high percentage of mafic minerals in much of the rock along the proposed Cooks Lane Tunnel alignment, groundwater is expected to be highly alkaline.

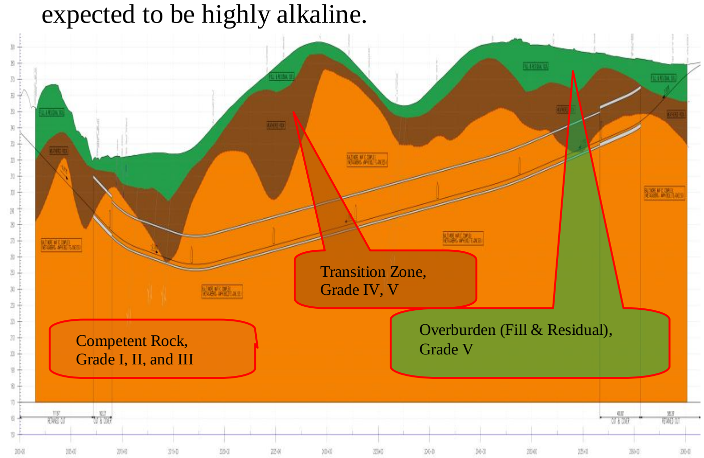

Fig. 2. Geological Profile of the CLT

4. CONSTRUCTION METHOD

The challenging geologic conditions at Cooks Lane Tunnel project required a detailed study to determine the most appropriate and cost effective construction technique for the tunnel. The factors that will contribute to the preferred excavation method include: overall construction cost, construction schedule, suitability of a particular method to the ground conditions, project site constraints, tunneling lengths, tunneling risks, and availability of appropriate expertise. Each of the construction methods offers advantages and disadvantages in their application for construction of CLT.

As discussed earlier, the Cooks Lane Tunnel project offers a unique challenging situation as excavation close to the two ends of the tunnel, need to take place in transition group layer, which is practically soil like material as well as mixed phases of soft soil interfaced with hard competent rock. It is also important to note that approximately 3,200 feet, or 67% of the tunnel drive is situated in competent rock with at least 1 to 2 diameters cover over the crown. The tunnel alignment once in the competent rock must traverse through metamorphic and igneous rocks of the Baltimore Mafic Complex and Chopawamsic Terrane, affected by minor brittle faulting hydrothermal alteration, and younger granite and granite pegmatite intrusions with the following engineering properties.

Unconfined Compressive Strength 13,000 to 42,000 PSI

SINTEF TEST RESULTS:

Drilling Rate Index (DRI):	Extremely Low
Bit Wear Index (BWI):	High to Very High
Cutter Life Index (CLI):	Medium

These types of test results are indicative of a hard rock zone that would require drilling and blasting or a TBM with hard rock cutting capability. The construction methods considered were;

4.1 Cut and Cover Method of Excavation

Use of a cut-and-cover tunnel, though technically feasible, it was eliminated from further considerations due to high cost and its disruptive impact on the surface roads and neighboring properties.

4.2 Sequential Excavation Method (SEM)

For the SEM, excavation can be done using either drill-and-blast method or by using road header machines, or a combination of the two. The advantage of this method is the adaptability, relatively quick commissioning and lower capital investment as compared to a TBM, while offering a mechanized method to mine through rock.

Prior excavation experience through Transition Group material near CLT project site has shown that this material is highly unstable once disturbed requiring extensive stabilization efforts. The other issue is the abrasiveness and high strength of the competent rock formation along the majority of the CLT alignment that limits the excavation method to drilling and blasting. The process is time consuming and will have numerous other limiting factors that make the method not viable.

4.3 Tunnel Excavation by TBM

TBMs offer significant advantages with respect to advancing rate, vibrations, face stabilization and ground settlement control. The use of a TBM will allow for significantly faster production rates as compared with other methods of tunneling. It can be estimated that a TBM will be able to bore through the anticipated ground conditions at the Cooks Lane Tunnel at an average rate of 40 feet/day. The use of bolted and gasketed, pre-cast concrete segments as permanent liner by the TBM supporting system allow for economies of scale and the use of assembly line fashioned mechanized ground excavation, installation of segmental liner, grouting application and machine propulsion will result in cost effective method of construction.

Use of a TBM also offers comparative benefits with respect to impacts on the adjacent properties. For most part, all of the construction activities will be focused around the launch pit, which is located away from most of the stakeholders. At the end of the run, the TBM machine will have to be extracted at Edmondson Avenue that is a short duration activity.

A critical element of this project is control of groundwater inflow and pressure. Under similar ground and groundwater conditions near the Cooks Lane portal locations, compressed air TBM was employed in a similar project to maintain ground and groundwater control which resulted in many complications. With the anticipated poor ground behavior especially within the transition group materials and anticipated mixed faces combined with the relatively large excavation (~23 ft), use of compressed air TBM would be a risky endeavor.

Tunnel excavation in challenging environment such as CLT, in the past 20 years, has made spectacular improvements with excavation control by the application of pressurized-face shielded TBMs; such as Earth Pressure Balanced (EPB) or Slurry (SF) TBMs. Regardless of the TBM type used, there are challenges when tunneling in mixed grounds such as uneven/unbalanced cutter force distribution at excavation face between the rock and soil. In such situation the cutters on rock attract more applied thrust than that on soil causing frequent impact loading and intense hammering effect on cutters and bearings resulting in high cutter wear and damage. The TBM operator will need to lower both thrust pressure and reduce advancing rate resulting in lower cutting efficiency. Other potential issues include excessive over-cutting of soil, leading to large ground settlement, high groundwater seepage at interfaces, jam of roller and cutter bearings, and difficulties in removal of mixed muck from the excavation chamber.

An alternative for circumventing the potential complications for excavating tunnels in mixed ground using TBM is to either modify the design of TBM to suit the ground conditions or conditioning the ground to suit the available TBMs.

Design Modifications to the TBM

- Change the cutterhead to improve the flow of material to the plenum:
- Decrease the number of cutting discs;
- Replacing the cutterhead with larger area of openings and less number of cutters.
- Modify the screw conveyor:
- Adding a second screw conveyor behind the existing one; or replacing the existing one by a single, longer screw conveyor.
- Modify the conveyor belt, making it slightly less inclined.
- Operating TBM at lower rpm at mixed face.

Conditioning of the Ground to suit available TBMs

- Conditioning of the grades III/IV and V materials, to make the grade III/IV less permeable and the grade V more stable.
- Jet grouting in grade V materials and permeation grouting in grades III/IV materials.
- Temporarily lowering down groundwater table to reduce water pressure and water inflow.

For the Cooks Lane Tunnel, it is anticipated that the TBM will traverse through competent rock for approximately 65% of the run while the remaining 35% is either in transition group material (soil like), mixed face, and highly jointed rock within the fault zones. For this reason, it is necessary to use a modified EPB machine that is able to handle good quality rock, as well as fractured/weathered/decomposed rock and soft ground conditions. Therefore, a hybrid EPB machine capable of switching its operational mode from a pressurized mode where needed to an open unpressurized mode when it is in rock and vise versa is recommended.

5. A SINGLE OR TWIN BORE TUNNEL

In order to reduce risks associated with tunneling under major utilities, a minimum clearance of 10'-0" is established for evaluation purposes. Use of 10'-0" clearance above the tunnel will have adverse impacts on project profile for the large diameter single bore option and will push the profile gradients beyond the project established criteria of 7% gradient. The use of smaller diameter TBM will better allow the project profile to satisfy the project criteria and further minimize certain construction risks, but exacerbate other risks. Technical, but risk-mitigated, though not risk-absent, solutions for tunneling directly underneath major infrastructure are possible and employed on routine basis. That, of itself, should not be the metric to eliminate a potential construction option.

The cross-sectional requirements are similar for either the large diameter bored tunnel or the twin bored smaller tunnels. However, the out-to-out cross-sectional requirements for a twin bore TBM tunnel will likely violate the limits of the Right of Way in some locations, particularly near the turn from Cooks Lane onto Edmondson Avenue requiring easements. There are, however, driving concerns for each of the two, single and twin bore, options; these concerns are highlighted below:

5.1 Single Bore – Dual Track

The single bore option consists of dual tracks separated by a fire-rated wall to satisfy NFPA 130 requirements. Due to the need for dual tracks and a fire-rate wall, the preliminary tunnel diameter is established at 37 feet (Fig. 3). This results in the following key concerns:

a. A minimum 900 ft turn radius is required, resulting in increased private property impacts at the curve onto Edmondson Avenue.

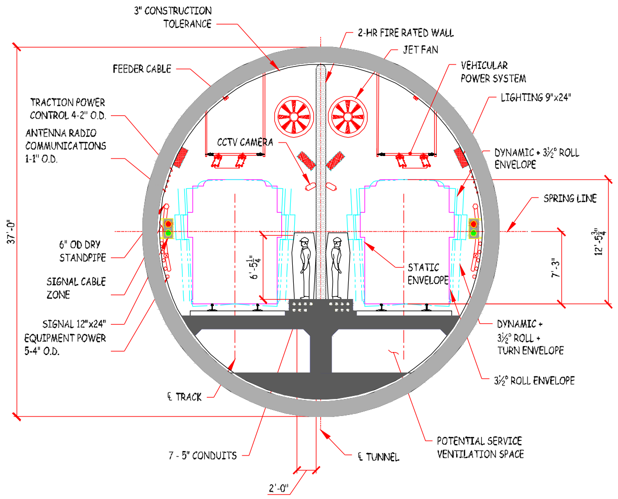

Fig 3. Typical Single Bore TBM Cross Section

b. Due to the larger turn radius, and in order to meet the minimum half diameter cover requirements, the retrieval pit will need to be located on the turn from Cooks Lane to Edmondson Avenue; the location of the retrieval pit and the associated cut-and-cover operations would adversely impact the Maintenance of Traffic on Edmondson Avenue during construction.

c. At the point at which the single bore tunnel passes under the private properties in the vicinity of Cooks Lane and the Edmondson Avenue, the cover to the tunnel crown is exactly one-diameter and decrease to six-tenth of diameter as it completes it run under the private properties. The challenging aspect of this is that the tunnel faces advance transition material to mixed face conditions, just as the TBM begins to bore under the private properties.

d. Use of a 37'-0" diameter generates approximately 36% more excavated volume, when compared to the twin bore option. Handling is more difficult since the rate of production is much higher than for twin bore option; disposal is more costly due to the increase in quantity.

e. The tunnel face for the drive is approximately 280% larger than for a single bore option than for the twin bore option. While use of an EPB machine helps mitigate the construction risks associated with mixed face and soft ground tunneling, it does not eliminate it; the increase in the tunnel face (as compared to twin bore option) will increase the mitigated risk.

f. At the western end of the tunnel, maintaining clearance (minimum of 10 feet) to existing utilities (in particular the 84" diameter storm drain) in the vicinity of the west portal with a Single Bore TBM will drive the track profile lower and increase the already steep grade needed to tie-into the segment near I-70.

As a general note, all of the items noted above are technically addressable, but there are project risks and cost associated with each one of them.

5.2 Twin Bore – Single Track

The twin bore option consists of driving parallel tunnels between portals, each of the tunnel carries a single track. This results in a tunnel diameter equal to 22 feet, approximately 15 feet smaller than the single bore option.

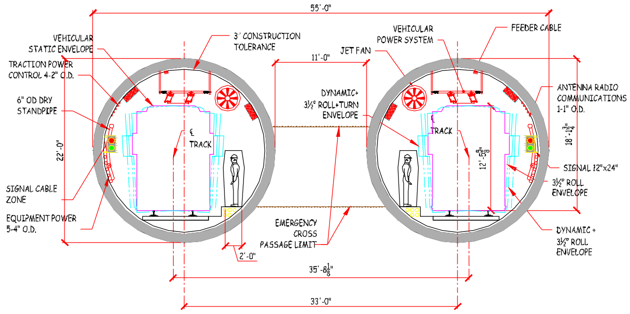

Fig 2. Typical Twin Bore TBM Cross Section

The use of twin bore option results in the following key concerns:

a. Pillar between twin bores is approximately one-half of the tunnel diameter. While technically it is feasible, use of pillar size one diameter or greater is preferable to avoid construction risks. Detailed analysis will need to be performed to substantiate use of such pillar size, as well as to determine any necessary segmental lining modification or ground improvement measures while driving the second bore. Risks are mitigated by the use of single shield system where the TBM thrusts forward from the segments thus sharing jacking loads between segments and ground.

b. Surface impacts due to twin bore need to be studied more carefully, as dual drive will have accumulative effects on the surface, in terms of degree of settlement, as well as the extent of the settlement trough.

c. Increased cut-and-cover tunnel length required at Edmondson Avenue to allow adequate space to transition track centerlines from twin bore position to retained cut position.

d. Requires significantly larger footprint for temporary works and for permanent cut-and-cover segment.

e. Requires installing ventilation system in much tighter space, as opposed to larger overhead room in a single bore option.

f. Twin bored tunnels require use of cross-passages to satisfy NFPA 130 emergency egress requirements. Cross-passages will need to be mined using SEM methods and will require penetration of the tunnel pre-cast segmental liner. Where rock is highly abrasive with high unconfined compressive strength, use of drill and blast method will be required.

With respect to project site constraints, and accessibility and construction staging, it does not appear that there are significant impediments. The entire area around the I-70 on/off-ramps can be used for staging. A comprehensive study is underway on pros and cons for each of these two alternatives and even though for the sake of uniformity with the downtown tunnel it has been recommended to have a twin bored tunnels, the jury is still out on this issue.

6.0 GROUNDWATER CONTROL

Based on the anticipated ground and groundwater conditions along the proposed Cooks Lane Tunnel alignment, a convertible hard rock TBM capable of operating in both open and pressurized-face modes has been recommended. The machine will be operated in pressurized-face mode during tunneling through all soft ground, mixed-face conditions, Transition Group, and short stretches of fractured rock with high groundwater inflow and should be converted to open mode (i.e., unpressurized) during tunneling through competent rock.

The TBM-bored tunnels, because of the use of pressurized-face machine require a gasketed pre-cast concrete segmental lining which will prevent the inflow of groundwater into the tunnel over the lined portion of the tunnel. The groundwater control measures should therefore provide positive control of the inflow from the advancing tunnel face. Groundwater control during pressurized-face tunneling using a convertible Earth Pressure Balance TBM is achieved by the formation of a soil plug inside the face plenum (i.e, excavation chamber) to balance earth and hydrostatic pressures. The face pressure is primarily maintained by the screw conveyor operations and the presence of a soil plug.

Should the inflow of groundwater or loose materials during open mode tunneling in rock start to increase, it can be controlled by changing the operation mode from open face into a pressurized face mode to control the groundwater and material. For the pressurized face mode in rock, ground conditioning material will need to be added to facilitate the formation of the plug inside the screw conveyor since rock spoil typically has characteristics that are not conducive to plug formation.

6.1 Dewatering at the Tunnel Face

If the inflow of groundwater from the face is not detrimental to the safety and construction activities and if there is no risk of ground settlement due to drawdown of water table, the groundwater may be allowed to simply drain into the TBM muck handling system. The infiltrated groundwater will then be collected and disposed of properly. Groundwater treatment will be required prior to disposal if the water is contaminated. However, this method is not possible while excavating in the

Transition Group materials due to their inherent instability below the groundwater table.

6.2 Drainage from Probe Holes

Probe holes are drilled ahead of face to verify ground and groundwater conditions to be encountered by the TBM and provide information for TBM operation and control. These holes will pre-drain the rock and other materials. Pre-drainage in the Transition Group materials is possible but they generally would also require supplement with pre-grouting and ground pre-support measures.

6.3 Rock Mass Grouting

Groundwater control can be achieved by the use of probe-drilling ahead of the face followed by pre-grouting of the rock mass. The primary purpose of a pre-grouting scheme is to establish an impervious and stable zone around the tunnel periphery by reducing the permeability of the most conductive features in the rock mass. Groundwater inflow into rock tunnels occurs at joints, bedding planes, and other discontinuities. Grouting will seal these conduits and therefore effectively reduces or completely eliminates the inflow of water.

Pre-excavation grouting from the ground surface may be possible depending on the availability of ground surface staging area for grouting operations and the depth of the zone that needs to be grouted.

Open mode tunneling through Transition Group materials with grouting requires special consideration. Furthermore since they retain relict rock structures such as discontinuities, these relict structures also "take" grout and can transmit groundwater. As stated previously, open mode tunneling through these materials generally requires a combination of pre-drainage, pre-grouting and ground pre-support.

7. CLT MUCK HANDLING

The properties of the TBM muck vary depending on the type of soils encountered and the additives used in the excavation system. TBM muck consists of a mixture of whatever soil and rock materials that is present at the tunnel face plus appropriate conditioning agents. The TBM in EPB mode passing through soft ground, conditioning agents are added to the muck in order to produce a paste-like or sludge-like material. The resulting material enables the TBM to resist groundwater pressure and support loose or raveling material at the face of the TBM. The consistency of the conditioned muck also facilitates removal of the muck through the screw conveyor and conveyor belt. Conditioning agents are also used to reduce the frictional wear of the muck on the cutterhead, thereby reducing abrasion, improving cutterhead life, and facilitate cooling of the cutterhead during operation.

Soils are conditioned with the use of various additives. Soft clays and silts excavated under groundwater may be formed into a paste without much conditioning. Stiff clays and silts may require the addition of water and other agents to improve workability. Foams and polymers are injected into granular soils to improve the apparent cohesion and consistency of the overall muck. Very granular soils, such as clean coarse sands and gravels, may require the addition of bentonite or other clay minerals.

Therefore, muck from an EPB TBM excavating through the overburden material and transition group layers will come to the surface as a watery paste or sludge-like material consisting of a mixture of fines, granular particles, water, and conditioning agents. Handling of this material will require proper processing to remove water or otherwise stabilize it for transport. Processing may also be needed if the material is to be stored or stockpiled.

For the CLT project more than 65% of tunneling will be done in rock, where the TBM can operate in open face mode. Muck resulting from hard rock chipping is predominantly granular and includes a high percentage of gravel and possibly small cobbles size particles. The gravel and cobble size particles are elongated in one direction as a result of the mechanics of chipping excavation. The process of chipping also generates sand and silt-sized particles. Combined with infill in joints, fractures, and weathered seams, the resulting muck from hard rock TBM excavation is generally a coarse grained material consisting predominantly of gravel sized rock chips, but also includes significant percentages of sand and fines. This material generally classifies as a silty or clayey gravel depending on the natural and volume of fine-grained weathered rock or joint infill within the overall rock mass.

The portals for launching and retrieval of TBM for the CLT will be excavated using open cut method. Excavations will be supported using secant pile or solider pile walls and shotcrete lagging along with intermediate soil anchoring or soil nailing. Excavations of this type will involve two stages: excavation of the slurry filled shafts for secant piles or solider piles, concrete placement under slurry, and staged excavation of the box itself. Muck material produced during excavation of the vertical shafts for the secant or solider piles will need to be re-captured and processed prior to disposal. Processing of this muck, however, may just involve settling of solids rather than a large slurry processing plant, as the volume of excavation for the shafts may not be significant.

The open cut excavations will be performed using conventional earthwork equipment and will result in muck consistent with conventional bulk excavations. However, it is worth noting that the majority of the excavated materials will be below the groundwater table and may therefore be in a saturated condition when excavated. The portal excavations will proceed from the ground surface to the tunnel depths, and will therefore encounter all soil and rock strata above the base of the structure. As a result, mucks from these excavations through the fill material that may include miscellaneous debris and obstructions.

The excavation process for the portals does not include the use of additives, conditioners, or suspension fluids like TBM excavation. Therefore, the overall properties of the muck will not be significantly different than the in-situ soils except for the possibility of materials of different properties mixing together during excavation. The gradation of the muck may therefore be a combination of the in-situ gradations, and the overall muck will be a mixture of gravel, sand, silt, and fines depending on the effort made separate various soil materials at the point of excavation.

7.1 Hazardous Materials

The term "hazardous material" refers to naturally occurring materials and manufactured materials that may be hazardous to the environment or workers. Materials that are typically referred to as "subsurface contaminants" are considered man-made hazardous materials that have been placed as fill (if solid) or leaked into the ground (if liquid). Hazardous materials or contaminants may occur as solids, liquids, or gases, and may change phase during excavation. For example, volatile compounds may exist as liquid contaminants in the ground, but may vaporize upon exposure in excavations. A continuous air monitoring system needs to be implemented to provide screening for early warning detection of potentially hazardous air-born material.

Preliminary investigations indicated that naturally occurring asbestos minerals may be present in rock to be excavated for the CLT. These minerals pose a potential inhalation hazard if they are disturbed during excavation and allowed to become airborne, requiring worker protection and dust control. Specialized handling and disposal at an approved facility are also required for excavated asbestos-containing rock. Additional testing is required before naturally occurring asbestos can be ruled out along the CLT alignment.

Radon gas is another potential naturally occurring hazardous material. The Red Line project is in the US EPA Radon Zones 1 and 2 (high to moderate radon potential). The radon source is most likely the quartz-rich crystalline rock, but pockets of high radon can also occur in sediments. Radon gas would not pose a hazard for workers during excavation because the tunnels will be ventilated, and the workers will not have long-term exposure. Gabbroic rock types such as those at Cooks Lane often contain sulfide minerals, including pyrite, as observed in recovered Cooks Lane Tunnel rock core samples. Sulfide minerals can potentially produce hydrogen sulfide gas as well as potentially corrosive ground water, both of which will require consideration for construction and muck handling.

The CLT segment passes through an area that has experienced urban development, re-development, and industrial activity since Baltimore was founded in 1729. As with many industrial activities over the last few hundred years, industrial practices have changed and developed over time. Manufactured hazardous materials are likely to have been discharged, either intentionally or unintentionally, into the subsurface due to the various commercial and industrial operations throughout this area. Both solid and liquid hazardous materials of varying concentrations are likely to be present in isolated locations within the general area of the CLT. This is typical of many cities of comparable age and development history throughout the country and is a potential issue on any large underground project.

Based on the presence of a gas station near the proposed alignment, contaminated soil and groundwater are potentially present and will require special handling and treatment for disposal. Tunnel construction may also affect the direction and transport rate of any existing contaminant plumes. A detailed assessment of the depths and strata that may include hazardous contaminants has not been performed yet. Further study is underway to assess whether the mined tunnels will encounter these hazardous contaminants or if the tunnels will be deep enough to pass under them. The open cut excavations that encounter petroleum contamination will involve treating contaminated soil, dewatering effluent, and disposal of contaminated soils if the contamination levels exceed permissible limits based on safety standards.

7.2 Muck Removal Methods

The muck can be transported and removed from the tunnel by rail cars or various conveyor belt technologies. The choice of the muck transportation and removal method depends on many factors such as tunnel size or diameter, length of excavation from each heading, type and consistency of the excavated material, the grade of the tunnel, surface access (shaft versus portal), method of excavation (SEM versus TBM), and type of TBM for a TBM-bored tunnel.

7.3 Traffic Impacts

The largest source of construction traffic will be the transport of excavated materials from the tunnel to various permanent disposal areas. Tunnel excavation will generate large volumes of muck. It is anticipated that tunnel construction will proceed as one heading at a time from the west portal. Muck will be hauled away using 3-axle dump trucks (maximum 20 cubic yard capacity), assuming a maximum allowable fully loaded truck weight of no more than 55 kips – based on the State of Maryland regulations. The daily truck traffic volume is proportional to the volume of the excavated material per day; for the bored tunnels, this will be directly proportional to the TBM advance rate; for the retained cut and the cut and cover segments, it will be proportional to the staged excavation progress. The total estimated muck volume for the CLT is presented in table1.

The estimated number of construction truck trips per day for one tunnel heading and excavation advancing rate of 40-ft/day is 62 truck loads per day. For TBM excavation, an average advance rate of 40 feet per day is currently utilized based on the anticipated ground conditions along the Cooks Lane Tunnel alignment. However, the advance rate will be modified as laboratory and additional site data becomes available.

If there are restrictions on the hours during which muck truck traffic to and from the site is allowed, then the on-site muck storage must have sufficient capacity to store the muck produced during the restricted period.

Table 1- Total Bulk Volume of Muck for Each Ground Class

Ground Class	Bulk Volume Yd^3
Fill	87,949
Transition Group Material	136,778
Rock (I,II,III)	289,188
Total	513,915

8. TUNNEL NUMERICAL ANALYSIS AND DESIGN

A two-dimensional finite element analysis was performed using PLAXIS computer program in order to evaluate the deformation and stability of the tunnel excavation, structural adequacy of 10-inch thick reinforced concrete liner, the impact on the adjacent buildings and utilities, and finally the impact of excavation on the soil or rock pillar between the two parallel tunnels. For the numerical modeling, each TBM excavation sequence is simulated in the analysis in separate but consecutive stages to calculate soil structure interaction at each stage. A typical numerical model is shown in the Figure 3.

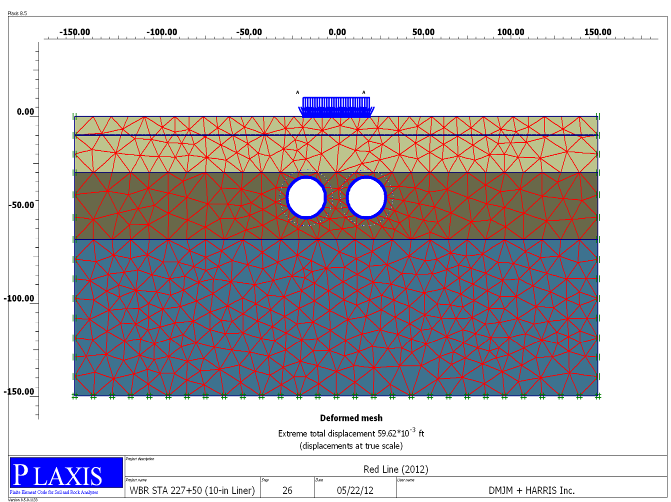

Fig 3. A Finite Element Model of CLT

The following excavation sequence is assumed for the modeling and calculations: excavate one foot length the first tunnel, install the 10-in reinforced concrete liner and apply 0.5% contraction of soil around the liner to simulation ground loss, then, excavate one foot length of the second tunnel followed by installation of concrete liner and application of 5% ground contraction. The geotechnical parameters used in the analysis and modeling are presented in the Table2. The imposed 5% contraction is due to 4-inch over-excavation by the TBM cutter head ahead of the shield. A portion of the annulus space created as the result of over-excavation is continuously filled by cement grout injected just behind the cutter head. However, ground around the shield will contract to certain extent.

Table 2. Geotechnical Parameters

Ground Type	*Fill*	*Transition Group, Ground Class V*	*Rock, Ground Class III*
Modulus of Elasticity (ksf)	*144*	*864*	*26000*
Poisson's Ratio	*0.35*	*0.31*	*0.25*
Unit Weight (pcf)	*120*	*130*	*190*
Cohesion (psf)	*0*	*350*	*2400*
Friction Angle (degree)	*28*	*34*	*45*
Lateral Earth Pressure Coefficient	*0.53*	*0.44*	*0.5*

8.1 Distortion of Tunnel Liner

The concrete liner once installed need to carry the vertical overburden loads, lateral earth pressure excreted by the surrounding soil, as well as hydrostatic groundwater pressure. This will cause deformation of the concrete liner. By further disturbance and plastification of the soil as the result of excavating the second tunnel parallel to the first one, the degree of distortion and ovalization of the first tunnel increases. The original displacement and final displacements of the existing tunnel after the excavation of the second tunnel are presented in Figure 4. The magnitude and direction of the additional displacements imposed on the liner of an existing tunnel due to excavation of an adjacent parallel tunnel strongly depend on the support conditions and the magnitude of displacements allowed in the second tunnel

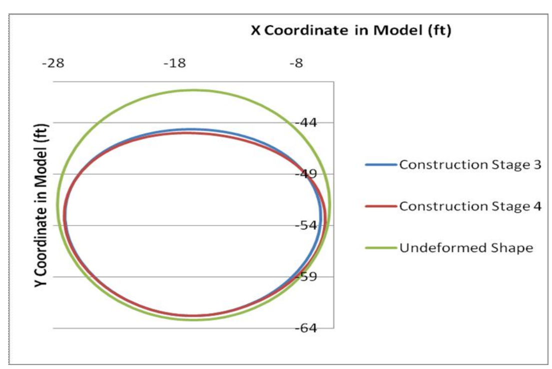

Fig 4. Deformed Shape of the Tunnel (Exaggerated)

8.2 Ground Settlement

Based on the numerical analysis, the ground and building movement, the shape of the ground settlement trough, and the angular distortion and lateral strain induced in the buildings were then estimated. The results were further used to evaluate the responses of buildings and utilities to the ground movements and to determine whether or not buildings or utilities are potentially at risk of being damaged.

For assessing the potential damage levels in buildings, the latest version of Boscardin *et al.* 1989 proposed damage criterion was adopted. In this approach, building damage levels are correlated with the induced angular distortion and lateral tensile strain developed at the foundation level of the building. Angular distortion and lateral strain were calculated for the buildings in the proximity of tunnel excavation using the results of finite element analysis.

Furthermore, the findings of this analysis formed the basis of recommendations to optimize the tunnel excavation sequence in order to mitigate the potential impacts of induced ground movements on the adjacent existing buildings and underground utilities.

Effect of tunneling on ground settlement is shown in Fig 5. The construction stage 3 and 4 shown in this fig depicts the ground settlement trough created upon completion of one of the twin tunnels and curve depicted as stage 4 is the ground settlemet trough created as the result of excavating the second tunnel.

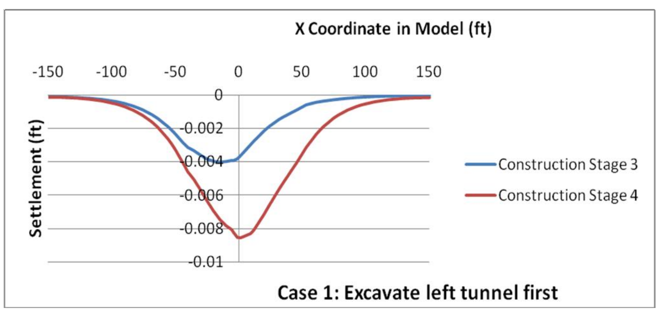

Fig 5. Vertical Displacements after Completion of First and Second Tunnels

8.3 Impact of Tunneling on the Pillar

For the two parallel tunnels, the construction of first tunnel modifies the state of in-situ stresses and displacements within the pillar between the two tunnels as well as around the second tunnel to be followed in excavation. The second tunnel excavation will be within disturbed soil or rock and will impose additional stresses in the medium and additional force on the first lined tunnel. The interaction of the two parallel tunnels and the influence of such interaction on stresses, forces and displacement around the tunnels were also evaluated through numerical modeling. Several cross sections along the tunnel profile, where the two tunnels were situated in the transition group material, competent rock, and various cases of mixed phases of ground conditions were modeled and analyzed. Fig 6 shows the relative shear stress within the pillar when the two tunnels are located in the transition group material. The figure shows that with a pillar of 10-ft between the two tunnels, the material confined between the two tunnels have exceeded its shear strength capacity and plastified. In other words, the TBM excavating the second tunnel will be working in much looser material on the side closer to the first tunnel. This will impact the way TBM operator steers the machine through a layer with different consistency from one side of the excavating face to the other. It also imposes additional bending moment and axial force on the lining of the first tunnel.

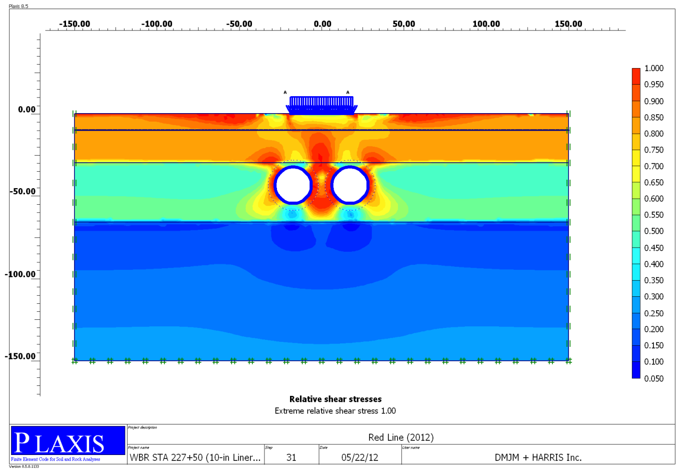

Fig.6 Relative Shear Stress within the Two Tunnel Pillar

9. CONCLUSION

This paper presents the process and most important attributes the design team had to consider during the Preliminary Engineering of the Cooks Lane Tunnel. The preliminary design was done based on initial geotechnical and geological information that was available during this phase. The geotechnical investigation for the Redline project is still ongoing and will impact the design as more information becomes available. The paper also describes the current proposed design and construction methodology. Different alternatives for the CLT including double-track large-diameter TBM-bored tunnel, single-track twin TBM-bored tunnels, and mined (NATM) tunnel are discussed in this paper. The paper also presented ground water control during construction, and tunnel muck removal.

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