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Selection & Performance of TBM in Karstic Limestone SMART Case

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Abstract

The implementation of SMART Project poses challenges with exceptional features which require a methodical risk analysis. These challenges include the large drilling diameter of 13.25m, karstic limestone bedrock, low overburden of 10m~20m, a considerable tunnel length of 12,000m, traversing beneath urban infrastructures, building foundations, and under ground water table. The city centre has a large number of ex-mining areas mainly consisting of heterogeneous loose soil over the limestone.

Two no of 13.25m diameter Mixshield TBM have been commissioned to start tunneling from about mid-way of the whole alignment; one is the North Drive while the other is the South Drive.

The North Drive has completed 115 no of rings while the South Drive has just commenced tunneling.

This paper highlights the following main points:

1. Selection of TBM equipment.
2. Difficulties encountered tunneling in highly variable karstic limestone conditions.
3. Special features in the TBM to handle the geological conditions.
4. The extensive geophysical and soil investigation together with real time instrumentations on site.
5. Evaluation of TBM performances in difficult excavation conditions.
6. Allocation of risk and risk assessment of the project with respect to geological conditions and TBM performance.

1.0 Introduction

1.1 Project Description

The business center of Kuala Lumpur is getting flooded by the Klang River with increasing frequency. The traffic grinds to a standstill; cars are submerged in the underground garages. On the overloaded ring roads, the cars crawl for hours at flood times. (Figure 1) Recent construction on the river banks makes it impossible to widen the flood plains.

The only feasible method of flood control is to tap the water upstream and divert part of the water before it enters the critical area. The problem can be solved by a large, 11,83m inner diameter 9km long tunnel to store and divert the flood water. The flood water is diverted at the confluence of the Klang and Ampang rivers into a holding pond.

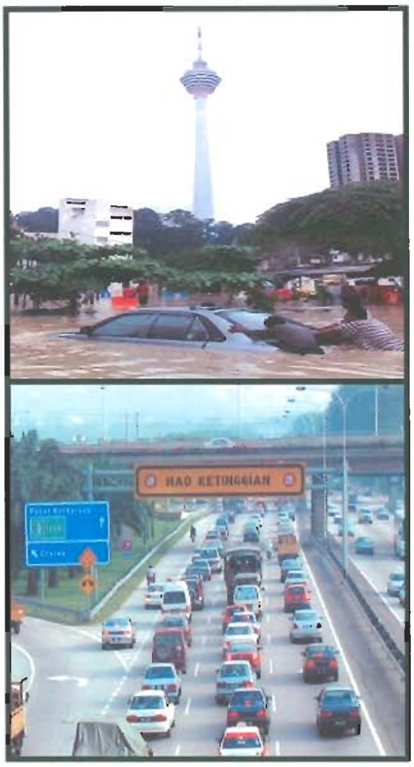


Figure 1 : Flood in the city and traffic at Sungai Besi

From there the water through the tunnel gets into the Taman Desa pond and from there via a box culvert discharges into the Kerayong River. (Figure 2).
The government accepted the innovative proposal of two Malaysian companies, MMC and GAMUDA, to reduce the cost of the scheme for the government. The proposal was to use a central 3km long section of the water tunnel as 2x2 lane road tunnel (with one emergency lane on each level) when the flood diversion is not in operation. The road tunnel would alleviate the congestion of the southern road arteries of the city. The firms proposed to build the road tunnel section at a cost to be recovered by toll collection concession from the government.

1.2 The organization of the SMART Project

The project owner, the Government of Malaysia is represented by JPS, the Drainage and Irrigation Department and by LLM, the Malaysian Highway Authority.
The project consultants are SSP in association with Mott MacDonald.

The project promoter is the MMC - GAMUDA Joint Venture. MMC - GAMUDA Joint Venture also set up the concession holder company called Syarikat Mengurus Air Banjir & Terowong Sdn Bhd (or SMART Sdn Bhd).

The EPC contractor is the MMC - GAMUDA Joint Venture.

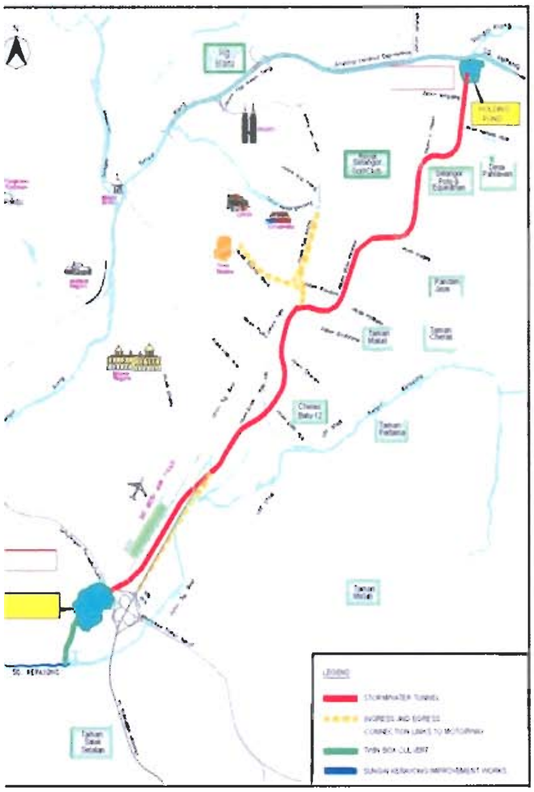


Figure 2: Location of the tunnel in Kuala Lumpur

2.0 Geological investigation and assessment

2.1 Engineering geology profile

The tunnel transverses the Kuala Lumpur limestone formation at shallow depth (see Figure 3). The mature karstic formation is covered by loose silty sand, peat or, at some places, mine tailings, the remnants of the extensive tin mining in the region.

The groundwater table is 1.5-2.0m below the surface. The permeability of the rock is generally low. Drastic differences are expected in karstic areas or at fissure zones.(see Figure 4).

The tunnel from north to south runs in alluvium for about 2,5kms. Mixed face conditions are expected for 0.7km, then with the exception of short mixed face sections, the tunnel transverses limestone. The last 200 m is in residual

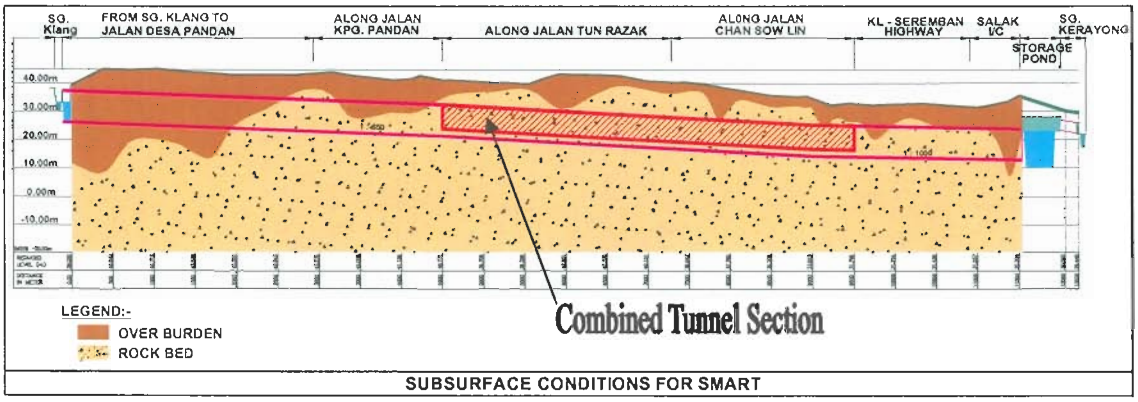


Figure 3: Subsurface conditions for the SMART Tunnel

The quaternary alluvial deposit is generally 4-5m thick; however at karstic areas the unpredictable rockhead may suddenly drop 20-30m. The mean UCS value is 50 MPa; the maximum value is 120 MPa, not very abrasive. The average "Q" value is 22.

Figure 4: Exposed karstic rockhead at a tin mine

soils of granite in the Kenny Hill Formation. The full cover of the tunnel ranges between 0,8-1,8 diameters. Typically in rock the cover is expected to be 3-7m.

The area is very sensitive to groundwater drawdown. The reduction of groundwater level is known to trigger sinkhole incidents in karstic areas, sometimes in considerable distance from excavations. The alluvial cover produces differential settlements in proportion to the thickness of the cover on the undulating rockhead. Hence only excavation methods preventing the drawdown of the groundwater may be selected.

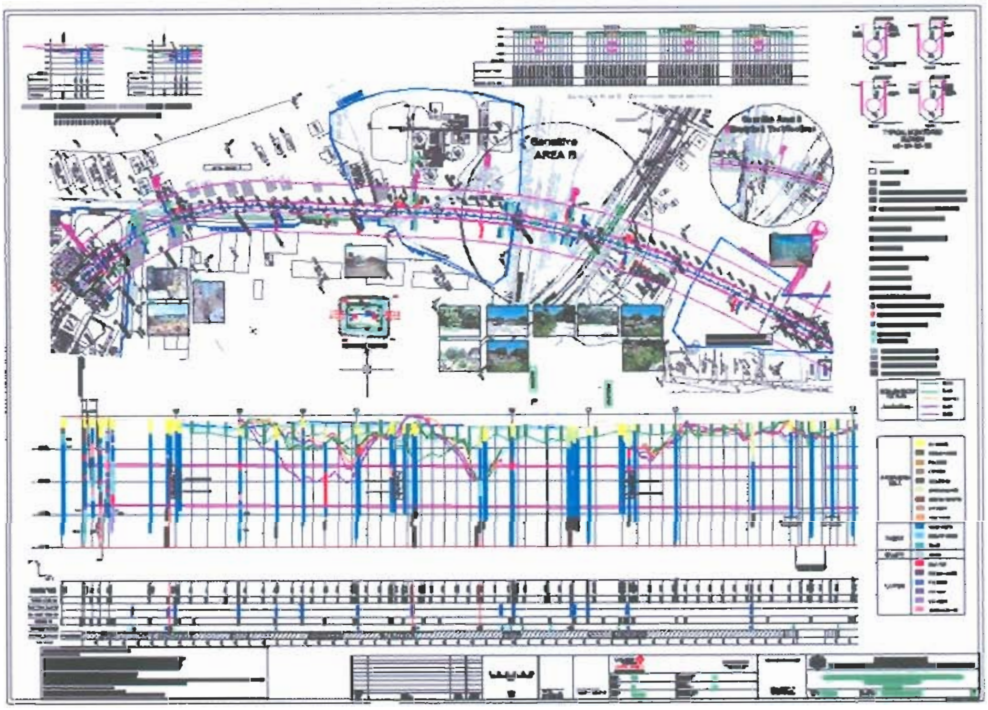


Figure 5: Geological Plot of Rock Profile and Location of Cavities

2.2 Soil Investigation

Even though there was soil investigation carried out to determine the profile of the rock face, it is found to be inadequate to evaluate and understand better the highly variable karstic limestone so as to preempt the ground conditions as far as possible. The following additional soil investigations were carried out:

a) Three stages of soil investigation cumulating to more than 334 no of bore holes over 12 km of length. Sample of a section of geological profile plot with rock profile and location of cavities is depicted in Figure 5.

b) Microgravity Survey conducted over sections where there is significant drop in rock head and presence of cavities.

c) With the above data superimposed further tests such as Resistivity Tests and Seismic Tests are being carried out. Such tests cover nearly 50 % of the entire alignment.

d) Based on combined results and field judgments, Sensitive regions with urban infrastructures such as highways, railway lines, existing bridges and adjacent buildings were identified.

e) These Sensitive regions have intensive instrumentations coverage as well as ground treatments to stabilize the ground where the TBM transverses. In total there are 1300 no of instrumentations on site (see Figure 6).

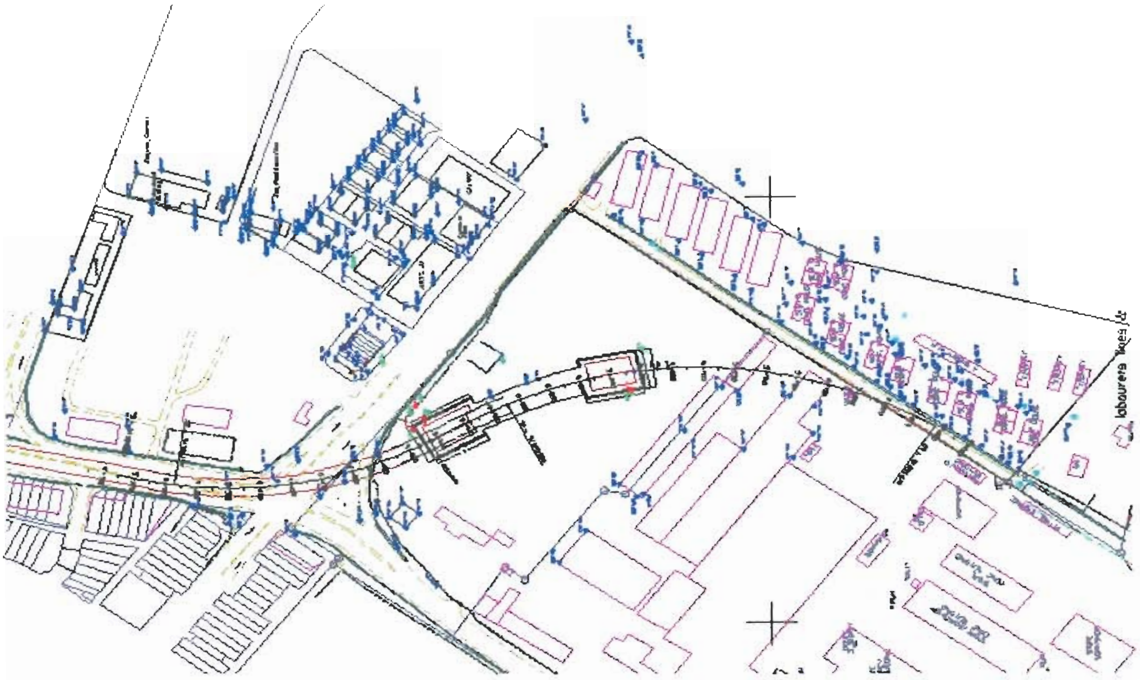


Figure 6 : Instrumentation of north Drive After NVS

f) Focus is still ongoing on the available data and attempting to narrow down the locations of possible cavities, especially the unfilled cavities which poses high risk in the Sensitive zones.

3.0 Geological Risk sharing model between Client and Contractor

The risk sharing between the contractor and client is based on the FIDIC Red Book. Foreseen risk at the time of signing the contract is taken by the contractor. Any unforeseen risk is by the client. All geological mapping data is continuously made available to the contractor. This limits the risk to the contractor for unforeseen circumstances such as loose excavated funnels or columns of undetected fillings.

4.0 Selection of type of TBM machine

Mixshield TBM is necessary for tunneling below water table and passing through karstic nature of the ground condition.

4.1 Criteria of selection of TBM supplier

The selection of the TBM supplier involved the following criteria:

a) The alignment had very tight radius of 250m from the land acquisition point of view. The tunnel alignment had to be under road reserve as far as possible.

b) The overburden is shallow with only 10m to 20m cover.

c) Air bubble based control system to control face support pressure in order to prevent triggering of sinkholes incidents.

d) The machines have to work in predominantly limestone environment. Several sections are expected to have either filled karstic caverns or sudden drops of rockhead.Both machines have to be able to work in mixed face conditions.

4.2 The Tunnel Boring Machines/Special Features

Two identical 13,25 m diameter Mixshields were purchased from Herrenknecht, Germany. The first TBM was delivered within 12 months and the second machine within 14 months of order. The cutterhead configuration selected was for mixed face conditions. The double rotational head had to be able to effectively excavate medium rock and soft soil or mixed face conditions.

Special emphasis was placed on the spherical main bearings. It allowed the cutterhead to tilt in the direction of the curve to negotiated, thereby reducing the difference of ram loads on the segment ring face. The cutterhead had also to be shoved out by a maximum of 400 mm through the drive unit housing. (See Figure 7) This feature allowed the pull-back of the head for cutter change and inspection in rock face conditions.

The machine is equipped with two air locks and a smaller material lock to facilitate near continous compressed air work to change tools on the cutterhead.
The machines are equipped with two probe drilling rigs and a seismic ground/rock detection system to investigate conditions ahead of the machines.

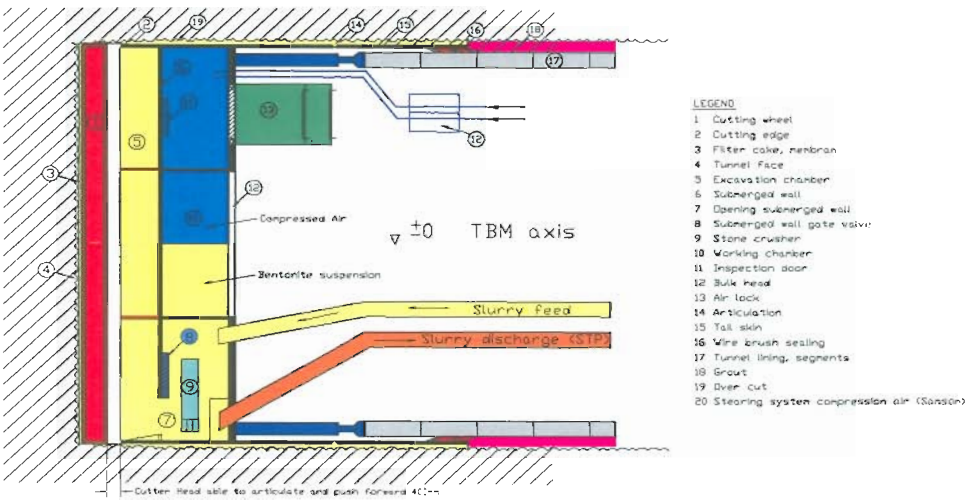


Figure 7 : Major Component of Mix Shield TBM

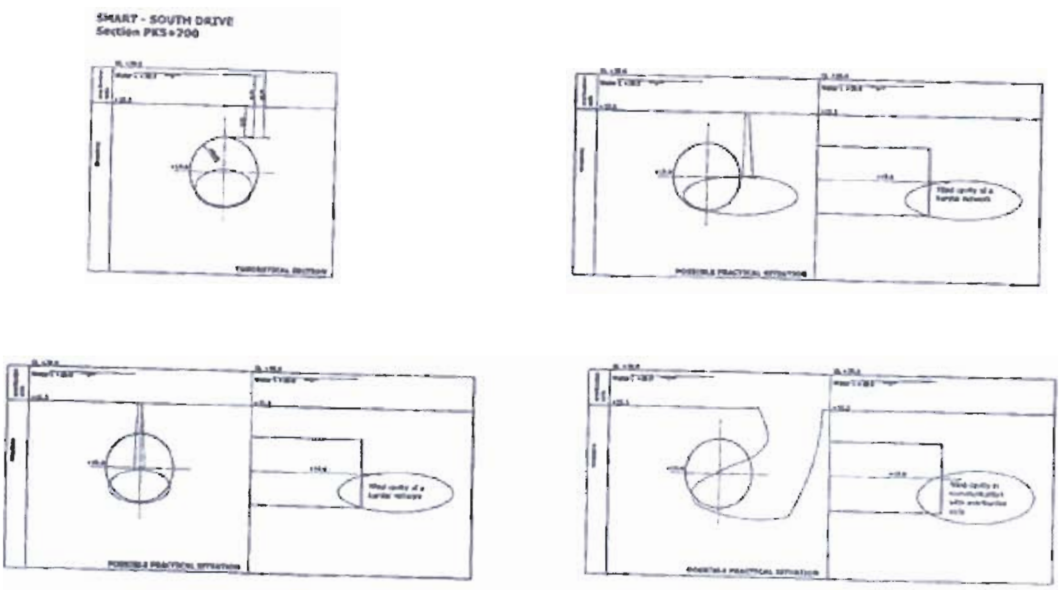


Figure 8 : Scenarios of cavities formation

5.0 Technical and practical countermeasure in the case of difficult excavation conditions

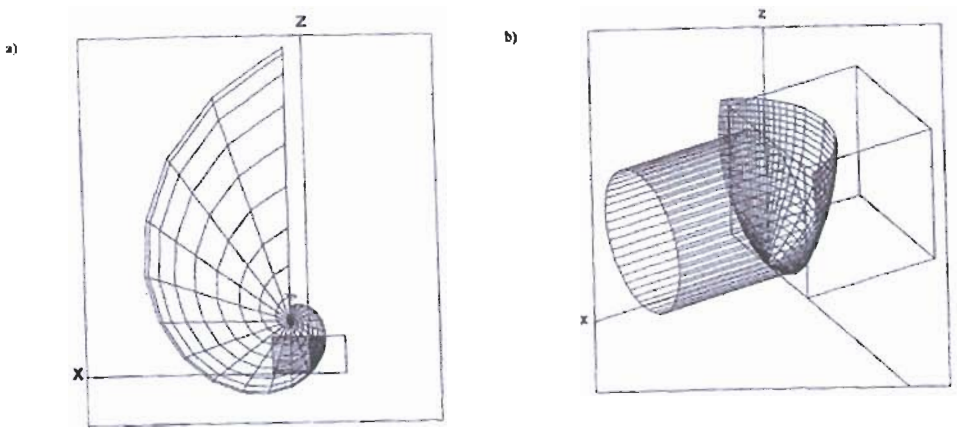
Difficult excavation by the TBM was envisaged due to the potential risk of settlements, existence of karstic limestone and ground cavities. Loss of bentonite would lead to collapse of ground surface, tunnel face, surface heaving and bentonite intrusion to ground surface.

In order to overcome the potential risks and mitigate the loss of bentonite, there are four Technical countermeasures and five Practical countermeasures described below:

5.1 Technical countermeasures

5.1.1 Confinement pressure was computed for various scenarios of cavities formation in terms of size and location in front of drive face (see Figure 8) using Mohkam Model (See Figure 9).

5.1.2 Specifying correct TBM parameters for each of the following scenarios i.e. tunneling through homogeneous ground condition, mixed ground conditions (i.e. rock and alluvium), interface conditions and ground cavities, (see figure 10).



- Figure 9 : MohKam's Failure Plane
- Spiral logarithmic
- a) Global Surface, longitudinal view
- b) Failure surface in front of the excavation face

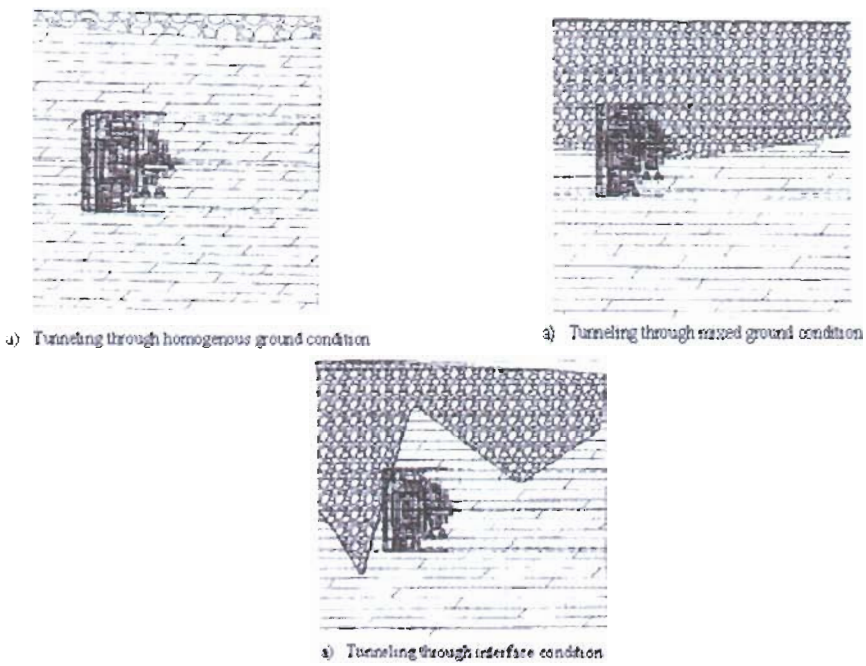


Figure 10 : 3 types of ground conditions during tunneling

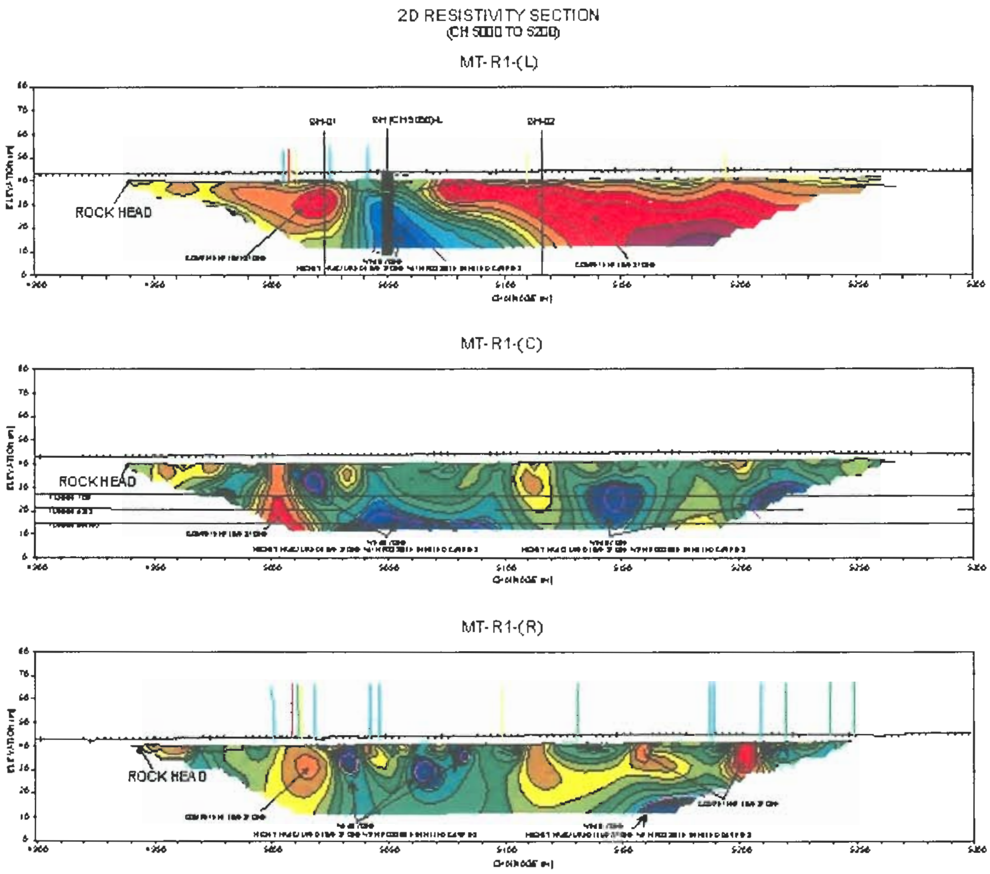


Figure 11 : 2D Resistivity Imanage Between Ch5000 and Ch5200

5.1.3 Extensive site investigations involving geophysical methods, boreholes, piezometers etc. Geophysical surveys have been calibrated and correlated to SI results and used to cover areas between SI boreholes. This provides the coverage to anticipate possible cavities ahead of the TBM drive. Attached is a sample of results showing cavities with low density portrayed with different color using Resistivity and Seismic Survey (see Figure 11 and 12).

5.1.4 Real time settlement monitoring on the surface to mitigate any surface settlement or blow up situation by controlling the face pressure during excavation in various ground condition.

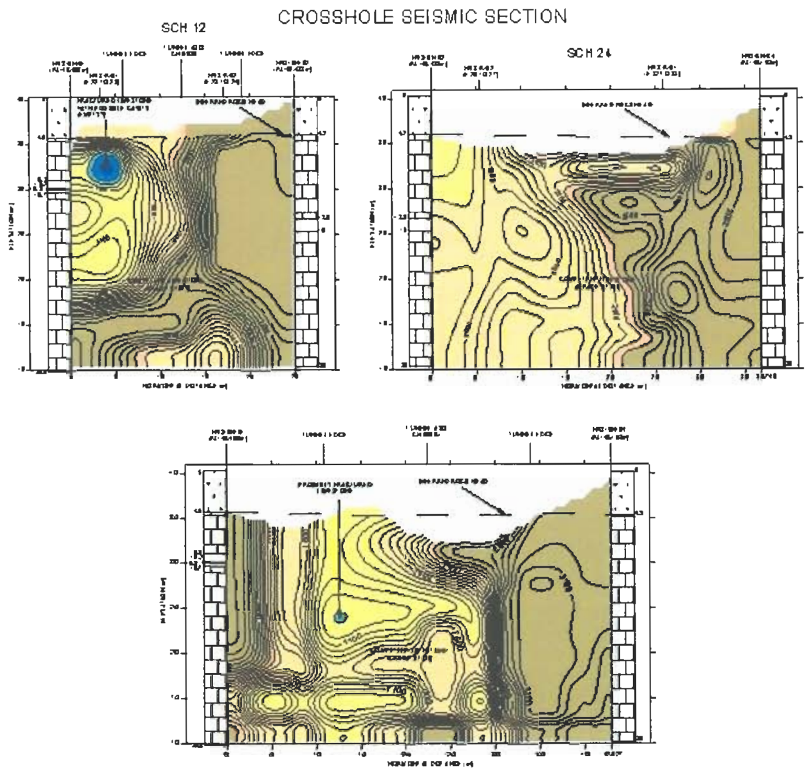


Figure 12 : Crosshole Seismic Tomograph Image On The South Face of North Ventilation Shaft

5.2 Practical Countermeasures

5.2.1 TBM probe drilling to reconfirm 40m section in front of TBM face and to check if there is any cavities at the invert of face. (see Figure 13)

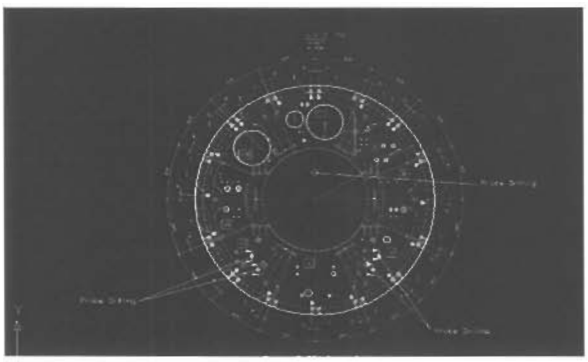
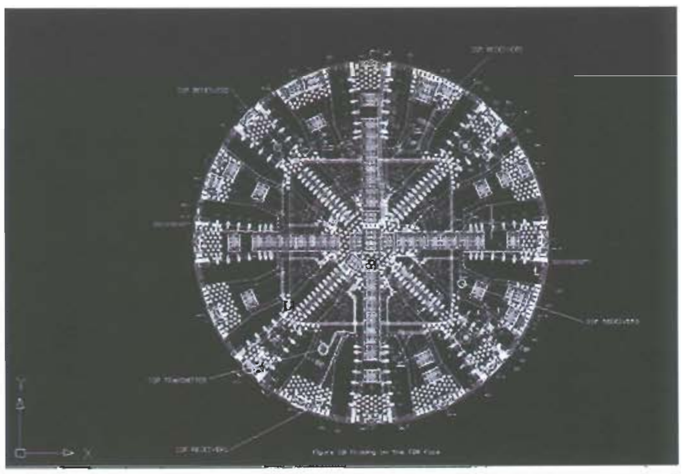


Figure 13 : TBM Probe Drilling

Figure 14 : Probing on the TBM face



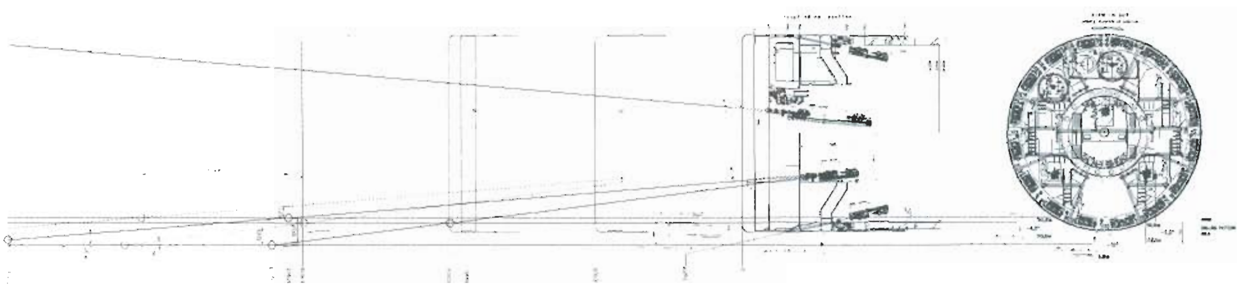


Figure 15 : TBM Grout Tube Grouting Instrument of TBM

5.2.2 Seismic probing which identifies area of different densities in front of TBM face (see Figure 14) and cavities will show up as different color contours. The interpretations still require correlations to develop further understanding.

5.2.3 Adjustment of slurry composition and slurry volume to compensate face loss.

5.2.4 At the sensitive zones, drilling and grouting from the ground surface ahead of TBM using three different types of grouting namely compensation grouting, compaction grouting and rock fissure grouting works. These grouting works differ in sequence of works and grout mix.

5.2.5 The three types of grouting can be carried out from within the TBM though grouting from the surface offers cost and scheduling advantages.(see Figure 15)

6.0 Evaluation of the TBM performances in case of difficult excavation conditions

For the North Drive TBM, currently a total of 115 rings had been completed.

TBM has crossed from full rock condition to mix faced as depicted in the longitudinal plot showing TBM progressing with face pressure and key parameters over varying soil conditions see Figure 16.

The face pressure or confinement pressure plot (see Figure 17) over the 83 rings shows that the pressure values are about 2 bar which corresponds to the calculated pressures shown in Figure 16. The actual settlement is about 40mm below the calculated value of 50mm. There was no blow up nor serious settlement at the surface. This indicates that the face pressure has successfully supported mix faced condition.

As for the South Drive TBM, currently the first permanent ring has been completed.

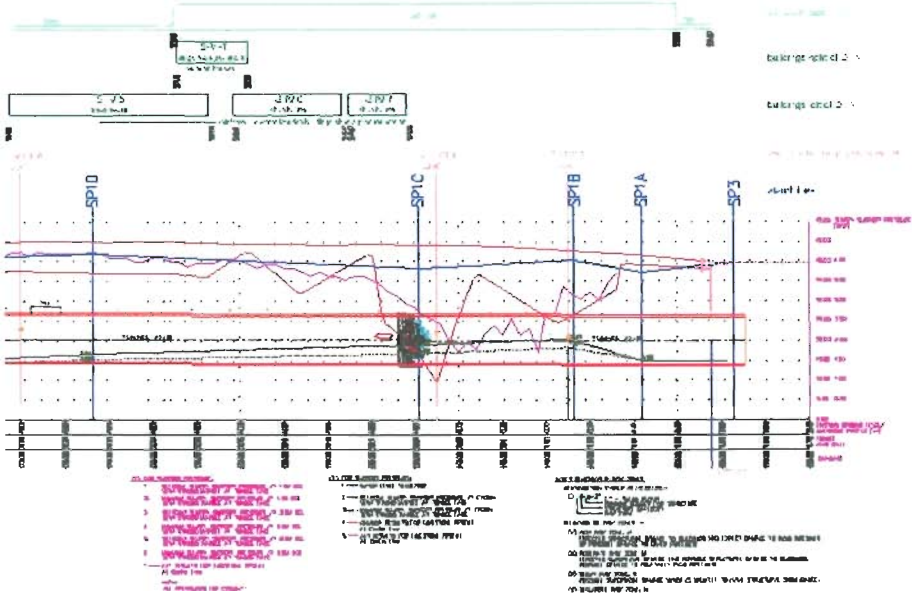


Figure 16: Confinement Pressure and Key Parameters over soil conditions.

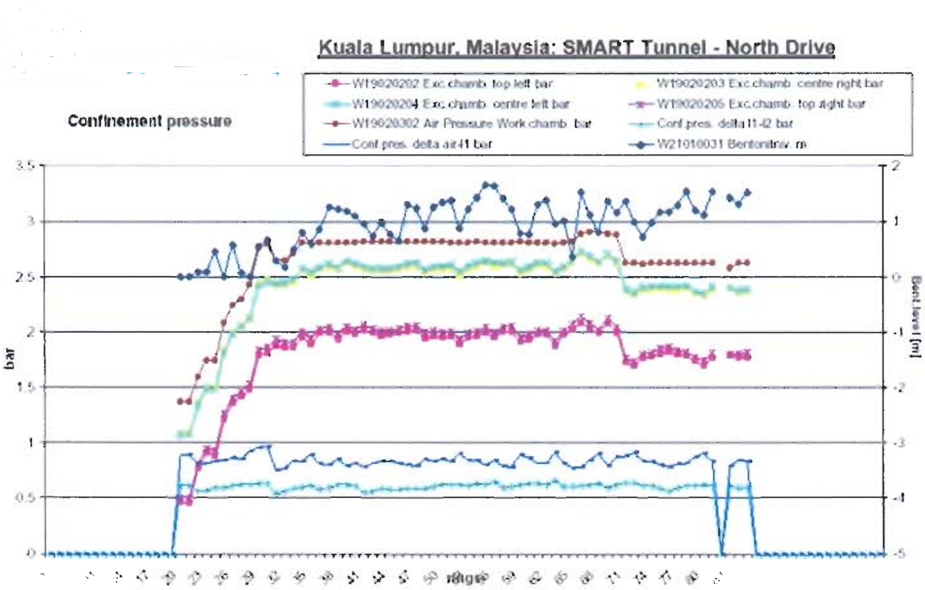


Figure 17 : Confinement Pressure plot over 83 rings of North Drive

7.0 Evaluation of TBM performances and innovation against further errors

In karstic limestone conditions, the face pressure (confinement pressure) is considered critical. In the principle of equilibrium of hydrostatic and earth pressures with the face pressure using slurry support pressure, as long as the cavities in front of the TBM are filled with water or soil, the equilibrium will be maintained. As such, encountering filled cavities at the front face has controllable risk.

The determination of face pressure support and the subsequent observation during tunneling shows that if there is no loss of slurry and no heave on the surface then the face pressure calculated reflects the actual pressure requirement.

Cavities which are not filled or partially filled pose a serious risk. Such cavities will potentially cause the loss of slurry pressure and could lead to face collapse and ground settlement. The contingency is that the Separation Plant has 1000 m3 of fresh bentonite and 1000m3 of used bentonite available for filling any unfilled cavities. Where water filled cavities are encountered, the most likely event is the reduction of confinement pressure. This only constitutes a risk if at the same time the rockhead is dropped and the crown is in soft ground. Under these conditions, density of slurry can be increased to a maximum of 13 kN/m^3.

Similar risks can occur if the TBM hits a loosely filled well or funnel of loose material like in mining areas. In such events, the TBM will have to reduce face pressure to hydrostatic pressure and grout from the surface.

8.0 Capacity of Slurry Separation Plant together with other logistic support in relation to TBM performances

In determining the capacity of separation plant, the speed of spoil removal requires careful evaluation especially in a site where there is space constraint and continual traffic congestion which would stop the movements of the disposal trucks within the site. The other main consideration is the speed of advancement of TBM in rock which is a function of combined output of the TBM and its entire support logistics i.e. separation plant, grout plant, segment feeder etc. (See Figure 18) In the SMART case, the combined output has been specified at 10m of tunneling per day.

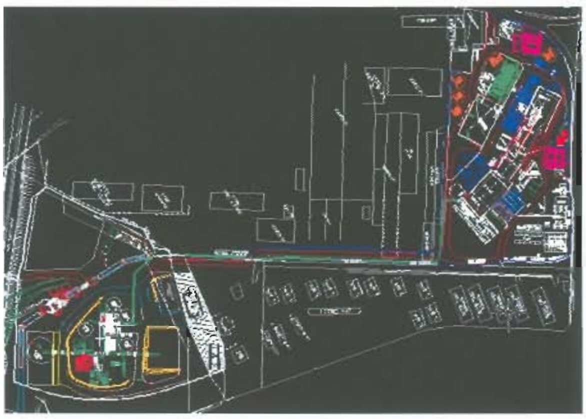


Fig 18: Logistics Arrangement of Shaft and Separation Area for Launching of 2 TBM

9.0 The influence of the management of the personnel on the Learning Curve and on TBM

The main factors for management to consider are as follows:

a) The chain of command is linear .Any one component stops, the whole process stops. As such, a competent and directive head is required and supported by a compliant tunnel crew.

b) This tunnel crew will be supported by competent and consultative technical staff.

c) Cross-functional competency is essential for mitigating risks faced by the entire team.

d) The team work spirit is equally essential for a collective tunneling effort.

Conclusion:

The selection of type of TBM together with the support logistics is correct given that the TBM has performed its required functions and the steps taken to mitigate geological risks have so far proved adequate.