Tunnels, Tiebacks, and Piles: A Design Case History of dealing with Obstructions

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ABSTRACT

The proposed Baltimore Red Line light rail project includes a 3-mile-long downtown tunnel with five underground stations and twin TBM mined tunnels. The vertical alignment includes the requirement for the proposed Inner Harbor Station to connect to an existing Metro station. During design, it was discovered that basements along both mined Inner Harbor Station approaches were constructed with soldier piles and tiebacks. These elements pose significant risks, including direct conflicts with TBM excavations. Mitigation options considered include frequent TBM interventions, cut-and-cover and sequential excavation method sections to remove obstructions, and alignment changes. Projects with similar precedence were evaluated, including the Central Subway in San Francisco, Regional Connector in Los Angeles, and projects in Europe and Korea. Alternatives, advantages and disadvantages, and ultimate solution are discussed.

INTRODUCTION

The Baltimore Red Line (BRL) project is a proposed light rail transit line for the Maryland Transit Administration (MTA) that will run from 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 will be mined using pressurized face tunnel boring machines (TBMs). The stations are two or three levels underground and have approximate plan dimensions of 66-feet wide by 285-feet long. Portals, stations, and the pedestrian tunnel will be built using cut-and-cover techniques with slurry walls (concrete diaphragm) utilized for both temporary support of excavation (SOE) and permanent structural walls.

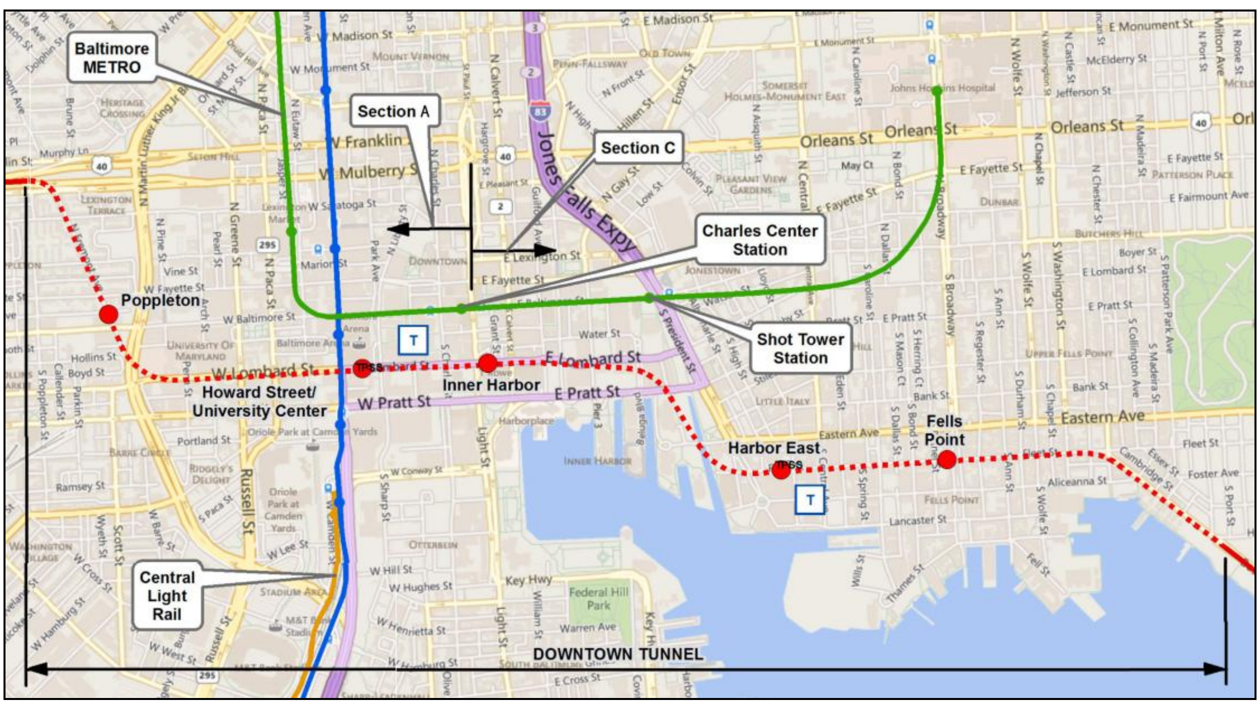

Figure 1: DTT alignment location

A section of the DTT runs parallel to part of the existing Baltimore Metro subway. The Metro, built in two phases (Section A and Section C), runs under Baltimore Street north of the DTT as shown in Figure 1. The existing Charles Center Metro Station, located at the intersection of Baltimore and Light Streets, is located north of the proposed Inner Harbor Station, located at the intersection of Lombard and Light Streets. The Pedestrian Tunnel will run north-south under Light Street and connect these two stations as shown in Figure 2.

The existing Charles Center Metro Station is a two level underground station. In order to meet the required grades for the Pedestrian Tunnel, the proposed Inner Harbor Station was initially designed as a two level station with a depth to invert of approximately 65 to 68 feet. As a result, the invert depth of the mined running tunnels on the east and west approaches to the Inner Harbor Station was initially about 60 feet below existing grades.

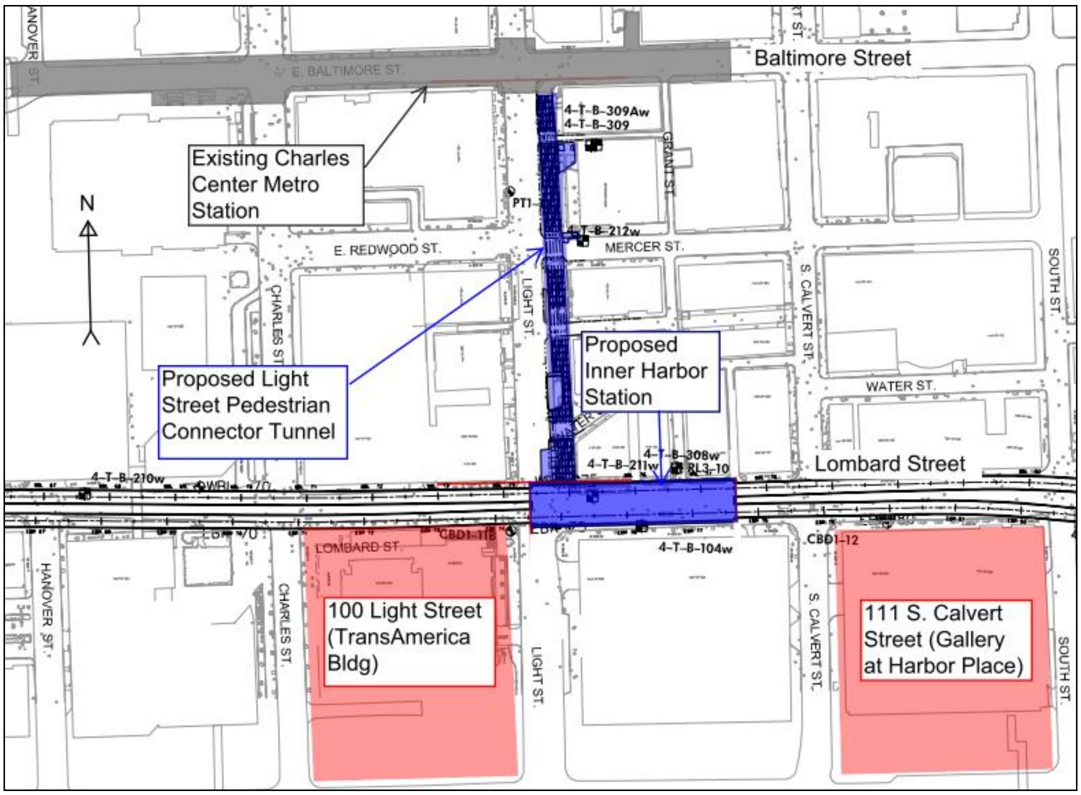

Figure 2: Location of Inner Harbor Station

GEOTECHNICAL CONDITIONS ALONG THE ALIGNMENT

The tunnel invert depth varies from 45 to over 100 feet, with the majority of invert levels in the range of 60 to 85 feet in order to connect at the two- and three-level underground stations. Subsurface conditions along the DTT consist of variable fill and Coastal Plain sediments overlying crystalline rock of the Piedmont Plateau. Rock types consist primarily of amphibolite and gneiss, with lesser amounts of schist, marble, and other rock types.

Overlying the rock are Residual Soil and Transition Group materials, which are derived from in-situ weathering of the parent bedrock. These materials are very dense or hard based on SPT N-values. Coastal Plain sediments consisting of Cretaceous and post-Cretaceous sediments lie on top of the Residual Soil and Transition Group materials. Cretaceous sediments are highly variable and include sand, gravel, and clay, but primarily clean to silty or clayey sand and gravel. Cretaceous soils are very dense.

Post-Cretaceous sediments are present within the eastern portion of the DTT, from the Inner Harbor Station to the east portal. These soils are similar to the Cretaceous sediments but are generally medium dense. The eastern portion of the DTT also includes areas of in-filled marshes or waterfront which have loose sands and soft organic silts.

Fill overlies the post-Cretaceous sediments in the eastern section and the Cretaceous sediments in the western section of the DTT. Fill is highly variable in density and composition and includes brick, timbers, and other debris.

Groundwater levels are generally within 5 to 15 feet of the ground surface along the entire DTT. The Cretaceous soils are regional aquifers and a limited tidal influence is observed along the existing and former waterfront.

The DTT running tunnels encounter all of the materials except fill. The majority of the tunnels run through rock, Transition Group, and Cretaceous sediments. Mining conditions vary from full face conditions in rock, Transition Group, and Cretaceous soils, to mixed ground conditions consisting of a combination of these materials. The station and portal excavations will encounter all of the materials described above, although not all of the materials are present at every excavation. Several stations will extend into rock.

Design Implications of Geotechnical Conditions at the Inner Harbor Station

Conditions at the Inner Harbor Station include fill, soft organic silts, Post-Cretaceous and Cretaceous sediments, Residual Soil, and Transition Group materials. Depth to rock varies from approximately 64 to 84 feet.

In addition to meeting the design grades for the Pedestrian Tunnel, the two level design of the Inner Harbor Station kept the station above rock. This simplified the design and minimized cost. Extending the excavation into rock would require a modified support system because the slurry walls would have to stop at the top of rock; the excavation would have to “step in” to create a bench for support of the wall toes; and the excavation into rock would need rock anchors and/or bolts with a permanent cast-in-place station wall. Rock excavation will require blasting, which increases the unit cost of excavation and requires considerations for explosives and vibration control.

DISCOVERY OF POTENTIAL TBM TUNNEL CONFLICTS

The area surrounding the Inner Harbor Station is part of the central business district of downtown Baltimore. It is a heavily developed urban area with mid and high rise buildings. As part of the assessment of the impacts of the proposed BRL construction as well as research into similar projects in the area, available sources of information were investigated. These included building plans on file with the City, records kept with building management of various properties, previous project records, and published case histories or work in the area. Review of these sources indicates two potential conflicts with the TBM tunnels for the west and east approaches to the station.

100 Light Street (TransAmerica Building)

The TransAmerica Building is located at 100 Light Street, along the south side of Lombard Street on the western approach to the Inner Harbor Station, as shown in Figure 2. It was built in the early 1970s and has 37 floors above grade and a three level basement. Building plans obtained from the City indicated cast-in-place concrete walls for the basement. Requests were made to review available records with the building management. Shop drawings from the construction were found that indicated driven soldier piles with lagging and two rows of soil tieback anchors were used for SOE (Schnabel Foundation Company, 1970). Soldier piles were to be installed from within the excavation such that the tops of the piles were about 10 feet below street elevation. An attempt was made to locate as-built or installation records through the designer, but such records did not exist.

Shop drawings were overlaid on cross sections along the running tunnel as shown in Figure 3. The soldier piles were 3 feet outside of the building right-of-way (ROW) line, within the City ROW of Lombard Street. Thirty-eight soldier piles were in a line parallel to the eastbound (southern) tunnel.

Potential construction deviations were considered for both tieback anchors and for the driven soldier piles. Tiebacks were estimated to be about 6 to 10 feet above the tunnel based on planned installation as well as a deviation of 5 degrees from the planned inclination. Soldier piles were estimated to have a clearance of about 4 feet from the edge of the tunnel based on planned tip elevations and verticality. With consideration for deviations during driving installation and maximum alignment deviation of TBM mined tunnels, the clearance could be as little as 1.8 feet. Because the soldier piles were installed below existing grades and the basement walls were cast-in-place, there was no access to verify the locations of the existing piles or tiebacks.

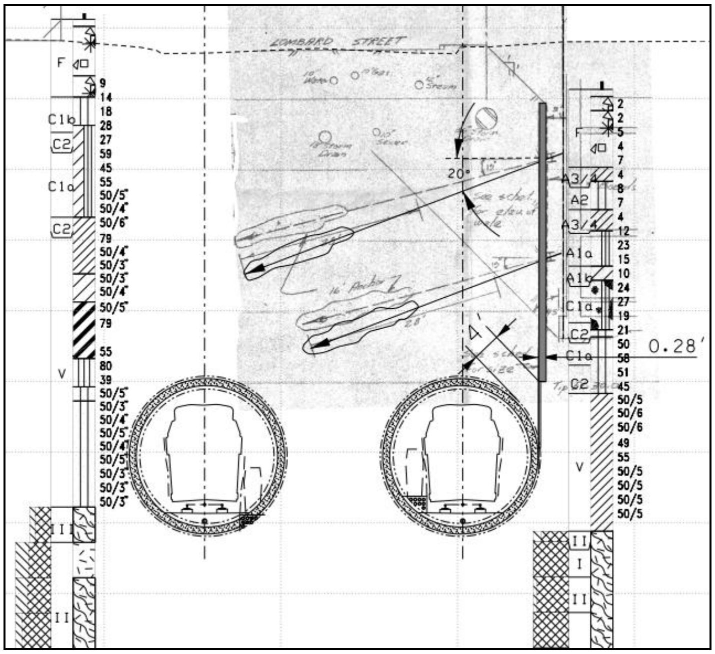

Figure 3: Estimated Proximity of Soldier Piles and Tiebacks to TBM tunnels, West Approach to Inner Harbor Station

111 South Calvert Street, the Gallery at HarborPlace

The building at 111 South Calvert Street is the Gallery at HarborPlace (the Gallery). It consists of a high rise building with 28 floors above grade and a four level underground garage. Available record plans through the City did not provide any indication of potential conflicts. Plans from building management did not include any additional information; no shop drawings were available. However, published information indicated that significant tieback obstructions for the TBM tunnels exist at this location.

The available information regarding the Gallery came to light while investigating previous slurry wall precedence in Baltimore. Similar to the proposed BRL stations, the basement excavation for Gallery at Harbor Place was constructed using slurry walls for temporary and permanent ground support. A published paper described the basement construction, including construction of the slurry walls and the use of multiple rows of soil tieback anchors for support of the walls (Gifford & Wheeler, 1992).

Based on the paper, four rows of tiebacks were installed in sediments and residual soil or weathered rock. Tiebacks consisted of 4 to 6 multi-strand cables that were installed using a “lost point” procedure in which a sacrificial steel drive point was used to facilitate installation. Issues occurred with obtaining tieback capacity, so additional anchors were installed in some areas. The tiebacks were only used for temporary support; the permanent support of the walls was achieved with post-tensioned floor slabs (Gifford & Wheeler, 1992).

Several attempts were made to follow-up on the information in the paper to better estimate the locations of the tiebacks. The authors of the paper and the companies who performed the slurry wall and anchor installation work were contacted. In many cases, staff who worked on the project had moved on and had no records of the work, and other contacts at the companies could not find records of the work. No shop drawings, installation records, or other documentation aside from the published paper could be found for these anchors.

The only available information with regard to the orientation and length of the tiebacks was from illustrative figures in the paper. These figures were overlaid on cross sections of the tunnels. The results indicated two to three levels of tiebacks could be encountered within the TBM excavations as shown in Figure 4.

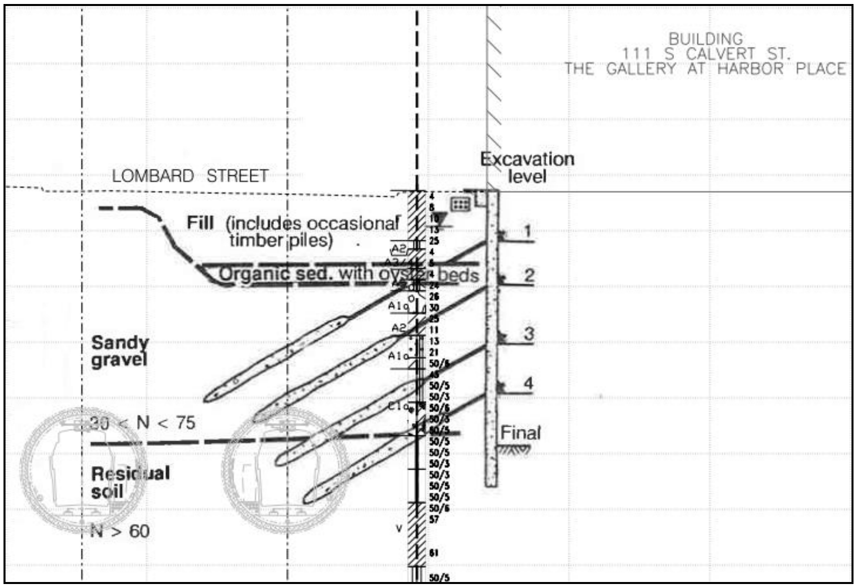

Figure 4: Overlay of Tunnel Cross Section with Figure of Gallery Tiebacks (anchor image from Gifford and Wheeler, 1992)

A site visit to the Gallery basement was performed to investigate the location and number of anchors. The tieback ports were found behind an architectural block wall. The tieback heads had been disconnected and the ports sealed. The ports were surveyed, and independent calculations performed to estimate tieback lengths. The estimated tieback lengths and surveyed port locations were used to develop an overlay of possible obstructions along the tunnel alignment as shown in Figure 5. The tiebacks appear to only interfere with the eastbound tunnel.

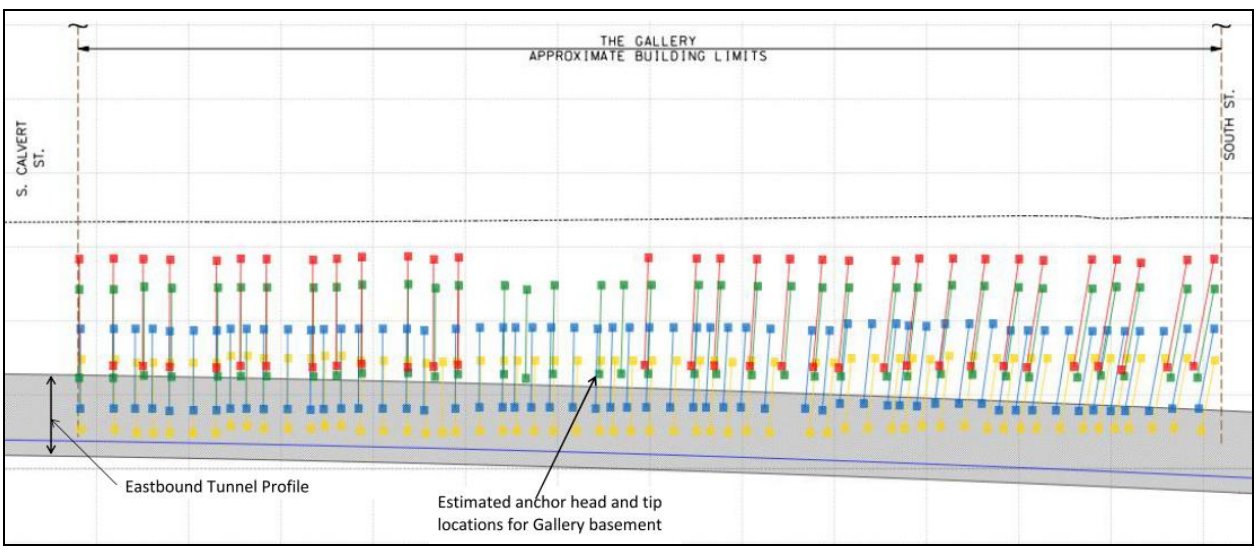

Figure 5: Tunnel Profile with Estimated Anchor Obstructions

MITIGATION OPTIONS AND PRECEDENCE

The eastbound tunnel was expected to encounter some portion of 122 anchors when passing the Gallery on the east side of the Inner Harbor Station. More anchors could be encountered depending on installation deviations. The evaluation of mitigation options was focused on this area, although there was also a risk that the eastbound tunnel could encounter soldier piles on the west side of the station if installation deviations of the soldier piles were large.

Mining through the anchors was not considered viable. Based on the survey of the ports, the spacing between anchors was as little as 2.5 feet along the lowest row. Given the volume of anchors and considering the steel strands and the "lost points" used for installation, the potential for TBM damage was considered too great. Discussions with TBM manufactures indicated that it should not be assumed that the TBM could mine through these obstructions.

Options for Anchor Removal and Precedence

Several options for removing the anchors were considered, along with the feasibility and precedence for each option.

Anchor removal from tunnel heading during mining. Removing the anchors from the tunnel heading during mining was considered. This had been performed for the Seattle Bus Tunnels which encountered approximately 450 tiebacks within the tunnel heading (Critchfield & MacDonald, 1989). However, there are major differences between the Seattle project and the BRL. The Seattle tunnels were mined in the late 1980s, prior to the devleopment of modern closed face TBMs that will be used for the BRL. An open face machine was used to facilitate removal of the extsing tiebacks. Dewatering was also used during the Seattle tunneling.

By comparison, the BRL will be mined with closed face pressurized TBMs; dewatering will not be allowed for the tunnel mining due to the potential for settlements of the soft organics and post-Cretaceous sediments. Section C of the Baltimore Metro was mined using open face machines and compressed air and experienced numerous construction issues including settlements, face instalbility, and subsurface contaminants (Edwards & Merrill, 1995; Smith, Eisold, & Schrad, 1993). To avoid these issues and take advantage of modern tunneling capabilities, pressurzied TBMs are required for the BRL.

Therefore, the only way to remove the tiebacks from the tunnel heading during TBM mining would be to perform frequent compressed air interventions, possibly with ground improvements, as the tiebacks are encountered. This would be a cumbersome and time consuming operation as the tiebacks are spaced over a distance of about 330 feet, but are spaced as closely as 2.5 feet. This would make the mining very time consuming, expensive, and add risk, in effect defeating the purpose of requring pressurized TBMs. Also, the location of the tiebacks are not well known, so it is still possible that the TBM could encounter tiebacks and damage could occur. For these reasons, this option was not considered further.

Anchor removal from within the Gallery basement ahead of TBM mining. Consideration was given to removal of the anchors from within the basement of the Gallery building. This would require drilling through the tieback ports and over-drilling around the anchors to remove them from the ground ahead of TBM mining.

A case history of precedence was found for this type of work from a project in Leipzig, Germany (Babendererde & Elsner, 2007). On the Leipzig project, tieback anchors for an underground garage had to be removed ahead of a proposed transit tunnel. The building owner was responsible for removing the tiebacks because the proposed transit line was planned when the basement was built. Five anchors were removed by excavating a small diameter pipe-jacked tunnel parallel to each anchor and cutting them out by hand. The jacked tunnel required compressed air working conditions because groundwater was present below the basement elevation.

Although successful on the Leipzig project, only five anchors were removed in this fashion. This would not be practical for removal of over 100 anchors. It is not clear if other types of over-drilling or over-excavating might be feasible to remove the anchors and "lost points" from within the Gallery; no other similar precedents could be found.

Also, the logistics would be difficult due to the spacing and location of the anchors relative to the permanent basement floors. It would be difficult to access some of the ports due to lack of headroom between the ports and the permanent floors. The architectural block wall would have to be removed and replaced, and a portion of the garage would be taken out of service during the work. Drilling out the anchors, if feasible at all, could impact the water tightness and structural integrity of the wall depending on the size of the holes. The Leipzig project used 48-inch inside diameter jacked pipes, which would be much bigger than the original ports and holes used to install the anchors at the Gallery. Based on the uncertainty regarding the applicability of precedence and feasibility of the work, as well as potential impacts to the building, this option was not considered further.

Anchor removal using surface based excavations. Two surface based excavation alternatives were considered. The first was to use drilled shaft or slurry wall equipment to “chase” out the anchors; the second was to build a cut and cover excavation to remove all of the anchors.

On the Leipzig project, 15 anchors were removed using bored pile and slurry wall excavators. Bored pile holes were drilled to locate, break-up, and remove sections of the anchors. Every single bucket of excavated material had to be closely inspected to determine if tiebacks had been hit, and if so, how many strands and at which elevations, in order to map out which tieacks had been recovered. Slurry wall excavators were used to remove the remaining sections of the anchors that were found by the rows of bored piles. (Babendererde & Elsner, 2007).

Although successful, the Leipzig project removed 15 anchors in this fashion, whereas the BRL would need to remove at least 122 anchors from within the tunnel horizon. In addition, those 122 anchors are below the upper rows of anchors, which would have to be drilled through to reach the lower rows. Therefore, a total of 180 anchors would have to be excavated out. This volume of anchors and the uncertainty with regard to length and alignment would make recovery of the anchors from this type of excavation challenging and difficult to verify that it was completely accomplished. For these reasons, a complete cut-and-cover excavation was considedred a better alternative.

A cut and cover section would involve installation of an SOE system followed by an internally braced excavation to the lowest anchor level, about 60 feet below grade. This alternative is shown conceptually in Figure 6. Due to high groundwater and compressible soils, the SOE would have to be water tight and would therefore consist of secant piles or slurry walls. This alternative has the advantage that if successful with regard to installation of the SOE, there is a high level of confidence that the anchors within the tunnel would be completely removed.

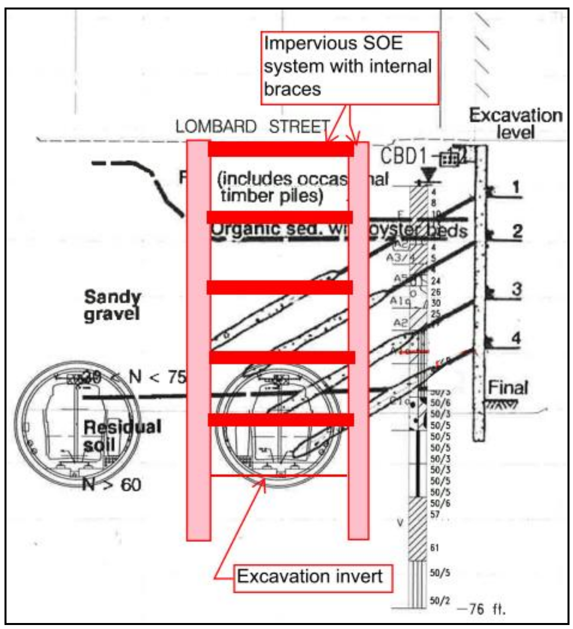

Figure 6: Concept of Cut-and-Cover Excavation for Tieback Removal

A similar concept is being used on the Los Angeles Regional Connector Project (Hansmire & Roy, 2014). A section of the project is proposed to be built using cut-and-cover techniques due to the presence of several hundred existing tiebacks that have to be removed. Similar to the BRL, the majority of the LA Regional Connector is to be constructed using pressurized face TBMs and it is considered too risky to mine through the tiebacks with the TBMs.

A deep cut-and-cover excavation along Lombard Street would require significant maintenance of traffic and utility relocation in order to construct, similar to the logistics of building the underground stations. The additional disruption to the Central Business District, especially in such close proximity to the disruptions for the Inner Harbor Station, made this alternative undesirable from the public impact standpoint.

In addition, there were concerns regarding the feasibility. Although precedence exists for cutting through tiebacks with drilled shaft equipment for the Leipzig project, the number of anchors for the Gallery is significantly greater and the anchors are relatively tightly spaced at deeper depths. The LA Regional Connector cut and cover section is conceptually depicted as using piles and lagging for the SOE. Under such a system, the anchors could be cut out by hand between driven soldier piles, which eliminates the issue of feasibility of drilling shafts through the network of anchors. Also, the LA Connector is a design-build project which had not been procured as of the date of the design assessment for the BRL, so the successful construction of that project had not yet been achieved.

Anchor removal using SEM ahead of TBM mining. An SEM tunnel was considered for mining the eastbound TBM tunnel to remove the anchors, as shown in Figure 8. The SEM tunnel would offer the advantage that the tunnel heading would be exposed and there would be confidence that all anchors were removed.

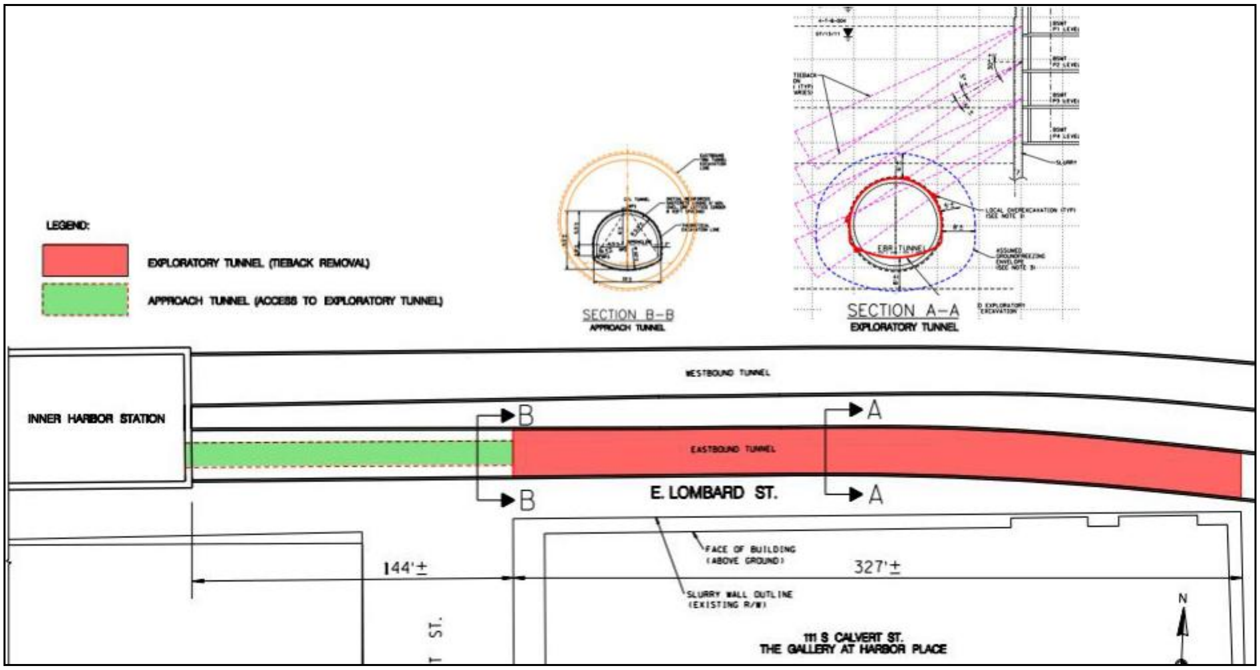

Figure 8: Concept of SEM Tunnel for Tieback Removal

The SEM tunnel could be started from the Inner Harbor Station or from a shaft within Lombard Street, although starting the SEM tunnel from the station would eliminate the surface and utility disruption that a shaft would cause. The SEM alternative would require ground improvement or ground freezing from the surface of Lombard Street, and so would still require some surface disruption. For this alternative, the SEM tunnel would be mined to remove the tiebacks, then backfilled, then the TBM would mine the backfilled tunnel. The SEM tunnel would be 327 feet long, plus an additional 144 feet long SEM “approach” tunnel to get from the station to the location of the tiebacks.

A precedent for the SEM concept was found in the Seoul Metro (Author unknown, 2009). On that project, two sections of TBM tunnel were changed to SEM to remove tiebacks ahead of TBM mining. The SEM tunnel construction was reportedly successful, however, the available information is limited. Details of the construction were not available, so comparison to the BRL and assessment of potential isssues were difficult to make.

Design Change Options for Mitigation

The previous options all involve removal of the Gallery tiebacks. All of these options appear to have some precedence and potential for success, however, each option has risks that the proposed construction may encounter difficulties or feasibility issues. The previous options also add significant cost to the project. None of these options address the potential risk of encountering a soldier pile along the TransAmerica Building. Although the risk of encountering a soldier pile is less of a certainty than the tiebacks, the consequences to the TBM would be severe.

Changes in the design of the alignment were also considered. It was not possible to change the horizontal alignment; the alignment had to remain on Lombard Street (i.e. could not be shifted to another parallel street) and it was not possible to shift the eastbound tunnel far enough north to avoid the tiebacks and connect to the Inner Harbor Station.

A design change consisting of lowering the vertical alignment was investigated. This was evaluated in two concepts. The first concept was to keep the station depth the same and lower the alignment as much as possible moving east from the station. The original alignment dropped on a gradual slope to a low point east of the station. This was modified to increase the drop as much as possible immediately east of the station to try to get the tunnel below the tiebacks. Although the number of tiebacks to be encountered was reduced, there was not a significant reduction in the number of obstructions. Also, this did not reduce the risk of encountering soldier piles on the west approach.

The second concept was to lower the Inner Harbor Station and redesign it as a three level station. This would drop the vertical alignment for the west and east approaches and reduce the risk of encountering both soldier piles and tiebacks. A similar consideration was used on the Central Subway in San Francisco; the running tunnel alignment was lowered during design to avoid existing tiebacks that were installed for the basement excavation of the Moscone Convention Center. The alignment was lowered beneath the lowest tiebacks to avoid conflicts (Smirnoff, 2013).

For this to be feasible, the entrance of the station and connection to the Pedestrian Tunnel had to be reconfigured to accommodate the deeper station while maintaining the Pedestrian Tunnel design grades. The station invert would be lowered approximately 20 feet, which would increase the cost of construction due to excavation into rock. In addition, changing the station design could delay of the project schedule. However, this option had the advantage that the lower alignment would completely miss all potential obstructions as shown in Figure 9.

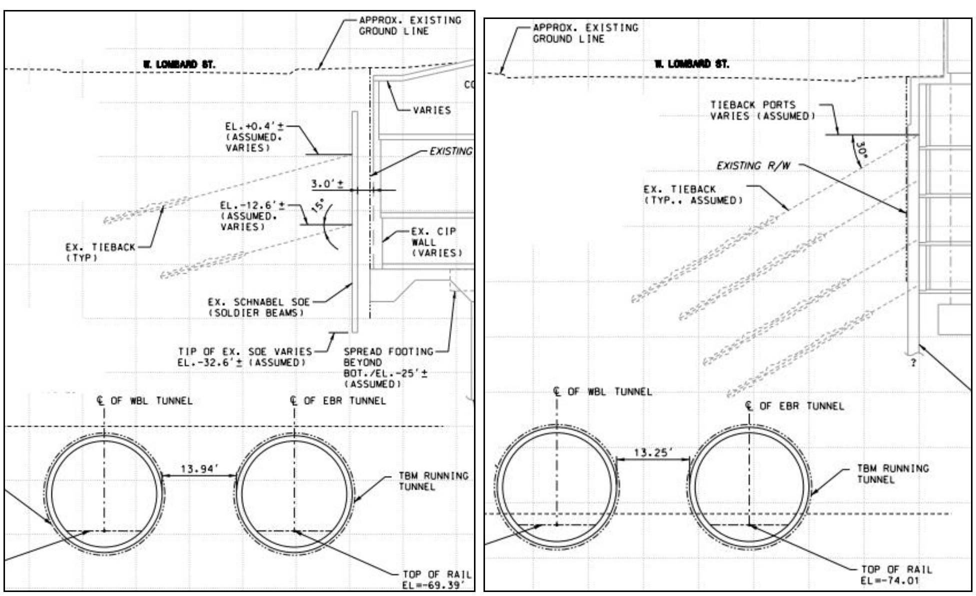

Figure 9: Sections at TransAmerica and Gallery Buildings for Three Level Inner Harbor Station Alignment

FINAL SOLUTION

The mitigation measures were discussed with the MTA, including the relative risks and costs. The MTA felt it was best to avoid creating additional disruptions to the public. In addition, during the time of this evaluation a high profile TBM breakdown occurred on another tunnel project, and the MTA had experienced similar challenges on the construction of the Northeast extension of the Baltimore Metro. The MTA decided it was best to minimize the potential for a potentially foreseeable TBM breakdown for the BRL.

The decision was made to lower the Inner Harbor Station and change it to a three level station. A caveat of the change was that the overall design schedule had to be maintained. The project was progressing from 30 to 65 percent level of design at the time of this change. It was recognized that the redesign of the Inner Harbor Station would lag at the 65 percent design stage, but that it would have to be advanced at an aggressive pace to be consistent with the rest of the design for the subsequent design milestones so that the procurement would not be delayed.

In addition to lowering the alignment at the Inner Harbor Station, a detailed review of the remainder of the alignment was performed to identify building locations where additional tiebacks may exist. The tiebacks and soldier piles that created these conflicts were part of SOE systems and were not indicated on any recorded plans. Several other locations of buildings with deep basements were identified, and conceptual tieback levels and orientations were developed for possible unknown SOE systems to evaluate if potential obstructions may exist at those locations. No additional potential obstruction locations were identified from that assessment.

SUMMARY AND CONCLUSIONS

During design of the BRL, two locations of potential obstructions were found that could seriously impact TBM operations. A review of precedents led to the conclusion that the best option was to lower the alignment to avoid the obstructions. Precedence existed for obstruction removal options, but the number, depth, and uncertainty of the obstructions, plus the geotechnical challenges, created greater risks for removal of these particular obstructions.

A significant lesson learned is that all possible record sources should be investigated and outreach should be performed to various parties that have worked on adjacent or similar projects. The majority of the information that was most valuable in this assessment was obtained through personal contact, outreach, and knowledge sharing including published papers and conference proceedings. Shop drawings for the TransAmerica Building SOE system were obtained through outreach to the building management. The information for the Gallery Building was found in a published paper regarding slurry wall construction. Precedence for dealing with similar obstructions was found through published papers and knowledge sharing of other design professionals.

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