Construction of Rail Tunnels Using Slurry Machines on Circle Line Stage 3, Singapore

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ABSTRACT

The Land Transport Authority (LTA) of Singapore is responsible for the implementation of the Mass Rapid Transit (MRT) System on the island. Underground construction for the rail network in Singapore commenced in the early 1980s, and to-date, a total route length of 138km of rail has been laid. The rail network is currently being expanded with the Circle Line (CCL) Project and when ready, 29 underground stations and 34km of route length will be added to the existing rail transit network. Commuters will be able to transfer between lines at 6 new interchange stations without having to go through the existing interchanges in the city centre. Bypassing the bottleneck at the city centre, the CCL will alleviate commuter congestion, better distribute the passenger load more uniformly across the network, increase connectivity and significantly cut down on the travelling time.

Circle Line Stage 3 (CCL3) is part of the CCL Project and comprises 5 stations and 5.7km of route length. The tunnel construction for this stage of the CCL Project was challenging. This was due mainly to the fact that the ground was so varied with different types of weathered granite and the presence of a large number of houses situated directly over the alignment. Establishing an alignment for CCL3 proved to be highly challenging, as there are no major road corridors between stations. This meant that tunnels must pass directly beneath a number of private houses, and very close to the foundations of others. The choice for the type of Tunnel Boring Machines (TBM) to be use in this tunnel alignment becomes critical. A decision was made to opt for the use of slurry machines, for the first time in Singapore’s rail tunnelling history. This paper describes the challenges face during the course of tunnelling, the impact to the houses above the tunnel alignment and LTA’s risk management methodology.

1. INTRODUCTION

1.1 General

Singapore’s newest metro line, the Circle Line (CCL), is set to be complete in 2010 and is expected to cut travelling time and allow commuters to bypass busy interchange stations like City Hall and Raffles Place. Costing $6.7 billion, the CCL is a fully underground orbital line linking all radial lines leading to the city. This new line will intersect the existing North-South Line, East-West Line and North East Line (see Fig 1).

Construction of the CCL has been broken into five(5) stages with Circle Line Stage 3 (CCL3) encountering the most challenging stretch of tunnelling works constructed so far in Singapore. The locations of the stations resulted in the tunnel alignment not having the luxury of passing beneath major arterial roads but rather for most stretches, the alignment passes beneath densely populated areas comprising of low and high rise residential houses and other infrastructures.
Contract 853 (C853) of Circle Line Stage 3 was awarded to Taisei Corporation, at S$167mil, on 31 July 2003. The scope of work for this Contract includes the construction of Marymount (MRM) station, the twin bored tunnels between MRM and Bishan (BSH) stations (see Fig 2) using two slurry TBMs and twin tunnel drives from BSH station to Lorong Chuan (LRC) station using two EPBMs. The stretch of tunnelling work between MRM and BSH stations is approximately 1250m in length with an internal diameter of 5.8m. Although the orientation of MRM and BSH station were fixed nearly perpendicular to each other, a horizontal curve of 300m radius was introduced to the tunnel alignment to avoid the foundations of two condominiums located along the alignment. Subsequently, the alignment dives to about 42m below ground level as it underpassed approximately 47 numbers of low rise residential houses so as to minimise any impact to the foundations of these buildings and to tunnel through competent ground. Most of these houses were originally built in the 1950s and were founded predominantly on shallow footings. A substantial number of houses had undergone extensive renovations and in some cases, additions were made to the original structure, resulting in some of the structures to be founded on mixed foundations.

Towards the end of the drive just before docking into BSH station, the tunnels underpasses BSH Road which is a utility service corridor, with a high pressure gas transmission pipeline, water mains, 22kV cables etc. The TBMs then docked into the new BSH station which is beside the existing Bishan station and the docking is directly under the existing operational North-South (NS) MRT Line.

1.2 Geological Condition

The geology along the tunnel alignment is predominantly Bukit Timah Formation consisting of the various weathering grade of granite with ground water at approximately 2.5m below the ground level. The compressive strength of the granite is between 3MPa for highly weathered granite to about 180-200MPa for moderately weathered granite. At approximately mid way of the tunnel alignment, there is presence of about 10m Estuarine Material from the Kallang Formation above the Bukit Timah Formation. Estuarine Material can be described as an unconsolidated black to blue grey mud, muddy sand or sand with high organic content.
Due to the occurrence of mixed face condition in the face of the TBM cutterhead, there is high risk of large volume losses and seepages during tunnelling. This mixed face zone is the interface between soil and rock, and is highly permeable with high pore water pressure. Taking into consideration that directly above the tunnel alignment is a densely populated residential area with many buildings on shallow foundations, settlement is a major concern. Based on the geotechnical evaluation report, (using volume loss estimated as 1.5% , LTA Design Specifications), condition survey reports of the buildings, building damage assessment reports by a Professional Engineer, the estimated maximum settlement of 15mm was expected and it was determined that this would not result in any of the buildings requiring any protective works. As such to minimise this risk of excessive settlement, it was included into the tender documents for the Contract that the contractor was envisaged to employ slurry TBM for this section of the tunnelling works.

2. SLURRY SHIELD TUNNELLING OPERATION

2.1 Slurry Shield TBM

The contractor, Taisei Corporation, adopted two Slurry Shield TBMs, one for each bound of the tunnelling drives for the twin bored tunnels from MRM to BSH stations. These Slurry TBMs were manufactured by Kawasaki Heavy Industries in Japan and the main technical specifications for the machine are as follows:

Table 1. Slurry Shield TBM Parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation Diameter</td>
<td>6720 mm</td>
</tr>
<tr>
<td>Overall Length</td>
<td>9900 mm</td>
</tr>
<tr>
<td>Cutter Motor (Electric)</td>
<td>180 kW x 6</td>
</tr>
<tr>
<td>Thrust Force</td>
<td>2000 kN x 20</td>
</tr>
<tr>
<td>Cutter Head Speed</td>
<td>0 to 4 rev/min</td>
</tr>
<tr>
<td>Max Jack Speed</td>
<td>70mm/min</td>
</tr>
<tr>
<td>Roller Cutter Single &amp; Double</td>
<td>39 nos. &amp; 4 nos.</td>
</tr>
<tr>
<td>Cutter Bit</td>
<td>160 nos.</td>
</tr>
<tr>
<td>Gauge Cutter</td>
<td>16 nos.</td>
</tr>
<tr>
<td>Copy Cutter</td>
<td>2 nos.</td>
</tr>
</tbody>
</table>

2.2 Slurry Transportation System

The slurry transportation system supplied by Aktio Corporation (Japan), is a system to pressurise the slurry TBM cutterface and to convey excavated material from the cutterhead to the slurry treatment plant for separation process (see Fig 4). The slurry feeding line generally consists of 2 main pumps, the P1 and Pm pumps. P1 pump is the feeding pump located near the regulating tank at the slurry treatment plant to pump slurry to the front of the TBM cutterhead. The Pm pump is face pressurising pump that operate during the stop of the excavation to maintain face pressure on the cutting face if required.

The slurry discharge line consists of P2 pump, relay pumps, PE pump, and P0 pump. The rock crusher, pressure sensors, density and flow meters are also found along the discharge line. P2 pump located behind the rock crusher at the TBM back-up, is use to pump excavated material from the TBM to the launch shaft bottom. At the shaft bottom, PE pump is use to pump the excavated material to the slurry treatment plant. A series of relay pumps located at every 250m is positioned to assist the P2 pump as the excavation proceeds further. P0 pump installed at the discharge line and connected to the feeding line is use to increase/maintain the circulation flow from the TBM cutterface to the rock crusher to prevent blockages cause by settling of slurry material or the excavated material.
2.3 Slurry Treatment Plant

The slurry treatment plant supplied by Kankyo Engineering (Japan), is for the separation of excavated material from the slurry discharge line and return the treated slurry to the feeding line. There are 3 basic stages consisting of Primary, Secondary and Tertiary treatments for the operation of the slurry treatment plant. Primary Operation is for the separation of small size rocks, gravels and sand from the discharge pipeline. For each bound of the tunnelling drive, the equipment comprises of one gravel separator and two sand separators (with cyclones).

Excess slurry from the Primary Operation will be treated at the Secondary Operation. At this stage, the excess slurry will be pump into the slurry tank and coagulant is added to it form flocks of clay and silt. The mixture is then compressed by high pressure pumps into the filter press for dehydration to form mud cakes. Tertiary Operation is an automatic process to treat the filtered water produced from Secondary Operation. Excess filter water is pumped into the raw water tank for waste water treatment equipment. Coagulant is added to form suspended solid and further removed by the sedimentation process. Water pH is adjusted by adding carbon dioxide (CO$_2$) gas before allowing to be discharged into the public drain.

3. SLURRY SHIELD TUNNELLING MANAGEMENT

3.1 Tunnelling Below Houses

3.1.1 Building Protection

As the tunnel alignment will be passing beneath numerous residential houses, studies on settlement analysis and building protection were carried out early during the design stage by LTA’s Consultant, Montgomery Watson Harza (MWH). A complete list of the buildings and structures were identified within the tunnelling zone of influence based on settlement analysis. This zone of influence was divided into 4 main areas based on the possible effects caused by bored tunnelling.

Zone A: Immediately overlying the tunnel
Zone B: Outside Zone A but within 0.5 tunnel diameters from the tunnel extrados
Zone C: Outside Zone B but within 3 tunnel diameters from the tunnel extrados
Zone D: Outside Zone C but within the influence zone

For the tunnel alignment in C853, there are a total of 47 buildings (mostly low rise residential houses) that lies within Zone A and B. A methodology was formulated to assess the need for protective works for these buildings as illustrated by the flow chart in Figure 6.

From the flow chart, the buildings are colour coded to assess the need for protective works. Where foundations are unknown, assumption based on the worst case condition is assumed and are assigned either by Red or Orange coding. For this project, there are 6 houses along the tunnel alignment classified as red with no foundation details and of which, 2 houses are directly above the tunnel alignment. These residential houses are single storey with similar structural layout and all built in 1950s.
Coincidentally, prior to our tunnelling work, one of the owners was demolishing his house to rebuild it to a 2 storey detached house with basement. From the information gathered, the old foundation was found to be about 1.5m from the ground level. It was safely assumed that all these 6 houses with unknown foundation have shallow foundation and hence reclassified as Green.

Are the foundations of the houses likely to be intercepted by the tunnel or be close enough to lose capacity such that Factor of Safety (FOS) drops below 1.5 and the house is likely to be unsafe for repair if no protective works undertaken before tunnelling?

No

Is foundation capacity likely to be affected by tunnelling?

Yes

Plan for undertaking remedial works based on anticipated damage and/or loss of foundation capacity. Is house likely to be unsafe for repair if no protective works undertaken before tunnelling?

No

Yes

Strategy Code: Green

No protective works required before tunnelling

Strategy Code: Orange

• No protective works required before tunnelling if occupants relocated during tunnelling.
• Design and implement protective works if occupants are not relocated during tunnelling unless Contractor can satisfy the Engineer that such relocation is not necessary.

Are assessed damage due to tunnelling likely to induce excessive settlement?

Yes

Strategy Code: Red

Protective works required before tunnelling

No

Fig. 6. Assessment Methodology – Need for Protective Works.

3.1.2 Condition Surveys
Before the award of the civil contract, LTA engaged a consultant to inspect and obtain photographic records of the conditions of the structures and facilities along the tunnel alignment. The extent of the photographic records stretched 100m beyond the centre line of the tunnel alignment. This exercise enabled LTA to assess the need for the types of protective or underpinning works required for the structures and to capture photographic evidences of the structure conditions before the tunnelling works. After the award of the contract, another series of the pre-construction condition survey was carried out by the contractor. An independent report on building assessment endorsed by a Professional Engineer was also submitted by the contractor to identify critical structures along the tunnel alignment and to affirm the need for any kind of protective works.

3.1.3 Real Time Monitoring Instruments
LTA has stipulated in the contract document to the contractor the need to provide real time monitoring for the houses above the tunnel alignment. As such, the contractor had installed at least 2 numbers of 3-Dimensional optical prisms for every house above the tunnel alignment. 2 numbers of Robotic Total Stations were placed at strategic high ground to detect the optical prisms. Raw data from the Total Stations were transmitted to a computer where the data was processed for viewing. The viewing format was designed such that pre-determined trigger values were colour coded so that any breaches could be observed easily from the computer monitor.

Another feature arising from the real time monitoring instrument is the “SMS Alarm” alert system. Using a wireless modem, SMS text alarm was send to the mobile phones of the relevant personnel informing them of breaches in the trigger values. This feature allows swift action plan be developed as means of risk mitigation measures.
3.1.4 Slurry Excavation Management

The understanding and monitoring of slurry excavation is the most important aspect in managing slurry TBM tunnelling. The measurement of excavation volume is critical to validate and ensure against the occurrence of over-excavation and to prevent large volume loss that will result in excessive settlement.

In C853, the excavation volume for the Slurry TBM was monitored and recorded automatically in real-time and display in the central control room. To maintain the face pressure in slurry TBM, it is important to have a balance between the volumes of slurry feed into the chamber against the quantity of slurry and excavated material being discharged. The principle behind it is that it being a closed and balanced system, the quantity of slurry introduced into the system and the volume of excavated material brought in through the feeding line must be equivalent to the amount of slurry and excavated material (soil solids and groundwater) transported out through the discharge line. It is used as an instantaneous indicator against over excavation and constitutes the first layer of slurry excavation monitoring.

\[
Q_f, \text{ feeding flow rate (m}^3/\text{min)} \\
Q_s, \text{ rate of intake of excavated material (m}^3/\text{min)} \\
Q_d, \text{ discharge flow rate (m}^3/\text{min)}
\]

In a balance state,

\[
Q_d = Q_f + Q_s
\]  
(1)

Rearranging Eq. (1):

\[
(Q_d - Q_f) - Q_s = 0
\]  
(2)

This indicates an ideal situation where the difference of the slurry feeding rate and the discharge rate is equivalent to the rate of excavation. By introducing a parameter, \(df\) (deviation flow) for an non-ideal situation, the formula becomes,

\[
(Q_d - Q_f) - Q_s = df
\]  
(3)

\(df > 0\) : The quantity of discharge slurry is greater than the volume of feeding slurry and excavated material. This indicates that more excavated material is being brought in than in the balanced state which is an indication of over excavation. The slurry face pressure is less than the actual ground pressure and the former has to be increased.

\(df < 0\) : The quantity of discharge slurry is less than the volume of feeding slurry and excavated material. There is a net loss of slurry into the ground through the cutterhead. Slurry face pressure is greater than the ground pressure.

In normal tunnelling operation, the deviation flow \(df\), was kept slightly negative. This implied that the face pressure from the feeding slurry will be kept slightly higher than the ground pressures thus forcing the feeding slurry into the ground and preventing over excavation.

The second layer of monitoring requires information on the volume of material excavated by the slurry TBM. Deriving from equation 1,

The volume of soil excavated in one minute can therefore be represented by:

\[
Q_d - Q_f = \Delta d
\]  
(4)

\(Q_d\) : Discharge Flow Rate (m\(^3\)/min)
\(Q_f\) : Feeding Flow Rate (m\(^3\)/min)
\(\Delta d\) : Excavated soil volume and ground water (m\(^3\)/min)

As such the total excavated volume for one complete ring is,

\[
Q_s = \sum \Delta d = \int_0^\infty (Q_d - Q_f) \, dt
\]  
(5)

The cumulative total volume is plotted and compared against the theoretical excavated volume throughout the entire excavation cycle to validate that the measured amount of ground excavated tallies with that of the theoretical volume to monitor that there is no over excavation. The control
tolerance of the excavation volume consists of the Upper Control Limit (UCL) and the Lower Control Unit (LCL) through the use of statistical approach using previous rings record. It is important to understand that the use of total excavated soil volume is limited to that of a volume control indicator only as it does not distinguish the soils solids from the ground water in the excavated material. As such, it is important to determine the volume of dry soil (Δk) in the excavated volume to more accurately gauge the actual volume of ground that has been excavated as shown in eq (6). The volume of dry soil could be determined by using geotechnical empirical formula with the necessary input of the density and flow rate from the feeding and discharge lines.

\[
\Delta k = \frac{Q_d (\gamma_d - 1.0) - Q_f (\gamma_f - 1.0)}{(G_s - 1.0)}
\]  

\(\Delta k\) : Excavated dry soil volume (m^3/min)  
\(\gamma_d\) : Discharge slurry density  
\(\gamma_f\) : Feeding slurry density  
\(G_s\) : Dry soil density

The volume of dry soil is the important factor for controlling and monitoring the volume of excavation for slurry TBM because it indicates the volume of ground water and soil that has been excavated and monitor whether there is a collapse at the tunnel face. If the excavation face is stable, the excavated dry soil (Δk) will be increasing linearly with the TBM jack stroke length. If there is a collapse in the tunnel face, Δk value will show irregular line as a result of a mass of soil flow into the slurry discharge pipe.

4. CONCLUSION

Both bound of the tunnels from MRM to BSH stations were successfully completed in August 2006. The advance rate for the slurry TBMs averaged at 3.5m/day which include cutterhead interventions, downtime and weekly maintenance. However, and more importantly, the impact of the tunnelling works to the houses above the tunnel alignment was kept to a minimum. The building settlement markers and real time monitoring recorded settlement that ranges from 4mm to 6mm. While tunnelling below the existing NS MRT Line, settlement ranges from 4mm to 8mm was observed and caused no disruptions to the operation of the trains.

The risks were managed and mitigated with the implementation of an effective excavation management system and extensive instrumentation plan. As Singapore’s underground rail network expands, it becomes increasingly more difficult to identify a route that solely follows that of the main road. Driving TBMs below buildings and critical structures have now become inevitable and possess more challenges to the tunnelling works. The risks have to be identified and managed early, right from when the planning begins to lay grounds for a successful tunnelling work.

REFERENCES