Slurry Walls, Tiebacks, and Tiedowns: Maximizing the Efficiency of Underground Station Space

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ABSTRACT

The proposed Baltimore Red Line light rail system includes a 3.4 mile downtown tunnel (DTT) with five underground stations. The design of the underground stations involved overcoming several challenges, including limited right-of-way, high groundwater and uplift pressures, and metamorphic rock within the station depths. An innovative design was developed to maximize the internal station space while minimizing cost. The station designs use slurry walls for temporary and permanent support and groundwater control. Depths within rock are supported with cast-in-place concrete walls, the thickness of which are minimized through the use of permanent rock anchors for support of the rock mass and slurry wall toes. Permanent tiedown anchors are used for uplift resistance, which minimizes the station depths, volume of rock excavation, and the volume of deadweight concrete. Design considerations regarding individual elements and overall integration of the slurry walls, CIP walls, and multiple anchor types are presented.

INTRODUCTION

The Baltimore Red Line (BRL) project is a proposed light rail transit line for the Maryland Transit Administration (MTA) that runs east to west through Baltimore City and County. The project includes the Downtown Tunnel (DTT) consisting of 3.0 miles of twin running tunnels, two portals, five underground stations, and a pedestrian tunnel, as shown in Figure 1. The tunnels have an outside diameter of 21.8 feet and are designed to be mined using pressurized face tunnel boring machines (TBMs). The stations, portals, and the pedestrian tunnel are designed as cut-and-cover structures using slurry walls (concrete diaphragm walls) for both temporary support of excavation (SOE) and permanent structural walls. The dimensions of the five underground stations are summarized in Table 1. Design challenges included limited right-of-way (ROW), challenging soils conditions, strong metamorphic rock within the station depths, and high groundwater conditions. The final station designs included innovative use of slurry walls, tieback anchors, rock anchors, and tiedown anchors.

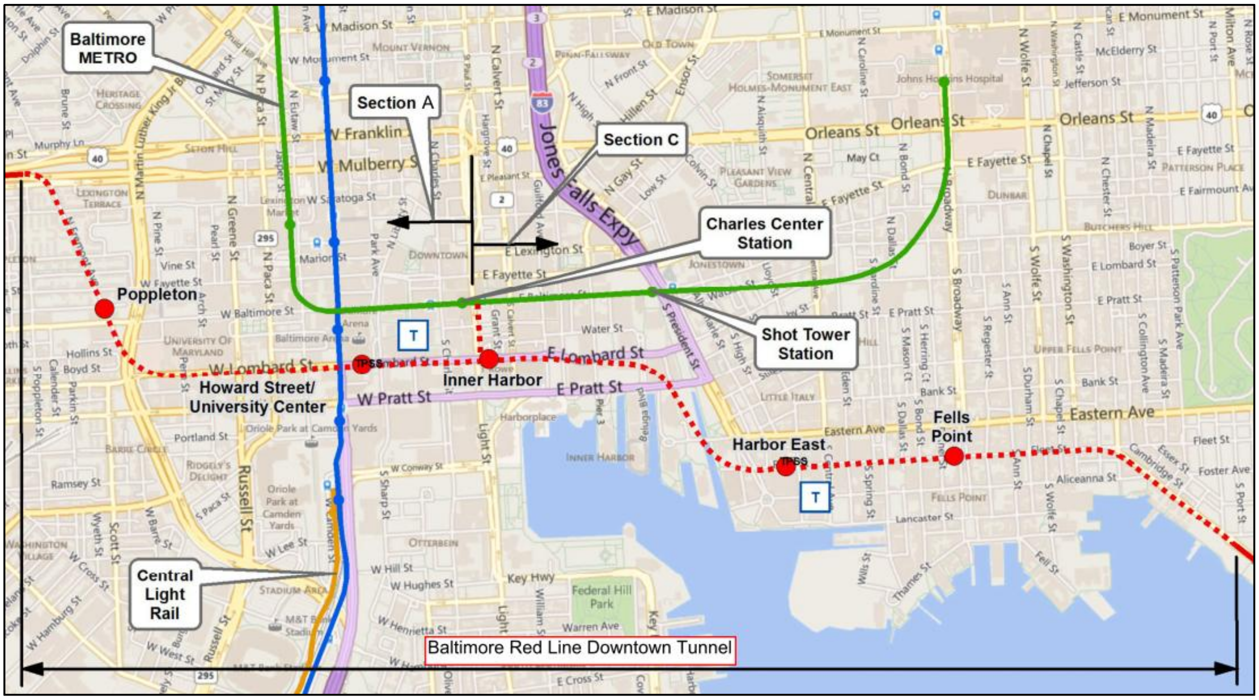

Figure 1. Baltimore Red Line downtown tunnel (DTT) alignment location

Table 1: Summary of Underground Stations along DTT

Station	Length (ft)	Width (ft)		Number of Underground Levels	Maximum Depth below grade (ft)
		Station box	Station box and ancillary/entrance		
Poppleton	281	66	136	2	73
Howard Street / University Center	292	66	119	3	93
Inner Harbor	313	70.25	127	3	90
Harbor East	287	63	143	3	87
Fell's Point	300	63	186	3	98

Note: Station width is measured from outer face of walls

PROJECT CONDITIONS

Site Conditions

Ground surface elevations drop along the alignment from west to east. The western half of the alignment, including Poppleton and Howard Street Stations, is in an upland area with ground elevations of approximately 95 feet descending to 20 feet. The eastern half of the alignment, including the Inner Harbor, Harbor East, and Fell's Point Stations, is in a lowland area along the Inner Harbor waterfront with ground elevations ranging from about 8 to 15 feet and includes flood plain areas. This lowland area includes areas of reclaimed land of former open water or marshes.

Subsurface Conditions

Subsurface conditions consist of variable fill and Coastal Plain sediments overlying crystalline rock of the Piedmont Plateau. Fill consists of miscellaneous uncontrolled urban fill including debris such as rubble, brick, concrete, cinders, etc., as well as possible timber cribs, wharves, or bulkheads in areas of reclaimed land including the Inner Harbor and Harbor East Station locations.

Post-Cretaceous soils underlie the Fill in the lowland areas along the waterfront; these soils are not present in the upland areas. These soils consist primarily of medium dense sand and gravel mixtures classifying as SW, GW, SP, SM, and SP-SM in accordance with the Unified Soils Classification System (USCS). Medium stiff to stiff clay and silt (CL, ML) layers are also present, especially at shallower depths. At the Inner Harbor and Harbor East Stations, within areas of reclaimed land, Post-Cretaceous soils also include soft fine grained silt, clay, and organic silt (CL, ML, OL, OH) within the upper 25 feet.

Underlying the Post-Cretaceous soils are Cretaceous soils consisting of heavily overconsolidated sediments, mostly clean sand and gravel mixtures classifying as SW, GW, SP, SP-SM. Occasional very stiff to hard clay or silt layers (CL, ML) up to 20 feet thick are also present within the Cretaceous.

Below the Cretaceous group are Residual Soil and Transition Zone materials derived from in-situ weathering of the parent bedrock. These materials are soil-like in appearance, but the Transition Zone includes relict rock structure and joints. Intact materials consist of a mixture of sand and fines (SM, ML, CL, MH, CH) and are characterized as very dense or hard. However, the overall strength of the Transition Zone is influenced by relict rock joints and is weaker than implied from soil test data alone. These materials also experience strength loss when exposed in the presence of water.

Beneath the Transition Zone are intermixed igneous and metamorphic rock types. Table 2 presents a summary of the rock types and relative percentages of each at the stations as well as whether rock is encountered within the station depths. Unconfined compressive strengths (UCS) of these rock types range from 2,800 to 35,000 pounds per square inch (psi), with median values in the range of 12,000 to 25,000 psi, indicating strong rock that will be difficult to excavate. Rock quality designation (RQD) values are generally high at the stations that encounter rock above station subgrade, with most values in the range of 70 to 100 percent. Stations with rock below subgrade elevation generally have poorer quality rock with RQD values less than 50 percent on average. Rock is generally the least pervious stratum based on in-situ testing, with permeabilities two orders of magnitude less than the overlying Transition Zone and three orders of magnitude less than the Cretaceous group.

Groundwater is between five and ten feet below grade at all stations except Howard Street Station. The Inner Harbor and Harbor East Stations are also located within the 100 year flood plain.

Figure 2 presents a profile at the Inner Harbor Station that includes all of the units described above.

Table 2: Summary of Rock Types at Underground Station Locations

Station	Percentage of each rock type						Top of rock within station depth?
	Amphibolite	Granite/ Tonalite	Gneiss	Mica Schist	Pegmatite	Other	
Poppleton	54%	46%	0%	0%	0%	0%	Yes
Howard Street / University Center	59%	36%	0%	0%	5%	2%	Yes
Inner Harbor	50%	39%	0%	0%	9%	1%	Yes
Harbor East	20%	21%	41%	2%	15%	1%	No
Fell's Point	20%	0%	58%	0%	23%	0%	No

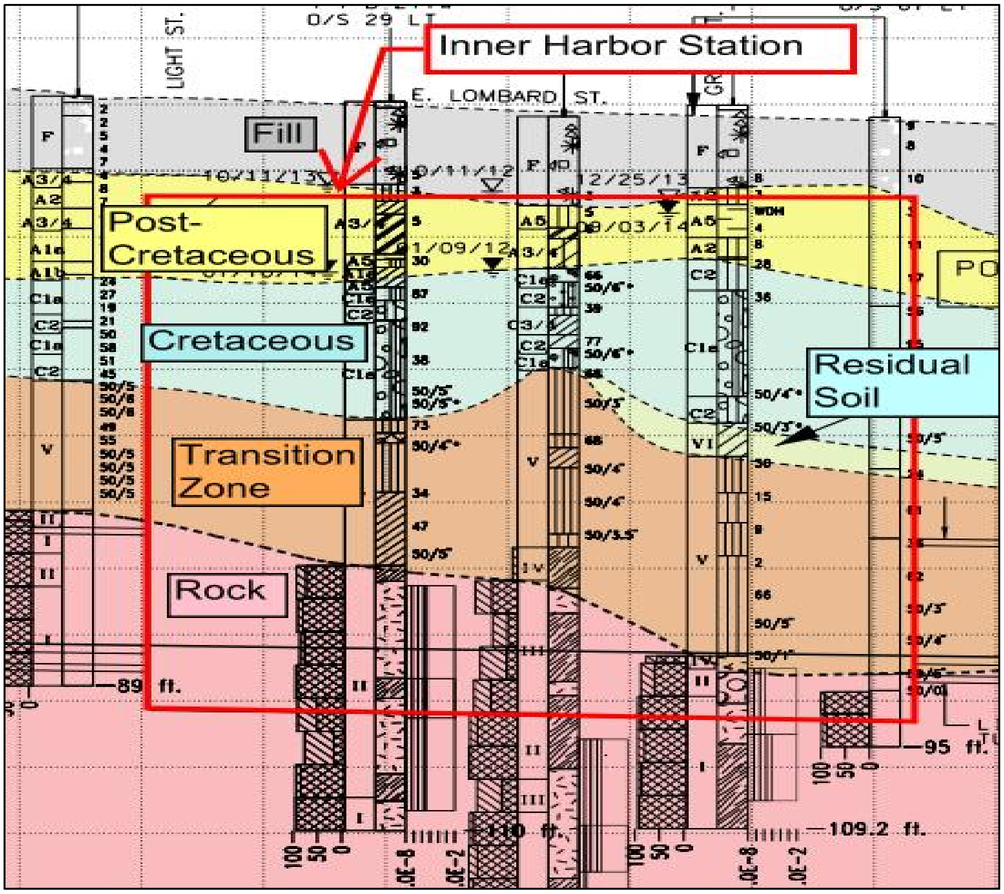

Figure 2. Subsurface profile at Inner Harbor Station

STATION DESIGN CHALLENGES

Challenges due to Project Constraints

Limited ROW. The DTT tunnel alignment generally follows public ROW within City streets. The main station box structures are located within City streets. Entrance and ancillary structures extend outside of the main station box onto side streets or adjacent properties that will be acquired. Available public ROW for the main station box is severely limited, varying from 66 feet to approximately 90 feet. The limited ROW resulted in the need for a one-pass wall system that could be used for temporary excavation and permanent structure support. Even with such a system, construction tolerances will be very tight.

Existing Buildings. There are existing buildings adjacent to all station locations, including registered historic structures, structures of historical character or construction from the late 19th and early 20th Centuries, structures on deep foundations bearing within the station depths, and buildings on shallow foundations. Historical structures are both shallow bearing and sensitive to movement due to age and condition. The distance from the ROW line to the face of adjacent structures varies from less than 2 feet to approximately 10 feet. Examples of station layouts and the proximity of adjacent structures are shown in Figure 3 for the Inner Harbor and Fell's Point Stations.

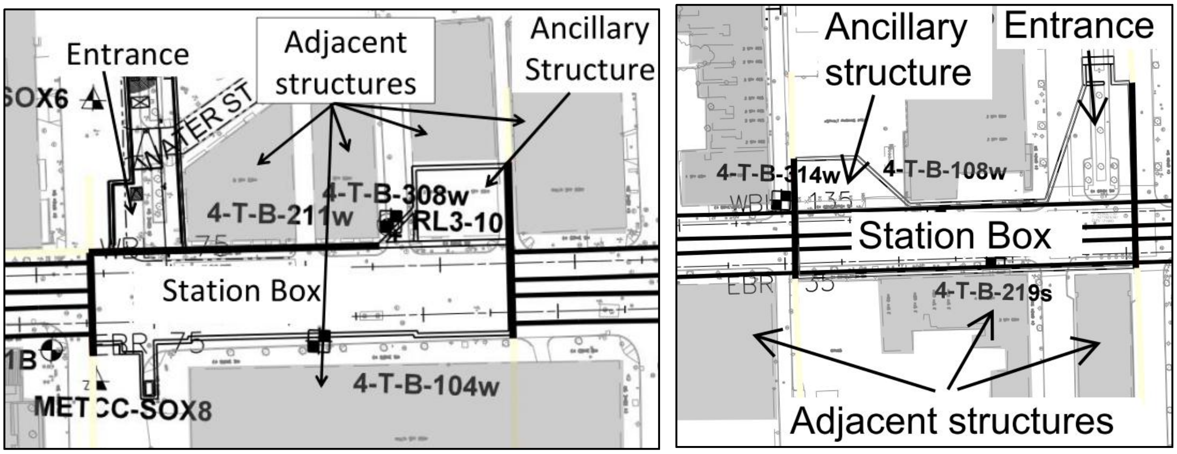

Figure 3. Examples of station layout and proximity of adjacent structures (Inner Harbor and Fell's Point Stations)

Challenges Due to Subsurface Conditions

Soft Soils. The soft soils present at the Inner Harbor and Harbor East Stations are former marsh or estuarine deposits. These soils are highly susceptible to settlements due to changes in stress conditions such as those caused by lowering of the groundwater table in response to dewatering. Similar soils near the Shot Tower Metro Station, indicated in Figure 1, resulted in several inches of settlement during construction of the Metro tunnels; the metro tunnels were excavated using compressed air and limited dewatering. The MTA wanted to avoid similar issues with the design of the Red Line stations.

Lateral Earth Pressure Loads. The stations extend to depths up to 98 feet below existing grades in variable soil conditions. Because the permanent structure walls are restrained at the top and bottom, at-rest pressures are applicable. The project design criteria use the AASHTO LRFD Bridge Design Specifications (2012), which includes determination of K_o with consideration for consolidation history:

$$K_o = (1-\sin\phi)(OCR)^{\sin\phi} \quad \text{(AASHTO, 2012)}$$

In which OCR is the overconsolidation ratio and ϕ is the angle of internal friction. Consolidation tests indicated OCR values for Cretaceous soils in the range of 7 to 12, indicating very high locked-in lateral stresses due to high preconsolidation loads. These OCR values result in K_o values greater than one.

However, because the stations are to be built with cut-and-cover techniques and a one-pass wall system, deflection of the walls will occur during excavation. Some amount of movement or creep of the soils will be required to re-establish at-rest conditions following construction. This creep will result in lateral stress relief and therefore a lower K_o value. A limiting upper value of K_o = 1.0 was used for design of the permanent structure considering this movement and stress relief. This value recognizes that there will still be high locked in lateral stresses due to preconsolidation, but limits the lateral pressures to the existing overburden pressure in recognition of the stress relief that will occur during creep.

Rock. Several of the stations require excavation through rock to reach the station subgrade elevation. The SOE walls will terminate at the top of rock, with excavation proceeding below the walls in rock. Because the wall system is a one-pass system, the walls will exert vertical loads on the rock mass for both temporary and permanent conditions. Many of the joint sets within the rock mass dip towards the station walls. Rock mass stability analyses were performed, as shown in Figure 4, to analyze the potential for rock wedge sliding under the vertical loads of the soil overburden and the one-pass wall system. Results indicated the potential for relatively high lateral loads on the walls from the rock mass.

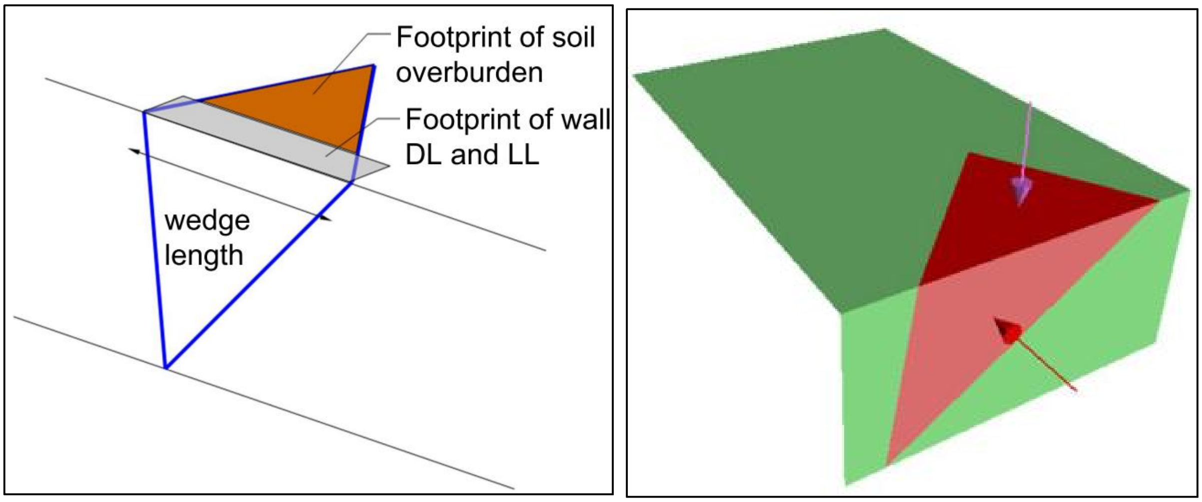

Figure 4: Illustration of rock wedge analysis and example wedge from analyses

Groundwater. For stations within flood plains, the maximum design water levels for the 100 and 500 year floods were considered. For structures outside of the flood plain, the highest observed water level was used, plus a contingency of 5 feet to account for possible future variations. The design water levels result in high uplift pressures due to buoyancy, with most stations located entirely under water.

DESIGN SOLUTIONS

A complex design solution including considerations for wall type, methods to accommodate lateral loads, and measures to provide uplift resistance were developed to overcome these challenges.

Selection of Wall System

The limited ROW requires a single structural wall system that can serve as temporary SOE and permanent structural support. The wall system has to be relatively stiff in order to limit deflections and settlements during excavation, as well as impervious to avoid groundwater drawdown and resulting settlements. These requirements narrow the feasible systems to slurry and secant pile walls.

Slurry walls were chosen because of lower anticipated cost, fewer joints and potential leaks, more uniform finished surface, and successful local precedence. Slurry walls were used for temporary and permanent support on the Shot Tower Metro Station (Patel and Castelli, 1992), the Gallery at Harborplace (Gifford and Wheeler, 1992) near the Inner Harbor Station, and the Four Seasons in Harbor East (Fantaye, et. al. 2008) near the Harbor East Station. Slurry walls were also used as a stiff SOE system to limit settlements at the Charles Center Metro Station, near the Inner Harbor Station, (Zeigler, et. al. 1984). These projects provided confidence that slurry walls could be effective for the proposed stations.

Wall Configuration for Stations above Rock

The slurry walls will provide an effective support for the entire station depths where rock is below the excavation invert (Harbor East and Fell's Point Stations). At these locations, the walls will extend below the base of the structure and toe into rock. Beneath the wall toe, the rock and the rock-wall interface will be grouted after wall installation but prior to station excavation to ensure an impervious connection. This will provide a stable toe-in for the SOE system to minimize deflections, and a water-tight SOE system to limit external groundwater drawdown during excavation. Figure 5 presents an illustration of this concept for the Fell's Point Station.

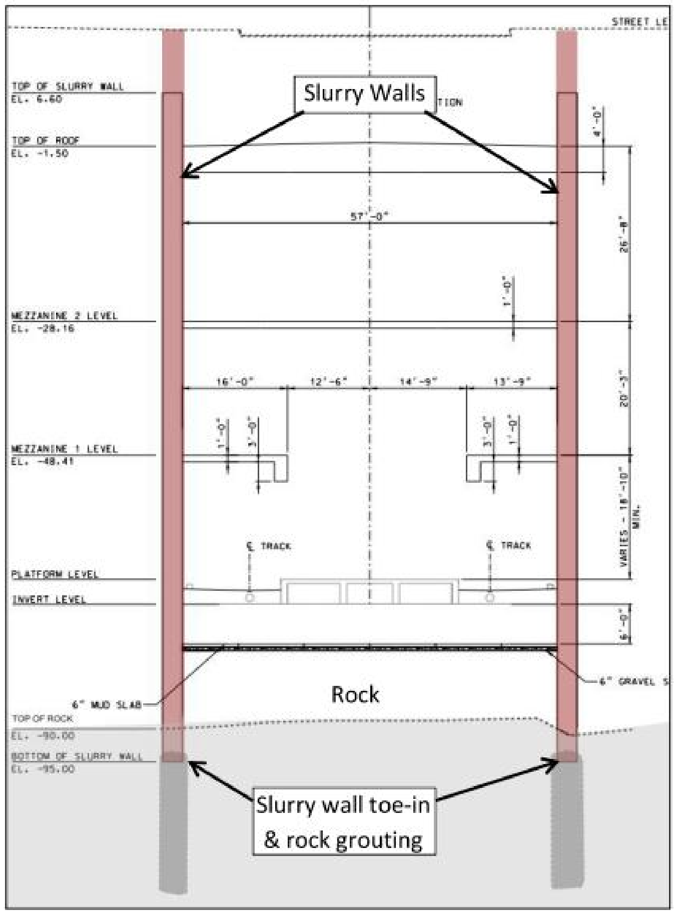

Figure 5: Station section for rock below station subgrade (Fell's Point Station)

Wall Configuration for Stations within Rock

A modified concept is used at the stations where rock is above the base of the station. Slurry walls will toe into rock for support of soil and groundwater loads. The excavation will extend below the slurry wall toe in rock to the station subgrade elevation. Grouting of the rock-wall interface, as well as the rock through the station depth and a distance below, is required after wall installation but prior to excavation to ensure that the excavation below the slurry wall and through rock is relatively water-tight.

Once the station subgrade elevation is reached, the station base slab and a cast-in-place (CIP) wall are constructed. The CIP wall extends up above rock and overlaps with the slurry wall to the mezzanine level. A structural connection at the mezzanine slab provides structural continuity and load transfer between the CIP wall, slab, and slurry wall. The overlap between the CIP and slurry wall help provide continuous support of lateral earth and water pressures, and the structural connection at the mezzanine slab provides transfer of the uplift forces on the invert slab through the CIP wall into the rest of the station structure. Figure 6 presents an illustration of the wall system for stations within rock.

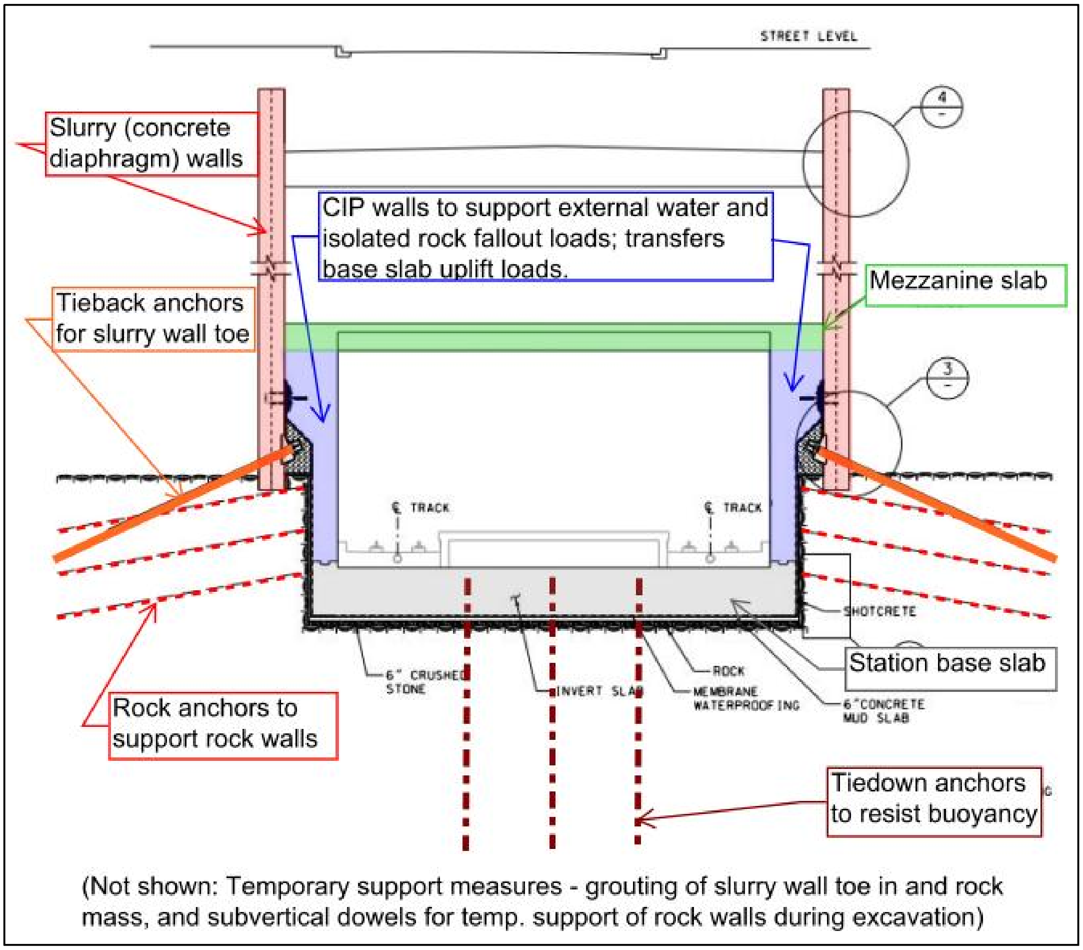

Figure 6: Station design concept for stations within rock (Poppleton Station)

During excavation, the lateral forces on the slurry wall toe will make it deflect into the excavation. A rock ledge is required in front of the wall toe to maintain the integrity of the wall-rock interface. The width of the rock ledge must be minimized because it encroaches on the interior space of the station structure as well as the construction tolerances between the TBMs and the slurry walls. Therefore, tieback anchors were included to restrain the slurry wall toe during excavation.

Based on the rock wedge analyses, the CIP wall had to be up to three feet thick to support the external sliding wedge loads and the groundwater loads. This encroached too much on the internal station space at the platform level. The design was modified to include permanent rock anchors to support the rock in place and prevent wedge sliding loads on the CIP wall. The CIP wall only has to support external water pressures and isolated rock fallout between anchor heads. The tieback anchors for the slurry wall toes were incorporated into the permanent structure design to further minimize loads on the CIP walls. These measures reduced the CIP wall thickness to 18 inches at the platform level.

The rock anchors are double corrosion protected bar anchors spaced approximately every 5 feet on center. The slurry wall toe anchors are spaced farther apart in plan view, generally every 10 to 20 feet depending on the station and the lateral loads, and are located between rows of rock anchors. The slurry wall toe anchors are designed as double corrosion protected strand anchors in order to develop higher capacity per anchor based on the spacing. Permanent easements for depths within rock under adjacent properties were pursued to eliminate conflicts between anchors and future deep foundations; existing adjacent deep foundations bear in Transition Zone or on rock, but do not extend into rock.

Temporary support elements were also included in the design. Subvertical rock dowels in front of the slurry wall toe (angled slightly off of vertical, extending under the slurry walls) installed before rock excavation will help maintain the integrity of the rock during excavation, prior to rock anchor installation. A layer of shotcrete is required to prevent localized fallout prior to CIP wall construction.

Design for Uplift

Four stations are entirely below the design water levels, resulting in high uplift forces due to buoyancy. Additional concrete to add deadweight was investigated as a possible solution but was not practical. The slurry walls or interior slabs could not be thickened due to interior space, ventilation, and acoustic requirements. Increasing the backfill weight over the station only produced a nominal improvement and required structural strengthening of the roof slab. The use of heavy weight concrete using metal aggregate (iron, magnetite, etc.) was investigated but ruled out due to lack of precedence and concerns about availability, stray current corrosion, or alkali silica reactions (ASR).

The invert slab thickness could be increased but would require significant additional excavation, mostly in rock. The structural design requires a six-foot thick invert slab. To provide enough deadweight for uplift resistance, slabs would have to be 12 to 30 feet thick depending on the particular station. This was ruled out because construction of such slabs would add significant rock excavation and concrete volume, plus additional risks associated with the excavation depths and blasting for rock excavation.

Skin friction on the slurry walls was also considered but ultimately ruled out. The slurry walls will deflect during excavations as part of the SOE system, which will result in possible loss of uniform contact (in cohesive soils or Transition Zone) and/or reduced normal forces on the exterior wall faces. This creates uncertainty with regard to the magnitude of the skin friction that can be mobilized.

The use of skin friction on wall sections embedded below the station invert was considered because these sections would be set primarily in rock or weathered rock and would not deflect much during excavation. However, substantial penetration, on the order of tens of feet, of the walls into rock would be required, which was questionable from a constructability standpoint because of the high rock strengths. This would also require a thicker invert slab to provide the transfer of the uplift loads under the station to the external walls. For these reasons, this alternative was ruled out.

Permanent double corrosion protected tiedown anchors in rock were assessed to be feasible, practical, and had precedence, including transit stations in Pittsburgh, Pennsylvania (Zick, 2008), Greece (Vrettos et al., 2013), Berlin, Germany, and Malmo, Sweden (DSI, 2014). Tiedown anchors have also been used for decades on other critical infrastructure such as dams. The main concern with anchors was the potential for long term corrosion. Published information indicates that the majority of corrosion issues experienced with anchors were due to inadequate corrosion protection occurring in older installations that pre-dated modern double corrosion protection (Bruce, 1988 and Ebeling et al., 2013).

The tiedown anchors are indicated conceptually in Figure 6. The layout of the anchors was adjusted depending on the uplift forces and rock properties. Where possible, anchors were clustered in rows in the center of the station; otherwise they were spaced 8 to 10 feet on center throughout the station.

Micropiles in tension were also considered but anchors were favored. Micropiles would be passive elements which would require displacement to mobilize, whereas anchors are locked off in tension. Also, all tiedown anchors will be proof tested, so they offered greater confidence in performance.

A detailed waterproofing design was developed to mitigate the potential for leaks through the invert slab around the tiedown anchors penetrations. A detailed construction procedure was developed to allow installation and testing of the anchors prior to construction of the base slab in order to mitigate the risk that the anchors would not have the required capacity if installed through the finished slab.

SUMMARY AND CONCLUSIONS

The underground stations for the Baltimore Red Line were designed to overcome challenges including limited ROW, soft soils, high lateral earth pressures, jointed rock, and high groundwater. The use of a slurry wall system for temporary SOE and permanent structure support helped fit the stations within available ROW as well as limit external groundwater drawdown and settlements. Stations in rock included a CIP wall and permanent tieback and rock anchors to minimize the impact of the design challenges on the internal station space. Tiedown anchors in rock were incorporated into the design for uplift resistance after reviewing a number of alternatives. Additional temporary measures for excavation support have been included in the design including grouting of the slurry wall toe and rock for groundwater cut-off and subvertical rock dowels and shotcrete for rock mass support. The result is an innovative design that met the internal station space requirements within available ROW.

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