Testing of a Muck Pumping System for EPB TBMs for Thomson-East Coast Line T307 Tunneling Works

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1 SINGAPORE THOMSON EAST COAST LINE – CONTRACT T307

ABSTRACT: Land is scarce in Singapore and roads have already taken up about 12% of the land area. The Singapore Mass Rapid Transit (MRT) serves as the key to a sustainable transport system with most of the lines built underground without the need for significant land use. Throughout the tunneling history in Singapore, significant development in tunneling techniques has taken place and new technologies have been adopted to address the challenges of underground construction in urban areas and in variable ground conditions. Earth Pressure Balance (EPB) Tunnel Boring Machines (TBM) are widely used in Singapore as the ground conditions are mostly Old Alluvium and Marine Clay. However, as the tunneling works are taking place in more congested urban areas, some measures are required to reduce noise and disturbances to the nearby population. Prospective T307 contractor at time of tender, Samsung C&T Corporation, proposed to use a muck pumping system (solid matter pumps) for spoil transportation from TBMs all the way to the surface muck pits as measure to enhance productivity along with certain operational advantage, closed system noise reduction at surface and smaller worksite, and the contract was awarded on this basis. As part of demonstration of workability of the method, this paper will introduce the preliminary testing for usage of a muck pumping system as a means of transporting spoil in EPB TBMs for Contract T307 of Thomson-East Coast Line.

1.1 Project Overview

The bored tunnels of the East Coast stretch of Thomson-East Coast MRT Line are 8.3 km long in total. Bored tunnelling works have commenced in the second quarter of 2017 and completed by the fourth quarter of 2019. The section that is covered in this paper is Contract T307 which is the construction of Marine Parade Station and Tunnels for Thomson-East Coast Line. The Contract T307 tunnel section of Thomson-East Coast Line includes 820m of twin-bored tunnels from Marine Parade Station to Amber Station (namely Changi-bound and Woodlands-bound respectively); 440m (Changi-bound) and 600m (Woodlands-bound) bored tunnels from Marine Parade Station commercial space to Marine Terrace station. Figure 1 shows the project location.

Figure 1. Bird's eye view of T307 tunnel and station works near Amber Road and Marine Parade

The prospective T307 contractor, Samsung C&T Corporation, submitted the proposal of muck pumping system at tender as measure to enhance productivity along with certain operational advantage, closed system noise reduction at surface and smaller worksite, and the contract was awarded on this basis. The advantages of muck pumping system are closed system noise reduction, direct discharge to muck pit negating use of hoisting skips, minimise risk of blowout and spillage in tunnel, especially in Kallang Formation fluvial sand geology, and minimise noise impact to built up area, reduce crane winching safety, and smaller site footprint.

As this proposal was not method previously used in Singapore for full drive, there was requirement that muck pumping and excavation management should be proven through a set of detailed field tests and that the contractor should provide comparison with suitable ongoing projects to demonstrate the method is workable prior to confirming TBM's specification, TBM's backup specification and working site utilisation. Otherwise, should the muck pumping method proved unworkable that the contractor should revert to traditional method of muck disposal. Based on this, the proposal was accepted with proviso that the contractor demonstrate with full scale pumping trials and any other tests required to demonstrate the workability of the method. This paper outline Samsung demonstration of workability of muck pumping system.

1.2 Geological Properties

The T307 project runs fully in Kallang Formation geology. Figure 2a and Figure 2b show the geological longitudinal cross sections of the project. The tunnels all lie above the interface to Old Alluvium and fully in Upper Marine Clay (UMC) and Lower Marine Clay (LMC). Several lenses containing Fluvial Sand (F1) and Fluvial Clay (F2), as well as Estuarine Clay (E) have been identified. While the Marine Clay is known to be very soft, it has been the Fluvial Sand that has posed challenges in past projects. Due to its high permeability, there was the requirement at tender to deploy special measures to mitigate risks tunnelling in the Marine Clays where sand lenses were identified. These measures could include extensive pre-grouting or adaptions to the screw conveyor to increase screw length, screw resistance or screw pressure. In this case, this risk has been effectively mitigated by proposing a closed pumping circuit.

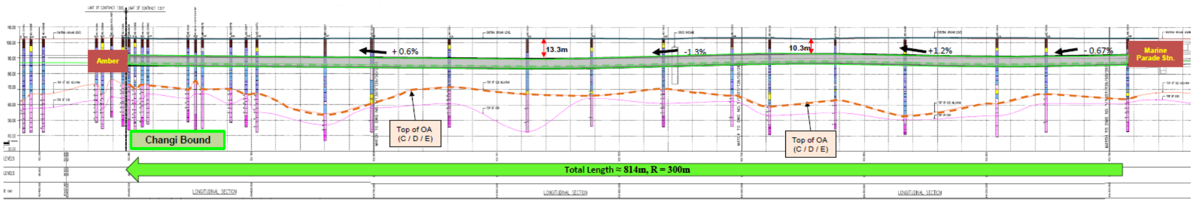

Figure 2a. Geological longitudinal cross section of T307 Alignment from Marine Parade Station to Amber Station (Changi-bound)

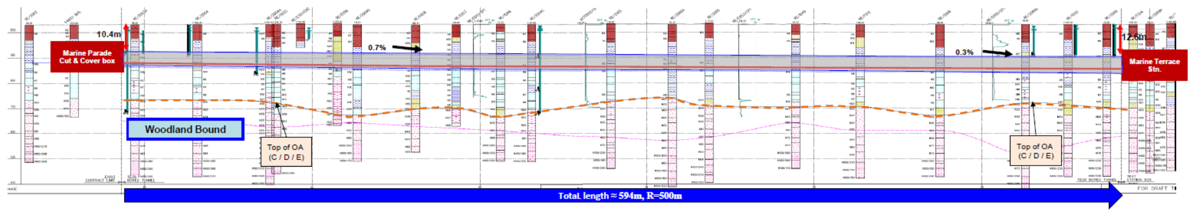

Figure 2b. Geological longitudinal cross section of T307 Alignment from Marine Parade Commercial Space to Marine Terrace Station (Woodlands-bound)

Table 1 shows the geotechnical parameters of the different geological formations in T-307. While the different clays of the Kallang Formation can be expected to behave somewhat similar with regards to excavation using an EPB TBM, the F1 Fluvial Sand immediately sticks out for its permeability being several orders of magnitude higher. Furthermore, the ratio of liquid limit to plastic limit suggest that the F2 Fluvial Clays would have a higher clogging risk to be expected.

The anticipated overburden of the tunnels ranges from very shallow sections down to around 10m overburden to a maximum of 31m. Therefore, design pressures of 4.5bars were chosen for the TBMs.

Table 1. Geotechnical Parameters of the Kallang Formation in T-307

Formation	γ [kN/m3]	c' [kPa]	ϕ' [˚]	I_p /I_c	C_u [kPa]	k_o [-]	E' [MPa]	K_v [m/s]
UMC	16.0	0	22	41/0.3	27.0	0.63	5.9	$1x10^{-9}$
LMC	17.0	0	22	36/0.3	30.2	0.63	7.5	$1x10^{-9}$
F2	19.0	0	24	29/0.7	50.0	0.7	12.5	$1x10^{-8}$
F1	20.0	0	30	-	-	0.5	13.2	$1x10^{-5}$
E	16.5	0	22	4.4/4	31.3	0.63	6.5	$1x10^{-8}$

1.3 Particle Size and Moisture Content of Singapore Marine Clay

Marine clay geology consists of upper marine clay (UMC) and lower marine clay (LMC). The moisture content of UMC is typically about 60% and the moisture content of LMC is typically about 47-50%. Bulk unit weights of marine clay range from 16 to 17 kN/m3. Table 2 shows the particle size distributions of Upper Marine Clay and Lower Marine Clay. Figure 3 also shows the Atterberg Limits, moisture content and SPT values of UMC and LMC. Marine clay to be encountered in contract T307 has a low SPT value, high plasticity and high natural moisture content. Such properties will be good for muck pumping system, and the high natural moisture content of Marine clay will keep the slump value of excavated soil > 80mm, which is envisaged to be conducive for pumping operations.

Table 2. Particle Size Distribution of Marine Clay

Soil Type	Partial Size	Mean (UMC)	Std. Deviation (UMC)	Mean (LMC)	Std. Deviation (LMC)
Clay	<0.002mm	51.9%	7.5%	54.8%	5.5%
Silt	>0.002mm – <0.063mm	46.1%	6.8%	44.5%	5.3%
Sand	>=0.063mm – <2.0mm	1.8%	5.4%	0.3%	7.0%
Gravel	>=2.0mm	0.1%	1.1%	0.5%	6.9%

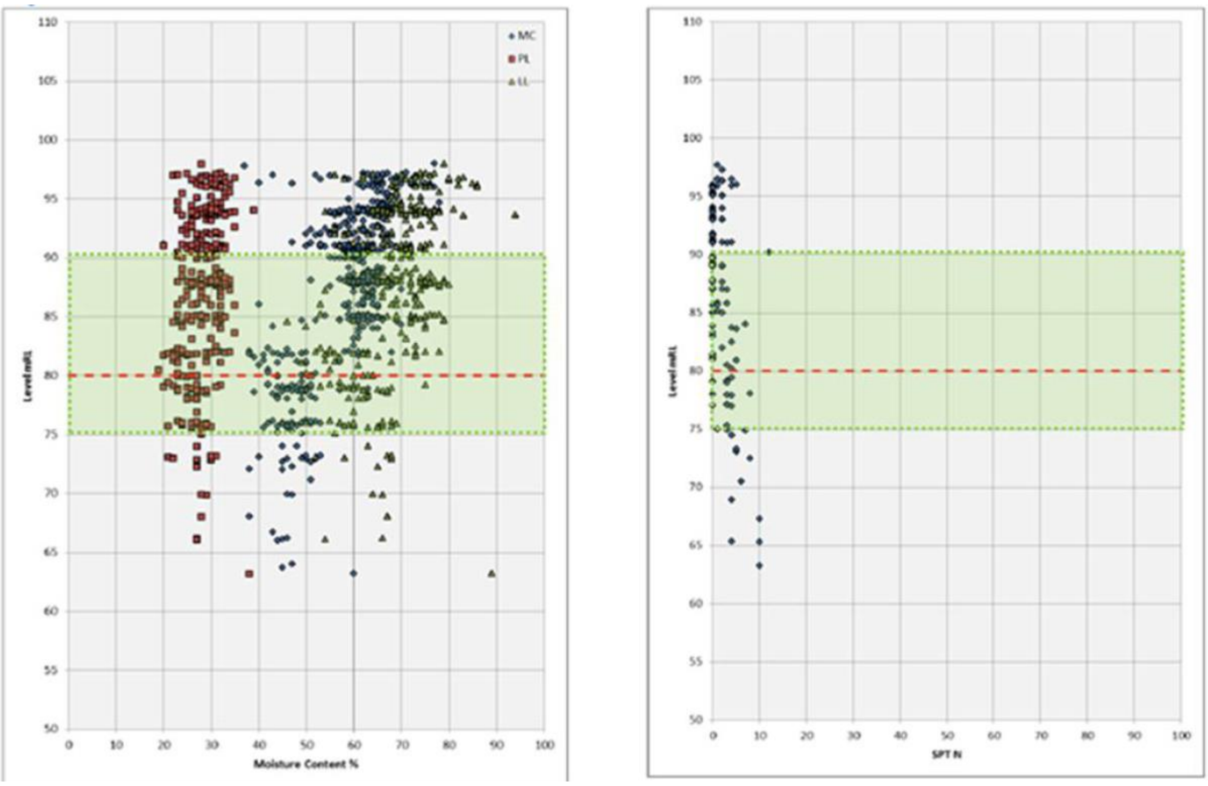

Figure 3. Atterberg Limits, Moisture Contents and SPT-N values of Marine Clay

The nature of good pumpable material is typical of high plasticity index, lots of clay particles/fines, good distribution of particle within range, water content within certain range**.** In order to ensure pumpability of the spoil, moisture content or water content is an important factor to be considered. If the moisture content of the soil is too low, water must be added in the chamber to increase the content and mix the water into the soil. One of parameters that are available to be varied is the water content, as it is simple to add water on excavation during pumping stage. Site trial focused in optimising moisture content for marine clay. This leads to the scope of full-scale muck pumping trial test which will be discussed in further sections, which is primarily to determine water content and reliability of proposed excavation management techniques.

2 EPBS WITH MUCK PUMPING SYSTEM

EPB TBMs are mainly used in plastic clay or clay can be made up with soil conditioning. All EPB TBM tunneling works require logistical processes for muck removal. Conventionally, muck car systems hauled by battery locomotives are used for horizontal conveyance before the muck skips are hoisted by gantry crane to be tipped at the muck pit. This process can be convoluted, and delays may occur during changing of the muck cars and noise may be generated during tipping of the spoil to the muck pit. Muck pumping systems have the potential to greatly simplify the site logistics of EPB jobsites. However, they require detailed knowledge and experience with the geology to ensure pumpability. As part of the planning for T307, the experiences from other projects around the world have been evaluated.

2.1 Pumping Application in Route 479 Shimizu Utility Corridor Tunnel

In order to demonstrate the muck pumping system at an ongoing job site with similar geological conditions and pumping system configuration, there was a joint Samsung C&T, Herrenknecht and LTA study trip to Route 479 Shimizu Utility Corridor (SUC) at Osaka, Japan. The tunnel is 2 km long and constructed under Route 479 from Tsurumi 5-chome of Tsurumi Ward to the boundary of Osaka City (Suzuki, 2015). The ground geology at the SUC tunnel consists of alluvium clay, alluvium sand and clay, and gravel (see Table 3). Figure 4 and Figure 5 show the pumping configurations which are similar to the proposed muck pumping system for T307 project.

Table 3. Geotechnical Properties of Route 479 SUC project

		Soil Particle Density (g/cm³)	Wet Density (g/cm³)	Natural Water Content (%)	Gravel (%)	Soil (%)	Silt (%)	Clay (%)	Liquid Limit (%)	Plastic Limit (%)	Liquidity Index T1
Backfill	B	--		--	--	--	--	--	--	--	--
Alluvial Sand	As	--		--	--	--	--	--	--	--	--
Alluvial Clay	Ac	2.64 ~ 2.70	1.54 ~ 1.56	72.6 ~ 78.8	0.0	0.0 ~ 30.9	34.4 ~ 41.2	31.7 ~ 65.6	35.1 ~ 109.4	29.3 ~ 35.3	0.57 ~ 0.75
Dliluvium Clay	Dc1	2.68 ~ 2.70	1.67 ~ 1.75	44.5 ~ 55.7	0.0	1.9 ~ 8.9	41.4 ~ 50.9	43.9 ~ 55.6	71.2 ~ 97.0	29.7 ~ 32.3	0.3 ~ 0.55
Diluvium Sand	Ds1	2.63 ~ 2.65		11.3 ~ 18.6	0.0 ~ 18.88	64.6 ~ 88.0	5.1 ~ 22.3		--	--	--
Dliluvium Clay	Dc2	2.64		28.5	0	30.9	42.6	26.5	40.6	21.7	0.36
Diluvium Gravel	Dg	2.64 ~ 2.65		7.9 ~ 10.6	23.9 ~ 56.3	23.5 ~ 56.0	4.6 ~ 20.1		--	--	--
Diluvium Gravel	Dc3	--		--	--	--	--		--	--	--
Diluvium Sand	Ds2	2.63 ~ 2.65		25.0 ~ 28.5	0.0	58.1 ~ 73.8	16.8 ~ 33.2	8.7 ~ 20.1	--	--	--
Dliluvium Clay	Dc4	2.66 ~ 2.68		25.2 ~ 37.1	0.0	1.2 ~ 44.6	26.8 ~ 71.8	27.0 ~ 42.0	42.7 ~ 79.2	21.5 ~ 31.8	0.09 ~ 0.34
Diluvium Sand	Ds3	2.664		21.7	0.0	66.1 ~ 72.9	12.0 ~ 16.7	15.1 ~ 17.2	--	--	--
Osaka Layer	Oc	--		--	--	--	--	--	--	--	--
	Os	--		--	--	--	--	--	--	--	--

Figure 4. P0 Primary Pump and P1 Secondary Pump (from Route 479 Shimizu Utility Corridor Tunnel, Osaka, Japan)

Figure 5. Telescopic Snake (left) and PE booster pump (right) (from Route 479 Shimizu Utility Corridor Tunnel, Osaka, Japan)

One major difference of the system in Route 479 SUC to the system that would be used on T307 is the pressure level and number of intermediate pumps. The system in Route 479 SUC has been designed to operate on a lower pressure level (setting pressure of 30 Mpa and maximum delivery pressure of 5 Mpa) which requires lower spec components. However, on the other side, this leads to the requirement for booster pumps along the tunnel line. It was observed that the pump adopted in Route 479 SUC has high hammer effect, in which there is need for pressure reduction valve (dampener) to limit the hammer sound to the surface.

The design that would be adopted in T307 on the other hand followed a high-pressure arrangement which does not require booster pumps in the tunnel but needs to work on a higher pressure level.

2.2 Further Global Track Record

Muck pumping systems have been applied in numerous projects worldwide. Table 4 shows a list (not exhaustive) of recent projects where muck pumping systems have been implemented. The majority of projects have been in cities which are well known for their soft underground. In Mexico City for example, muck pumping has been used on such a wide range of projects that it has become the premier mode of TBM operation in the city (Ferber, 2009). Besides applications where pumping systems have been used for complete tunnels, there have been those where this method was used only for the launch of the TBM or for vertical transport in the shaft for instance in Singapore.
In summary, the experiences in worldwide applications have produced a solid body of knowledge to build on

Table 4. Worldwide Application of Muck Pumping Systems in TBMs

Location	Project Name	TBM Diameter	Tunnel Length	Geology
Yokohama, Japan	MM21 Line	9.98 m	2 x 448 m	Alluvial Sand Gravel and Alluvial Clay
Netherlands	Botlekspoortunnel	9.76 m	3670 m	Clay, Coarse Pebbly Sands
Mexico City	Tunnel Emisor Oriente	8.70 m	6450 m	Lime, Clay and Sand
Mexico City	Rio de la Compania	6,30 m	6500 m	Clay, Muddy Clay
Mexico City	Rio Churrubusco	6.34 m	1850 m + 6072 m	Clay and Silt
Mexico City	Tren Toluca	8.50 m	4800 m + 5060 m	Weathered Tuff
Osaka, Japan	Hiranogawa Stormwater Storage Project	11.52 m	1690 m	Sand and Clay
Tokyo, Japan	Ogu Sewer Tunnel	3.28 m	1174 m	Alluvial Clay
Singapore	SPPA Cable Tunnel EW3	6.90 m	Only for Shaft	Old Alluvium
Singapore	Downtown Line C925	6.60 m	Only for Initial Drive	Old Alluvium
Singapore	Downtown Line C929a	6.60 m	Only for Initial Drive	Old Alluvium
Singapore	Thomson Line T228 (project was after T307 test)	6.71 m	1360 m	Treated Ground

In Singapore, a muck pumping system was proposed for North-East Line project contract C706 but never used as there was limitation in treating Old Alluvium soil to make it pumpable. It was employed in MRT Downtown Line Stage 3 MRT Line Contract C925 (Tampines East Station and Tunnels) to facilitate early commencement of the initial drive due to delays in station construction that hinder the deployment of traditional method of muck skips and gantry crane. Figure 6 shows the key components of the system. One specialty is, that the pipe extension has been located in the shaft with moving pipes. This allowed for efficient logistics.

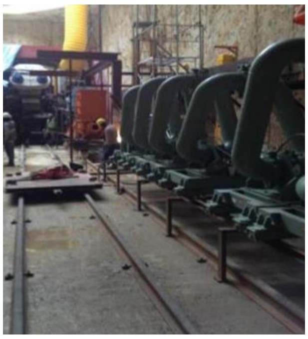

Figure 6. Muckpump Hopper (left) and Snake Pipe Extension (right) on Thomson Line C925

2.3 *Planned Configuration for T307*

Figure 7 shows the schematic of the proposed muck pumping system for T307 from the TBMs to the surface. The muck pumping system is a closed-type system which consists of a primary muck pump (P0) which is a proposed double piston with a pumping capacity of 140m3/hr. It is proposed to install directly at the discharge gate of the screw conveyor on a platform below the screw conveyor discharge gate. The muck pump is connected to the screw conveyor via a muck slicer which ensures all larger particles are broken down to a pumpable size. In the closed system, the existing earth pressure at the screw discharge is maintained throughout the pump. The pump later connects to the pipeline which is laid through the backup gantries which then is connected to a snake telescope which is installed on the TBMs backup system. Additional booster/relay pumps (PE) can be added to the pumping system depending on the tunnel length or the workability of muck conveyance.

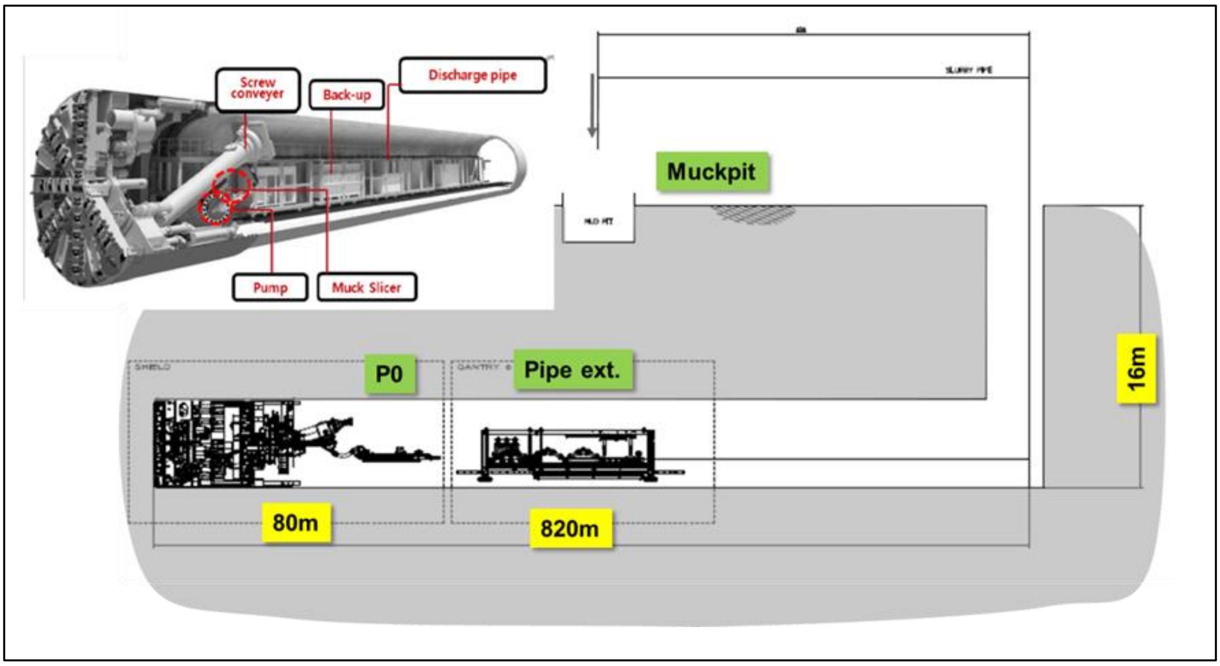

Figure 7. Schematic of the Muck Pumping System for T307

3 FULL-SCALE MUCK PUMPING TRIAL TEST FOR T307

In order to judge pumpability as well as the excavation monitoring system of the TBM, a full scale pumping test on the site at Marine Parade Road has been performed from 12-15 April 2016. The purpose of this full-scale is primarily to identify the percentages of water content; to identify the filling factor; and also test the reliability proposed excavation management system which is using stroke counter, flowmeter and soil tank measurement.

The proposed excavation management simulation for muck pumping trial involves three parts, which consist of primary measurement (flowmeter & density meter installed on discharge line), secondary measurement (stroke counter installed on primary pump near screw discharge gates) and tertiary volume measurement (soil tank measurement). For primary measurement, flowmeters and density meters were connected to the datalogger. For secondary measurement, the stroke counter measures total number of strokes made by pump. The volume of each stroke is known from cylinder capacity. For both flowmeter and stroke counter measurement, calibration factors are adopted to account for expansion of soil after excavation excluding conditioning (bulking adjustment factor), account for average filling rate of muck pumps (filling factor) and account for calibration for flowmeter and allows fine-tuning of measurement (flow factor). The tertiary volume measurement using soil tank measurement were also conducted to provide verification against volume derived from stroke counter and flowmeter/density meters.

3.1 Trial Preparations

To demonstrate the workability of pumping system and to demonstrate the requirements for muck reconciliation are met in such a system, the site pumping trial test was conducted in April 2016. The list of equipment and resources used are the following:

- Concrete Pump 95 cum/hr
- Excavator 0.3 cum bucket Capacity
- Lorry Crane
- 5.8m long Φ200mm Dia steel pipe line
- 1.5m long Φ125mm Dia steel pipe line 8mm thk
- 8” 90° Elbow-Various
- 8” 45° Elbow-Various
- 6” Dia Flowmeter Endress and Hauser
- Soil Tanks for Mixing
- Pressure Sensors-Various
- Data Logger
- Stroke Counter
- Welding Machine
- Dewatering Pump
- Endress & Hauser Promag50 flowmeter
- WIKIA S11 sensors

The schematic of the site pumping system is shown in Figure 8 and photos are shown in Figure 9.

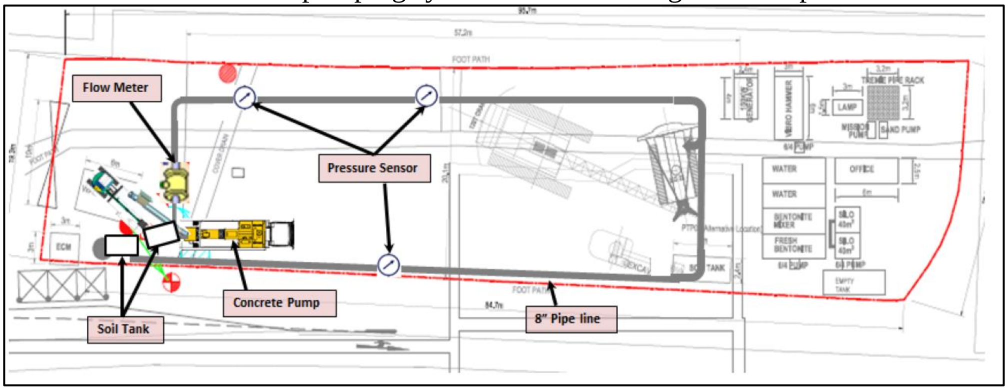

Figure 8. Layout of the Muck Pumping Test

Figure 9. Photos of the Muck Pumping Test

The pipeline configuration had been set up in a circuit with several bends to simulate actual tunnel pipeline. The total length was about 12% of the actual tunnel length (max 820m). As pipe bends produce higher pressure loss than straight sections, the actual and effective lengths with regards to pressure loss can be calculated. Table 5 shows the detailed configuration of pipeline for testing purpose.

Table 5. Pipeline Configuration for Muck Pump Testing

Component	Diameter [mm]	Nos.	Volume [m³]	Actual Length	Effective Length [m]
90° bend	125	1	0,0122	1,2	6
Straight pipe (1.5m long)	125	2	0,0368	3	3
Straight pipe (5.8m long)	200	15	2,733	87	87
Rubber Flexible Hose (6m long)	200	1	0,188	6	15
90° bend	200	3	0,0942	3,6	18
Total			3,064	100,8	129

The system comprises of a tank to allow mixing of marine clay and prescribed volume of water and a feeding tank mounted at the back of concrete pump. The dimension is shown at Table 6.

Table 6. Dimension of Mixing Tank and Feeding Tank for Muck Pump Testing

	Mixing Tank	Feeding Tank
Dimensions [m]	2.4 x 7.1	3 x 2.4
Full Volume [m³]	26	11
Spout Height [m]	N/A	1.6

The feeding tank and mixing tank were also prepared for the site pumping trial. The feeding tank was connected to the pump. The muck was loaded directly into the pump's hopper with the help of gravity through a spout welded on the side of the tank. The pouring was controlled by a manually operated gate-valve. The flow rate into the pump was dependent on current filling level of the feeding tank. The feeding tank size was 11 m3 in volume. (rearrange the paragraph.

The piston pump used during the test was a SANY LP9018. The pump was mounted on a truck chassis. The hopper volume was 0.6 m3 at the rear of the truck. The pump was similar to different piston pumps which had been used in TBM applications. Table 7 show the specification of the piston pump.

Table 7. Specification of Piston Pump for Muck Pump Testing

	SANY LP9018
Stroke length (mm)	1600
Piston diameter (mm)	230
Stroke volume (L)	66.5
Maximum output flow (m³ /h)	95

3.2 Experiment Plan

The experiment plan for the T307 site pumping trial contained different pumping scenarios and different muck properties with conditioning and without conditioning. Natural marine clay of 38% moisture content was used for the site pumping trial. Further mixing with water was conducted so marine clay can achieve 56% and 105% of moisture content which resembled the T307 expected geology after conditioning. See Figure 10 for photos of soil with various water contents.

a *b* *c* *d*

Figure 10. Tests carried out with (a) dry muck with 38% water content, (b) dry muck with 56% water content, (c) wet muck with 105% water content and (d) conditioned muck

3.3 Test Results

Based on different water content and varying level of conditioning either by water or by ground conditioner, the test demonstrated that the materials are pumpable. While the density increased due to conditioning, there was reduction in the pressure loss, which is very positive test to demonstrate workability of muck pumping system for actual project. Table 9 show the results of different soil properties after the pumping trial.

Table 9. Test Results of Varying Soil Properties

Test	Dry	Wet fast	Wet slow	Conditioned
Water content	56 %	105 %	105 %	< 105 %
Pump engine speed	2000	2000	1600	2000
Density (kg/m3)	1550	1350	1350	1520
Average filling rate	67 %	75 %	72 %	70 %
Average average pressure loss (bar/km)	N/A	33	33	19
Average maximum pressure loss (bar/km)	N/A	80	70	64

Figure 11 shows the results of comparison between volume measured by stroke counter and volume measured by flow meter for two datasets. For the volume measured by pump stroke, it was observed that the graph resembled was stair-like. It can be attributed to the measuring principle. Since the pump was not continuous (approximately pumping at 1 stroke every 6 seconds), the complete muck for each stroke was counted at one particular time. In reality the flow is more continuous as can be seen from the smoother measurement line of the flowmeter. Additionally due to the nature of the concrete pump and filling chute, the dry muck posed a problem and was not filling the pump properly. A filling factor **(**average filling rate of muck pumps**)** was introduced to account for this. It is expected this issue can be alleviated in the actual TBM operation as the screw will push the muck into the pump. The readings from the stroke counter and flow meter were well correlated in this test. The results were also compared with physical volume and this showed that the excavation management system worked well in this experiment.

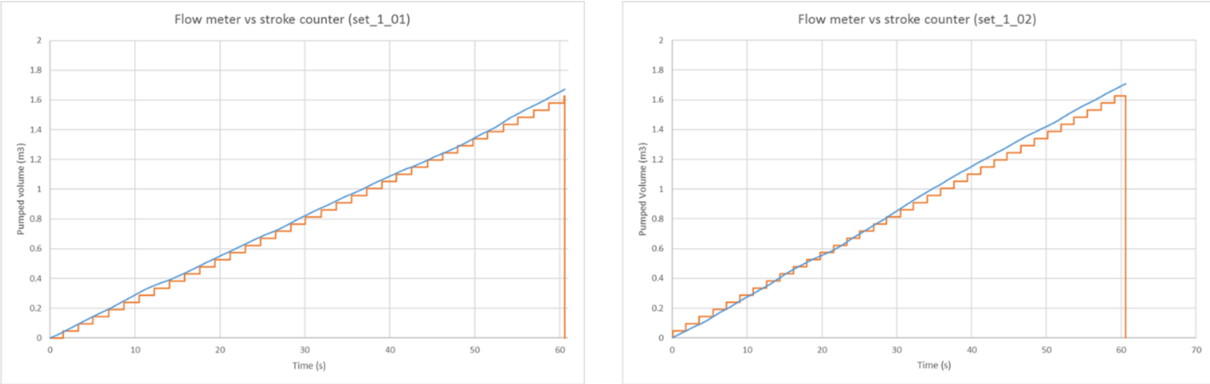

Figure 11. Comparison of flowmeter (blue) and stroke counter (green) measurement in two datasets

In a further measurement, the pressure loss in the pipes had been measured. The pressure loss in the pipes is strongly dependent on the consistency of the muck. Figure 12 shows the measurement for conditioned muck. While the actual pressure losses in the pumping system in the TBM cannot be fully predicted in the test due to scaling influences, a good qualitative result was obtained that showed the potential reduction of pressure loss by proper conditioning. This provided the confidence that no booster pump would be needed in the actual project.

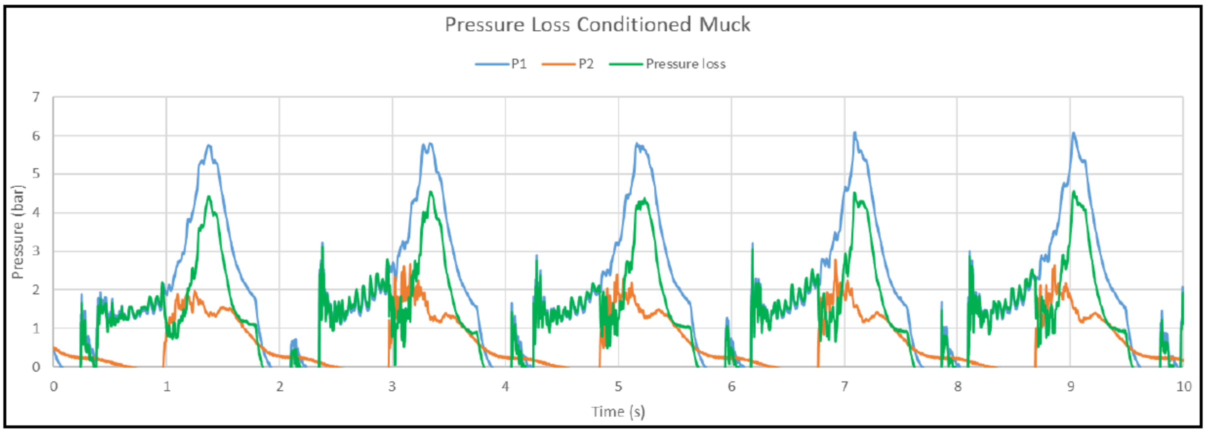

Figure 12. Pressure loss in the delivery pipe with conditioned muck

4 CONCLUSIONS

The muck pumping trial test was conducted and demonstrated the fundamentals of measurement that would go to create an effective excavation management system. The readings from flow meter and stroke counter were compared and consistency was proven throughout the process. The test also showed that the presence of conditioning materials such as bentonite and polymer contributed in reducing the muck pumping pressure loss and helped to make the muck more pumpable. It should be noted that the additional conditioning was not expected to be used as the minimum criteria for successful muck pumping has been achieved with water. With proper additional conditioning, a good qualitative result showed the potential reduction of pressure loss. This provided the confidence that no booster pump would be needed in the actual tunnelling works. The results presented demonstrated that Singapore marine clay can be pumped with minimum addition water and conditioning, and that measurements of flow and volume can be achieved in order to manage excavation in a full scale TBM system.

5 ACKNOWLEDGEMENTS

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