Design and Construction of Ho Chi Minh City Metro Line 1 Underground Section (Contract Package 1b)

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ABSTRACT: Contract Package 1b (CP1b) is a part of Ho Chi Minh City Metro Line 1 (HCMC MRT Line 1) project which consists of underground construction of two stations, bored tunnels, cut-and-cover tunnel, and transition structure. Each structure has its own distinctive features due to its geographical condition, underlying geotechnical condition and construction constrain. Opera House Station, whose construction method categorized as deep excavation (up to 30 m depth) is the first underground metro station in Vietnam which is situated in a cramped downtown and surrounded by old-sensitive shallow-founded buildings. It was built by top-down method as the method offers better control of retaining wall deformation to minimize settlement of adjacent buildings. The other station, Ba Son Station, located next to the riverside, was protected by double sheet pile structure during its construction. For cut-and-cover tunnel, the rigid steel pipe sheet pile (SPSP) was used to maintain stability for construction in the river and on the weak alluvium clay soil. The underlying alluvium clay layers also cause a negative skin friction issue in the design of pile for the transition structure in Ba Son area. As for tunneling beneath the city, the bored tunnel using Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM) was selected. The TBM was launched from Ba Son Station toward Opera House Station twice: one for the east-bound track, and the other is for the west-bound track. In this project, several instruments were deployed to monitor and to ensure the safety of construction works and surrounding buildings. The data from the monitoring works were also useful for back analyzing and reconfiguration of the construction method. Those features brought challenges for both design and construction stages. The design and construction experience of the project are shared in this paper.

KEYWORDS: Deep Excavation, Underground Station, Cut-and-cover Tunnel, Bored Tunnel, Monitoring

1. INTRODUCTION

To fulfil the needs of reliable mass transportation, Ho Chi Minh City is constructing its first metro system which covers a 19.7 km length in total and consists of 2.6 km of underground section and 17.1 km of elevated section. The underground section is situated in the downtown area where the space is insufficient for the elevated structure. Contract Package 1b (CP1b) as a part of underground section is covering 1.745 km (chainage 0+615 to 2+360) which consists of two stations, bored tunnels, a cut-and-cover tunnel, and a transition structure. The various geographical conditions, underlying geotechnical layers and construction constrain gives a unique challenge for each structure design and construction method. The other contract packages in HCMC MRT Line 1 are CP1a (cut-and-cover tunnel and Ben Thanh station), CP2 (elevated section) and CP3 (trackway, rolling stock and operation system). The map of HCMC MRT Line 1 and the layout of CP1b project are shown in Figure 1 and Figure 2 respectively.

In general, the soil layers in CP1b project is comprised of Fill, Alluvium and Diluvium material (Figure 3). Alluvial deposits of approximately 30-40 m thick overlay the harder and denser Diluvium layers. Alluvium Clay is divided into Alluvium Clay 2 (Ac2) with SPT-N value from 0 to 2 and Alluvium Clay 3 (Ac3) with SPT-N value from 4 to 21. In Ba Son Station and Cut-and-cover Tunnel, the Ac2 layer has an average of SPT-N value equal to 0. The Ac2 layer becomes thicker to the eastern end of the cut-and-cover tunnel section (transition structure area). For Alluvium Sand, it is divided into Alluvium Sand 1 (As1) with SPT-N value up to 10 and Alluvium Sand 2 (As2) with SPT-N value more than 10. Diluvium Clay (Dc) is considered an impermeable and hard layer. It lies just above Diluvium Sand (Ds) layer.

The design of the structure in HCMC MRT Line 1 project is based on two standards: Japanese Railway Standard in Design Standard of Railways Structure and Commentaries (DSRSC) published by Railway Technical Research Institute (RTRI); and Vietnam Standard (TCVN). Seismic force is considered in the design as the project location belongs to an area with a ground acceleration of 0.8048g (m/s^2) (TCVN, 2012). Accordingly, a liquefaction assessment based on DSRSC – Seismic Design **(RTRI, 2012)** using SPT-N value was carried out. The assessment result revealed that a part of bored tunnel section (west-bound track) and Ba Son Station were susceptible to liquefaction. Additional floatation check due to liquefaction was incorporated in the design for those sections.

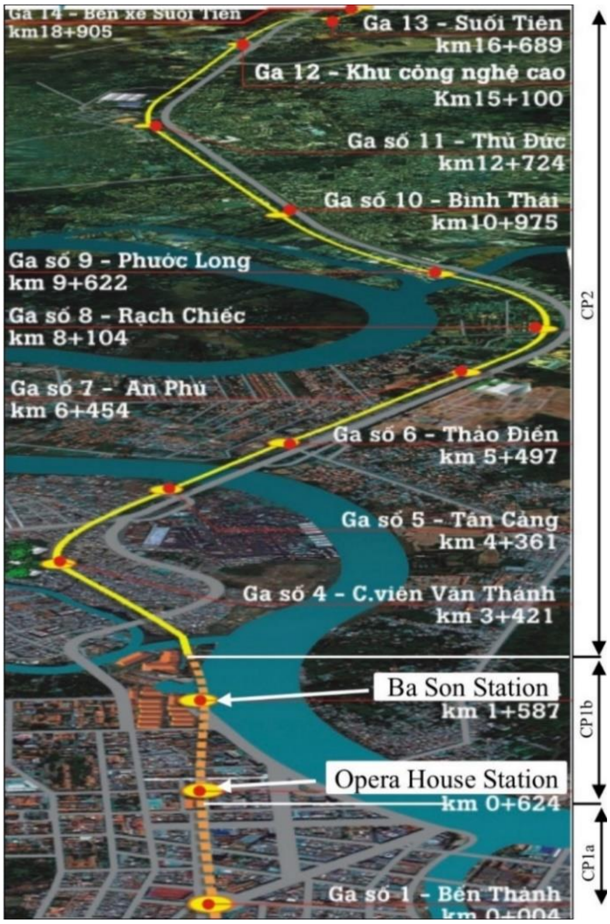

Figure 1 Map of Ho Chi Minh City Metro Line 1

Figure 2 Layout of CP1b project

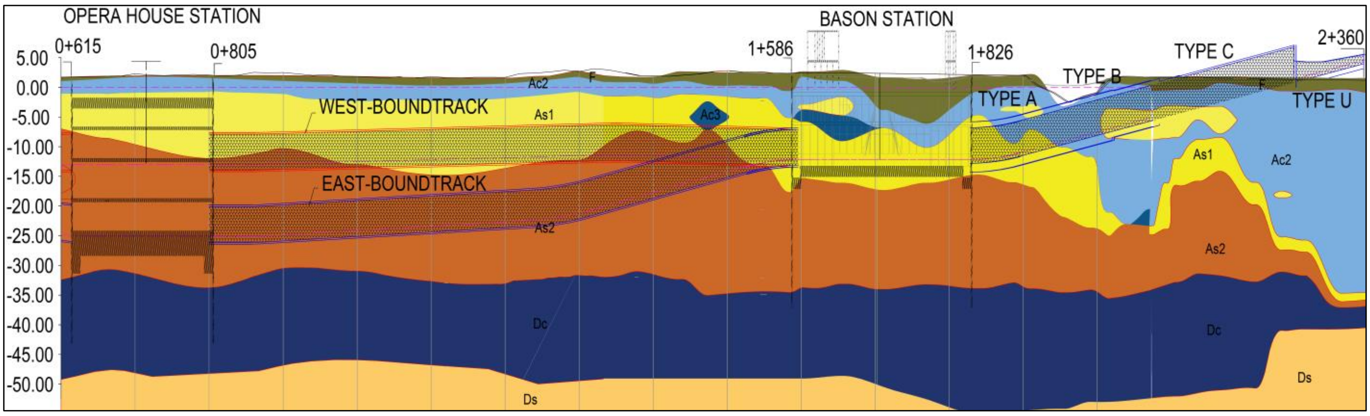

Figure 3 Soil profile in CP1b project

2. OPERA HOUSE STATION

2.1 General

Opera House Station is located in the downtown area. It is surrounded by historical and important buildings such as Opera House Building, Rex Hotel and Saigon Tourist building (Figure 4). Opera House Station has four level basements, one ventilation tower structure and five entrances. The length of the station is 190 m with a total floor area of 27,900 m^2. The depth of the basement floor is up to 30 m.

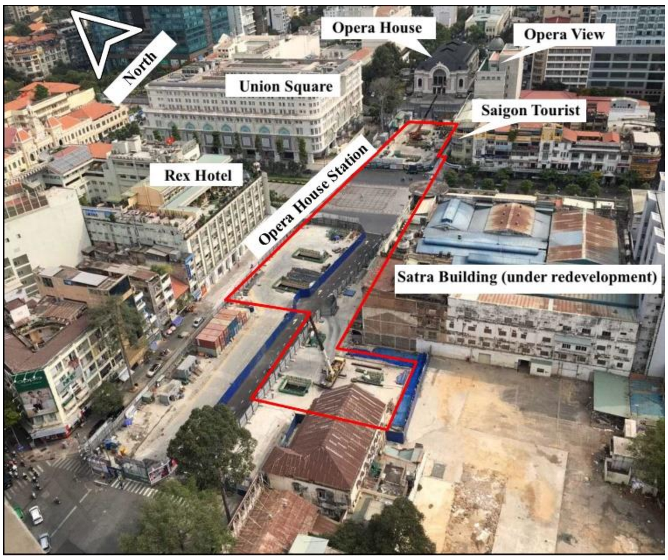

Figure 4 Location of Opera House Station and its vicinity

2.2 Design Concept

Opera House Station was designed as a station box supported by diaphragm wall (D-wall) (1.5 m thick; 44 m deep) as part of its permanent structure. D-wall is embedded into Dc layer which creates a water cut off boundary. Thus, dewatering during excavation progress will not cause ground water level down in the vicinity. The thick Dc layer (14 m) and the friction between D-wall and soil provide enough safety against uplift from aquifer water pressure below Dc layer. Temporary works of D-wall was designed by using elastoplastic method according to DSRSC – Cut and Cover Tunnel (RTRI, 2001). The D-wall deformation results from elastoplastic analyses then were used to predict ground settlement in Soil Plus (Soil Plus, 2016), a finite element method (FEM) software. As per requirement, the settlement in the area needs to be controlled to be the same or less than 20 mm. To fulfill this criterion, top-down construction which induces smaller D-wall displacement and ground settlement was chosen. Initial design also required horizontal strut arrangement with spacing of 2.5 m to meet the settlement requirement. The soil layer thickness is quite uniform in both transversal and longitudinal directions. However, the design section must be carried out in an asymmetric way because of unbalanced surcharge load from the adjacent buildings.

To ease the construction progress, inclined strut method was adopted compared to the initial design using horizontal strut. It could optimize the steel strut quantity and provided a sufficient working space as well. Typical cross section of Opera House Station for temporary works and permanent structure is shown in Figure 5 and Figure 6, respectively.

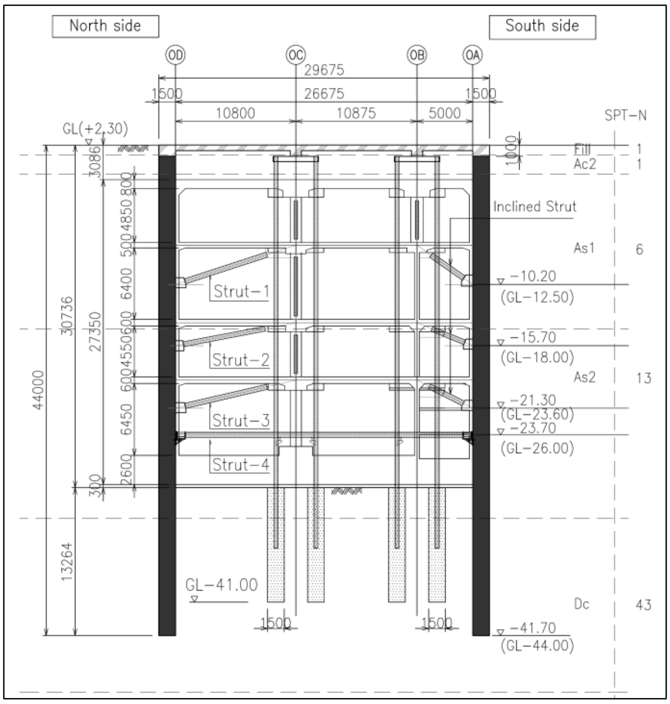

Figure 5 Typical temporary works section of Opera House Station

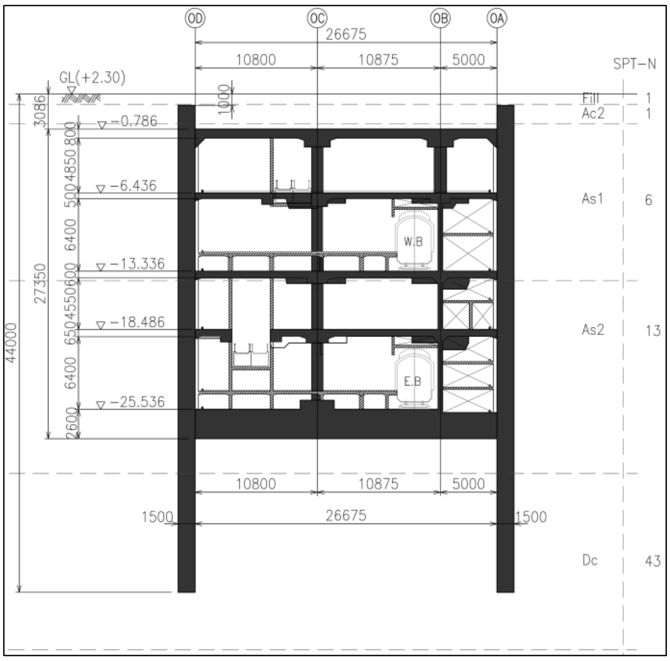

Figure 6 Typical permanent structure section of Opera House Station

2.3 Construction

The construction of Opera House Station was commenced from the center part of the station. There was a request from the owner to finish and reinstate the center part for further redevelopment of the area. Once roof slab was completed, it was backfilled and was handed over to the authority for construction of a new boulevard. Then, construction was continued from the western and eastern part toward the center part under the new boulevard.

Due to being located in the cramped building area, the construction of Opera House Station D-wall has a very close proximity (the closest is 2 m) to the adjacent buildings. The soil improvement by cement-bentonite piles (diameter=150 mm; depth=36 m) was carried out at some closest D-wall and building locations to improve the trench stability during to D-wall construction. Bored pile and vertical steel support (king post) were installed in the same period with D-wall construction. The concrete temporary deck was subsequently constructed. It serves as a working platform and strut as well. The excavation progress then was carried out from the openings. The typical construction sequence is: excavation, strut and waler installation, excavation to slab level, slab casting, and removal of strut (to be reused for subsequent level).

To ensure the safety of excavation progress and to verify the design assumption, the monitoring system has been applied. It covers D-wall deformation observation using inclinometer, D-wall stress, slab and strut stress using strain gage and load cell, ground water level using piezometer and observation well, adjacent building tilt and extensive settlement markers. The monitoring data was also useful for back-analysis and modification of construction step. In the eastern part of the station, the lowest strut could be removed earlier just after 30 cm lean-concrete casting (instead of after base slab casting) and could be reused for the western part. It was possible because monitoring data (D-wall deformation and stress) showed smaller value than design and the result of redesign produced insignificant increase of predicted D-wall deformation and ground settlement which is acceptable.

3. BA SON STATION

3.1 General

Ba Son Station is located in the east side of Opera House Station and is situated in the riverside (Figure 7). It has two level basements and one ventilation tower. Ba Son Station also has five entrances. The station is 240 m long, 18 m deep and has a total of 26,230 m^2 floor area. Ba Son Station area was used to be a shipyard. It was then redeveloped for residential area. Since there are no sensitive adjacent buildings in the vicinity, the settlement limitation is not as strict as Opera House Station case. In the case of Ba Son Station area, a ground settlement of up to 70 mm is allowed.

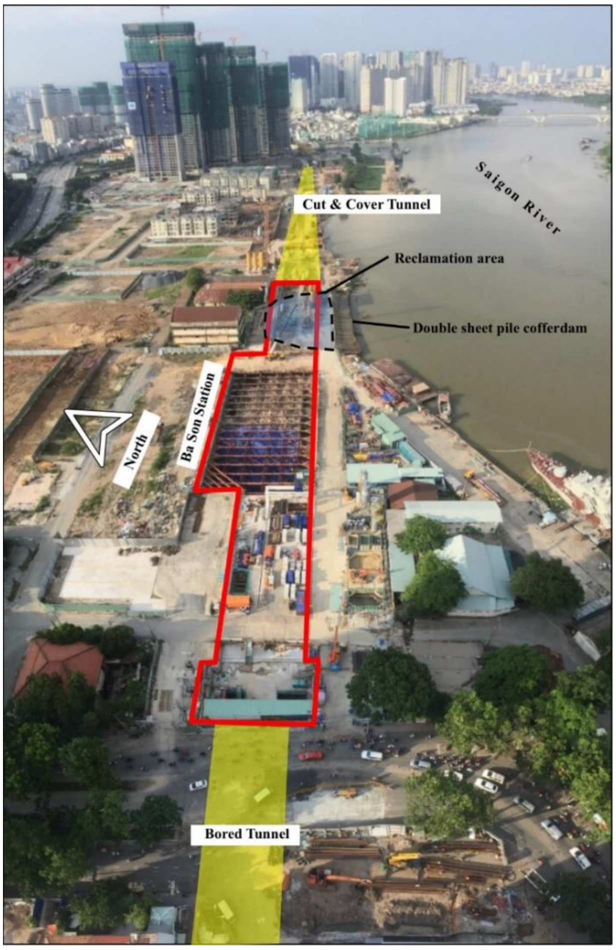

Figure 7 Location of Ba Son Station and its vicinity

3.2 Design Concept

Unlike Opera House Station, Ba Son Station is not surrounded by sensitive building therefore bottom up excavation method with four strut layers was chosen. An asymmetrical design has been adopted by considering a combination of water level fluctuation in the riverside and landside which differs by up to 1.55 m in high tide and 2.52 m in low tide. The station was designed by splitting it into five different cross sections due to variation of station structure and soil profile in the longitudinal direction. Ba Son Station D-wall has 1 m thickness, 31 m depth of reinforced area and up to 7.9 m depth of non-reinforced area at the tip of D-wall. The non-reinforced area was designed to be embedded into Dc layer and creates a water cut-off boundary to ensure a good workability during the excavation work. The typical cross section of Ba Son Station is shown in Figure 8 and Figure 9.

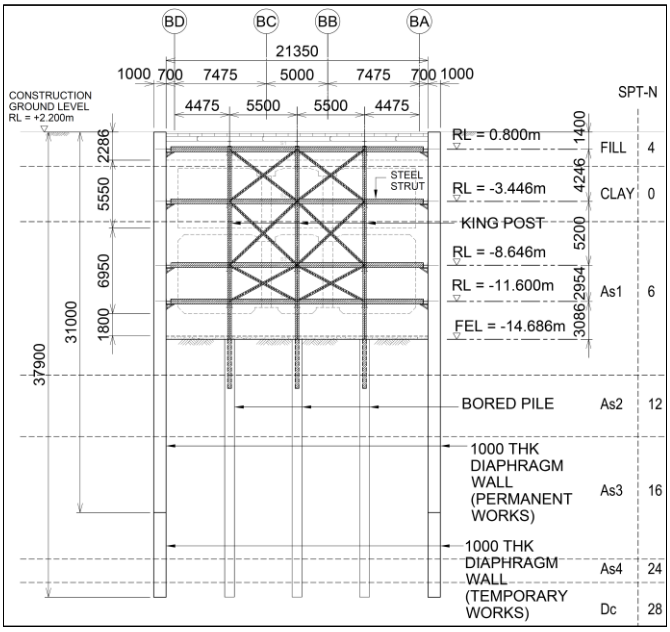

Figure 8 Typical temporary works section of Ba Son Station

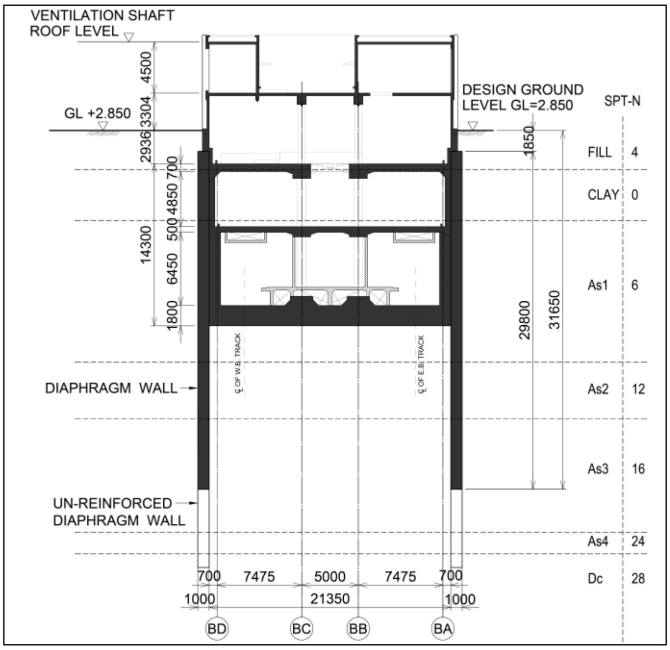

Figure 9 Typical permanent structure section of Ba Son Station

3.3 Construction

The construction of Ba Son Station was started from the western side to the eastern side. The western side must be completed earlier for preparation of TBM launching. The temporary design was adjusted to the progress of both construction. A water cut-off wall made from unreinforced concrete was constructed to demarcate the western side excavation area and the eastern side unexcavated area. A stable slope was maintained in front of the wall. The area of Ba Son Station is passing the old small dry dock; therefore, a temporary double sheet pile cofferdam is needed to create a protection for the reclamation area. The composition of thick Ac2 layer is quite troublesome in the early stage of reclamation. It was easily displaced and caused movement of cofferdam when additional surcharges from reclamation material were added. However, after putting counterbalance at the riverside, the movement could be stopped.

It is the same in Opera House Station: the construction of station box was started by drilling bored pile and installing king post and excavating and casting D-wall. Since the location was used as shipyard and perhaps a port in the past, obstacle such as wooden pier was prominent during the main excavation. A manual cutting using excavator and grabber was required to extract the obstacle and continue the excavation.

4. BORED TUNNEL

4.1 General

The tunnel segment connecting end of Opera House Station (chainage 0+805) and start of Ba Son Station (chainage 1+586) was built by bored tunnel method involving Earth Pressure balance (EPB) type of tunnel boring machine (TBM) with cutter head of scraper type as shown in Figure 10. Tunnel length is 2 x 781 m (for east-bound and west-bound tunnel). The tunnel segment lining has an outer diameter of 6.65 m, 300 mm thickness and 1.2 m length. Twin tunnel bored at similar elevation when commencing from Ba Son Station and made transition to a stacked profile before arriving at Opera House Station B2F and B4F. The maximum and minimum overburden depth is 22.3 m and 8.7 m, respectively.

Figure 10 Tunnel Boring Machine (TBM) for CP1b project

4.2 Design concept

The tunnel segment lining was designed using a two-beam-spring model in accordance with DSRSC – Shield Tunnel (RTRI, 2002). Modelling was done in SAP2000 software. The beam spring model is shown in Figure 11. The model represents segments of a tunnel as beams, the circumferential joints as rotational spring and longitudinal joints as shear springs.

The impact from tunnel construction to ground subsidence has been studied by performing FEM analysis. The analysis was carried out using Plaxis 2D software by modelling tunnel segment and introducing stress release ratio in the boring process (Brinkgreve, Kumarswamy, & Swolfs, 2017). A stress release ratio of 30% is used to predict the ground settlement for simulating the effect of tunneling induced ground movement. The 30% stress release ratio is adopted as this percentage is achievable according to our experience in Earth Pressure Balance TBM excavation in similar ground condition in Japan, since there are no local case histories found. For the important structure, i.e. Opera House building, where the settlement should not have exceeded 10 mm, special protective measure using jet grouting column was carried out as shown in Figure 12.

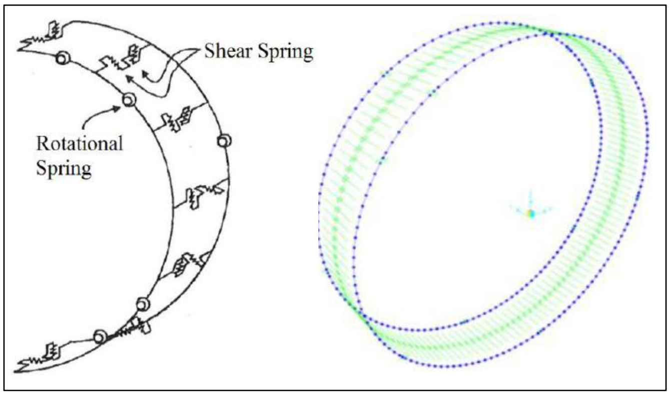

Figure 11 Structure model segment ring and model in SAP2000

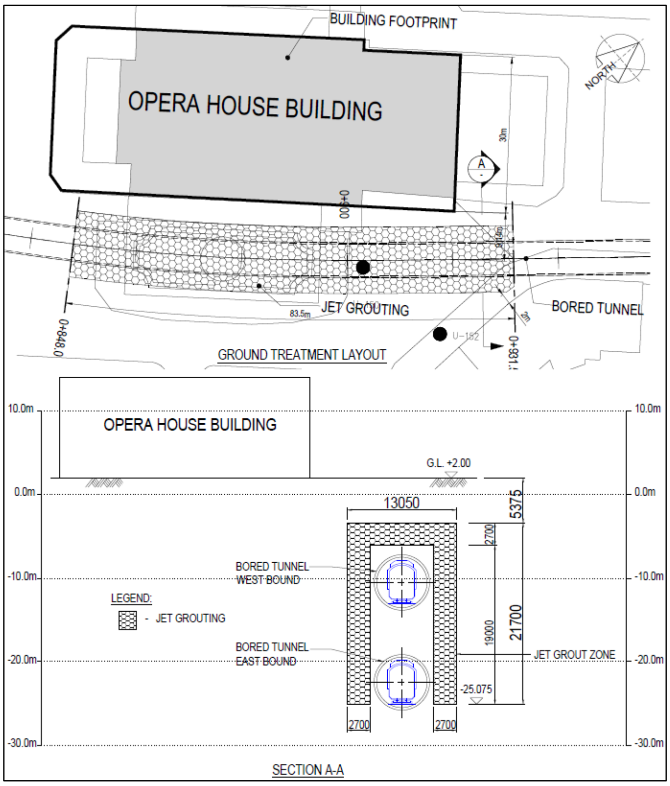

Figure 12 Jet grouting column as a protective measure against tunneling-induced settlement

4.3 Construction

The riverside location is beneficial for delivery of TBM through river by using barge (Figure 13). Soil improvement by jet grouting and chemical grouting were carried out in front of Ba Son Station and Opera House Station in horizontal and vertical locations to stabilize the ground at TBM initial driving and arriving locations. Tunnel construction started from a shaft in Ba Son Station. TBM bored and constructed the east-bound tunnel first which arrived at Opera House Station B4F. Then, the TBM was retrieved and relaunched from Ba Son Station again to construct the west-bound tunnel. The boring process of east-bound tunnel was smooth since the soil was homogenous and predictable.

Figure 13 TBM delivery by using barge

For receiving TBM in Opera House Station B4F, we applied a novel method by constructing isolated backfilling consists of foamed cement banking (FCB) and sand. The purpose is to counter unexpected water leakage due to high water pressure during TBM breakthrough. A combination of FCB and sand provided impermeable characteristic and sufficient self-weight of backfilling material that is able to suppress the water leakage in case of happening. Thus, allowing some time to initiate sealing grout to stop the leakage. Schematic figure, backfilling construction process and exposed TBM after its arrival are shown in Figure 14 to Figure 16 respectively.

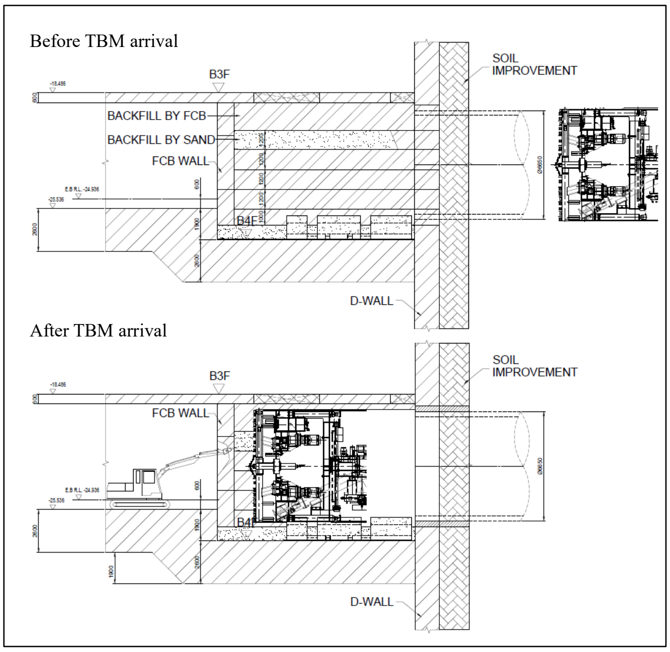

Figure 14 TBM arrival in Opera House Station B4F using FCB and sand backfilling method

Figure 15 Construction of FCB and sand backfilling used to receive TBM at Opera House Station B4F (number indicates construction order)

Figure 16 Exposed TBM after arrived in Opera House Station B4F

5. CUT-AND-COVER TUNNEL AND TRANSITION STRUCTURE

5.1 General

From chainage 1+826 to 2+360, the cut-and-cover tunnel and transition structure were constructed. This section is passing a small bay which used to be a big dry dock. The section comprises of box structure (Type A, Type B and Type C) and transition structure (Type U) (Figure 17). The end of the transition structure was connected to the elevated section of HCMC MRT Line 1.

Figure 17 Location of cut-and-cover area and its vicinity

5.2 Design Concept

Referring to the nature of cut-and-cover tunnel section, the design and the construction were divided into Type A, Type B and Type C. Type A is located just after Ba Son Station and mainly covers the existing landside area. The box structure for Type A was designed together with the D-wall as a permanent structure. Type B is occupying a former big dry dock area. As for Type B, initially its design was similar to Type A by using D-wall as retaining structure and foundation of box structure. In the initial design, reclamation would be required to construct the D-wall. However, it might cause potential problem due to settlement of Ac2 layer. Finally, a cofferdam made by steel pipe sheet piles (SPSP) with diameter 1300 mm and thickness of 15 mm (grade SKY490) were chosen instead of D-wall. The connections between the SPSP were grouted so it created a watertight environment inside cofferdam area (excavation zone). As foundation, the bored piles were constructed prior to excavation by using the SPSP with a diameter of 1000 mm as a temporary casing. The cut-and-cover tunnel Type C was located on the land side. Temporary retaining structure for this segment is designed by using sheet pile FSP-IV. The tunnel box was supported by a series of bored pile.

For the transition structure, or Type U, it consists of a U-shape structure supported by piles. Due to the thick clay layer in the area, it was revealed that the piles are susceptible to the negative skin friction. To solve this problem, the pile foundation was designed to use the pretension spun high strength concrete (PHC) piles with a friction cutter (de-bonding). The length of the friction cutter used was 25 m and 34 m long. The typical cross-sectional profiles of the cut-and-cover tunnel and the transition structure are shown in Figure 18.

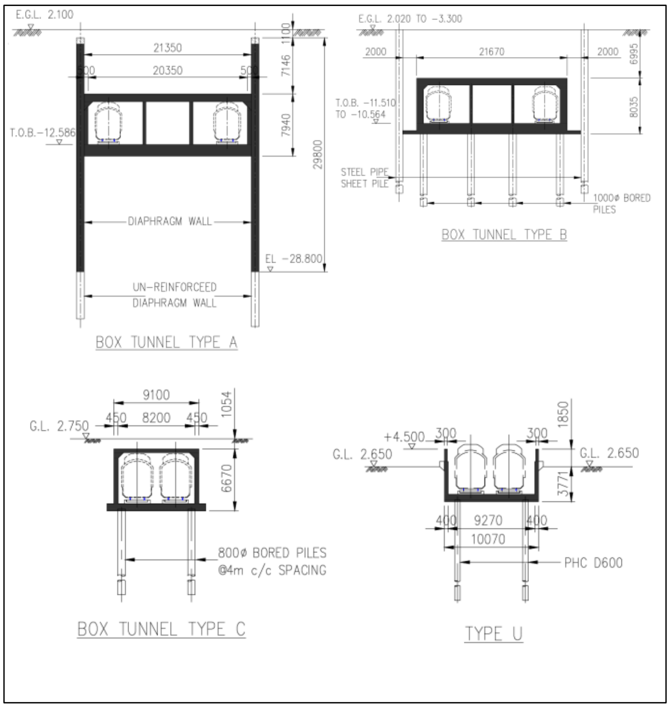

Figure 18 Typical cross section of cut-and-cover tunnel and transition structure

5.3 Construction

The construction of cut-and-cover tunnel and transition structure was carried out in parallel for each type. But, since the progress of excavation is different, demarcation walls were constructed between the types. For Type A and Type B interface, the demarcation wall was made from the unreinforced concrete. Meanwhile, between Type B and Type C, a sheet pile wall was installed. Due to the close proximity to the river, the fluctuation of the river water level caused unbalanced condition and frequent changes to the wall displacement. It required design of temporary work structures which consider critical case from several schemes of ground and river water level difference.

6. CONCLUSION

The scope of CP1b project which consists of various ground conditions provides comprehensive challenges. It covers many design aspects in geotechnical engineering such as retaining structures, deep excavation, soil-structure interaction, slope stability, tunneling and consolidation. The challenges arisen during the construction encourage the selection of the most optimum solution. The followings are some highlights from the design and the construction experience of HCMC MRT Line 1 CP1b:

- The deep excavation project in the city center requires a robust monitoring plan and a sufficient understanding of the existing structures in the vicinity. The selection of the top-down method was suitable for such a condition.
- The use of inclined strut optimizes the top-down construction method by creating bigger working space and reducing the quantity of steel strut compared to that of horizontal strut.
- FCB and sand backfill was effective as a preventive measure to avoid the leakage during TBM arrival into the station.
- The steel pipe sheet pile is proven to be feasible and practical to create a temporary cofferdam for construction in the river area.
- The selection of a solution for the negative skin friction risk shall consider the time constrain. Therefore, a friction cutter for pile was selected over the embankment for consolidation.

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