Latest Development in Horizontal Grouting for Cross Passages in Thomson-East Coast Line C1-C2

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ABSTRACT: Grouting has been extensively used in Singapore MRT projects in order to facilitate the excavation of Cross Passages. The most commonly used methods, as Tube-A-Manchette (TAM) grouting, jet grouting (JGP) and deep soil mixing (DSM) have been generally executed from surface. However, vertical grouting is not always possible. With the development of new lines, more often tunnels, including cross passages, run undercrossing roads/buildings and other critical infrastructure, resulting in horizontal grouting as the only feasible method. This paper describes horizontal grouting techniques applied to cross passage excavation, including analysis and interpretation of grouting results in rock and soil, and description of innovative solutions implemented for the Thomson-East Coast line C1-C2.

1. General Introduction

Thomson-East Coast Line will be the 6th Mass Rapid Transit line in Singapore. It will be a fully underground mass rapid system approximately 43km in length with 31 stations. The alignment of the line will be parallel to both the North-South line and part of the East-West Line. The Package TEL C1-C2 discussed in this paper consists of stations from Woodlands North to Mt Pleasant with a total of 8 tunnelling contracts.

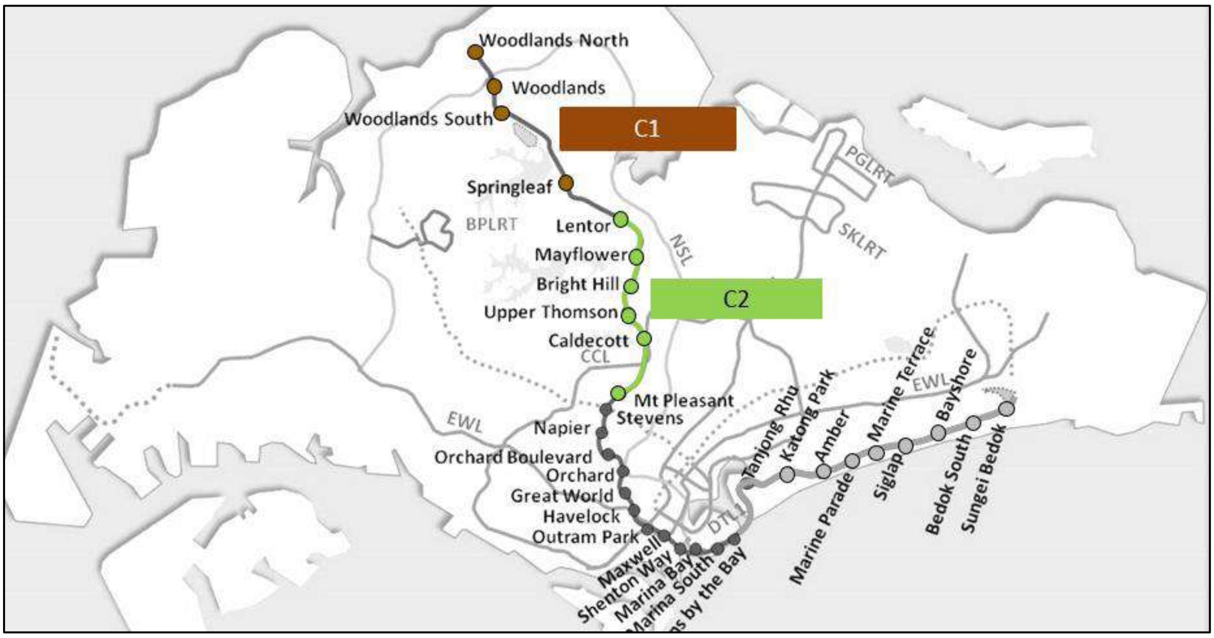

Figure 1: Thomson-East Coast Line, Packages C1 and C2

The tunnelling is carried out with the usage of 24 Tunnel Boring Machines both EPB and Slurry covering 32 drives with a total length of 31.75 km. 34 cross passages will be constructed throughout the package.

1.1 Geological Conditions of TEL C1-C2

Subsurface ground layers along the alignment for TEL C1-C2 were determined through site investigation works. Boreholes were generally drilled into and terminated within the Bukit Timah Granite. Undisturbed samples were taken, within the Kallang Formation and Bukit Timah Granite soil layers.

Standard penetration tests (SPTs) were carried out in all soil layers including Fill, Kallang Formation and Bukit Timah Granite to determine the relative density or consistency of soil, and to recover disturbed samples for visual inspection. Cyclic loading pressuremeter tests were carried out to determine the deformation properties of the ground. Field permeability tests were performed to measure the in-situ permeability of the soil surrounding the piezometer tip. Packer Tests were carried out to determine the permeability of the rock mass.

Based on the geological background and the site investigation works carried out, the subsurface ground layers along the tunnel alignment can be classified as follows;

Fill, was man-made ranging in thickness between 1 to 10m and consist of firm to stiff yellowish/reddish silty sand with hardcore.

Kallang formation was encountered at localised regions below the fill layer; consists of Estuarine Clay (E) Fluvial Sand (F1) Fluvial Clay (F2).

Underlying Fill and/or Kallang Formation or from the surface, there is Bukit Timah Granite.

1.2 Geological Conditions of the Cross Passages

The subsurface conditions of the Cross Passages (CP) in TEL C1-C2 are illustrated in Figure 2, 63% of the CPs are in full face soil and 34% are in rock. The geological conditions of the CPs can be generally classified as Bukit Timah Granite. This formation is one of the oldest in Singapore and is mainly found in the northern and central part of Singapore.

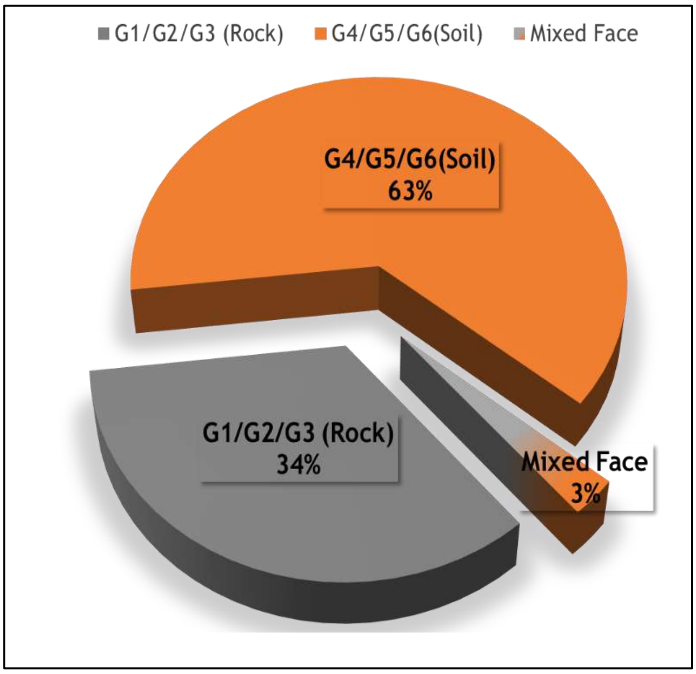

Figure 2: TELC1-C2 summary of Cross Passages geological conditions

The weathering grades of GV (completely weathered granite) and GVI (residual soil), represent ground conditions often requiring ground improvement due to high permeability and low SPT.

Based on GIBR, permeability for this category ranges from 1.5 E-6 to 8 E-9, SPT values generally vary between 10 and 50.

Ground improvement is also often required at the interface of soil and rock, typically at GIV (highly weathered granite) and GIII interface (Moderately Weathered Granite) (GIII)

The permeability for this group ranges from 1.2E-5 to 4E-9.

The UCS values varied between 1-300 MPA.

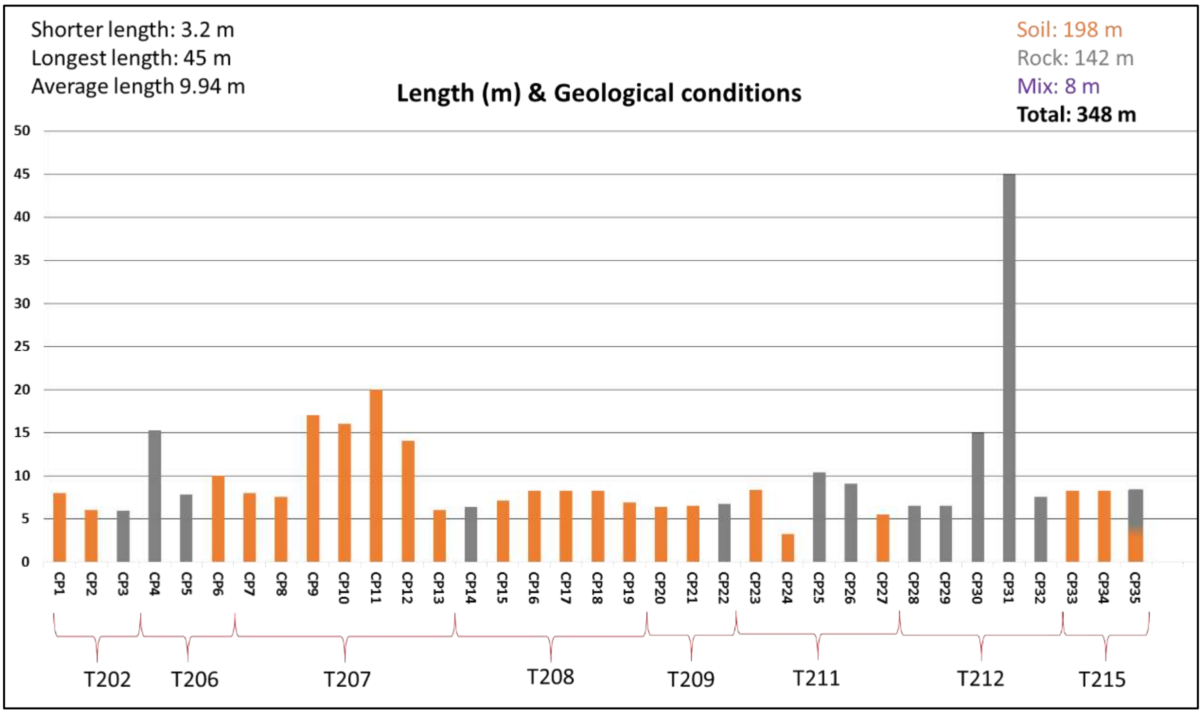

Figure 3: TELC1-C2 summary of CP length and geological conditions

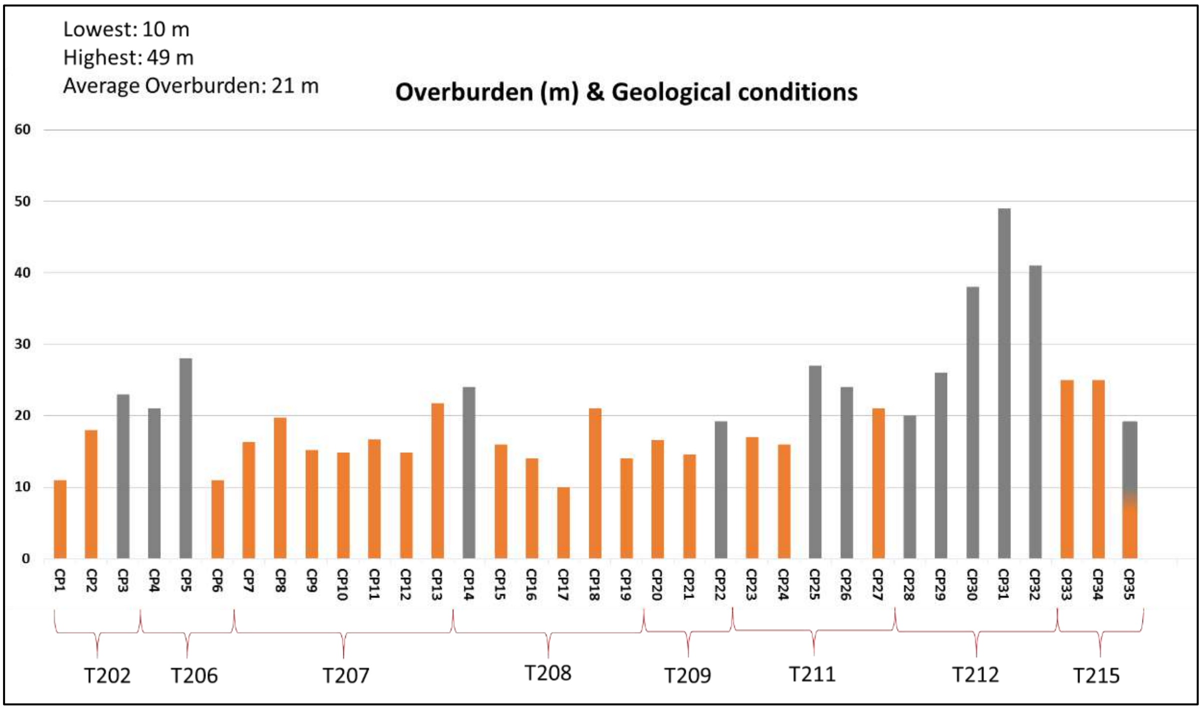

Figure 4: TELC1-C2 summary of CP overburden and geological conditions

1.3 Surface/Subsurface Condition and Their Impact on Grouting Methodology

Tunnelling in a metropolitan city such as Singapore poses a challenge with its large built up area consisting of buildings, roads, highways and other surface structures. Large impact on programme and cost due to the diversion of roads and utilities has always been a concern.

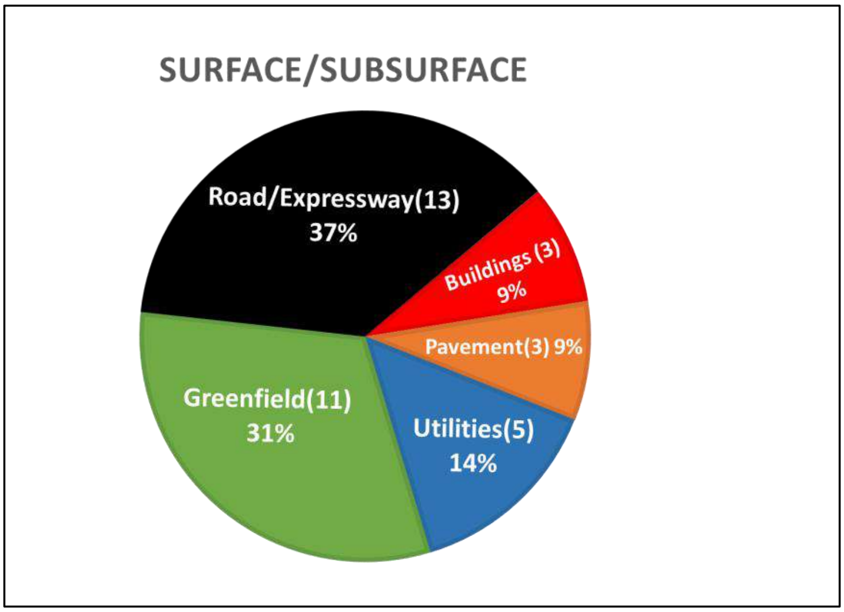

Figure 5: Surface and subsurface condition

In the recent years the challenges have intensified with the presence of subsurface structures and utilities within the influence zone of the cross passage construction. They are mainly existing MRT tunnels, SPPG tunnels as well as underground utilities. Figure 5 shows the percentage of surface and subsurface structures which are within the influence zone of the CP construction. Conventional grouting methods such as TAM and JGP which were used for ground improvement works prior to construction of cross passages are being constrained. The mobilisation of the rigs on busy roads/highways are difficult and hazardous.

1.4 Grouting Method used for the 34 CPs

Ground improvement, was done on 89% of the Cross Passages. Conventional methodologies of surface grouting included JGP, Compaction, Fissure and Tam grouting were planned.

Still, due to the surface and/or subsurface conditions as described in the previous paragraph, vertical grouting was not feasible for 31% of the CPs, where horizontal grouting is carried out from the bored tunnel.

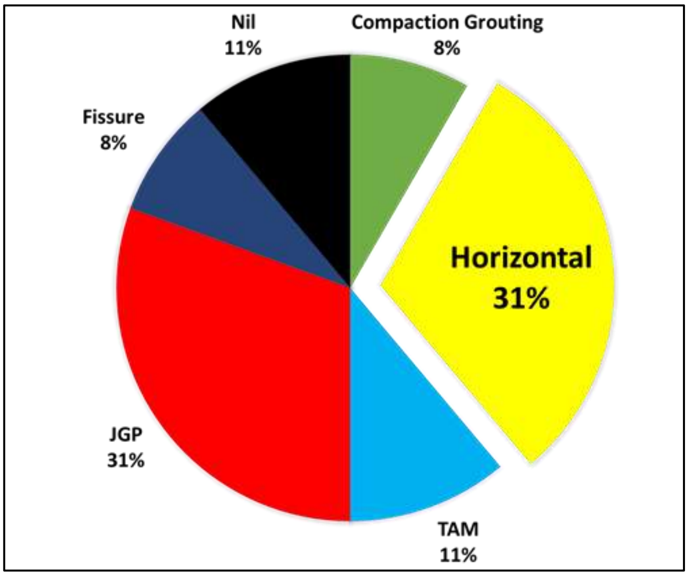

Figure 6: TELC1-C2 summary of grouting method for the 34 CPs

2. Conventional Grouting in previous projects (NEL, CCL, TEL)

TAM grouting has been commonly adopted as the ground treatment method for Cross Passage (CP) mining works since the construction of NEL line and CCL line as a preventive measure against water ingress and to improve face/crown stability during the excavation stage.

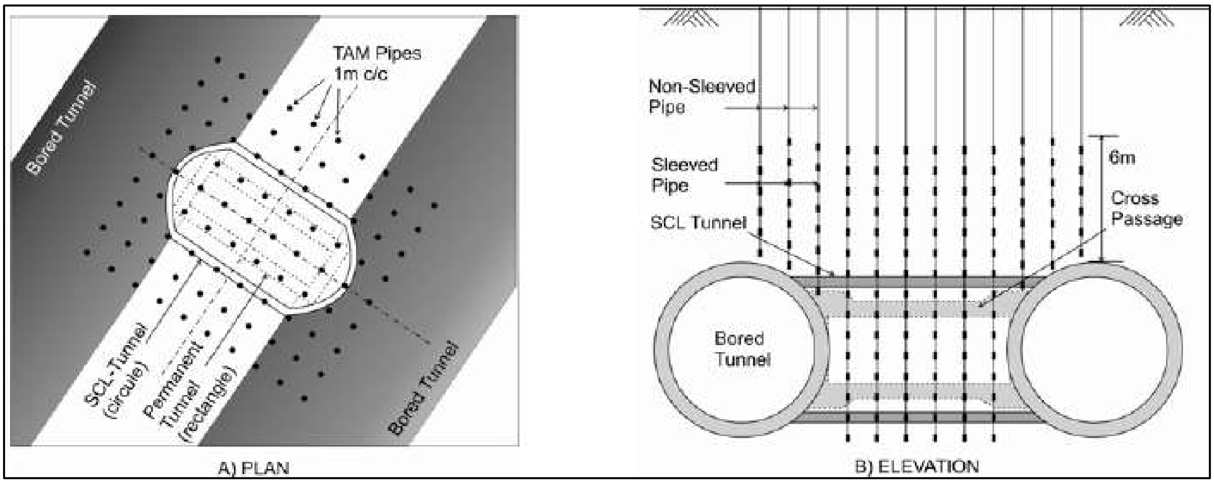

Figure 7: Typical vertical grouting scheme for Cross Passages

- Grouting Method: Double packer at steps of 1000 mm (sleeve spacing)
- Primary grouting: Ordinary Portland Cement (OPC)
- Secondary grouting: Microfine Cement (MFC)

Horizontal grouting has also been used in previous mined tunnel projects, as during the AYA tunnels construction, where grouting was done to stop water ingress during excavation.

- Grouting method: Open End tube method using a single packer.
- Primary grouting: Ordinary Portland Cement (OPC)
- Secondary grouting: Microfine Cement (MFC).

Horizontal grouting was also used during the construction of Cross passage 1 of Contract C855, where two tunnels connecting a diameter φ 6m escape shaft to the main bored tunnels were excavated in G-VI and where heavy inflow of water was observed and had to be addressed.

- Grouting Method: Single Packer (installed at shaft wall)
- Primary grouting: Ordinary Portland Cement (OPC)
- Secondary grouting: Microfine Cement (MFC).
- Sodium Silicate added once the termination criteria on pressure or volume was reached.

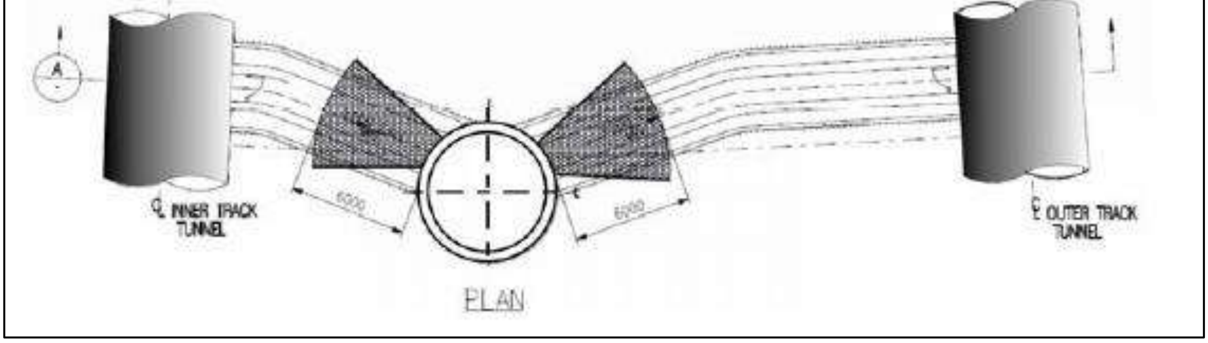

Figure 8: C855 CP1 horizontal grouting (stage 1)

3. Cross Passage Design Considerations and Implication on Grouting Work

3.1 Impact due to Permanent and Temporary Lining Profile (Geometry)

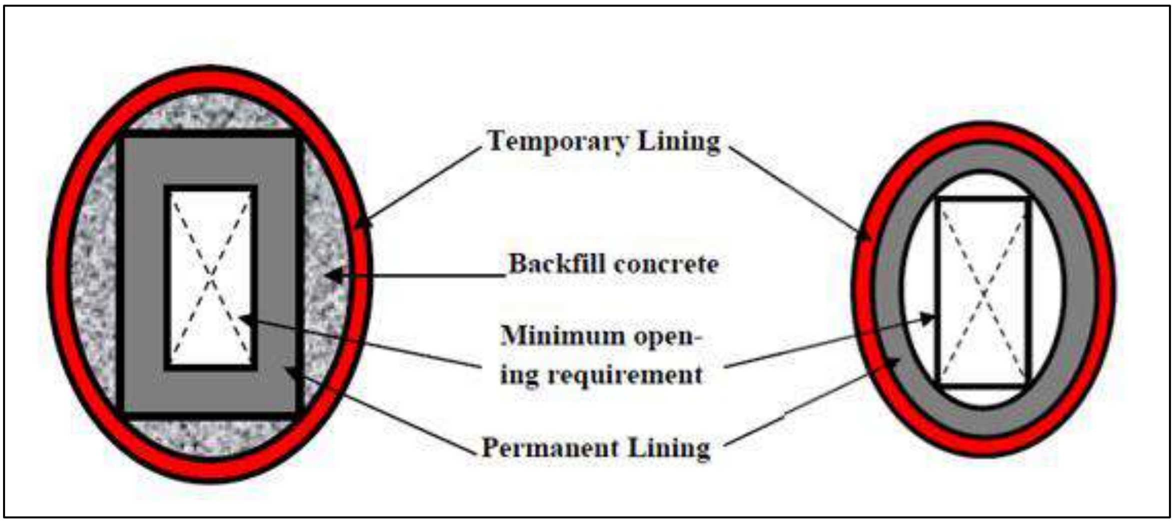

Figure 9: Rectangular and Oval permanent lining

The Cross Passages are mean for pedestrian evacuation, and requires a minima geometry (permanent lining) of 1.4m W x 2.8 m H. Over the years, consultants have been using two different approaches to design (geometrically) the Cross Passages Permanent lining:

- Rectangular permanent lining
- Oval shaped permanent lining

The Temporary Supports (by Sprayed Concrete Lining) generally follow the typical oval profile (in soil) or horse shape profile (in rock). The Rectangular Permanent lining is easier to be constructed, however it would require a larger excavation section as the rectangular permanent lining is enclosed in a large oval temporary shotcrete lining. A larger excavation would increase the extent of a ground improvement zone (when required). In TELC1 and C2 the permanent lining has been designed with the rectangular shape, with the consequence of requiring a large grout zone. This is not a major issue when grouting is done vertically and prior to bored tunnels, but could pose certain challenges when the grouting can be done only horizontally from the bored tunnels.

3.2 Impact Due to CP Short Length.

Normally the Cross Passages includes a collar section adjacent to the bored tunnels (for lintel frame installation and to address distortion of the Segmental lining). The central part of the CP is designed with a smaller then collar profile section. However in particular cases where the CP is relatively short, the consultant designed the CP with a single "collar" section throughout the entire CP, enlarging the excavation area thus the extent of ground treatment zone.

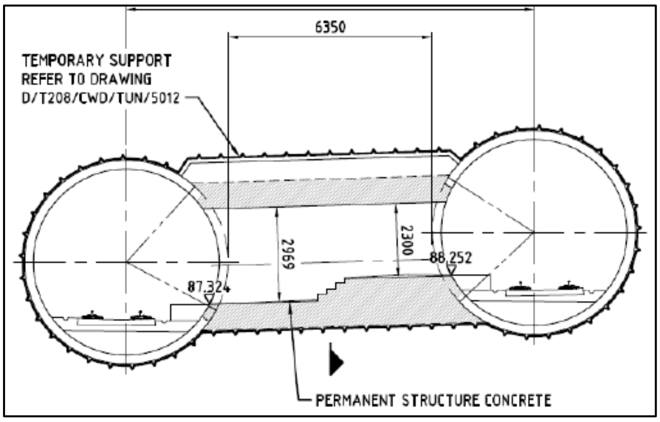

Figure 10: T208 CP profile, constant "collar" section

3.3 Impact Due to Allowable Opening of A Single Segment

Rings are installed in the bored tunnels to prevent distortion due to the CP excavation. In order to limit and optimise the design of the rings members, the ring system is designed to frame around.

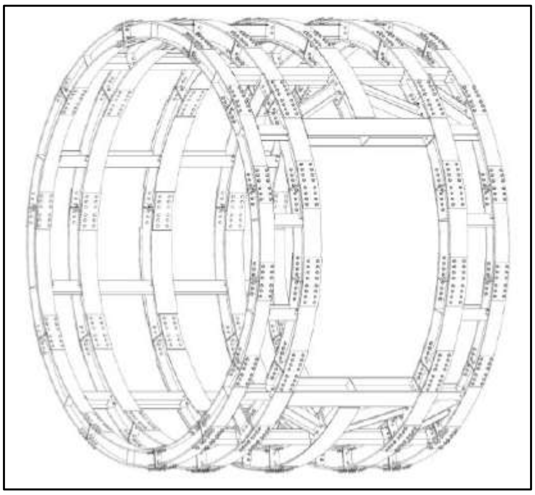

Figure 111: Typical bracing for bored tunnel.

Figure 12: C927 Excavation of CP using remote controlled excavator

Table 1: Summary of factors affecting the grouting work execution

Impact	**Grout from surface**	**Horizontal Grouting**
Large grout zone due to Permanent and Temporary Lining design	Low Impact if grout can be executed from surface	High Impact due to drilling constrains from bored tunnel
Large grout zone for Short CP design (constant collar section)		
Drilling allowed from one segment only	NA	High Impact and challenge in order to cover the design grout zone. Excavation sequence also affected.

4. Innovative Horizontal Grouting for Cross Passages

4.1 Provision of Additional Grout Ports

In TELC1 and TELC2, Contracts T207, T211 and T212, HDPE Additional Grout Ports (AGP's) have been installed in the segments at all the CP & Sump locations and 2 rings either side to aid grouting from within the tunnel if required. These give more options for safe drilling and ground treatment through ball valves screwed into the lifting point. On completion of ground treatment, probing will be undertaken to ascertain the permeability of the grouted mass prior to break out and CP or sump construction work.

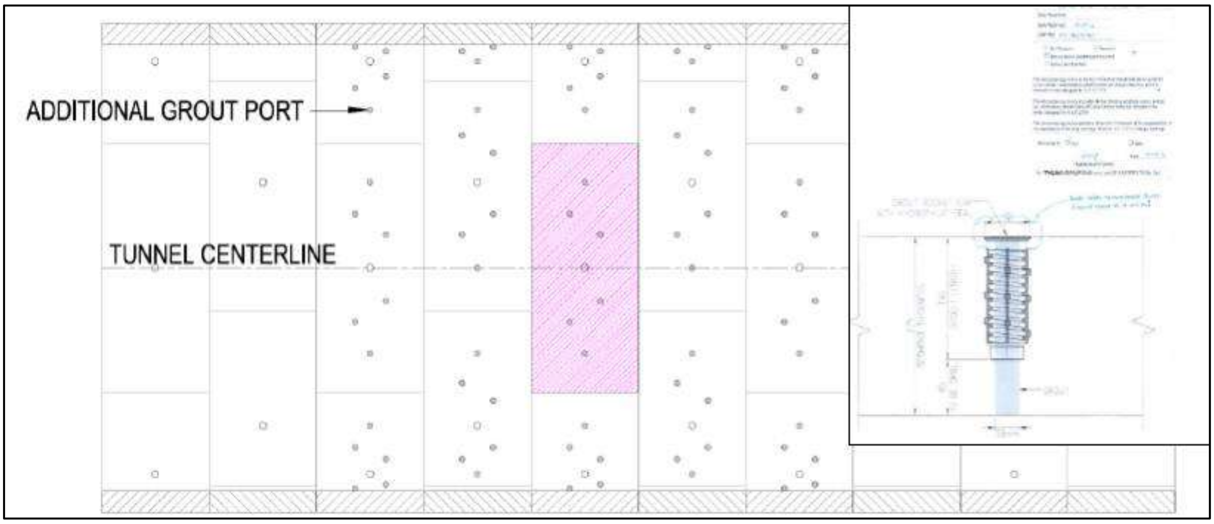

Figure 12: T211 Grout port arrangement, profile of bored tunnel

In TELC1-C2 contracts, the contractors had engaged their own professional engineers to determine the effect of the additional grout ports on the integrity of the segment. Conclusively, there is no reduction of reinforcements and due to the staggered positioning of the grout ports, the load will be distributed to the concrete and reinforcements around the sockets equally. Cracks around the port are mitigated by the usage of HDPE sockets and additional non-shrink grout will be installed after the completion of grouting.

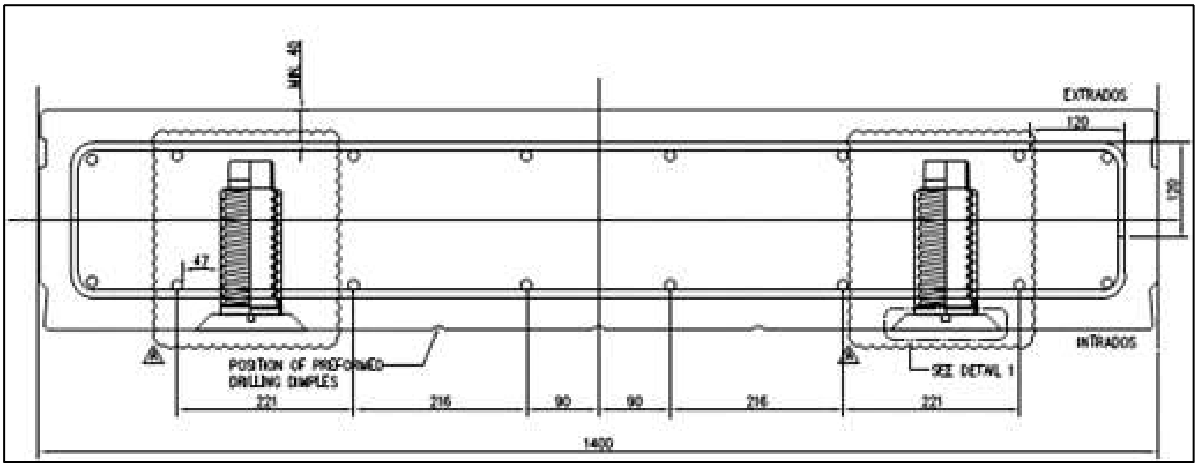

Figure 13: T207 Additional grout socket arrangement

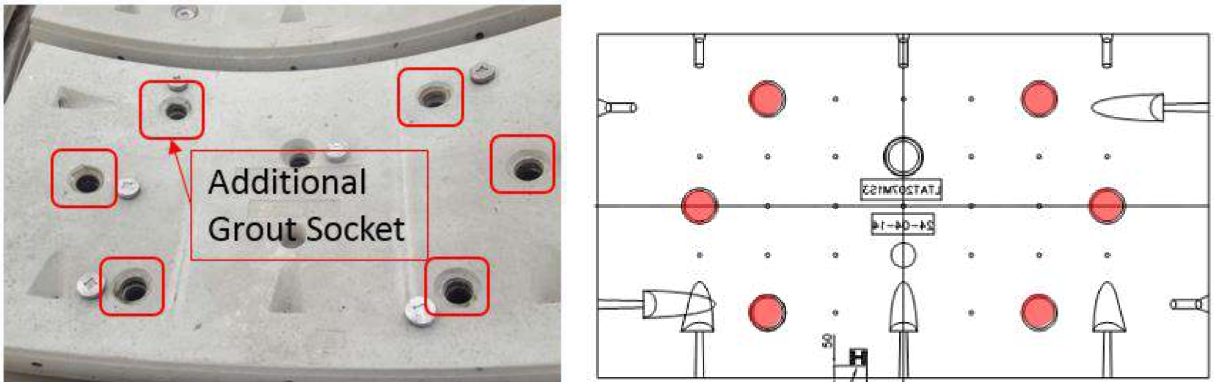

Figure 14: T207 Additional grout ports arrangement

With the usage of the additional grout ports, there is a great extent in the potential geometrical coverage of the horizontal grouting done from the bored tunnel.

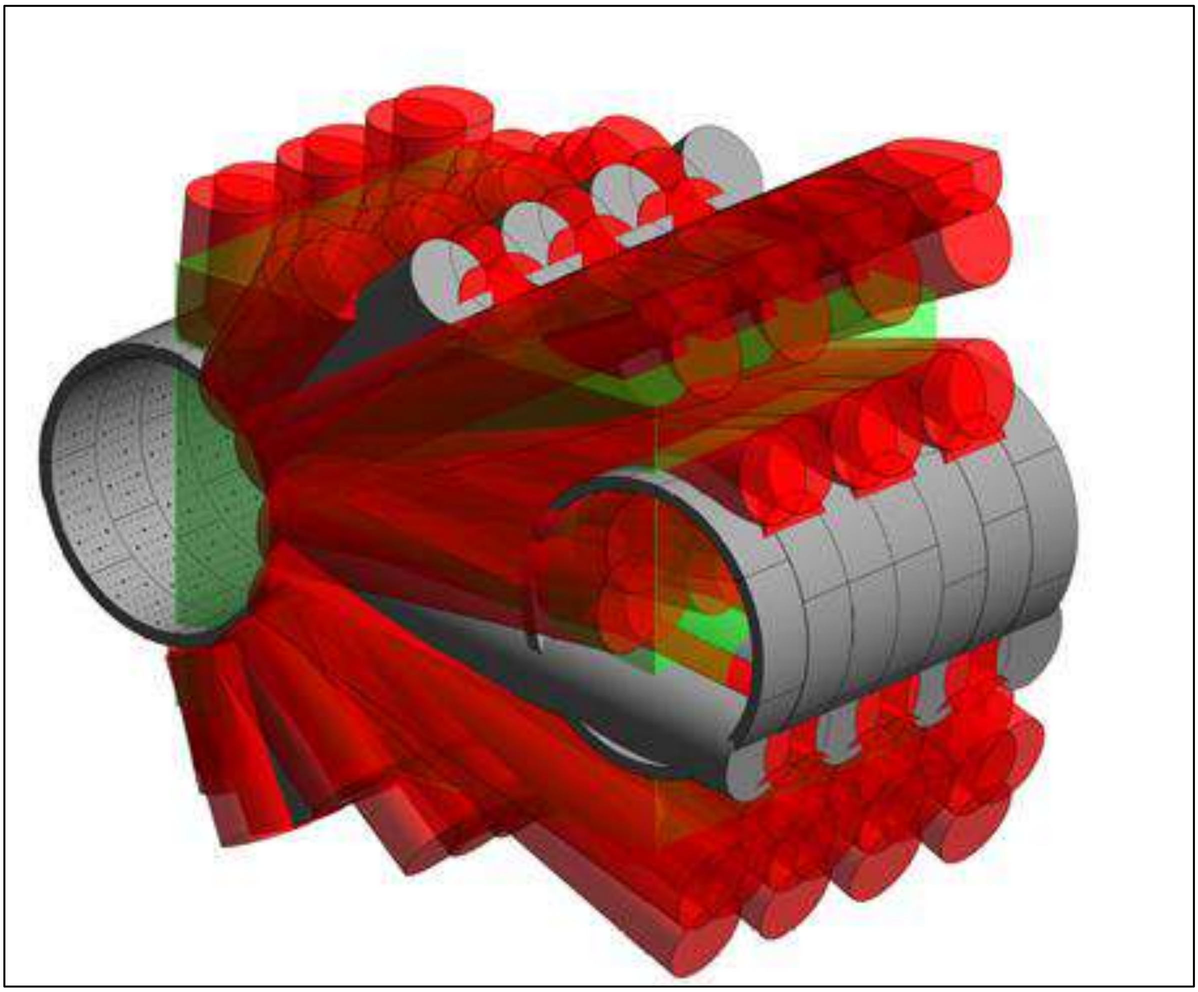

Figure 15: Coverage of horizontal grouting using the additional grout ports

4.2 Case Study 1: T207, Horizontal Grouting in Soil

4.2.1 General criteria/mix etc

Horizontal Single Phase Grouting Method is being adopted as the grouting method for the Adit Tunnel and some Cross Passages for T207. This is so as the Adit Tunnel and Cross Passages are underneath the busy roads of Seletar Expressway (SLE), which makes grouting from the surface challenging. Hence, it would be easier by grouting from within the tunnels. In order to avoid damages to the permanent tunnel segments, grout sockets have been pre-installed into the tunnel segments during casting.

The Single Phase Grouting is used to minimize the water ingress from the silty sand layer and strengthening the silty sand during the excavation works in Adit Tunnel and Cross Passages.

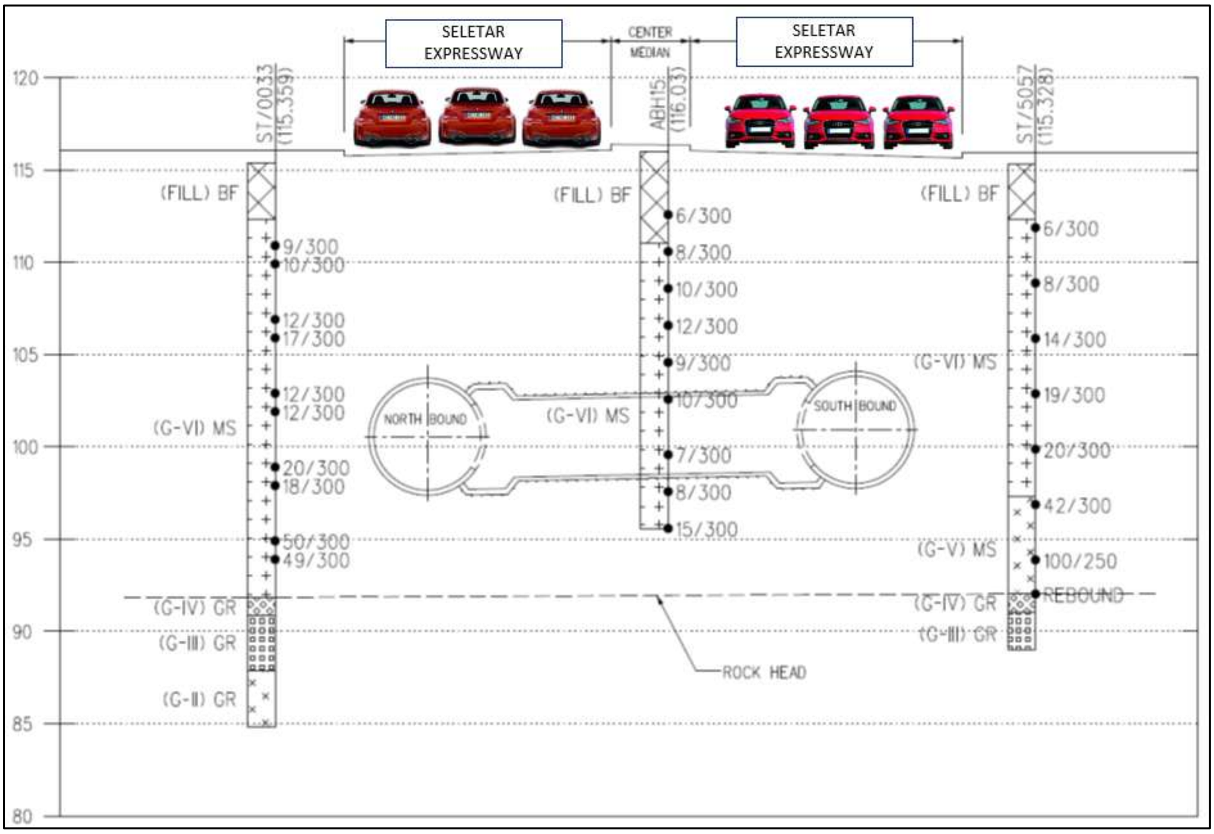

Figure 16: Cross section of Cross Passage 3 (CP3) under Seletar Expressway

4.2.2 Grout Mix Design

Grout with Sodium Silicate (LW) is used as the grout for horizontal soil grouting. It is a mixture of cement grout and sodium silicate grout, with a gel time of about 20 to 50 seconds. The appropriate setting time will be decided upon studying the condition of the LW grout that is discharged from a water release pipe with releasing underground water.

Agent A (Sodium Silicate Grout)		**Agent B (Cement Grout)**	
Sodium Silicate	100 liters	Cement	100kg (32.2 liters)
Water	100 liters	Water	167.8 to 200 liters
Total	200 liters	Total	200 liters

Table 2: Standard Mix Proportion of LW Grout

4.2.3 Grouting Termination Criteria by Pressure

For Single Phase Grouting, the grouting pressure will be varied depending on the underground water pressure. As recommended by the grouting specialist, the grouting pressure is normally set at 4 times higher than the underground water pressure and the maximum grouting pressure is capped below 10 bar.

The grouting pressure could not go any further so as to prevent any damage to the permanent segment lining from grouting force.The grouting pressure needs to take into consideration of the close proximity to the permanent segment lining as well as verifying against the capacity of the segment itself. A safe buffer zone for the grouting is required such that the grouting does not terminate right beside the segment lining.

4.2.4 <u>Grouting Termination Criteria by Ratio</u>

The grouting ratio is defined as the volume of grout to be injected against volume of target grouting zone to be improved. The grouting ratio is determined from the volume of pore space of target grouting zone, nature of target soil.

In order to achieve good cut off performance, the grouting ratio should be flexibly selected to achieve maximum effects in terms of grouting pressure. For T207, the grouting specialist has proposed for the grouting ratio to be set at 30% per one (1) meter cube of target soil.

Target Area (dia 1.0m) (m2)	Total Target Vol. (per m) (m3)	Grouting Ratio 30.0% Grouting Vol./metre (L)	Grouting Vol./step of 0.25m (L)
0.79	0.79	237	60

Table 3: Grout Ratio Calculations

4.2.5 <u>Grouting Ternination Criteria</u>

The grouting specialist proposed the following terminations criteria:

- Specified grout volume – 30% of one (1) meter cube of target soil
- Specified pressure – 10 bar

Other than relying on the two criteria as listed above, the grouting specialist would also monitor the behavior of the ground while drilling to grout.

4.3 Case Study T207a: Analysis of Horizontal Grouting at Adit Tunnel

Prior to the excavation works for the Adit Tunnel, horizontal grouting was carried out from both Adit Tunnel dome side and from Woodlands Bound (WB) bored tunnel side.

The grouting specialist has designed and custom-made a working platform specifically for T207, to better facilitate the horizontal grouting works carried out from within the tunnels.

With this platform, the execution of grouting work from bored tunneling can be done concurrently to the bored tunneling work

As illustrated in Figure 19, 54 points from the WB tunnel were being grouted. Subsequently, 2 numbers of probe drills were carried out to check the water ingress or the permeability of the ground after being grouted.

Figure 17 T207 Raito Working Platform

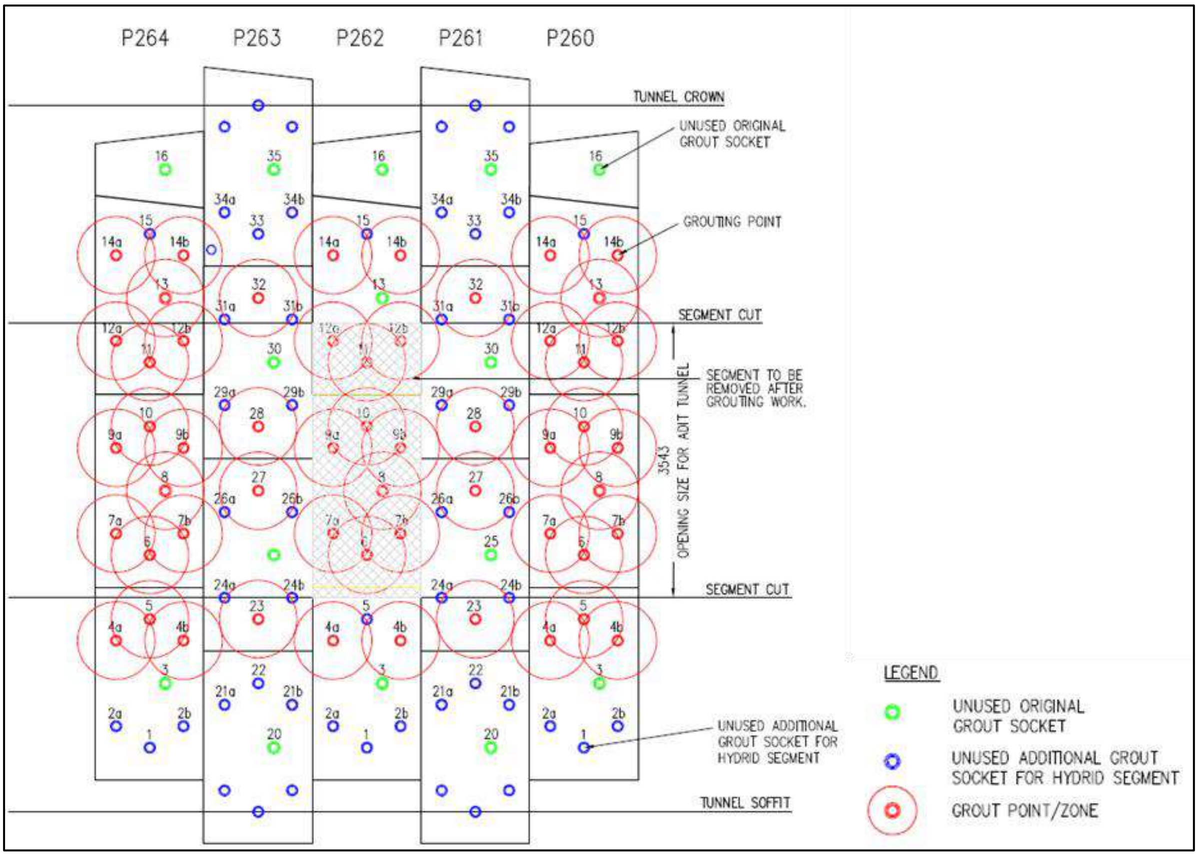

Figure 18: Adit Tunnel Grouting Points from Woodlands Bound

Figure 19: Adit Tunnel excavated face and soil sample showing grouting veins

The excavated face of the Adit Tunnel is shown in Figure 20. The grouting veins can be seen clearly on the excavated face and the soil sample shown on the right.

4.3.1 <u>Analysis of Actual Grout</u>

The comparison between the target and executed grout volume from the Woodlands Bound for the Adit Tunnel is being summarized and illustrated in Figure 21. Generally, most of the executed grout did not reach the target grout volume as the grouting pressure has reached the maximum of 10bar.

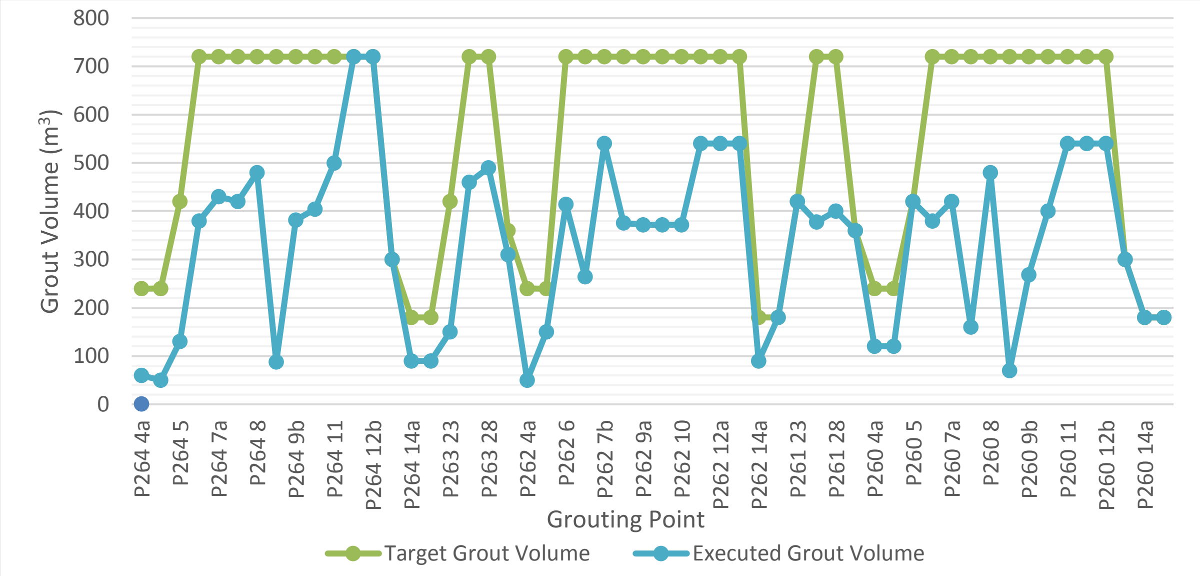

Figure 20: Grout Point vs Grout Volume Graph for Target Grout Volume and Executed Grout Volume for Adit Tunnel

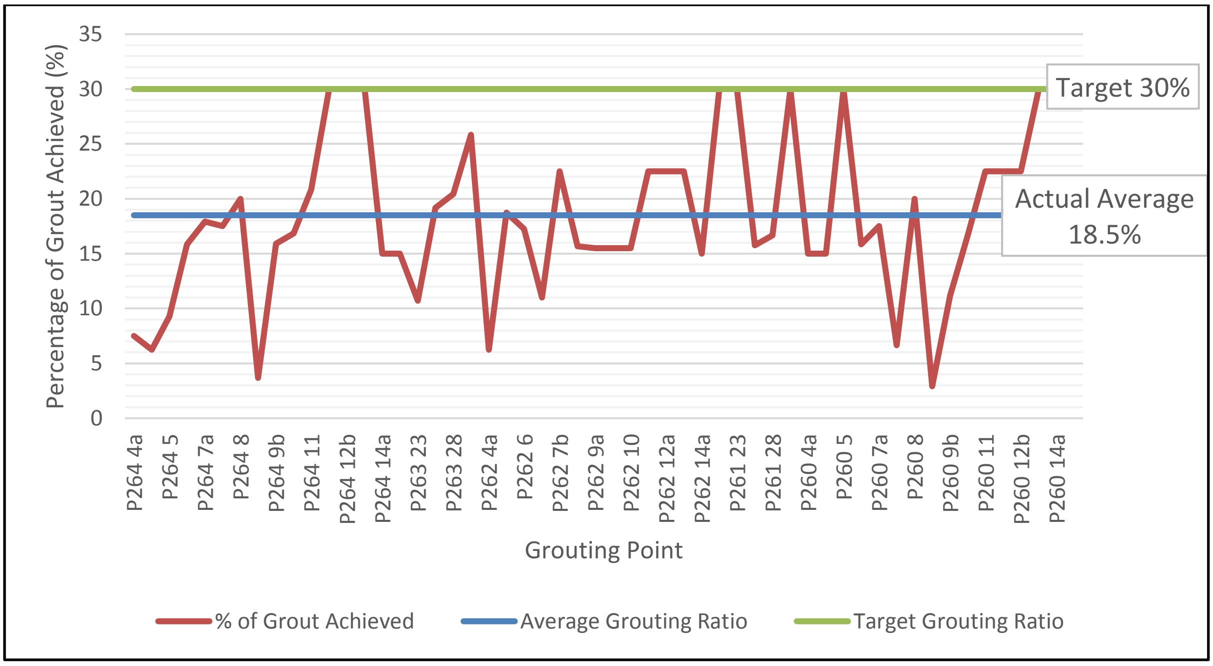

Figure 21: Percentage of Grout Achieved for Adit Tunnel

The 30% grout intake by volume as a general criteria for the horizontal grouting for all Adit Tunnel and Cross Passages was proposed by the grouting specialist. As seen from Figure 22, the grouting ratio was unable to reach the target of 30% grout volume intake and the average intake was tabulated as 18.5% instead. The percentage of grout achieved ranges widely from reaching the target of 30% to a low minimum of 3%. For the grout point with the lowest percentage of grout achieved (i.e. 3%), it can be assumed that there is low permeability hence low grout intake even though at 10 bar grouting pressure.

The grouting termination criteria by pressure will be more reliable. In order to better determine a more specific termination criteria by volume, the actual geological condition on the face should be looked into. This can be done through the Geotechnical Interpretative Baseline Report (GIBR), additional soil investigation, studies or publication. With target volume set more specific to the actual ground condition, it would be much easier to identify if there is any abnormality in the grouting performed.

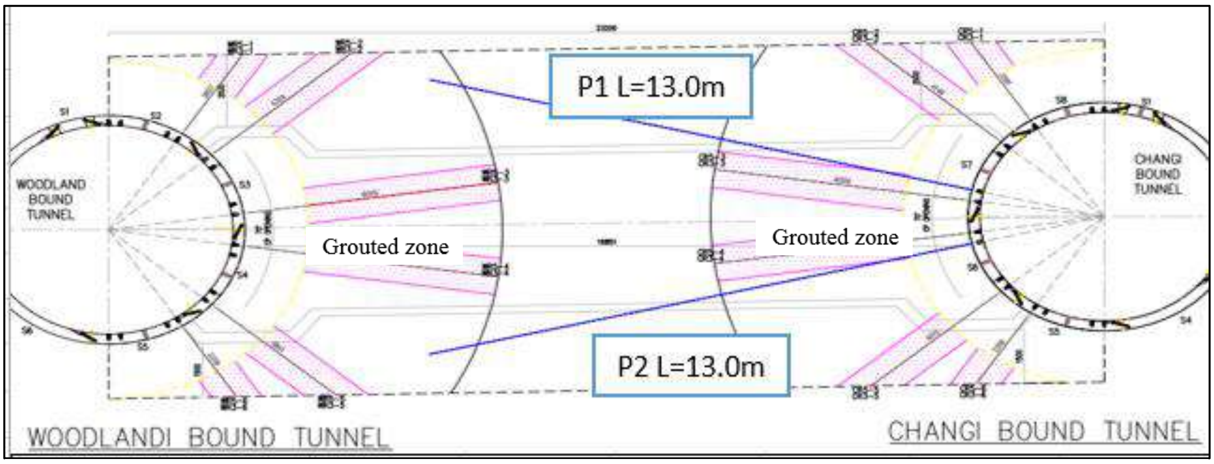

Figure 22: Probe Drilling from Changi Bound for CP3

4.4 Case Study T207b: CP3 Horizontal Probe holes: Water inflow VS Permeability

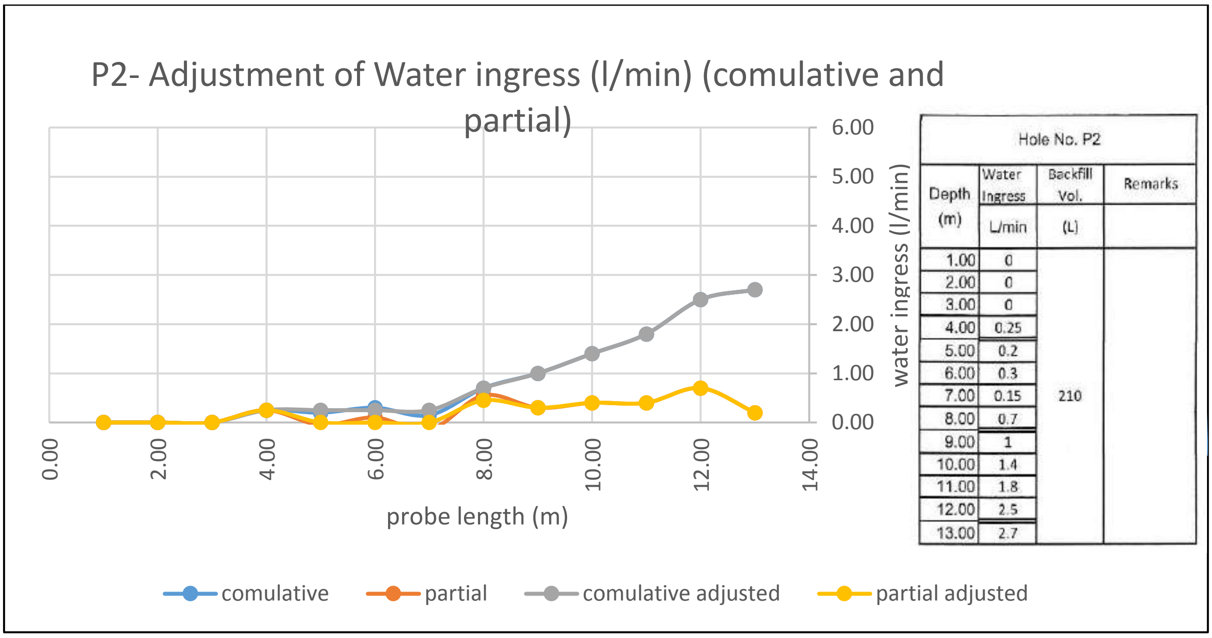

Figure 23: Water ingress with respect to depth

The chart shown in Figure 24 indicates the actual measurement done on the probe hole P2 in CP3.

The first step is to adjust the readings considering the assumption that the water ingress measured during a step by step progressive drilling shall be a cumulative value.

The second step is to calculate the partial water flow at each meter step.

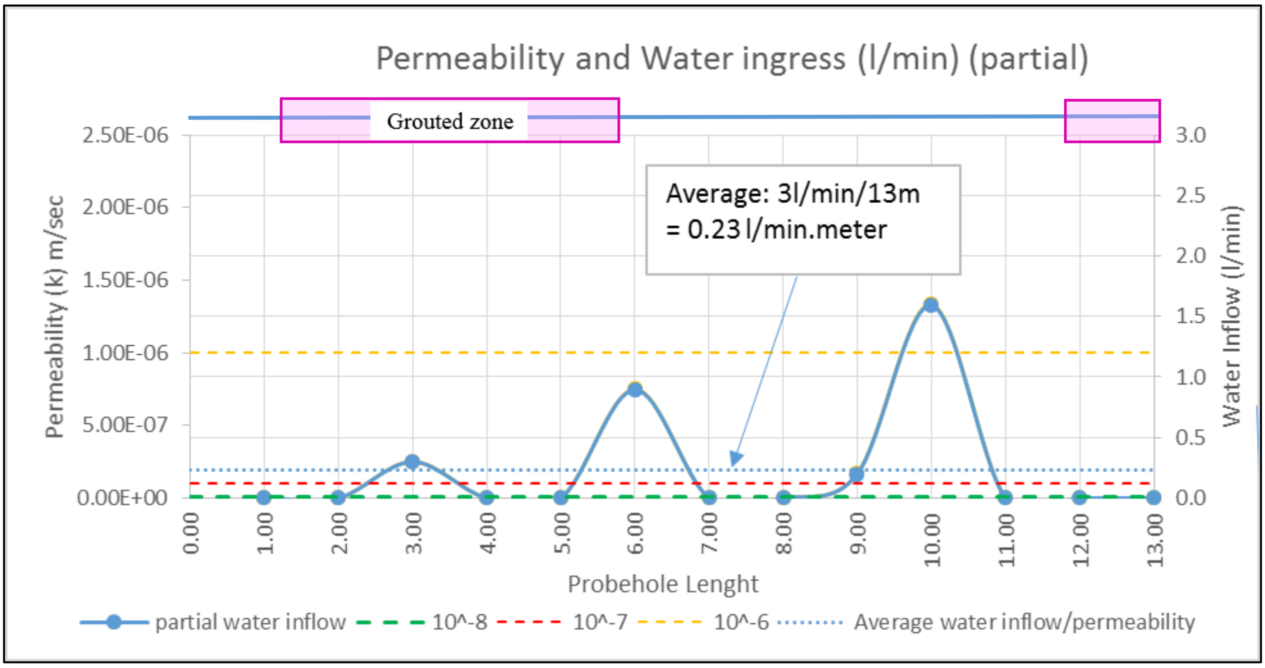

Figure 24: Probehole P2 - Permeability and Water Ingress chart

The chart in Figure 25 shows the difference between the average permeability value and the partial permeability value calculated step by step.

Using the average value of 2.7litres/minute/13metre length is equivalent to 0.21litres/minute/metre, which corresponds to a relatively low permeability of 1.72E-7.

However, if considering the calculation done step by step, the actual permeability as calculated for each individual step sometimes exceed the average value significantly.

As seen from the chart, the permeability for each step beyond 7m depth exceed the average permeability value greatly.

5. Case Study 2: T212 Horizontal Fissure Grouting for Cross Passage 17

Fissure Rock Grouting is the injection of grout into rock to reduce the permeability of the rock. Therefore, it applies to those grades of weathered rock which derive their permeability primarily from fissure, and not pore, flow, i.e. weathering grades I, II, III.

5.1 Correlation between Water Packer Test Result and Grout Intake

The specialist contractor proposed to execute a Lugeon test for every drilled hole prior to grouting, in order to measure the Lugeon Value and determine the type of grout mix to be used (OPC or Microfine Cement).

Lugeon value	Lu≦10	10<LU≦50	50<Lu
Initial mix (C:W)	1:4 (MFC)	1:4 (OPC)	1:2 (OPC)

The following chart in Figure 26 shows a correlation by the tested Lugeon value (normalized per meter of drill hole) versus the grout intake of each hole.

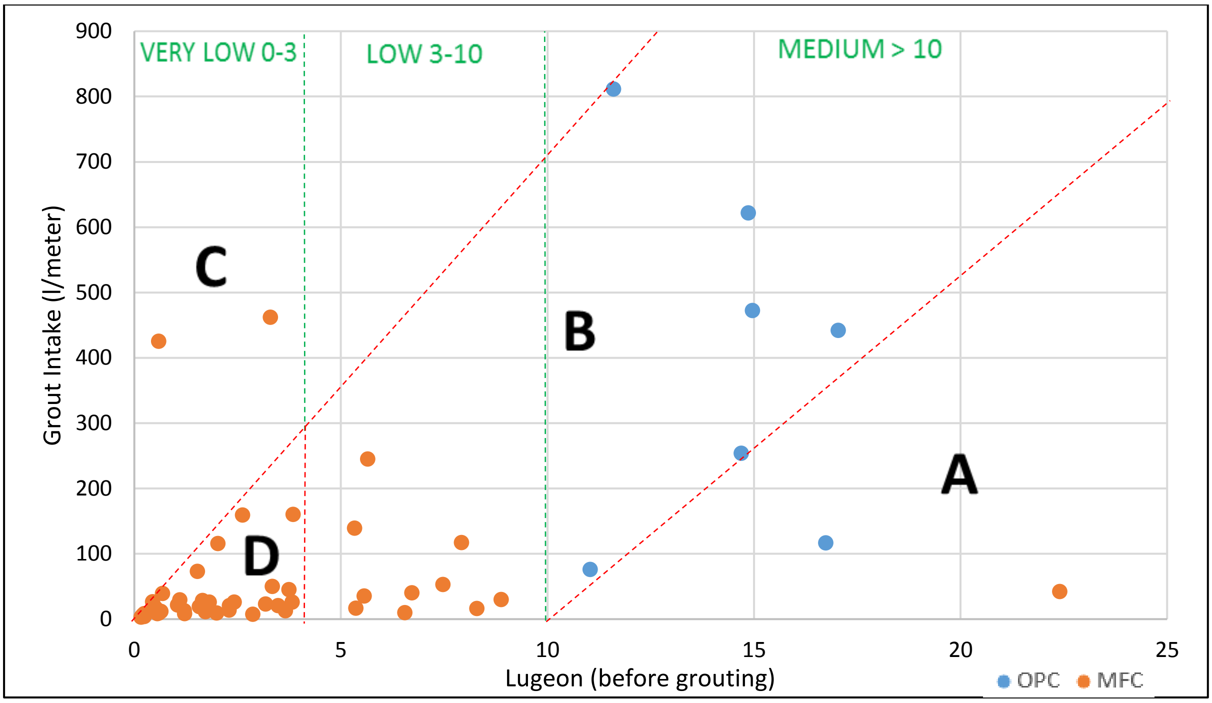

Figure 25: Graph of Grout Intake (Ordinary Portland Cement and Microfine Cement) VS pre-grout Lugeon value

From the chart above, the results can be classified into four (4) zones which can be used to explain the correlations between Lugeon test and grout intake:

Zone "A": High Lugeon value, but low grout intake: water can pass through the rock fissures, however the grout is unable too. This could be defined as High Permeability, but low groutability.

For one of the grout point (22.4, 42.5), the low grouting intake is present despite the use (as per record) of Microfine Cement

Zone "B": Proportional ratio: medium to high Lugeon, medium to high intake. Show grouting is required.

Zone "C": Low Lugeon value, but high grout intake: excessive pressure used, maybe hydro-fracturing. Fissure size increased resulting in higher grout intake

Zone "D": Low Lugeon, Low Intake: As expected. It defines a range where grouting might not be required (if specific criteria are met).

Based on the above analysis, the majority of the grouting is within zones B & D and only 4 out of 54 points could be consider as abnormal grout result.

5.2 Determination of Allowable Flow Rate of Water Seepage

5.2.1 Impact of hydrostatic pressure

Probe holes are generally done in order to verify the effectiveness of the grouting.

By measuring the actual water inflow it is possible to back calculate the rock mass permeability, thus verify if the specific criteria (generally given by the designer) are met.

The specialist contractor in T212 used the following formula for the determination of the Allowable water flow for a 45mm probe hole and a target permeability of 1.5E-07:

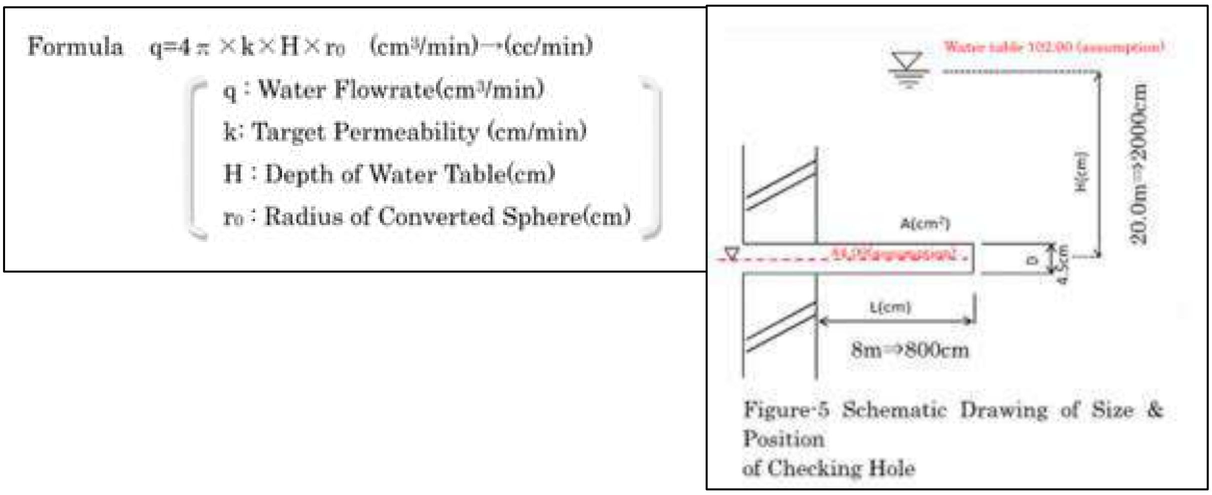

Figure 26: Formula for the determination of the allowable flow rate for a given permeability "k"

As seen from the formula, the impact of the Water Table depth is an important factor. This has been graphically presented in the following chart:

Figure 28 indicates the permeability on a log scale, and shows the calculated allowable water inflow to be measured by probe holes (as a grout execution or grout verification criteria) using 2 different depths from the water tables (hydrostatic pressures).

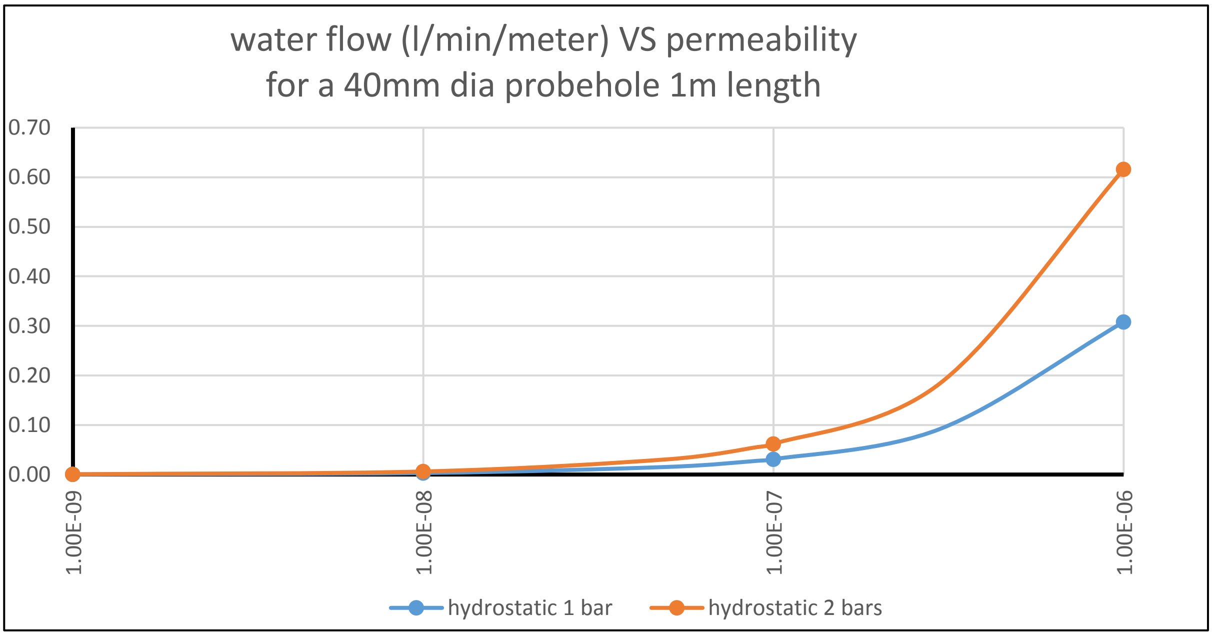

Figure 27: Graph of Water Ingress against Permeability for 1bar and 2 bar hydrostatic pressure

While the difference might not be so significant for very low permeability values, it becomes more significant at permeability greater than 10^-07.

5.2.2 <u>Formula for the determination of allowable water ingress</u>

As described in paragraph 7.1, the formula used by the specialist subcontractor for the determination of the allowable water inflow is:

$$q(1) = 4\,\pi k H r_0$$

In this equation, the surface area of the probehole include both the perimeter one that the face. The ratio of face area over perimeter area will decrease as the length of probehole increases.

Using probehole measurement is relatively common and similar approached have been used in many tunnelling projects. Other formulas have also been used, either for determination of allowable water ingress for a certain (k) value, or to back calculate the hydraulic conductivity "k" based on a measured water inflow (Xu, Z. et al. 2015), or to determine the expected water quantity during a mined tunnel excavation (Yi, K.H. et al. 2015)

The following formula based on Goodman equation (Yi, K.H. et al. 2015) can be used to determine allowable water inflow. In the formula, "z" represent the distance from tunnel centre line to the surface and "h_1" the level of the water table in respect to the surface.

$$q(2) = \frac{2\pi k(z + h_1)}{2.3\ln(^{2z}/_{r})}$$

During the construction of the Jurong Rock Cavern projects, the water flow "q" measured from probeholes was used to estimate to rock mass hydraulic conductivity. The equation used to calculate the hydraulic conductivity is based on Goodman at al 1965 and Fernandez 1994, as reported by Xu, Z. et al. (2015). In the formula, "L" represent to probehole length, H represent the hydraulic head and r' represent the probehole radius.

$$k = \frac{2.3q}{2\pi kLH} log\_10(\frac{L}{r'})$$

The formula can be rearranged to calculate the allowable water inflow based on a certain value of hydraulic conductivity (k).

$$q(3) = \frac{2\pi kLH}{2.3 \log_{10}\frac{L}{r'}}$$

A comparison has been done of the different formulas, for a 40mm probehole, considering a hydraulic head (H) equal to 20m, and using a target permeability of 1.5E-07.

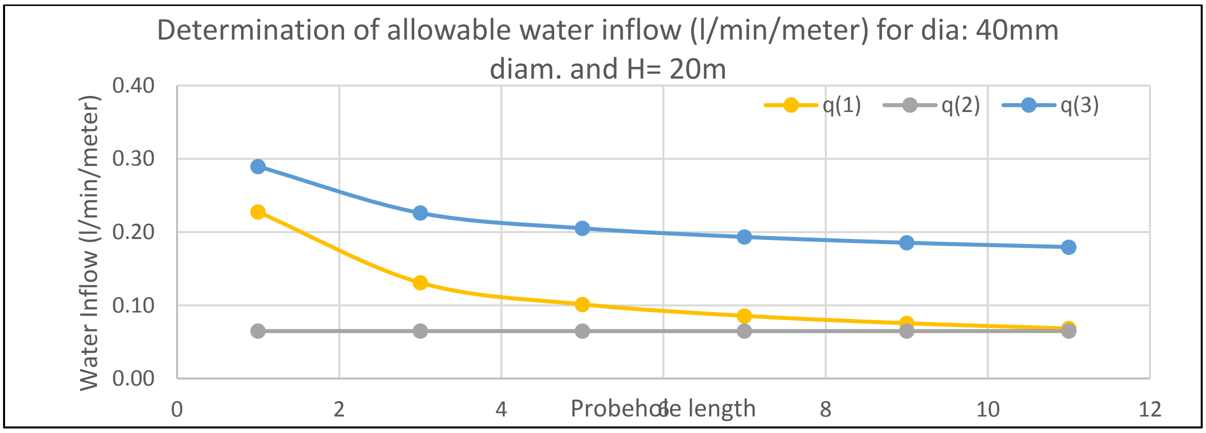

Figure 28: Comparison of formula for the determination of allowable water inflow

It can be seen that the formula been used in TELC1C2 (q1) would allow higher inflow at the beginning of the borehole (taking into account the face area and the formula approach), and after some distance the value would stabilize and get close to the values calculated based on

Goodman q(2). The values calculated by q(3) are higher (an higher water inflow would be allowed for same value of the rest of the criteria.

6. Conclusions

The construction of Cross Passages by mining method is generally considered a high risk activity. When horizontal grouting is the only feasible solution for ground improvement, there will be additional risks and challenges. For TELC1 and C2, 10 out of 34 CPs adopted the horizontal grouting method for ground improvement. Therefore, it is vital to ensure the quality of the ground improvement executed for safe excavation.

Some of those challenges have been addressed by the innovative horizontal grouting done in TELC1 and C2.

- With adequate equipment and logistic, it is possible to execute horizontal grouting from the bored tunnels concurrently to bored tunneling.
- Installing additional grout sockets on the segments allows grouting to be carried out from within the tunnels, and also allows greater extent in the geometrical coverage for the grouting.
- Using a custom-made working platform for horizontal grouting allows the execution of grouting to be done concurrently with bored tunnel excavation works.

From the actual grout analysis, the following deductions can be made:

- The termination grouting criteria set were based on the grouting specialist's past experience and their rule of thumb. The termination criteria by volume for the grout intake in soil could be further improved and be more specific with respect to the actual ground conditions. This can be seen from the case study, whereby the actual grout intake ranged from 3% to 30% for T207 Adit Tunnel.
- Using average water inflow to back calculate soil permeability could be misleading as the permeability might vary along the length of a probehole. The permeability shall be back calculate in short steps (i.e. 1 meter)
- A relationship between pre-grouting Lugeon Value and grout intake can be established. It could help to identify abnormal grouting. Since the graph formulated was based on single CP, data are deem as not sufficient to establish a reliable range, but this can be further developed with more data from other grouting works.
- When determining the allowable water inflow, it is important to remember that this value is dependent (proportionally) to the value of the hydrostatic pressure above the tunnel.

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