Geotechnical Design Challenges for Temporary Excavation Support at the Arbutus Station and Double Crossover for the Broadway Subway Project in Vancouver, BC

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ABSTRACT The Broadway Subway Project in Vancouver, BC is a 5.7 km extension of the Skytrain Millennium Line and will have six stations located along a route extending from the VCC-Clark Station to the intersection of Broadway and Arbutus Street. This paper will focus on geotechnical design challenges for temporary excavation support at the Arbutus Station and Double Crossover site which forms the western-most station with a footprint that extends the length of two city blocks. Excavation depths up to 20 m are required and the final design consists of four different shoring systems to accommodate the various design constraints which include non-encroachment areas. Excavation support is to be provided to adjacent buildings, utilities, a traffic deck, and Metro Vancouver's Capilano No. 4 and No. 5 water mains. The shoring system will also accommodate the tail track tunnels and an approximately 14.5 m wide by 21 m long open area to allow for removal of the tunnel boring machines using a large crane that will be seated immediately adjacent to the crest of the excavation. A collaborative effort and iterative design process between all members of the project team was required to complete this complex shoring design.

Introduction

The Broadway Subway Project is located in Vancouver, BC and is an extension of the existing Skytrain Millennium Line that is part of the local rapid transit system. The route will extend from the VCC-Clark Station to the intersection of Broadway and Arbutus Street and include six new station locations (Fig. 1). This paper focuses on the geotechnical design challenges for temporary excavation support at the Arbutus Station and Double Crossover site which forms the western-most station. The footprint of this station extends the length of two city blocks and is bounded by Cypress Street to the east, Arbutus Street to the west, and private properties to the north and south of Broadway as shown in Fig. 2. The Arbutus Station building occupies the western portion of this project site between Arbutus Street and Maple Street. The Headhouse providing access from ground surface to the station level is located at the west end of the structure along the east side of Arbutus Street (Fig. 2). The Double Crossover, which facilitates trains to switch tracks, occupies the eastern portion of the project site from Maple Street to Cypress Street.

Excavation depths of up to approximately 20 m are required with vertical excavation slopes supporting adjacent buildings and infrastructure. The buildings located adjacent to the north and south sides of Broadway vary from at-grade, single level commercial buildings to multilevel residential and commercial buildings with basement levels. Many existing underground utilities that include storm, sanitary, water, telecommunications, gas, and electrical lines are located below the road and sidewalk areas of Broadway. Where practicable, relocation of existing above and below grade utilities would be carried out to facilitate the excavation and construction works. Significant existing underground infrastructure that require support includes two Metro Vancouver large diameter water mains called Capilano Main No.4 (CMN4) and No.5 (CMN5) and a large concrete BC Hydro duct bank. Design and implementation of excavation shoring is not permitted to disrupt these utilities and infrastructure. Furthermore, permission for excavation shoring elements to encroach into adjacent properties varies across the project site with minimum required offset distances to reduce potential conflicts and damage.

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Fig. 1. Broadway Subway Project and new station locations.

Fig. 2. Arbutus Station and Double Crossover Plan.

Subsurface Conditions

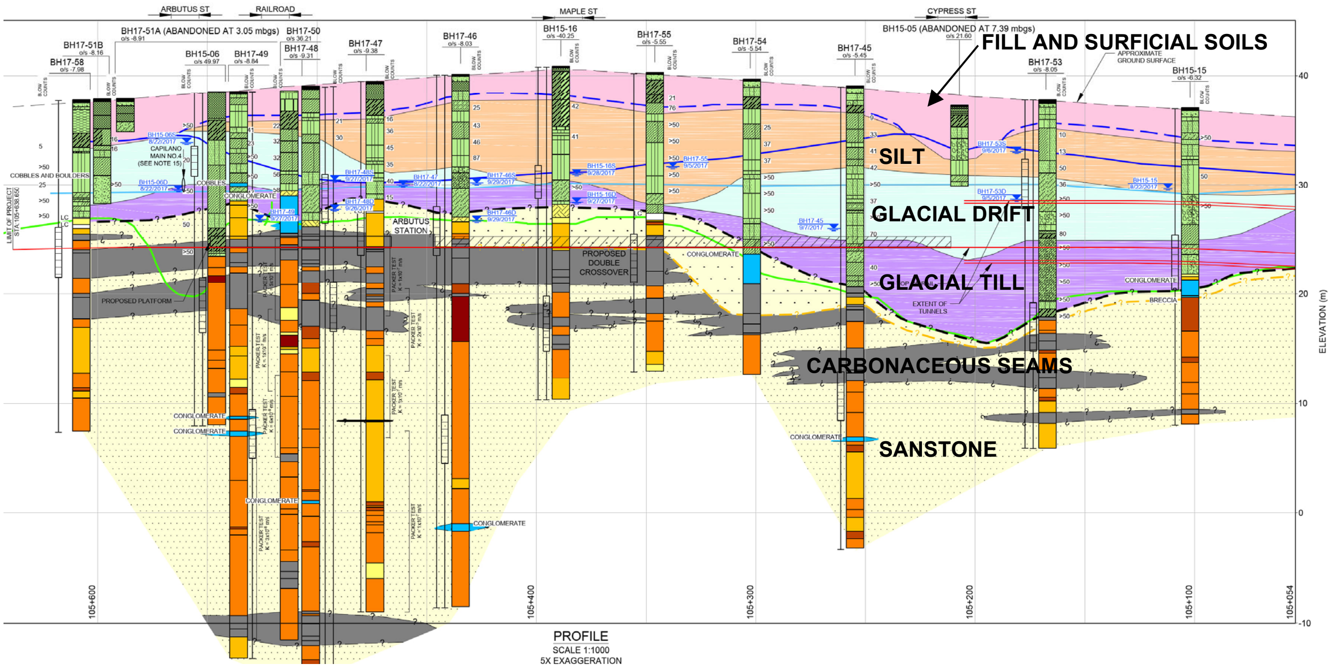
Surficial and Bedrock Geology

Based on published surficial geology information from the Geological Survey of Canada (Armstrong 1979), the site is underlain by Vashon Drift and Capilano Sediments. These surficial geology deposits generally consist of glacial drift that include lodgement till, lenses and interbeds of glaciofluvial sand to gravel, and lenses and interbeds of glaciolacustrine laminated stony silt. Bedrock is estimated to be at depth of 10 m or less below the ground surface. Subsurface investigations were carried out to characterize the local geology and groundwater conditions (Golder 2019a, Golder 2019b, and EXP 2021). An interpreted east-west geological section along the project site is shown in Fig. 3.

The general soil stratigraphy at the project site consists of fill to depths of about 0.5 to 2.8 m and underlain by surficial soil types typically comprising moist silty clay, clayey to organic silt, and clayey sand and silty sand soil types. These surficial soil types were generally present to depths of about 2.5 to 4.5 m; however, this soil stratum was encountered to a depth of about 6 m at the eastern end of the project site which coincides with a buried creek channel at Cypress Street. The fill and surficial soil are underlain by a stoney / stoneless silt stratum that generally consisted of moist to wet, non-plastic to low plastic silt, clay, and sandy silt soil types to depths ranging from approximately 9 to 12 m but with variable thickness across the site. The consistency / compactness of the stoney / stoneless silt stratum varied from very stiff to hard / dense to very dense. Glacial deposits underlie the fill, surficial soil, and silt stratum.

The glacial deposits are subdivided into Glacial Drift and underlain by Glacial Till which in turn is underlain by Bedrock. Glacial Drift generally consists of dry to moist, silt, sand, clay, and gravel soil types that are present to depths of about 10 to 13 m and with stiff to hard / compact to very dense consistency / compactness. Glacial Till generally consists of moist to dry, clay, silt, sand to gravelly soil types that include cobbles, boulders, and occasional cemented soil fragments. The Glacial Till was found to have consistency / compactness of hard / very dense and present to depths of about 18 to 20 m. Bedrock within the depths of interest generally consisted of extremely weak to weak sandstone with interlayered mudstone and siltstone that are extremely weak to very weak. The sandstone may include comparatively small siltstone clasts and

Fig. 3. Geological section along Broadway Street at Arbutus Station and Double Crossover site.



carbonaceous fragments in addition to having laminations, sealed joints, gouge infill, and brecciated zones. Conglomerate may also be present at discrete portions of the bedrock. The uniaxial compressive strength of the bedrock is estimated to range from about 0.25 to 5.0 MPa.

Groundwater

Perched groundwater may be encountered in the fill and surficial soil types and where the excavation cuts into granular backfill of utility trenches and surrounding buildings. The groundwater table at areas located in the vicinity of Arbutus Street was interpreted to vary from approximately 3.5 to 4 m below site grades and generally correlated with the top of the glacial drift. From about Arbutus Street to Maple Street, the groundwater table was interpreted to be at approximately 9 m below site grades and generally correlated with the top of the glacial till. From about Maple Street to Cypress Street, the groundwater table was interpreted to gradually rise to shallower depths of about 4 to 5 m below site grades. Preferential groundwater flow may be encountered in zones with greater hydraulic conductivity such as sand seams. Groundwater may also be expected from open fractures, joints, and other discontinuities in the bedrock. It is expected that groundwater levels and seepage rates would fluctuate seasonally. No artesian groundwater conditions were encountered at the test holes advanced in the general vicinity of the project site.

Design excavation depths are expected to terminate in bedrock with an exception at the eastern approximate 100 m of the excavation footprint where glacial deposits are expected and bedrock is at greater depths.

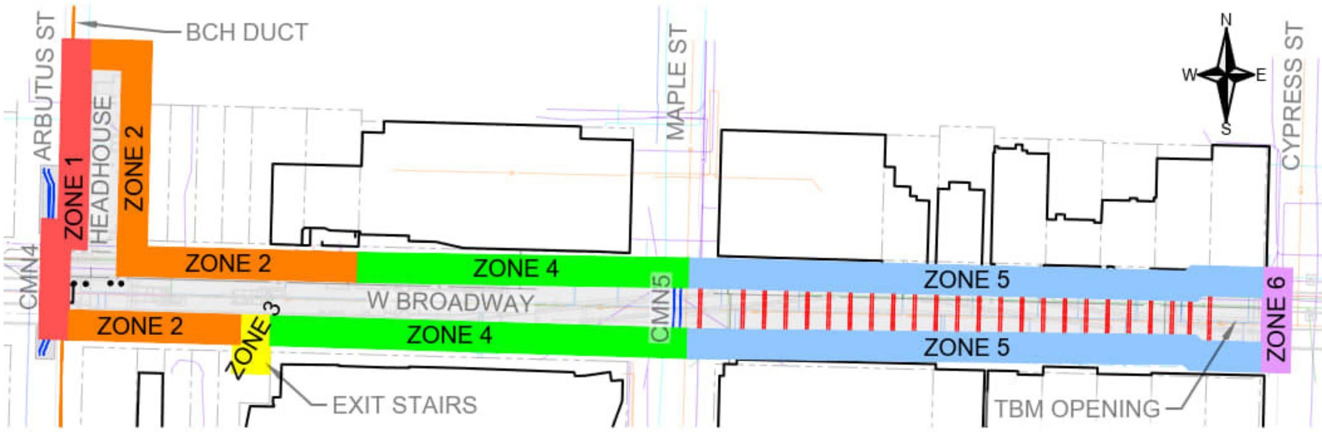
Design Challenges

The geotechnical design challenges for excavation shoring at the project site can be divided into 6 zones as conceptually shown on Fig 4. Each zone has site-specific design considerations and constraints that the shoring strategy is required to address. The shoring system for each of these zones is also required to be optimized with respect to design and construction to provide cost-effective solutions in addition to preferentially utilizing materials that have been secured for other components of the overall Broadway Subway project. Design of the shoring systems are also expected to manage ground deformations to tolerable limits as determined by structural assessments for the adjacent buildings and underground infrastructure.

In conjunction with the excavation shoring, pairs of piles will be installed along the north and south sides of Broadway as support columns for the traffic decks that will provide public access over the construction site. These traffic piles are considered free standing from the shoring system; however, where the shoring system consists of secant piles or braced soldier piles, the traffic deck will be supported on these piles that are part of the shoring system. Furthermore, components of the shoring system, such as tie-back anchors and shotcrete infill panels, will be required to accommodate the locations of the traffic piles.

Any shoring elements, such as solider piles, foundation piles for the traffic deck, shotcrete walls, and tie-back anchors, that will permanently remain in the ground will be required to be demolished and backfilled or fully grouted to

Fig. 4. Design challenge zones for Arbutus Station and Double Crossover



a minimum depth of 1.5 m as specified and approved by the City of Vancouver (City of Vancouver 2019). Therefore, design solutions need to be practicable with respect to methods and materials.

Zone 1 is located along the west excavation face beside Arbutus Street and will be required to support the CMN4 and a concrete BC Hydro duct bank in addition to accommodating openings through the shoring face where tail track tunnels will be created. Encroachment of shoring elements, such as tie-back anchors, are permitted into adjacent areas; however, these anchors are required to have prescribed offsets from the CMN4 to ensure damage is avoided.

CMN4 is located along and under Arbutus Street at depths of about 2.0 to 5.5 m at locations adjacent to the west excavation face. Assessments of the CMN4 were carried out as part of the project and determined to require an approximately 50 m long segment of the pipe to be relocated to address potential risk associated with station excavation and the tail track tunnel works (BSCGP 2023a). The relocated segment CMN4 will be located approximately east of the existing pipe and at higher elevations. Connection of this new pipe segment to the existing CMN4 pipe will occur in caged areas located west of the Headhouse and outside of the southwest corner of the excavation footprint.

The BC Hydro duct bank contains various conduits and is aligned approximately parallel with Arbutus Street. The northern approximate 50 m of this duct bank is situated about 1 m or less from the back of the west excavation face and thus would be supported by the excavation shoring. However, the west excavation face has a jog in the footprint that moves the shoring face about 4.7 m to the west which results in the duct bank to be located in front of the shoring face for a length of about 26 m before intersecting the south excavation face. Relocation of this duct bank is not permitted; therefore, the duct bank needs to be suspended above the construction area.

The tail track tunnels will result in two openings through the west excavation face at areas adjacent to the southwest corner of the project site. The bottom of these tunnel opening will be at elevations slightly above the excavation base. Each tunnel opening will be about 6 m wide by 6 m high with about 6.5 m of separation between the two tunnels. These tunnels extend westward from Arbutus Station and are intended to facilitate the future terminus box. Use of steel reinforcing, such as welded wire mesh, in the shoring face or metallic tie-back anchors at these tunnel openings are to be avoided due to potential conflict with or damage to tunnel excavation methods. Furthermore, cementitious shotcrete with a compressive strength of greater than 35 MPa should also be avoided.

Zone 2 is located along the north and east excavation faces at the Headhouse, and the western approximate 63 m and 55 m of the north and south excavation faces along Broadway, respectively. The excavation shoring system will need to support adjacent buildings with no deep basement levels and typical underground utilities. The north and east excavation faces at the Headhouse are also required to support a maximum 15 kPa vertical surcharge pressure from machinery/vehicles placed within approximately 7 m behind the excavation face. Encroachment of shoring elements, such as tie-back anchors, are permitted into adjacent properties.

Zone 3 is an approximately 10 m deep excavation area located behind the south excavation face where exit stairs are to be constructed. The footprint of this excavation area is less than 6 m wide by 9 m long and is connected to the station excavation via an approximately 4 m wide by 5 m long access way. Widening this excavation footprint is not desirable since the public walkway in this area would be further restricted during construction.

Zone 4 is located along the north and south excavation faces of Broadway and generally extending approximately 95 m and 120 m west of Maple Street, respectively. The excavation shoring system will need to support adjacent buildings with basement levels and typical underground utilities. The excavation footprint in this zone jogs closer to the neighbouring properties to the north and south; thus, reducing the distance between the shoring face and adjacent buildings in comparison with Zone 2. At Maple Street, CMN5 is aligned approximately north-south and intersects the excavation footprint. CMN5 is to be suspended across the open excavation using pipe cradles at abutment girders located at each side of the excavation in addition to hangers evenly spaced and hung from a girder bridge (BSCGP 2023b). The excavation shoring at CMN5 will need to be stepped into the slope to accommodate the structural components for supporting the pipe.

Zone 5 is located along the north and south excavation faces of Broadway between Maple Street and Cypress Street. The excavation shoring system will need to support adjacent buildings with basement levels and typical underground utilities. Encroachment of shoring elements into neighbouring properties is not permitted. At the east side of the Maple Street and Broadway intersection, an unobstructed opening across the excavation footprint from the excavation bottom to ground surface is required. This opening extends about 19.5 m north-south across Broadway and about 11 m east-west along Broadway. A second opening located beside the east excavation face at Cypress Street will be required to facilitate removal of the tunnel boring machines. This second opening extends about 21 m north-south across Broadway and about 14.5 m east-west along Broadway.

Zone 6 is the east excavation face at Cypress Street. This excavation shoring system will need to support the traffic in addition to four 3 m by 3 m crane outrigger pads that exert an estimated 150 kPa surcharge pressure at each pad. The western set of outrigger pads may be setback 1.5 m from the excavation face. Below the outrigger pads, the tunnel boring machines will penetrate the shoring face to enter the excavation area. Each tunnel is about 6 m diameter with a separation of about 4 m between the tunnels. Design consideration include lateral stresses associated with the tunnel boring machine during penetration through the shoring face. Similar to Zone 1, use of steel reinforcing and metallic anchors are not permitted at the tunnel openings due to potential damage to the tunnel boring machines. Furthermore, the shotcrete strength is limited to 35 MPa or less.

Design Solutions

The design solutions developed for the excavation shoring zone as previously described required an iterative process with design team members and stakeholders. The design strategies needed to be flexible to adapt to updated information as verification of subsurface conditions was carried out. Moreover, changes to the design details would be required to address other considerations including construction sequencing, surcharge loads, available materials, and updated excavation geometries. The 4 general types of shoring system used in the design solutions consisted of:

- tensioned tie-back anchors and reinforced shotcrete infill panels,
- pipe piles with tensioned tie-back anchors and reinforced shotcrete infill panels,
- braced soldier piles with spiles and shotcrete infill panels, and
- secant piles with reinforced shotcrete waler and steel waler, tensioned with tie-back anchors.

Tie-back anchors are required to be recessed into the shoring face to facilitate the building construction. A summary of the design solutions applied to each of the zones are discussed as follows.

Zone 1

Due to the presence of the CMN4 pipe and hydro duct bank at depths above approximately 5 m, the design solution at the north portion of the west excavation face consisted of 150 mm diameter, Schedule 80, pipe piles installed with a 1.2 metre-on-centre spacing with 200 mm thick, reinforced shotcrete infill panels and tensioned tie-back anchors at depths below 3.5 m as shown in Fig. 5. The pipe piles function as a cantilevered retaining wall and are approximately 9 m long with the lower half of the pipe length secured to the excavation face by the tie-back anchors. Anchor lengths varied from about 4 to 14.5 m and are tensioned to provide lateral resistance to earth pressures and the pipe piles. At the southern portion of the west excavation face, an upper benched geometry was incorporated into the shoring geometry to facilitate the relocated segment of CMN4 and allow the pipe pile lengths to be shortened to about 5.5 m as shown in Fig. 6.

Where the BC Hydro duct bank is located in front of the shoring face, a series of hangers would be attached to the exterior of the pipe piles and include an arm that extends out to and above the duct bank. From these overhead hangers, the duct bank would be suspended above the excavation area. Where the excavation face jogs in the area beside the tail track tunnel opening, additional pipe piles extending below the excavation bottom would be installed to provide additional support to the duct bank.

Fig. 5. Shoring solution at north portion of west excavation in Zone 1

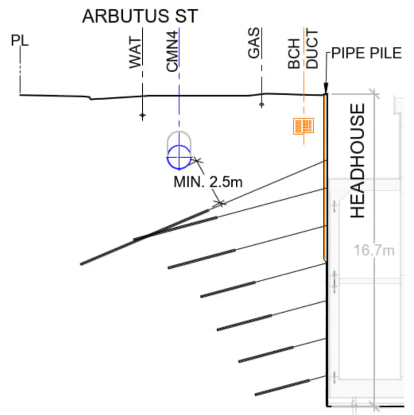
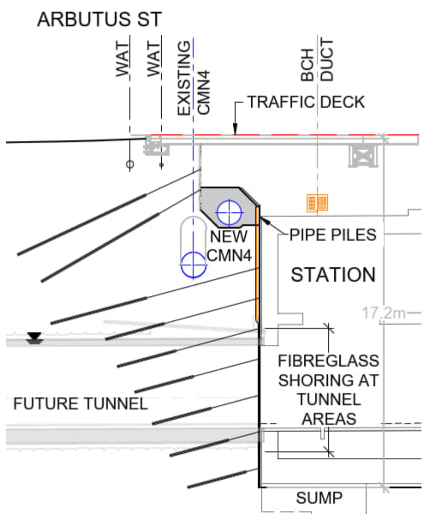


Fig. 6. Shoring solution at south portion of west excavation in Zone 1



At the tail track tunnel openings, the design solution utilized 35 MPa shotcrete with fibre rebar mat as reinforcement and fibreglass anchors for tie-backs. These materials were confirmed to be compatible with the tunnelling works. At elevations above the tunnel openings, pipe piles with tensioned tie-back anchors and reinforced shotcrete infill panels were use in the design solution as shown in Fig. 7. To address an area where a pipe pile could not be located, additional 15M horizontal reinforcing steel bars were included in the shoring face design to span across adjacent pipe piles.

Zone 2

Tensioned tie-back anchors and reinforced shotcrete panels were utilized for the design solution as shown in Fig. 8. Anchor lengths varied from about 3 to 13 metres using #7 to #9 anchor bars installed with 1.8 m horizontal spacing. This design accounted for the surcharge pressure from machinery/vehicles placed behind the excavation face.

Zone 3

The design solution consisted of pipe piles with walers to form a frame and included struts to laterally brace the tunnel entrance area as conceptually shown in Fig. 9. Reinforced shotcrete infill panels would be included between the pipe piles. This design solution provided the open space to construct the stairs and did not require a larger excavation footprint. Furthermore, this “top-down” design solution addressed a constructability constraint in which a drill rig could not operate in this excavation footprint to install tie-back anchors.

Zone 4

Due to the closer proximity of the excavation face to the neighbouring buildings, lateral support of the upper portion of the excavation face utilized pipe piles with tensioned tie-back anchors at depth. The upper rows of anchors require installation with steep dip angles to avoid the adjacent basement foundation walls as shown in Fig. 10. Pipe piles varied up to 11 m long and in some locations required 250 mm diameter, Schedule 80 pipes to manage design loads and deformations.

At the CMN5 support abutment locations, a bench was advanced to depths of 5 m with the balance of the excavation face advanced to design depths for the building structure. At areas immediately adjacent to this bench, pipe piles with tie-back anchors and shotcrete infill panels would be used for the excavation support. The bench cut extended about 2 m into the slope and about 3.5 m wide at the excavation face. The side walls of this bench cut are laterally supported by pipe piles and 15M horizontal steel bars in the shotcrete panels. Pipe piles also bound the edges of this bench in elevation as shown in Fig. 11.

Zone 5

Braced soldier piles with spiles and shotcrete infill panels are utilized for the design solution since there is no permission for encroachment into neighbouring properties. Struts extending from the north to south excavation faces are connected to walers and provide lateral support to the soldier piles as shown in Fig. 12. For the opening located beside Maple Street, additional walers and struts were required in the shoring elements forming the edges of this open area. For the opening beside Cypress Street, the larger open area and ground conditions required additional double walers and multiple struts to create a frame as conceptually shown in Fig. 13.

Zone 6

The design solution consisted of 900 mm diameter secant piles with reinforced shotcrete waler and tensioned tie-back anchors. Reinforcements installed at secondary secant piles that do not intersect the tunnel opening will consist of H-beams. Secant piles located above the tunnel footprints

Fig. 7. Elevation view of shoring solution at tail track tunnel openings in Zone 1

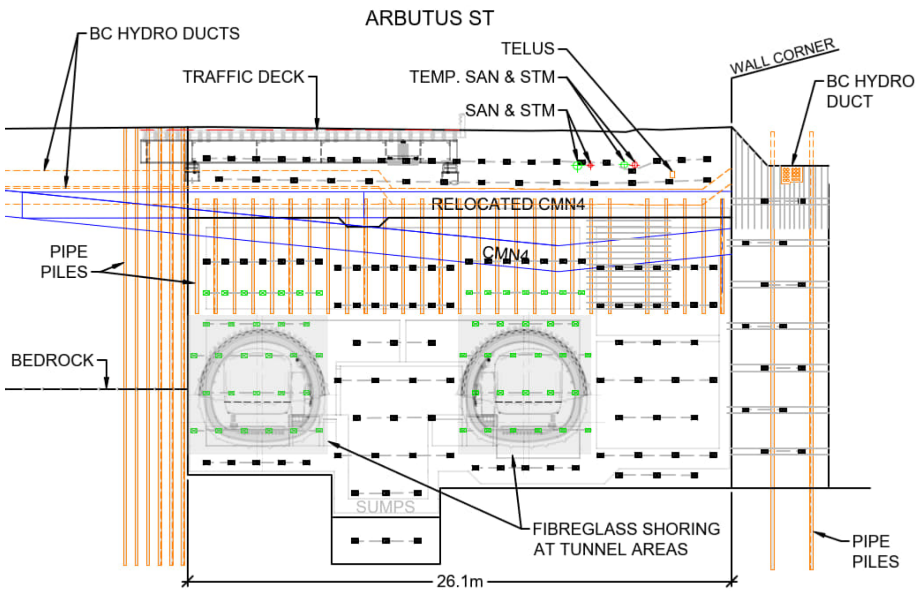


Fig. 8. Zone 2 shoring solution using tie-back anchors and reinforced shotcrete

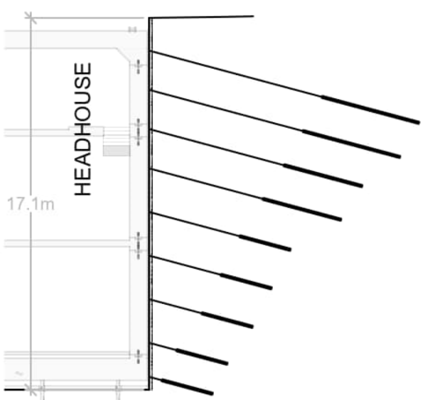
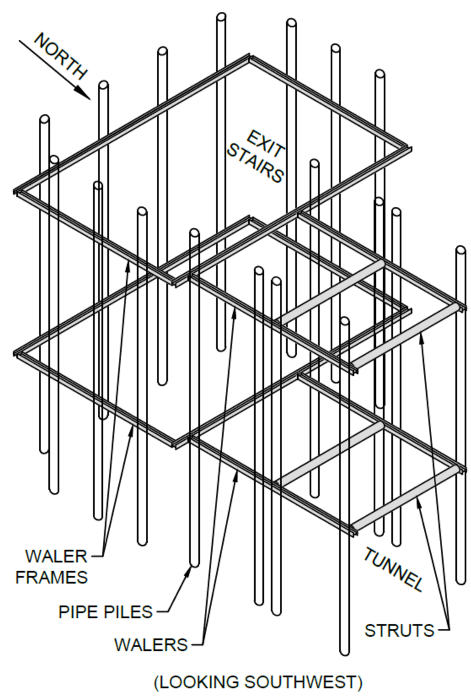


Fig. 9. Conceptual design solution for Zone 3



are designed to be installed as a hybrid primary and secondary pile. For these hybrid secant piles, a steel cage would be suspended at elevations in the pile that are above the top of tunnel micropile canopy. The balance of the pile at lower elevations would not have reinforcing steel and would function as primary piles. Concrete used in the piles that intersect the tunnel openings would have a maximum strength of 10 MPa to allow the tunnel boring machine to penetrate the shoring face. The design of this shoring face requires careful planning to avoid conflict with the tunnel components. In addition to low strength concrete, fibreglass tie-back anchors would be used at the tunnel openings.

Details for this shoring solution are complicated and require compatibility with the shoring system in Zone 5 used to provide the open area that will facilitate removal of the tunnel boring machines. Furthermore, surcharge loads from crane outrigger pads and adjacent traffic are included in the design details. An elevation view of this design solution is shown in Fig. 14.

Instrumentation and Monitoring

As part of the construction risk management for this project, pre-construction surveys of buildings and existing infrastructure were carried out. Instrumentation and survey

Fig. 10. Typical pipe pile and tie-back anchor shoring solution in Zone 4

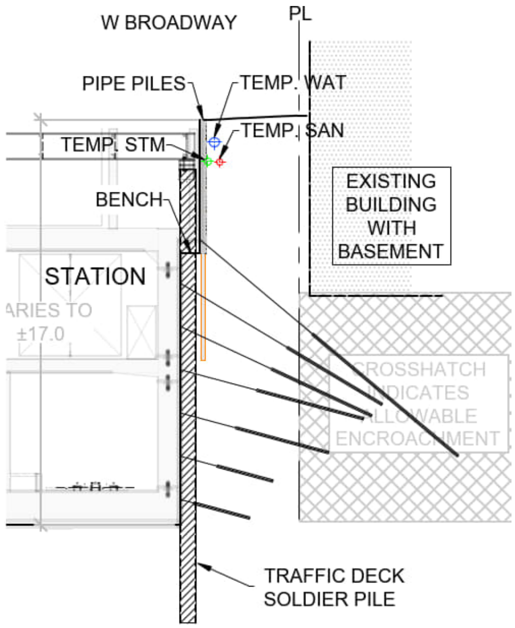
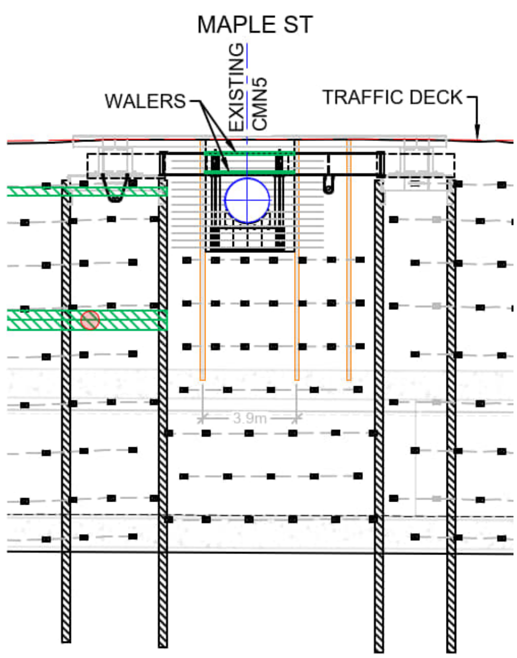


Fig. 11. Elevation view of shoring solution for CMN5 abutment area in Zone 4



monitoring for buildings, the CMN4 and CMN5 pipes, and excavation faces are included in the design. For CMN4, the instrumentation and monitoring will include settlement monitoring gauges along the length of pipe that may be impacted by the tail track tunnels and station construction works and visual inspections during excavation. For CMN5, the instrumentation and monitoring will include settlement monitoring gauges at either end of the in-ground portion of the pipe, survey targets and nano sensor tilt meters on the exposed portion of the pipe, strain gauges on the girder bridge components, and visual inspections during excavation. The instrumentation and monitoring for the excavation shoring will include optical survey targets on buildings and excavation faces, inclinometers, strain gauges on select struts, nano sensor tilt metres, and InSAR satellite surveys. Measured movements would be compared with defined threshold values that trigger specific reviews to be carried out and responses to avert unacceptable risk conditions for excavation slope stability or damage to infrastructure, utilities, and buildings.

Fig. 12. Typical braced soldier shoring solution in Zone 5

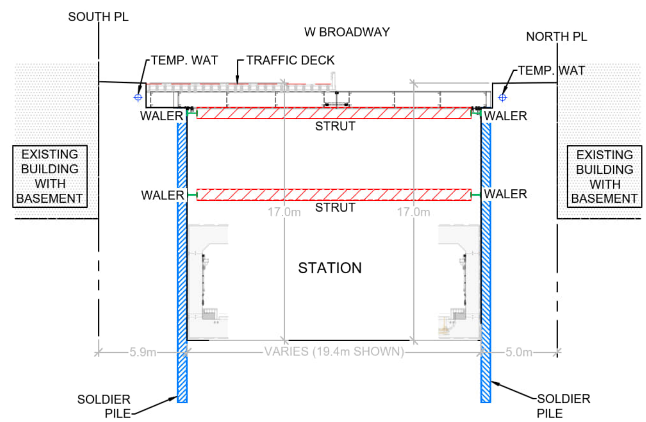
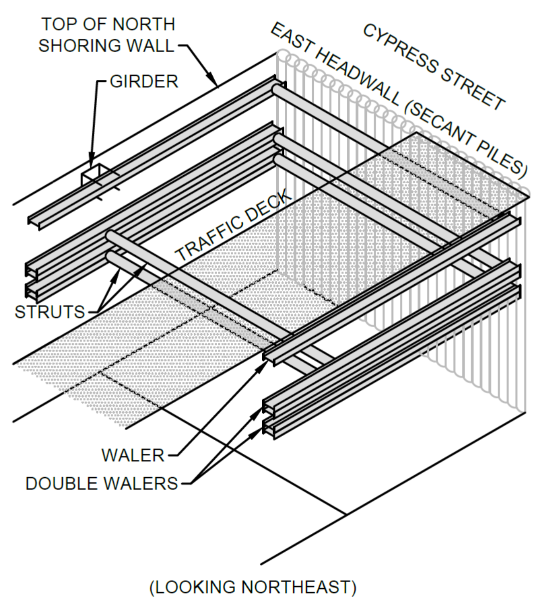


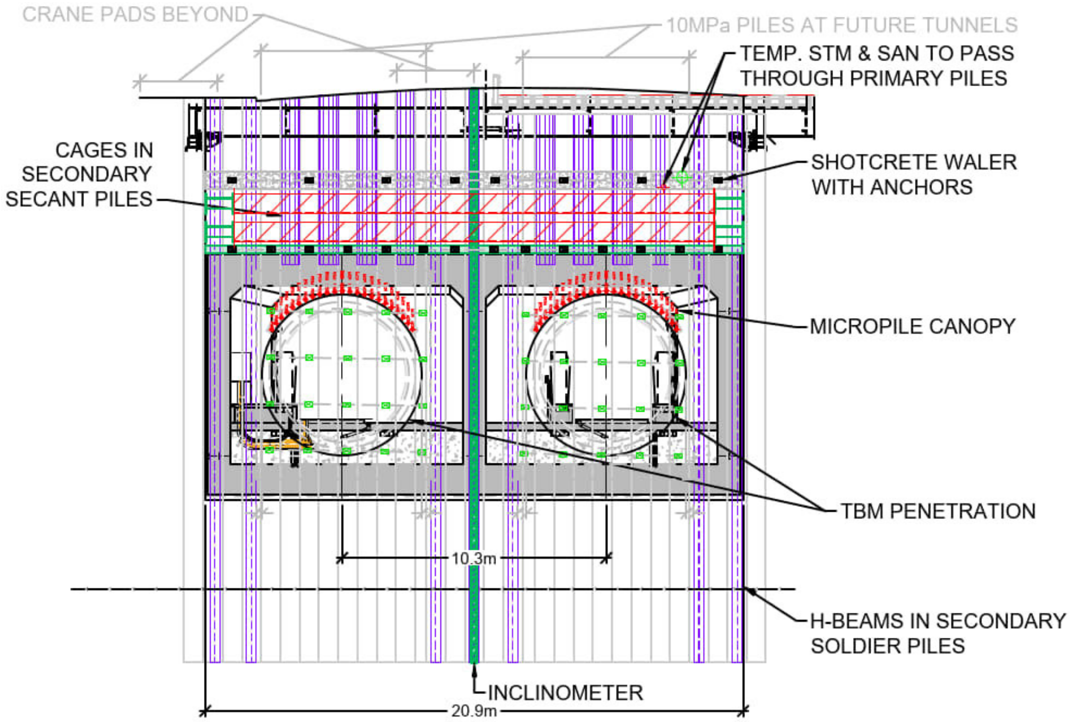
Fig. 13. Conceptual shoring solution using walers and struts at Cypress Street opening in Zone 5



Conclusions

The geotechnical design challenges encountered at the Arbutus Station and Double Crossover project site required an iterative design process to develop practicable solutions

Fig. 14. Elevation view of shoring solution at Cypress Street in Zone 6



for the temporary excavation supports. Collaborative effort and communication between design team members were important to avoid conflicting details where different designs and purposes interface. The different complexities in the design solutions for this project reflect the range of constraints that govern practicable design options. Where there are less design constraints, a comparatively more straightforward design solution can be used. Conversely, increased number of design constraints resulted in more complicated design solutions. Another important factor that assists with managing the design challenges is additional verification of subsurface soil and groundwater conditions, locations of underground utilities, and locations of adjacent underground structures, such as basement foundation walls. By accurately determining these constraints, the design solution can be more optimal in addition to having better risk management associated with potential impacts to these utilities and structures.

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References

Armstrong, J.E., Hicock, S.R. 1979. Geological Survey of Canada, "A" Series Map 1486A.1 sheet.

BSCGP 2023a. CRIAR Report – Capilano Main No.4 Water Pipeline. BSP-BSCGP-DES-RPT-00021.

BSCGP 2023b. CRIAR Report – Capilano Main No.5 Water Pipeline. BSP-BSCGP-DES-RPT-00022.

BSCGP 2023c. CRIAR Report – Arbutus Station and Double Crossover. BSP-BSCGP-DES-RPT-00023.

City of Vancouver 2019. Construction Specifications, First Edition.

EXP 2021. Geotechnical Design Report for Capilano No. 4. BSP-BSCGP-GEO-RPT-00024 RB.

Golder 2019a. Geotechnical Data Report. Broadway Subway Project. 1419105-050-R-Rev1.

Golder 2019b. Geotechnical Characterization Report. Broadway Subway Project. 1419105-056-R-Rev0.