LARGE DIAMETER PIPE ROOF BOX EXCAVATION FOR PASSENGER LINKWAY TUNNEL

F. Saffiyah BADURDEEN[1], G. T. SENTHILNATH[2],
[1] Ed. Zublin AG Singapore
[2] Geoconsult Asia Singapore

Abstract:

With the construction of new underground public transportation systems, there is a need to construct underground pedestrian linkways that connect the stations with the publically accessible entrances and exits. In the past, the preferred underground linkway construction method was using cut and cover with temporary excavation retaining walls and strutting. This requires multi-staged traffic diversions and either, advance utility diversions or utility support within the excavation resulting in utility gaps within the excavation. Recently, several other options such as pipe roof with steel frame support, RC box jacking with rectangular Tunnel Boring Machines (TBM) or multi-staged mined tunnel excavation have been implemented. The pipe roof method is a closed trenching method in which pipes are installed to match the shape of the final tunnel. Together with the steel frames that support the pipes; the pipe roof forms a temporary support while the final tunnel is being constructed.

This paper presents a case study about the construction of a 6m x 8.5m cross sectioned and ~120m long Bukit Panjang Underpass. The project consists of a pipe roof box system that was constructed using 2.0m diameter steel pipes with steel frame supports. The various aspects associated with the large diameter pipe roofing system including the challenges encountered during construction have been discussed in this paper. This was the first time large diameter pipes had been used to form the pipe roof box in Singapore.

Keywords: Pipe roof support, Pedestrian Linkway, Pipe jacking, excavation methods

1.0 Introduction

Construction of underground tunnels for pedestrian linkways using the pipe roof box method has become common in the recent past. However, most of the projects use smaller diameter pipes (~0.8m) to form the closed box structure. The pipe roof which is installed by pipe jacking (prior to excavation) creates an advance roof support system. It forms a structural part of the ERSS and reduces the stress relaxation in soil. The tunnel excavation for the Bukit Panjang Underpass was designed and constructed using large diameter pipes (2m diameter) to outline the pipe roof box. Although an established mining method, the pipe roofing system presented in this paper is customized in order to develop the most effective engineering solution that tackles difficult ground conditions and ensures that the structures above and surrounding the excavation were affected minimally.

2.0 Project Description

Located in the western region of Singapore, the LTA contract 9057 Bukit Panjang Underpass project was introduced to construct an additional MRT Station entrance and underpass connecting to the existing Bukit Panjang MRT Station. The underpass spans approximately 120m undercrossing Bukit Panjang Road together with several utilities including a 13m wide canal and a large diameter water main pipe. The overview and layout plan of the project are shown in Figure 1 and Figure 2. The tunnel has a cross section of 8.5m width x 6m height while the overburden above tunnel crown varies from 6m to 13m.

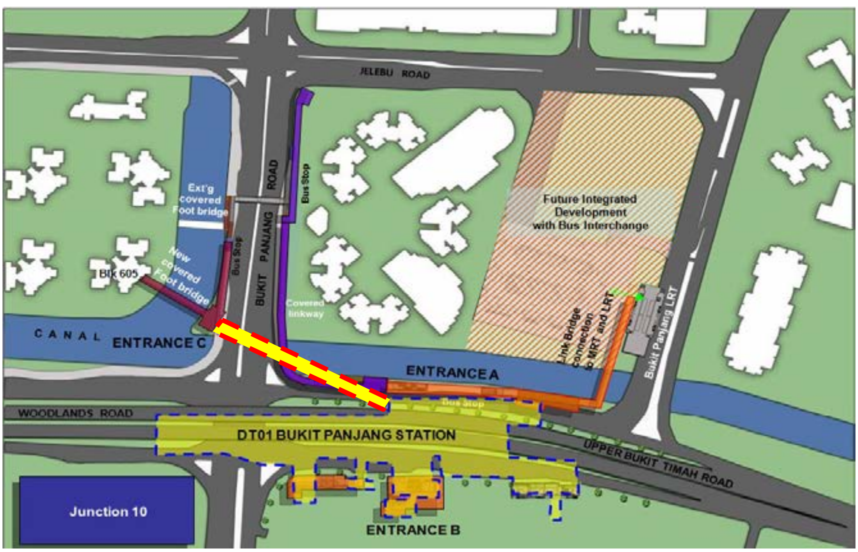

Figure 1: Project location – Overview

A typical pipe roof system is formed by jacking several small diameter steel pipes from one end of the tunnel (jacking shaft) to the other end of the tunnel (receiving shaft) using either a micro-TBM or the soil-displacement/hammering method. Upon completion of the pipe roof, excavation of the tunnel takes place in small round lengths / spans (limited by the bending capacity of the small diameter pipes). During the staged excavation of the tunnel, the pipe roof is supported using a temporary or permanent structure support system. A long linkway tunnel constructed using the typical pipe roof system would therefore result in longer project duration (due to short excavation spans). Moreover, installation of steel pipes within allowable tolerances using pipe jacking for a tunnel of ~100m would require an intermediate shaft.

Having considered the setbacks of a typical pipe roofing system, the decision to use large diameter pipes was made. The selection of large diameter pipes enabled using a more powerful TBM that not only facilitated a longer tunnel length without the need of an intermediate shaft but also allowed the introduction of a retractable machine. The number of pipes required to be driven was also reduced to 13 nos (compared to 42nos using 0.813m dia pipes).

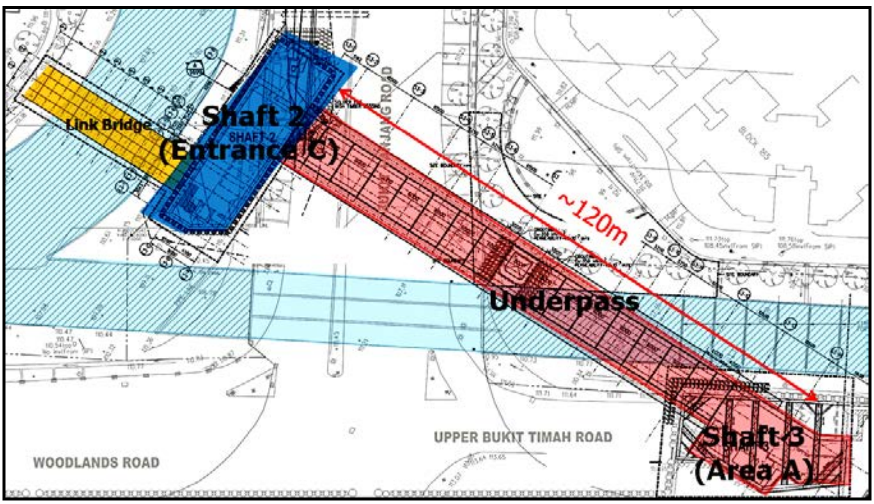

Figure 2: Bukit Panjang Underpass Layout Plan

3.0 Geology and Ground Condition

The underpass tunnel extending up to 13m below ground was expected to encounter mixed ground conditions. The ground condition generally comprised of about 3m of fill, and Kallang formation which included fluvial sand, fluvial clay underlain by weathered Bukit Timah Granite GVI to GIV. The bedrock of Bukit Timah Granite (GIII – GII or better) was located at about 18m to 20m below ground level. Based on the geological profile as shown in Figure 3, the invert of the tunnel was expected to be in GIV or better Bukit Timah Granite.

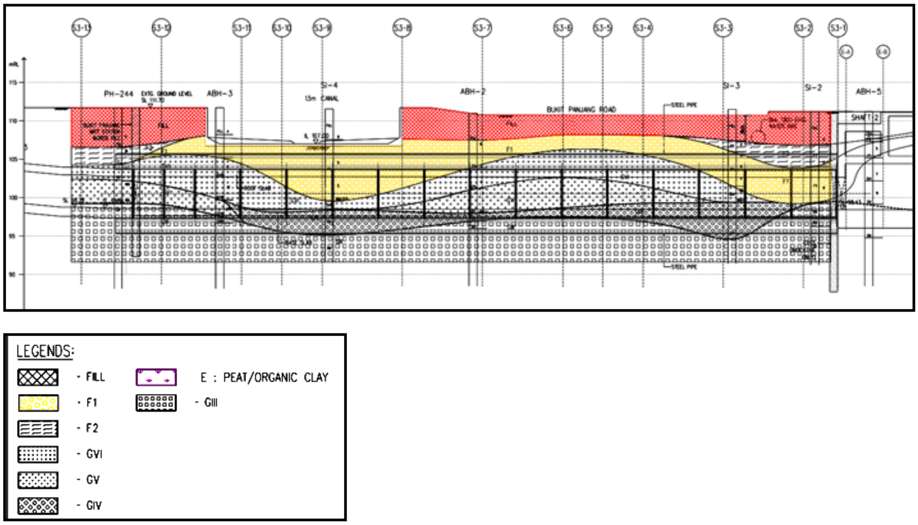

Figure 3: Geological profile along the tunnel

Field permeability test indicated permeability for the weathered granite in the range of 1x10^{-7} m/sec at invert level.

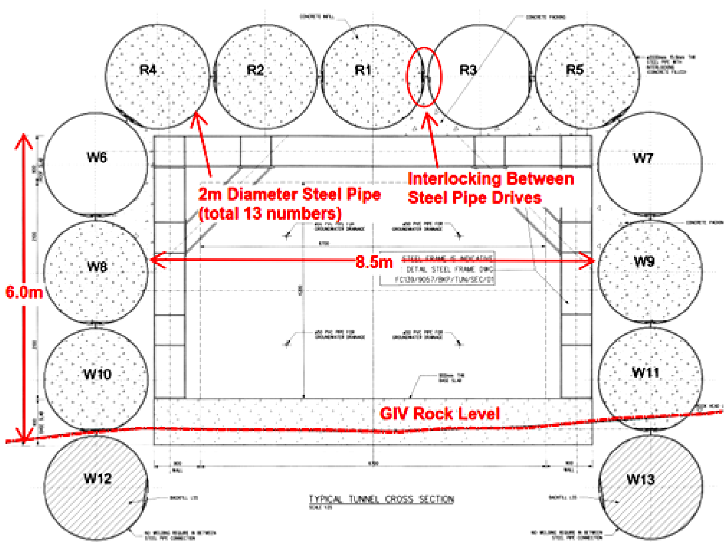

Figure 4: Typical cross section of the linkway

Certain stretches of the linkway tunnel was expected to have F1 / sandy GVI at the tunnel crown which introduced the risk of face instability within the pipe roof during tunnel excavation. Although this would not cause any global failure, the possible collapse of a tunnel face would result in increased ground surface settlement.

4.0 Design Concept

The proposed temporary support for tunnel excavation consists of steel pipes with temporary steel frame as shown in Figure 4. The pipe roof box was constructed using 13 numbers of 2m diameter steel pipes that were jacked surrounding the tunnel boundaries using a micro-TBM. 2D Plaxis [1] with an approximated plane strain using Mohr-coulomb material model was used to analyze and design a typical cross section. In order to account for ground movement due to pipe jacking, a negative volume strain was considered for each pipe in the FE model. The mesh used around the tunnel is illustrated in Figure 5.

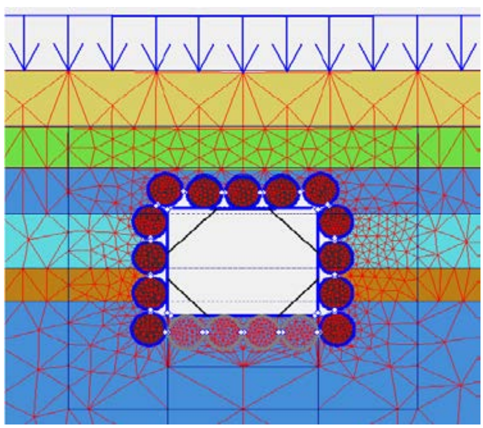

Figure 5: FE model for analysis

The pipe roof system was not closed at bottom as it would be resting on GIV or GIII. However, in order to control the water ingress during the linkway tunnel excavation, post grouting was recommended. In addition, allowable water ingress during excavation was established using a 2D flow analysis model and was set to be less than 25 l/min, for a maximum round length of 10m.

Ground settlement was expected to happen during 2 stages (a) during pipe-roof installation and (b) during excavation of the linkway tunnel and support frame installation. The latter would be controlled by round length and the stiffness of the pipe roof element while the former would be dependent on various factors such as face stability, overcut and water ingress during cutter tool replacement etc.

4.1 Factors influencing face stability

Face stability calculations are required to determine the likelihood of the excavated face moving or collapsing into the void created during excavation. Face stability depends upon the type and variability of the ground being excavated, the ambient stress, the ground water conditions, the rate of advancement and the construction methods adopted. The methods for calculating stability of tunnel faces are generally well-established and are adjusted for pipe jacking / micro-tunneling in terms of rate of advance, size of face and face support conditions [2]. A face pressure of 0.7 to 1.4 bars was recommended based on the soil condition at face and the depth of the pipe.

4.2 Jacking force

Minimum jacking force is calculated based on the minimum required force to overcome the skin friction along the pipe contact surface area and maximum jacking force is calculated based on the pressure transmission along the steel pipe and joint configuration between the pipes using ATV nomograms [3].

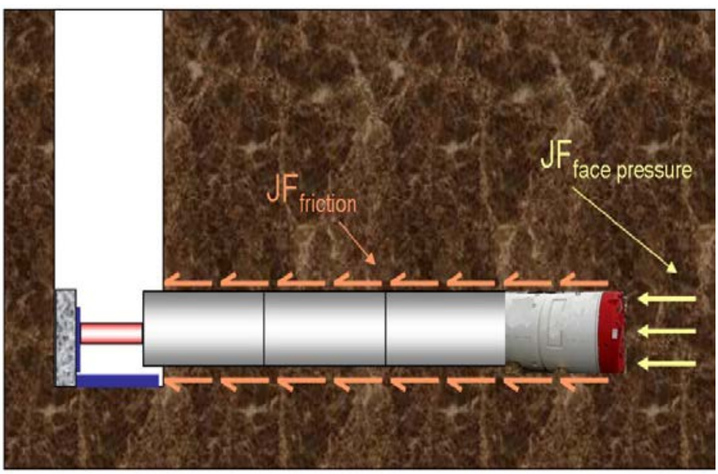

Figure 6: Jacking force estimation

Once the pipe roof system forming the outer boundary of permanent works was installed, the design intent was to carry out excavation from both ends of the tunnel. An intermediate temporary shaft was proposed by the contractor to expedite the excavation works giving four working fronts for the tunnel excavation. Taking advantage of the higher bending moment capacity of bigger roof pipes, steel support frames were designed for a typical spacing of 6m. 800 series and 900 series UB steel members were used as support frames. Typical support systems for a similar excavation would consider support members for invert location as well. However in this case, since the tunnel invert was in competent ground (GIV and better), the permanent RC slab was used as the temporary tunnel invert support. A typical tunnel linkway section with RC base slab is shown in Figure 4. Casting the permanent RC slab during excavation and installing the temporary steel frames at longer spans facilitated to carry out permanent works faster.

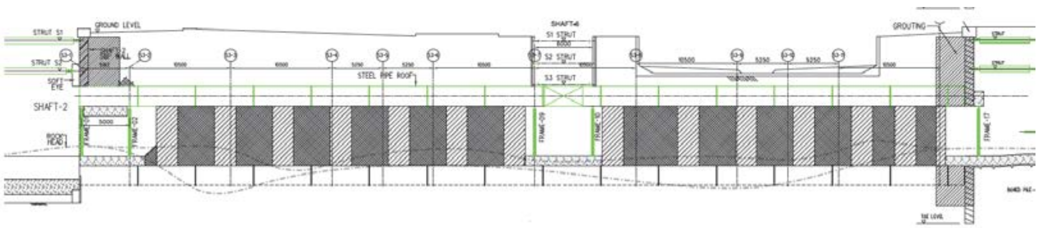

Figure 7: Temporary intermediate shaft for additional excavation face

5.0 Excavation and Support System

5.1 Machinery and Equipment

The retractable micro-TBM, M-1896M AVN 1500TB was used to install the 2m diameter steel pipe drives along the underpass tunnel. With a torque of more than 450kNm and the ability to maintain face pressure up to 1.5 bar, the M-1896M had the advantage of driving through mixed ground conditions. The larger size of the machine enabled to change the cutter tools while driving through GIII or better ground conditions.

The TBM setup which takes place before commencement of each drive consists of setting up the jacking frame, the launching seal and the back plate. 2 numbers of 700 ton capacity hydraulic jacks were used for the pipe jacking operation. Figure 9 shows the typical jacking set up used in this project.

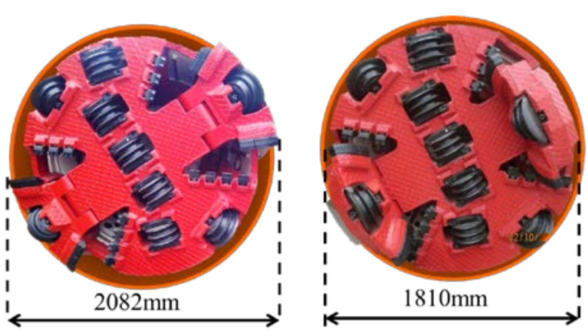

Figure 8: Collapsible cutter head

Figure 9: Pipe Jacking Setup

The collapsible cutter head shown in Figure 8 was used in this project so as to retract the TBM to the launching shaft without the completion of a receiving shaft. During the TBM driving mode, the cutter head extends to a diameter of 2.082m while during the retraction mode, the cutter head is folded to diameter of 1.810m. The outer shield of the TBM is sacrificed to allow for the retraction and the TBM is pulled back to the jacking shaft using a winch system.

The TBM comprises of an inbuilt hydraulic conveying system which includes a feed and slurry pump together with the respective pumping lines. During the TBM operation, clean suspension (water or bentonite) is transported to the tunnel face through the feed pumping system maintaining the required face pressure at the tunnel front. Concurrently excavated soil is transferred to the slurry treatment plant which includes a centrifugal and de-sanding system (shown in Figure 10). Bentonite is injected to the voids between the steel pipe and soil to stabilize the surrounding ground until annulus grouting is complete.

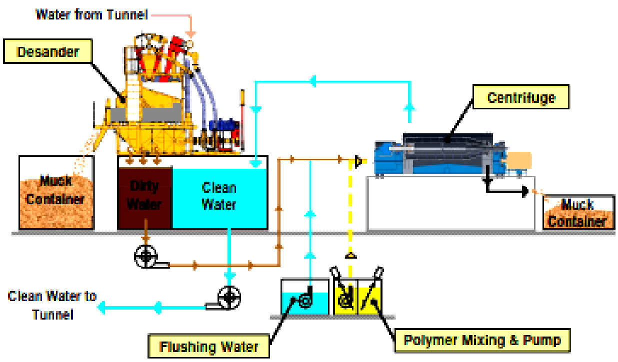

Figure 10: Muck management and slurry treatment system

5.2 Measures to limit settlement and water drawdown

During the pipe jacking operation, ground water drawdown and surface settlement was controlled by maintaining a target face pressure at the tunnel front close to hydrostatic pressure (0.7 to 1.4 bars). During excavation, the ground water drawdown was controlled through the water tight system formed by the inter-connected steel pipes. In addition, the following measures were taken to minimize the ground water drawdown and ground surface movement.

- Annulus grouting around the pipe roof – Upon completion of every steel pipe drive, annulus grouting was carried out from inside the steel pipes to form a layer of cement grout surrounding the steel pipes. Not only did the grout layer seal the overcut caused by the pipe jacking operation but it also prevented water or soil entering the tunnel through the gaps of the interlocking during excavation.

- Casting permanent base slab during tunnel excavation – Due to the omission of the bottom row of pipes forming the pipe roof box, water ingress from the rock face at the tunnel invert was expected. To seal off the rock face at the tunnel invert, the permanent base slab was cast immediately upon excavation of every span.

- Jet Grouting Piles (JGP) within the tunnel – At the initial stages, soil improvement to treat the sandy F1 and GVI layers within the tunnel was considered to be impossible due to the major utilities along Bukit Panjang Road. Introducing large diameter steel pipes enabled to carry out JGP from within the steel pipes. JGP blocks were formed at 6m intervals along the tunnel to hold the tunnel face at every excavation span and prevent face instability / ahead-of-face ground relaxation. A view of the grout block formed is shown in Figure 11. The micro JGP machine which was used to carry out the ground improvement work from within the pipe roof is shown in Figure 12.

Figure 11: Jet Grout Piles – Visible during excavation of tunnel

Figure 12:JGP rig in limited headroom condition (inside roof pipe)

- Installation of recharge wells surrounding the tunnel – 6 numbers of recharge wells were installed along and close to the tunnel alignment. 3 out of 6 numbers of recharge wells were installed close to the jacking shaft where majority of the water loss was expected. Water loss was mainly experienced during the pipe jacking operation in mix face condition and full face rock (during cutter tool change).

- Shimming and concrete packing – Each round (6m) of excavation was followed by the casting of permanent base slab and the installation of temporary steel frame. As described in Section 4.0, the temporary steel frames were designed to support the pipe roof which would require completed contact between the steel frame and the steel pipes. In order to enable complete contact between the steel pipes and the steel frame, the gap between them was closed by installing shim plates or concrete packing. This minimized the settlement expected during the tunnel excavation.

Figure 13: Temporary steel frame

6.0 Instrumentation and Monitoring

In order to monitor the impact of the pipe roofing and tunneling work on the surroundings, several instruments including ground settlement markers, utility settlement markers, water stand pipes, piezometers, extensometers, strain gauges and 3D prisms were installed. As it could be seen from Figure 14, majority of the ground settlement and ground water drawdown was observed during the steel pipe jacking activity. As an exception, a single settlement marker recorded a maximum settlement of up to 76mm during the steel pipe installation. The settlement plot versus time for the settlement markers along the tunnel alignment is show in Figure 14. Incremental settlement after pipe jacking activity was in the range of 20mm and some of this settlement bounced back when the excavation was completed and the ground water table stabilized to initial values. The ground was recharged during the pipe jacking operation to maintain the water table within alert levels. Figure 15 shows the time history of piezometer reading during the project duration. As it could be inferred from the plot, the piezometer remained stable during initial pipe jacking operation. However, there was a sudden drop in piezometer (and hence associated settlements) when the cutter head encountered mix face conditions and during cutter tool change in full face rock. The recharge wells helped to restore the water table once the pipe jacking was complete. After the installation of pipes, a water tight structure was achieved and there was no further significant fluctuation of water table.

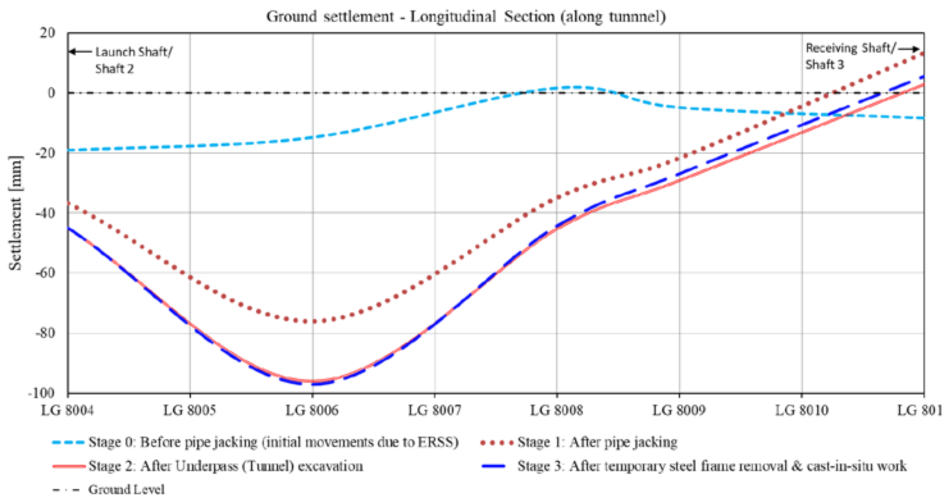

Figure 14: Ground settlement progress during pipe jacking & excavation

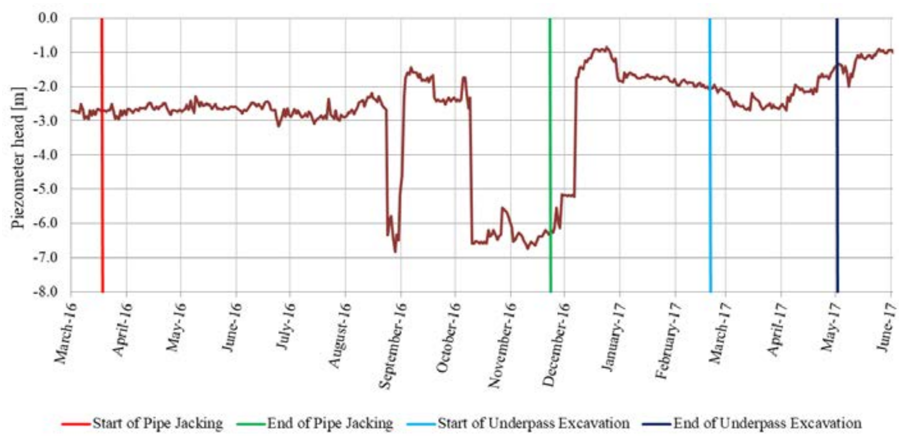

Figure 15: Piezometer Head vs Time

7.0 Construction timeline and Project status

Currently, the tunneling work for the Bukit Panjang Underpass project has been completed remaining permanent structure construction work. The installation of 13 drives of 2m dia steel pipes using the pipe jacking was completed within approximately 8 months from March to November 2016. Pipe jacking at the mixed face/ soil-rock interfacing area took relatively longer than pipe jacking in rest of the ground condition.

The 120m long linkway tunnel excavation was completed within 2.5 months from February to April 2017 while the permanent structure casting and removal of steel frames which was the final stage of the tunnel work was completed within the 2.5 months between May and July 2017. Since the concerns of water ingress and face stability were addressed before commencement of the tunnel excavation work, there were no major challenges during the tunnel excavation itself.

8.0 Discussions and Conclusion

The Bukit Panjang Underpass project has demonstrated the use of large diameter pipes for pipe-roofs and its advantages. The project has established that by the use of larger diameter pipes, improved speeds of tunnel excavation and high construction productivity can be achieved while ensuring safe tunnel excavation.

Although disturbance of overburden is almost inevitable in any tunnel construction, especially with the presence of cohesive soil such as Kallang formation, this project was able to record a total settlement within the range of 20 to 50mm while limiting the surface settlement during tunnel excavation to less than 20mm. The influence on the surrounding soil due to water drawdown and consolidation of Kallang formation caused by the water ingress during pipe jacking operation was effectively reduced during tunnel excavation owing to the pipe roof structure adopted in this project. The expected settlement due to tunnel excavation was also well controlled due to the soil improvement work carried out from the roof pipes.

Experience gained from this project confirmed that a robust pipe roofing system can be formed using large diameter pipes while JGP within the tunnel effectively improved loose soil (F1) at the crown proving to be excellent material to provide a stable face during tunnel excavation.

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