Constructing the Cut-and-Cover Tunnels and Bored Tunnels of the Singapore Downtown Line

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ABSTRACT: The Downtown Line (DTL) is a major MRT line under construction after the completion of the Circle Line in Singapore. This paper will review the ground conditions for the DTL and how the ground condition has influenced the decision on the selection of the support systems adopted for the excavation for the stations which are constructed using cut-and-cover method, and also the selection of tunnel boring machines for the bored tunnelling works. The key features of the temporary support systems will be presented in the paper and their performance will be reviewed in terms of ground movements and ground water table drawdown and its impacts. Issues encountered during the excavation, in particular for DTL Stage 2 in the soils and rocks of the Bukit Timah Granite Formation will be presented in the paper and the effectiveness of various measures implemented will be discussed based on the experience and observations during the construction. The key features and parameters of the TBM used in the projects will also be presented.

KEYWORDS: Deep excavations, Tunneling, Singapore geology, Downtown Line construction, Management of construction and commercial risks, TBMs in DTL

1. INTRODUCTION

The Downtown Line (DTL) will be the fifth Mass Rapid Transit (MRT) line in Singapore following the completion of the Circle Line. It links people directly from the northern and eastern parts of Singapore into the downtown area and provides a quick, convenient, affordable and comfortable means of transport. Figure 1 shows the overall map of DTL in relation to existing and upcoming MRT lines in Singapore. The DTL is being implemented in three stages. DTL Stage 1 (DTL1) with 4.3 km of underground tunnels and 6 underground stations has been completed and was opened to service in December 2013. DTL1 hugs around Singapore city, and runs from Chinatown to Bugis which are interchange stations with North-East Line and East-West Line respectively. DTL Stage 2 (DTL2) with 16.6 km twin tunnels and 12 underground stations plus a cut-and-cover box for tunnel operation, and was opened to service in December 2015. DTL2 runs from Bugis up along the corridor embodied by Bukit Timah Road and Upper Bukit Timah Road, and ends up at Bukit Panjang in the north-west of Singapore. DTL Stage 3 (DTL3) with 21 km of tunnels and 16 underground stations is under construction and scheduled for revenue service in 2017. DTL3 runs towards the eastern part of Singapore from Chinatown Station to Bedok and Tampines, and ends as an interchange with Expo station on the East-West Line.

Figure 1 Map of Downtown Line in Singapore

In this paper, a review will first be undertaken on the ground conditions for the DTL and how the ground condition has influenced the decision on the selection of the support systems adopted for the cut-and-cover excavation for the stations. The key features of the temporary support systems are in the paper for the stations which are constructed using the cut & cover method. The final part of the paper examines the type of tunnel boring machines used to construct the bored tunnels in the DTL project, and shows how this is related to the geological conditions.

2. IMPROVING MANAGEMENT OF CONSTRUCTION AND COMMERICAL RISKS

It is noted that the DTL was the test-bed for several initiatives to manage the contractual and construction risks before calling tender to procure the construction contracts. This arises from several lessons learned in the Circle Line project, and some of the key initiatives included geotechnical baselining, visual inspections of buildings, setting minimum performance specifications on the Earth Retaining and Stabilising System (ERSS), and instituting a project safety review process to mitigate construction risks from concept and design phase.

- Geotechnical baselines were introduced as part of LTA's initiatives to achieve a more equitable tender process based on a common understanding of ground conditions and associated construction risks, and to provide better transparency on the information and on how subsurface risk is to be shared between client and tenderers. The baseline report in Singapore deviates slightly from the North American guidelines (Essex, 2007), but would typically include a description of the geological setting of the project, the subsurface and site conditions derived from the geotechnical information and data gathered from site investigation, a discussion of the critical issues along the alignment for the design and construction of the works, the minimum requirements of geotechnical design parameters and the basis of their derivation, and finally the baseline conditions for which the geotechnical conditions are defined.
- Visual inspections were carried out for buildings and structures within the influence zone of the underground construction activity, together with the obtaining of as-built information from the building authority, building owners, and other relevant parties. This will ensure that buildings in poor condition could be identified, and sufficient mitigative and/or protective measures prescribed into the tender process, so that contractors can take sufficient measures prior to and during construction.
- A minimum performance specification on the excavation support systems was also pre-scribed for base tender. This was implemented generally in terms of a minimum stiffness for the retaining wall, any additional ground improvement and other

measures that would be necessary, and at times the maximum allowable wall movement adjacent to sensitive structures. This ensures that the contractor would price in correctly the cost of the retaining system, although he would still be responsible to develop the design for construction – except in Build-only contracts.

- A risk management approach was implemented to systematically manage major hazards from concept phase, to design phase, and then to construction and handover. This is termed as Project Safety Review (Safe-to-Build), which aims to identify various major foreseeable hazards in the projects and address these at each phase to protect health and safety of workers and general public. The philosophy is to reduce risk at source and to attempt designing out high impact risks rather than to leave it to the construction phase to manage.

Subsequently, the civil contracts in DT were procured under a combination of Design & Build model and Build-only model, whilst the civil contracts in DTL2 and DTL3 were procured using Design & Build model and Build-only model respectively. Table 1 shows details of the procurement for the various DTL contracts.

Table 1 Procurement of DTL contracts

Procurement model for civil contracts	DTL1		DTL2	DTL3
	Design & Build	Build-only	Design & Build	Build-only
Associated civil contracts for station construction	C902, C906, C907, C908, C909	C903	C911, C912, C913, C915, C916, C917, C918, C919, C920, C921	C922, C923, C925, C925A, C926, C927, C928, C929. C930, C931, C932, C932A, C933, C935, C936, C937

3. GEOLOGICAL SETTING

The geology in Singapore can be broadly classified into the predominantly soft clays and loose sands of the Kallang Formation (Tan et al, 2003), the igneous rocks and weathered soils of the Bukit Timah Granite (Leong et al, 2003), the metamorphic rocks and weathered soils of the Jurong Formation, the various weathering grades of the sedimentary soils of the Old Alluvium (Chiam et al, 2003), and the colluvial deposits of very strong sandstone or quartzite boulders in a hard matrix characterizing the Fort Canning Boulder Bed (Shirlaw et al, 2003). Figure 2 shows the Downtown Line superimposed onto the Geological Map of Singapore.

The Bukit Timah Granite, which is one of the oldest formations in Singapore, is widely distributed in the central and northern parts of Singapore Island. The intrusion of the Bukit Timah Granite is believed to have taken place during late Permian to middle Triassic period (200 to 250 million years ago).

The Jurong Formation covers the south, southwest and west of Singapore with a variety of sharply folded sedimentary rocks, including conglomerate, sandstone, shale, mudstone, limestone and dolomite. It was deposited during the late Triassic to early or middle Jurassic (235-175 million years ago). The formation has been severely folded and faulted in the past as a result of tectonic movement. Old Alluvium is mainly on eastern Singapore. The typical thickness varies from a few tens of meters to more than 200 meters. It is made up of sediments brought down by closely connected rivers and deposited in a deep basin in eastern Singapore that formed in late Tertiary to middle Pleistocene (5-0.5 million years ago).

Kallang Formation is extensively found in river valleys, river mouths, river plains, coastal areas and near offshore. Kallang Formation consists of buried marine clay, beach sand, river sand, organic peaty mud, and coral which have been deposited during rising sea levels. It formed in late Pleistocene to present (0.14 million years ago).

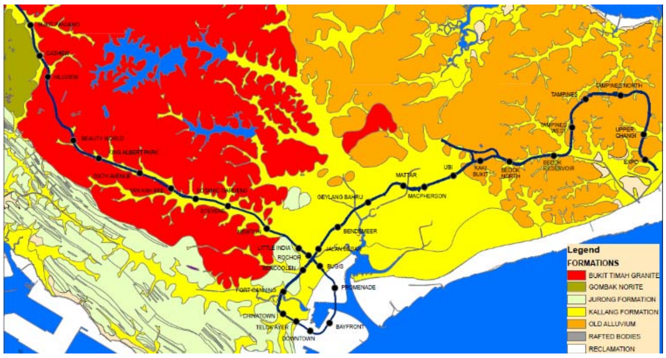

Figure 2 Downtown Line and the Geological Map of Singapore

Annex A shows the geological profile along the entire alignment of the Downtown Line with the stations and tunnel depths through various geological formations. DTL1 runs within the Central Business District of Singapore, and is mainly in the soft Kallang Formation which includes the Singapore marine clay, the fluvial sands, and the fluvial clay. DTL2 swings from the central district out into northwestern part of Singapore towards Bukit Panjang, and runs mostly along the Kallang Formation tributary through Bukit Timah corridor before moving off into the Bukit Timah Granite Formation along Upper Bukit Timah Road. DTL3 swings out into the eastern part of Singapore, cutting through the Kallang Formation at Kallang Basin before moving into the competent Old Alluvium Formation characterising the geology in the eastern part of Singapore.

4. EXCAVATION SUPPORT SYSTEM IN DOWNTOWN LINE

The stations in the DTL were all built using cut-and-cover method of construction. Annex B summarises all the maximum excavation depth, the typical soil conditions, and the ERSS employed in each of the stations of the DTL. The type of excavation support systems were defined in the tender documents by LTA's consultants (either by the advance engineering consultants or the architectural & engineering consultants depending on whether the civil contract would be procured through Design & Build approach or Build-only approach) and these were defined as base specifications for tender. The major factors constraining the selection of the ERSS were geological conditions, excavation depths, and proximity to sensitive buildings and infrastructures near the excavation.

Apart from the conventional retaining wall system comprising of diaphragm wall and secant bored pile (SBP) walls, the use of cross-walls was also evident in several of the excavations summarized in Annex B. Prior to these, cross-walls have been successfully implemented in past LTA projects – the pioneering use being an LTA in-house design to construct the Circle Line Paya Lebar station in order to protect the existing East West Line MRT viaduct and the mosque adjacent to the excavation. Other notable use subsequently included the KPE project adjacent to HDB blocks at Pelton Canal and during the construction for Circle Line Pasir Panjang station adjacent to the piers of the viaducts supporting the Pasir Panjang Semi-Expressway (Chua et al, 2009). These past successes have encouraged the industry to use cross-walls as a means to control wall deflections and reduce movements induced onto adjacent structures.

In DTL1, the ground in the city area is typically a thick layer of soft Kallang Formation overlying the more competent Old Alluvium and Jurong Formations, where a significant portion of the Kallang Formation belongs to the compressible Marine Clay. In fact, two stations (Bayfront and Downtown) were built in the reclaimed Marina

Bay area, where the typical depth of Kallang Formation was 40m. Being in the city district also meant that the stations would be excavated in close proximity to buildings. For example, Telok Ayer station was constructed alongside the conservation shophouses in Chinatown, Bayfront station was adjacent to the Marina Bay Sands development (Lim and Owain, 2013), and DTL Promenade station was constructed abutting the CCL Promenade station (Loh et al, 2011). Consequently, a very robust ERSS comprising of diaphragm walls and cross-walls was implemented in most of the station constructions.

DTL2 was implemented mostly in the Bukit Timah Granite Formation, which is well known for its variability in the bedrock level and attributed to the deep tropical weathering explained by Shirlaw et al (2000). In particularly, as seen in Annex B, the typical level of bedrock observed at the station locations in DTL2 could be as shallow as 11m to as deep as 40m. As it could be very difficult to install diaphragm walls into the rocks of Bukit Timah Granite, a conscious decision was made to adopt a SBP wall system for areas where the rockhead was expected to be high. Furthermore, one key risk associated with excavation in the Bukit Timah Granite was that of groundwater drawdown through its fractured rocks where the ERSS walls cannot embed sufficiently to ensure adequate hydraulic cut-off. As such, fissure grouting was implemented in several excavation sites together with contingency plans using recharge wells. In particularly, Shirlaw et al (2011) explained how a rock fissure grouting trial was conducted at Bukit Panjang Station and illustrated how the rock permeability could be reduced successfully as the grouting progressed.

As seen in the geological map, the soil conditions in DTL3 changes from predominantly that of Kallang Formation for the southern stretch between Fort Canning Station and Ubi Station, to predominantly Old Alluvium for the northern stretch between Kaki Bukit Station and Expo Station. As seen in Annex B, the ERSS for the stations in the southern stretch were mostly using diaphragm walls with some form of ground improvement using jet grouting or deep soil mixing to mitigate excessive wall and ground movements, where Kallang Formation is thick and up to the final excavation level. The only exception was for Bencoolen Station where the Kallang Formation was underlain by the Fort Canning Boulder Bed, in which significant difficulties were encountered in the past during the diaphragm walls works for the neighbouring Bras Basah Station (Osborne et al, 2003). Hence, a SBP wall was employed in lieu of a diaphragm wall retaining system. For the northern stretch between Kaki Bukit Station and Expo Station, diaphragm walls were also used for the stations (mainly for the purpose of an integral permanent wall system), but without any ground improvement due to the significantly better ground conditions.

5. BORED TUNNELS AND TUNNEL BORING MACHINES

The mainline tunnels for the DTL were constructed using shield machines and bored tunnelling technique. The internal diameter of the bored tunnels is 5.8m, and the thickness is 275mm thick. Each ring consists of 5 segments and 1 key segment, and the width of each ring is 1.4m. Radial joints are staggered to avoid cruciform joints, and radial joints are typically convex to convex with 2 bolts. Block joint with 3 bolts per segment and 1 bolt for the key segment are arranged for circumferential joints. Composite hydrophilic strip and EPDM gasket are adopted at the segment joints for waterproofing. The selection of tunnel boring machines (TBMs) for the DTL project was made in consideration of tunnel alignment, anticipated geological conditions, as well as operational requirements of the TBMs. Some considerations on TBM selection as identified by Lovat (2006) are as listed below:

- Good control of face pressure in achieving targeted volume loss.
- Muck handling shall be compatible with high water inflows and weak ground, and be able to efficiently collect the material under all conditions.
- In soft ground conditions, specially design provisions shall be included, such as increasing the overcut, lubricating the TBM shield skin, reducing the TBM shield length, using a tapered shield, limiting cutter head intervention at critical locations, monitoring tunnel deformation and earth pressure, and having the ability to flush out material from the annulus back towards cutter head.
- In rock material, the TBM shall have exceptional thrust capacity to overcome high strength or muck-packing conditions. The cutter tools shall be selected to mitigate the wearing effect in highly abrasive ground condition.

Dubnewych et al. (2010) highlighted some differences between slurry machines and EPBMs. Essentially, a earth pressure balanced machine (EPBM) maintains face pressures in cutter head chamber by matching the muck extraction rates with machine advance, whilst a slurry machine maintains face pressure using slurry flow and density in the cutter head chamber. An EPBM is generally simpler to operate, requires smaller site and launch shaft, and with better overall production rates over slurry machines, resulting in lower cost. A slurry machine is more suitable for handling rock and mixed face conditions as it is able to integrate rock crusher, requires lower torque and cutter head power, and with better controls on face pressure.

From the earlier tunnelling experiences for North-East Line and Circle Line, EPBMs have been found to be suitable for tunnelling in local soils such as Old Alluvium, Kallang Formation, and the completely weathered or residual soils of the Bukit Timah Granite Formation. Slurry machine are more suitable for Bukit Timah Granite Formation where the rock face and soil-rock mixed face conditions are anticipated. Consequently, a total number of 52 TBMs were used in the tunnelling works for DTL, of which 9 are slurry machines all employed in tunnelling through the rocks and mixed conditions of Bukit Timah Granite, and 43 are EPBMs.

The slurry TBMs used in DTL are manufactured by Kawasaki and Herrenknecht. In the case of shallower rock head and mixed face conditions, two independent man locks were provided for each slurry machine to improve cycling of compressed air crews and improve productivity for the high number of interventions expected. The opening ratio of cutter head was about 25% for the rock and mixed face conditions. Kawasaki machine is of a traditional model with a single bulkhead controlling face pressure by controlling the slurry flow from the main pumps while Herrenkencht introduced air bubble acting on the slurry in the plenum chamber. Kawasiki slurry machine was designed with a slurry flow of 450m3/hr. The Herrenknecht was designed with the slurry flow of 1200m3/hr. The slurry treatment plant for Kawasaki machine utilized a filter press to handle the fines. Herrenkencht adopted centrifuge technology for fines management in the slurry treatment plant. The configuration of the cutters is also similar from these two manufactures.

The cutterhead diameter of 6630 to 6680mm by Herrenkencht is generally smaller than those by other manufacturers, which is typically 6700 to 6720mm in diameter. The total length of slurry machine is either 11.3m or 13.2m and is longer than EPBMs of which in a range of 8.4m to 10.2m. Generally the TBM is selected to be shorter when the soft soil is anticipated. The Herrenknecht machines are mostly supplied with hydraulic cutter head drive whereas the machines from other manufactures tend to equip electric cutter head drive. The cutter head power is in a range of 1250 to 1750 kw of TBMs used in Bukit Timah Granite. The TBMs used in OA and Kallang Formation are equipped less power in the cutter head which is about 660kw to 1330kw with an average about 1100kw. The cutter head torque equipped in the TBMs used in Bukit Timah Granite is in a range of 5350 kNm to 7920 kNm. The TBMs used in Kallang Formation and OA are generally with slightly lower torque that varies from 4200 kNm to 6240 kNm. The equipped propulsion also known as thrust force of the TBMs are not very distinguished based on the ground conditions. The thrust force is from 39000 kN to 49000kN, 33000kN to 50668kN and 39000 to 50668kN equipped in the TBMs used in Bukit Timah Granite, Kallang Formation and OA respectively. For slurry machines, the conditioning mediums are slurry. Bentonite, foam and polymer are used as conditioning mediums for EPBMs. In Bukit Timah Granite, more disc cutters are configured in the cutter head compared with the machines used in Kallang Formation and OA. There are 41 to 51 disc cutters configured in each of the TBM used in Bukit Timah Granite. Some of the TBMs in OA and Kallang Formation are even not installed with disc cutters. The pick cutters used in the TBMs are generally within the same range regardless of the geology conditions. The numbers of pick cutters installed in the cutter head of TBMs in Bukit Timah Granite varies from 86 to 144 numbers, whereas the pick cutters are in a range of 40 to 192 numbers in the TBMs used in Kallang Formation and OA. The tail grout type to seal the tail is generally chosen to be bi-components such as cement plus accelerator. The commonly adopted accelerator is sodium silicate. The batch plant is always located on the surface on site. Pipes and hoses are used to deliver the tail grout.

More information of the key features of the TBMs used in DTL is listed with different geology in Annex C.

6. CONCLUSION

In this paper, a review of the ground conditions for the various implementation phases of the DTL and how the ground condition has influenced the construction methods for deep excavation and bored tunnelling was provided. This was set against the backdrop of a new paradigm to manage project risks prior to tender calling, where new initiatives implemented included geotechnical baselining, advance visual inspections, defining minimum performance requirements on the excavation support system, and instituting a project safety review process to systematically mitigate risks from concept design phase onwards.

Consequently, a varied earth retaining system (including diaphragm walls, secant pile walls, etc.) and a series of enhancement measures (cross-walls, ground improvement, fissure grouting, recharge wells) were implemented depending on the challenges posed by the geological conditions and the proximity to adjacent structures. In terms of bored tunnelling works, EPBMs are widely used in tunnelling through soils such as the Old Alluvium, Kallang Formation as well as completely weathered and residual soils of Bukit Timah Granite, whilst slurry machines were used for tunnelling in rock or in mixed soil-rock conditions.

Whilst it is important to tailor deep excavation retaining systems and tunnel boring machine specifications to site specific conditions, it is hoped that the information summarised in this paper can provide quick reference to future engineers undertaking underground construction in similar conditions.

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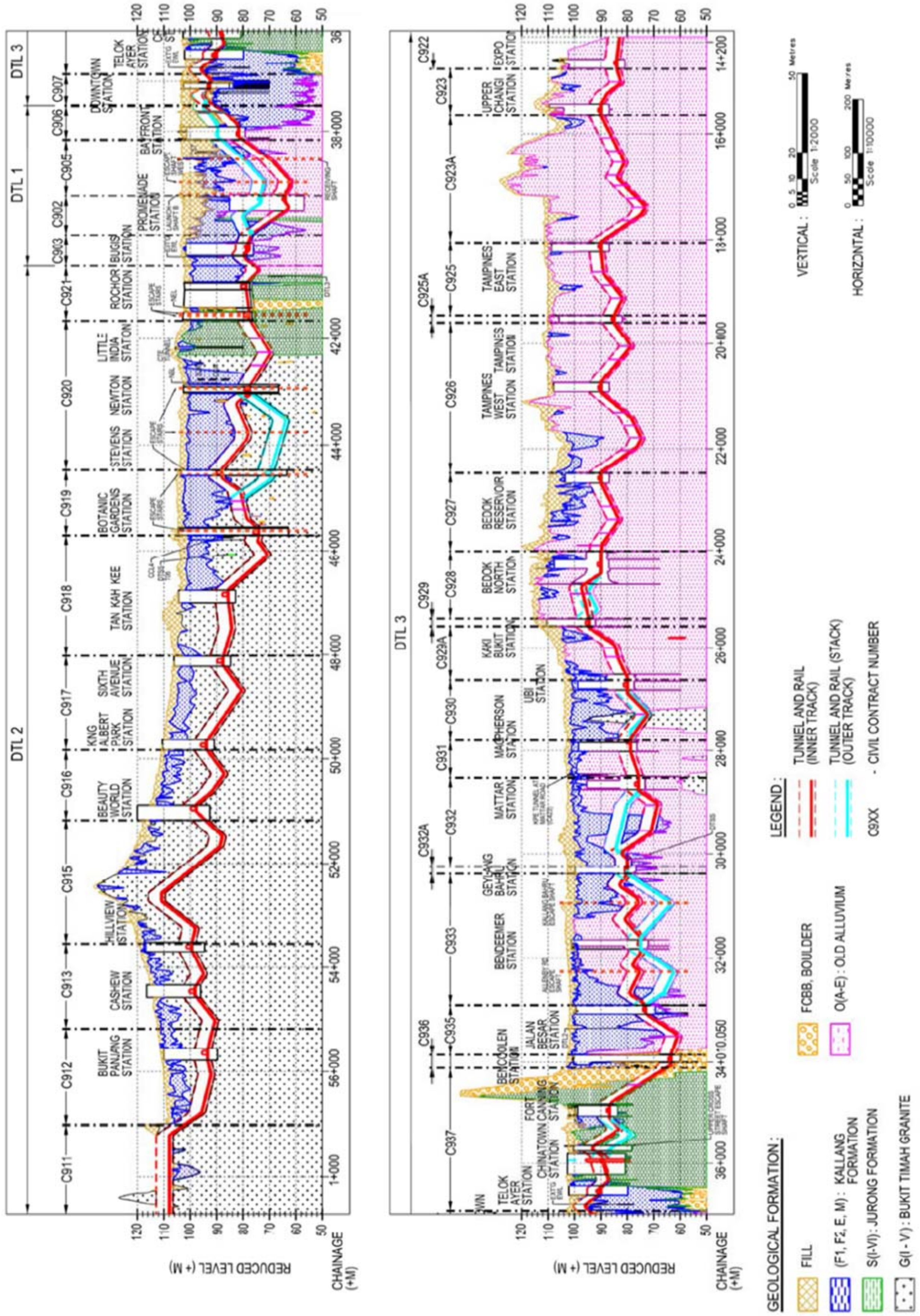
ANNEX A – Longitudinal geological profile along Downtown Line alignment



ANNEX B – Summary of earth retaining systems employed in DTL stations

Contract		Station	Max depth of excavation (m)	Typical Soil conditions	Excavation support system employed	Additional measures taken
DTL1	C902	Promenade	42	18m Fill / Kallang Formation overlying Old Alluvium	Diaphragm walls (1m, 1.2m, 1.5m)	1m thick, 2m deep cross walls
	C903	Bugis	27	23m Fill / Kallang Formation overlying Old Alluvium	Diaphragm walls (1m, 1.2m, 1.5m)	1m cross walls; jet grout piles
	C906	Bayfront	25	15m Reclamation Fill overlying 20m Kallang above Old Alluvium	Diaphragm walls (1.2m)	0.8m thick, 21m deep cross walls; deep soil mixing at entrance
	C907	Downtown	19.5	20m Reclamation Fill overlying 20m Kallang above Old Alluvium	Diaphragm walls (1.2m)	0.8m thick, 13m deep cross walls
	C908	Telok Ayer	14	20m Fill / Kallang Formation above Fort Canning Boulder Bed	Diaphragm walls (0.8m, 1m, 1.2m)	0.8m thick, 4m deep cross walls; jet grout piles
	C909	Chinatown	15	10m Fill / Kallang Formation overlying Jurong Formation soils and rocks	Diaphragm walls (1m, 1.2m)	
DTL2	C912	Bukit Panjang	22	9m Fill / Kallang Formation overlying 9m granitic soil (GV, GVI) above bedrock of Bukit Timah Granite	SBP walls (1.2m)	Fissure grouting + recharge wells
	C913	Cashew	20	5m Fill / Kallang Formation overlying 20m granitic soil (GV, GVI) above bedrock of Bukit Timah Granite	Diaphragm walls (1m)	Fissure grouting + recharge wells
	C913	Hillview	24	8m Fill / Kallang Formation overlying 10m granitic soil (GV, GVI) above bedrock of Bukit Timah Granite	Diaphragm walls (1m)	Fissure grouting + recharge wells
	C915	Hume tunnel	26.5	11-24m granitic soil (GV, GVI) above bedrock of Bukit Timah Granite	1.2m SBP wall in soil and rock bolts in bedrock	Fissure grouting + recharge wells
	C916	Beauty World	20	5m Fill / Kallang Formation overlying 10m granitic soil (GV, GVI) above bedrock of Bukit Timah Granite	1.2m SBP wall in soil and rock bolts in bedrock	Recharge wells
	C917A	King Albert Park	20	5m Fill / Kallang Formation overlying 44m granitic soil (GV, GVI) above bedrock of Bukit Timah Granite	Diaphragm walls (1m)	Fissure grouting + recharge wells
	C917A	Sixth Avenue	22	8m Fill / Kallang Formation overlying 25m granitic soil (GV, GVI) above bedrock of Bukit Timah Granite	Diaphragm walls (1m)	Recharge wells
	C918A	Tan Kah Kee	20	5m Fill / Kallang Formation overlying 18m granitic soil (GV, GVI) above bedrock of Bukit Timah Granite	SBP walls (0.9m)	Jet grout piles at Cut & Cover tunnel Fissure grouting + recharge wells
	C919	Botanic Gardens	34	8m Fill / Kallang Formation overlying 12m granitic soil (GV, GVI) above bedrock of Bukit Timah Granite	Diaphragm walls (1m, 1.2m)	Fissure grouting + recharge wells
	C919	Stevens	34	20m Fill / Kallang Formation overlying 10m granitic soil (GV, GVI) above bedrock of Bukit Timah Granite	Diaphragm walls (1.2m, 1.5m)	Fissure grouting + recharge wells
	C920	Newton	28	20m Fill / Kallang Formation overlying 10m granitic soil (GV, GVI) above bedrock of Bukit Timah Granite	Diaphragm walls (0.8m, 1m & 1.2m)	Fissure grouting + recharge wells
	C921	Little India	27	5m Fill / Kallang Formation overlying Jurong Formation soils of varying weathering grades	Diaphragm walls (1.2m)	
	C921	Rochor	19	25m Fill / Kallang Formation overlying Old Alluvium soils	Diaphragm walls (1.2m)	1m thick Cross-wall
DTL3	C922	Expo	23	2m Fill overlying Old Alluvium soils	Diaphragm walls (0.8m, 1m); CBP walls (0.6m)	

	C923	Uppper Changi	28	9m Fill overlying Old Alluvium soils	Diaphragm walls (0.8m, 1m, 1.2m); CBP walls (1m)	
	C925	Tampines East	24	4m Fill overlying Old Alluvium soils	Diaphragm walls (0.8m, 1m, 1.2m); CBP walls (0.8m)	
	C925A	Tampines	30	3m Fill overlying Old Alluvium soils	Diaphragm walls (1m); CBP walls (0.8m)	
	C926	Tampines West	22	4m Fill overlying Old Alluvium soils	Diaphragm walls (0.8m, 1.0m) ; CBP walls (0.8m)	
	C927	Bedok Reservoir	23	10m Fill / Kallang Formation above Old Alluvium soils	Diaphragm walls (1m); SBP walls (0.9m, 1.1m)	
	C928	Bedok North	25	5m Fill / Kallang Formation above Old Alluvium soils	Diaphragm walls (1m); CBP/SBP walls (1.2m, 1.5m)	
	C929	Kaki Bukit	20	3m Fill overlying Old Alluvium soils	Diaphragm walls (0.6m, 1m)	
	C930	Ubi	24	15m Fill / Kallang Formation above Old Alluvium soils	Diaphragm walls (1.2m); CBP / SBP walls (1.2m)	
	C931	Macpherson	28	15m Fill / Kallang Formation above Old Alluvium soils	Diaphragm walls (1m, 1.2m); SBP walls (1.3m, 1.5m)	
	C932	Mattar	28	5m Fill / Kallang Formation above Old Alluvium soils	Diaphragm walls (1m, 1.2m)	
	C932A	Geylang Bahru	26	20m Fill / Kallang Formation (average) above Old Alluvium soils	Diaphragm walls (1.2m)	Ground improvement by deep soil mixing & jet grout piles
	C933	Bendemeer	30	5m Fill / Kallang Formation above Old Alluvium soils	Diaphragm walls (1.2m); SBP walls (1m)	
	C935	Jalan Besar	33	35m Fill / Kallang Formation (average) above Old Alluvium soils	Diaphragm walls (0.8m, 1m)	1m thick cross-walls and two layers of ground improvement by WSM
	C936	Bencoolen	45	15m Fill / Kallang Formation (average) above Fort Canning Boulder Bed	SBP walls (1.2m)	
	C937	Fort Canning	20	11-20m Fill / Kallang Formation overlying Jurong Formation soils of varying weathering grades	Diaphragm walls (1m, 1.2m, 1.5m)	1m thick cross walls at entrance A

ANNEX C – Summary of the key features of the TBM used in DTL

Table C1 The key features of the TBM used in DTL with the major geology is Bukit Timah Granite

Contract Number	C913	C915	C916	C917/C917A	918A	918A	919	C920
Contractor	GS & TS JV	SK EC	MCD	Alpine (insolvent), MCD	SKEC	SKEC	SEC	STEC
TBM Type	Slurry	Slurry	Slurry	EPBM	EPBM	Slurry	EPBM	EPBM
TBM Manufacturer	Kawasaki	Kawasaki	Herrenknecht	Herrenknecht	Herrenknecht	Herrenknecht	Herrenknecht	HITACHI ZOSEN
Drive	CSH – HLV	HLV- BTW	BTW-KAP	KAP-SAV	TKK - SAV	TKK - BTN	BTN - STV	NTN - STV
Drive Length (m)	1200	2132	1000	1400	573	930	980	1442
Tunnel drives (No.)	2	4	2	2	2	2	2	4
TBM proposed (No.)	2	3	2	2	1	2	2	4
Outside diameter - cutter head (mm)	6720	6720	6640	6640	6640	6640	6640	6700
overall TBM length (m)	11.3	11.3	13.2	10.2	11.4	13.2	11.6	10.2
Cutterhead Drive								
Cutterhead Drive (Electric or Hydraulic)	Electrical	Electrical	Electrical	Electrical	Hydraulic	Hydraulic	Hydraulic	Electrical
Power(kW)	1250	1500	1,750	1600	1600	1600	1600	1200/960
Cutterhead Motors (No.)	5	6	5	8	8	8	8	10/8
Torque (kNm)	4620	7920	5050	5300	5300	6240	5540	6890
Cutterhead closed (%)	74~68	74~68	75	72	71	72	75	
Face Injection								
Face Ports (No.)	2	2	?	4	10	10	10	5
Bulkhead Ports(No.)	16	16	?	4	8	8	8	4/5
Conditioning medium	Slurry	Slurry	Slurry	Foam, polymer	Foam/ bentonite	Bentonite	Foam/ Bentonite	Foam
Cutters								
Total Picks(No.)	?	144	?	?	68	74	80	86
Total Discs(No.)	51	51	42	42	41	46	46	38~47
Copy Cutters(No.)	4	4	nil	nil	0	0	0	2
Overcut amount(mm)	?	25	?	?	25	25	20	150
Wear detector picks	?	2	2	2	2	2	2	4
Screw Conveyor								
Internal Screw Diameter (mm)	-	-	-	800	800	-	800	850/860
screw pitch (mm)	-	-	-	?	630	-	16.5	640
screw length(m)	-	-	-	14.3	12.6	-	16.3	14.35
screw capacity (m3/hr)	-	-	-	?	350	-	385	280
Maximum PRM	-	-	-	?	22	-	22	15
Power(kW)	-	-	-	315	315	-	200	180
Torque(kNm)	-	-	-	217	224	-	217	
Injection Ports(No.)	-	-	-	?	8	-	8	5

Retractable (Yes/No)/stroke(mm)	-	-	-	?	Yes/1000	-	Yes	Yes/750
Thrust Rams(No.)	20	20	16 Pairs	16 Pairs	16 Pairs	16 Pairs	16 Pairs	26
Stroke (mm)	2150	2150	2200	2200	2200	2200	2200	2050
Equipped Propulsion (kN)	49000	49000	42575	42575	42500	42500	42575	39000
Articulation								
Rams(No.)	12	12	14	14	14	14	10	16
Total capacity(kN)	3600	3600	8585	8585	?	?	2815	3200
Stroke (mm)	200	200	150	150	150	150	300	200
Gripper jacks(No.)	4	4	0	0	-	-	2	2
Total Power(kW)	1721	1721	2100	2100	2500	4000	2264	?
Grouting/Tailseals								
Grout ports(No.)	16	16	4	4	2x4	2x4	2x4	4
Location with respect to shield body	tailskin	tailskin	tailskin	tailskin	tailskin	tailskin	tailskin	tailskin
Tailseal brushes (rows)	3	3	3	2 + 1 spring plate	2	2	3	3
Annulus (mm)	140	140	275	275	?	?	?	?
Theoretical grout volume per metre of advance (m3)	5.5	5.5	4.2	4.5 to 5	2.9	2.9	3	?
Grout type	Cement + Accelerator)	Cement + Accelerator)	Grout and sodium silicate	Grout and sodium silicate	Bi-component	Bi-component	Bi-component	A+B component
Batch location	Surface	Surface	Surface - backfill grout plant	Surface - backfill grout plant	Ground Plant	Ground Plant	Surface	Ground Plant

Table C2 The key features of the TBM used in DTL with the major geology is Kallang Formation

Contract Number	C902	C921	C930	C931	C932	C933	C935	C937
Contractor	STEC	SsangYong	SK EC	HDEC	Sato Kogyo	Penta-Ocean	Leighton John Holland Jv	GS
TBM Type	EPBM	EPBM	EPBM	EPBM	EPBM	EPBM	EPBM	EPBM
TBM Manufacturer	Shanghai Tunnel	Herrenknecht	Kawasaki	Herrenknecht	Kawasaki	Herrenknecht	Herrenknecht	Robbins
Drive	PMN - BGS	RCR- BGS	UBI - MPS	MPS-MTT	MTT-GLB	JLB - KLB	KLB - BCL	FTC- BCL
Drive Length (m)	1100	300m	942	928	1354	4495	775	1800
Tunnel drives (No.)	2	2	2	2	2	4	2	4
TBM proposed (No.)	1	1	2	1	2	4	2	3
Outside diameter - cutter head (mm)	6680	6630	6720	6350	6630	6630	6660	6650/6630
overall TBM length (mm)	8.9	8.4	10.2	9.4	9.85	7.6	8.7	9.85
Cutterhead Drive								
Cutterhead Drive (Electric or Hydraulic)	Electrical	Hydraulic	Electrical	Hydraulic	Electrical	Hydraulic	hydraulic	Electrical
Power(kW)	1400	980	1320	1200	1320	1200	1200	1050
Cutterhead Motors (No.)	4	?	8	8	7	8	8	5
Torque (kNm)	5930	?	?	5538	6240	5538	4473/5348	5847
Cutterhead closed (%)	70	70	65	70	50	57	52	70
Face Injection								
Face Ports (No.)	5	8	?	10	8	8	8	5
Bulkhead Ports(No.)	4	4	5	4	4	2	3	6
Conditioning medium	Foam/polymer	foam	Polymer, Foam, Bentonite	Foam, Polymer	Foam/Polymer	Foam	water, bentonite, polymer-foam	Foam/Polymer/Bentonite
Cutters								
Total Picks(No.)	72	72	144	60 knives, 8 buckets	164	139	40	96
Total Discs(No.)	18	21	35	7 double disc cutters	26 Pre cutters, 2 Centre cutter	nil	33 single + 4 Twin	42
Copy Cutters(No.)	1	0	2	1.	2	2	0	1
Overcut amount(mm)	50	30	12	20	35	15	40	50
Wear detector picks	4	2	6	4	4	4	6	6
Screw Conveyor								
Internal Screw Diameter (mm)	910	900	?	180	850	700	800	900
screw pitch (mm)	700	630	850	630	600	630	630	420
screw length(m)	12	12.95	22	12.2	11.2	12.6	12.7	12.8
screw capacity (m3/hr)	400	?	25	265	250	~60	388	370
Maximum PRM	18.5	?	21	21	10.5	22	22.1	16
Power(kW)	250	?	14	110	220	110	200	225
Torque(tfm)	12.8	?	55	90	115	89	199	
Injection Ports(No.)	3	?	15	2 x 4 pcs	12	2	3	3
Retractable(Yes/No)/stroke(mm)	No	?	?	yes	1170	Yes,1000	Yes 1000	(YES)/660

General Thrust								
Thrust Rams(No.)	16 pairs	?	16	32	16 pairs	33	32	32
Stroke (mm)	2200	?	2150	2200	2150	2300	2200	2200
Equipped Propulsion (kN)	46300	?	46400	50668	46400	33000	50668	48000
Articulation/Pull Back Facility								
Rams(No.)	16	?	6	14	12	14	-	12
Total capacity(kN)	46500	?			36000	7389	-	35000
Stroke (mm)	190	?	200	150	200	150	-	290
Gripper jacks(No.)	Nil	?	Nil	Nil	Nil	Nil	Nil	Nil
Electrical Power								
Total Power(kW)	2500	?	1625	2500	1564	2000	2018	2200
Grouting/Tailseals								
Grout ports(No.)	4 + 4 spares	?	4	4	4	12	4	10
Tailseal brushes (rows)	3	?	2	3	3	3	4	3
Annulus (mm)	135	?	30		35	150	?	150
Theorietical grout volume per metre of advance (m3)	4.7	?	4.75	4.069	5.9	4	4.43	4.3
Grout type	Cement + Sodium Silicate	?	Cement + Sodium Silicate	Cement + Sodium Silicate	Liquid A & B	Cement Bentonite + Sodium silicate	Liquid A & B	Liquid A & B
Batch location	surface	?	At the surface	surface	Surface - Silo	via grout service lines.	Surface	At surface near Launch Shaft

Table C3 The key features of the TBM used in DTL with the major geology is OA

Contract Number	C905	C923	923A	C925	C 926	C927	C928	929A
Contractor	Shimizu	Samsumg	STEC	GS	CMC	CMC	Sato Kogyo	Nishimatsu
TBM Type	EPBM	EPBM	EPBM	EPBM	EPBM	EPBM	EPBM	EPBM
TBM Manufacturer	Hitachi	Herrenknecht	STEC	Robbins	STEC	Robbins	Kawasaki	Herrenknecht
Drive	PMN- MBS	UPC-EXPO	UPC-TPE	TPE-TPC	BDR-TPC	BTP- BDR	KBK-BDN	TSG-BTP
Drive Length (m)	2500	1000	2400	1600	5800	1327	1450	2110
Tunnel drives (No.)	5	4	4	2	8	3	2	1
TBM proposed (No.)	2	1	2	1	4	2	1	1
Outside diameter - cutter head (mm)	6590	6630	6720	6630	6720	6650	6700	6640
overall TBM length (m)	8.6	8.2	9.2	10	15	9	9.8	11.4
Cutterhead Drive								
Cutterhead Drive (Electric or Hydraulic)	Electric	Hydraulic	Hydraulic	Electric	Hydraulic	Electric	Electric	Electric
Power(kW)	660	1200	1260	1050	1327	1050	924	990
Cutterhead Motors (No.)	12	8	12	5	12	5	7	9
Torque (kNm)	5806	5537	5770	5848	?	8772	6240	4198
Cutterhead closed (%)	65	62	65	70	65	63	65	70
Face Injection								
Face Ports (No.)	3	10	5	7	5	5	5	10
Bulkhead Ports(No.)	4		4	6	8	6	4	4
Conditioning medium	Foam/polymer	Foam/Bentonote/Polymer		Foam/Bentonote/Polymer	Foam/Bentonote/Polymer	Foam/Polymer/Bentonite	Foam	Foam
Cutters								
Total Picks(No.)	120	60	0	?	60	96	192	?
Total Discs(No.)	-	20	12	-	8	42	-	0
Copy Cutters(No.)	2	-	1	1	32	1	2	2
Overcut amount(mm)	25	-	100	15		50	35	40
Wear detector picks	2	6		6	12	6	2	5
Screw Conveyor								
Internal Screw Diameter (mm)	850	700	850	900	?	900	850	900
screw pitch (mm)	?	630	600	245	850	350	600	630
screw length(m)	?	12.3	13	11.3	?	12.7	11.2	16.6
screw capacity (m3/hr)	280	285	420	370	600	370	250	450
Maximum PRM	1.06	19.8	22	16	11.8	20	14	22
Power(kW)	?	110		270	420	270	175	250
Torque(kNm)	?	104		-		96	115k	199
Injection Ports(No.)	3	3	2	3	12	3	12	12

Retractable (Yes/No)/stroke(mm)	Yes	yes/1000	1000	Yes / 450	Yes/1000	Yes / 680	Yes/ 600	yes, 1000
General Thrust								
Thrust Rams(No.)	26	32 (16 Pair)	32	32 no.(s)	32 (16 Pair)	32 (16 Pair)	32	16
Stroke (mm)	2050	2200	2200	2150	2200 mm	2200	2150	2200mm
Equipped Propulsion (kN)	39000	50668	50000	48000	50640	48000	46400	46000
Rams(No.)	16	14	12	12	12	12	12	12
Total capacity(kN)	?	?	46000	-	40380	36000	36000	36800
Stroke (mm)	200	150	210	-	190	190	200	300
Gripper jacks(No.)	NA	-	0	-	N.A	NA	None	0
Electrical Power								
Total Power(kW)	660	1900	1845	2850	2000	2610	1490	2000
Grouting/Tailseals								
Grout ports(No.)	4 + 2 spares	4+4 spares	8	4+4 spares	4+4 spares	4+4 spares	4	8
Location with respect to shield body	?	Tail Skin	?	Tail Skin	Tail Skin	Tail Skin	Tail Skin	Tail Skin
Tailseal brushes (rows)	3	3	3	3	3	3	3	3
Annulus (mm)	120	130	135	40	185	140	140	?
Theorietical grout volume per metre of advance (m3)	?	4	4.5	4 - 4.5	3.9	4.1	2.8	2.9
Grout type	Cement + Accelerator	liquid A & liquid B	?	liquid A & liquid B	A: Cement, B: Accelerator	Cement + Accelerator	Cement + Accelerator	Bi-components
Batch location	surface	On the surface	?	Surface	Surface	Surface	On site	Surface