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Considerations of Deep Excavation in Kenny Hill and Kuala Lumpur Limestone Formations at the KVMRT

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ABSTRACT: This paper presents the basic design considerations for deep retaining system for the construction of deep underground stations in a highly built up area within the Kuala Lumpur Limestone and Kenny Hill Formations. The KVMRT underground stations design criteria and design objectives are briefly discussed. The selection of type of retaining systems, strutting system, construction sequences and design parameters are elaborated with respect to a design and built contract. Some of the challenges encountered in design and construction as well as the instrumented performances of the retaining system are presented. Among the standout challenges are proximity to old and sensitive buildings, removal of pre-existing structural obstructions, multi-stage constructions, groundwater drawdown control and settlement mitigation measures. The measures adopted to address some of the above challenges are briefly discussed

KEYWORDS: Deep excavation, Retaining system, Kenny-Hill Formation, Limestone Formation, Settlement mitigations

1. INTRODUCTION

This paper presents the basic design considerations for deep retaining system for the construction of deep underground stations in a highly built up area within the Kuala Lumpur Limestone and Kenny Hill Formations from the perspective of design and build contractor.

It should be noted that the views expressed herein are those of the authors and not necessarily represent the views of MMC Gamuda KVMRT (T) Sdn Bhd (MGKT) and some of the facts have been simplified and may not be use out of context other than for the usage as a paper for this Journal.

The underground package of the Klang Valley Mass Rail Transit (KVMRT) project traverse approximately 9.3 km underground and passes through 7 underground stations, 2 intervention shafts, 1 escape shaft and 3 launch shafts. Four of the underground stations are underlain by the Kenny Hill Formation while the remaining 3 are underlain by the Kuala Lumpur limestone formation. The excavation depth of these stations varies from approximately 25 m depth to 44.5 m depth. The location and names of the underground stations are shown in Figure 1 below.

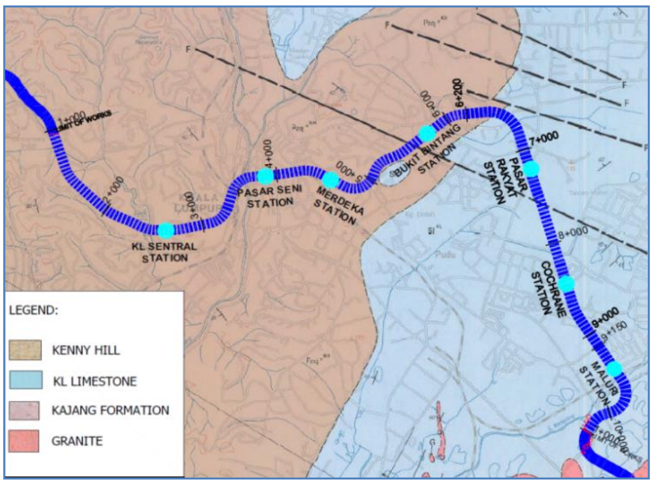

Figure 1 KVMRT alignment with underground stations superimposed on the Geology Map of Kuala Lumpur (1993)

2. GENERAL GEOLOGY AND SUBSOIL CONDITIONS

2.1 General Geology

From the general geological map of Map of Kuala Lumpur, the 149 KVMRT tender boreholes and an additional 63 boreholes carried out by MGKT during the tender stage; it was found that the site from Ch 1+048 to Ch 6+310 (approx. 5.262 km) is underlain by the Kenny Hill Formation and the remaining Ch 6+310 to Ch 10+307 (approx. 3.997 km) is underlained by the KL Limestone formation. Four of the underground stations namely KL Sentral, Pasar Seni, Merdeka and Bukit Bintang Station are within the Kenny Hill formation whilst the remaining 3, namely Pasar Rakyat, Cochrane and Maluri Station are within the KL Limestone formation.

The subsurface investigation boreholes carried out, shows that the Kenny Hill Formation along the alignment to be a sequence of interbedded sandstone, siltstone and shales / mudstone overlain by stiff over-consolidated soils predominately of sandy silty Clay and Silty Sand. At certain stretches, the formation have undergone metamorphic event resulting in changes of sandstone / siltstones to quartzite and schist/phyllite respectively. The variability of depth of the hard soil and depth of metamorphosed sedimentary rock for each station present unique design and construction challenges for the selection of the optimal type deep retaining wall systems.

From the Soil Investigation information available, the Kuala Lumpur Limestone Formation along the alignment is composed of fine to coarse grained, white to grey, predominantly recrystallised limestone, with local development of dolomitic limestone and dolomite with irregular level of rock below the alluvium and containing numerous voids and solution channels. These features are consistent with Extreme Karst classification according to Waltham & Fookes (2003). This Karstic features create many problems for the design and construction of deep underground retaining structures because the irregular rock levels and the unknown rock quality necessitated the selection of flexible and robust retaining systems with variable wall depth and thickness coupled with a grouting cut off system to prevent inflows and sinkholes during excavation.

2.2 Subsurface conditions

Presented below are the specific subsurface profile for each of the underground station which is summarised and then presented in a simplified graphic form.

2.3 KL Sentral Station

The Kenny Hill formation here consists of Medium to Stiff overburden soil with SPT ‘N’ values of between 4 to 20 within the first 5 m below ground level. Immediately underlying this layer was hard soil having SPT ‘N’ value greater than 100. Beyond 15m depth, some of the boreholes have recorded highly-fractured quartzite with some sandstone with RQD ranging from 0% to 30%, whilst the other remaining boreholes having 'N' values greater than 200 respectively. The uniaxial compressive strength (UCS) for the rock samples ranges from 13.1 MPa to 16.2 MPa, with an average of 14.8 MPa.

Figures 2A and 2B are the respective KL Sentral Station borehole layout and a section of the simplified subsurface profile.

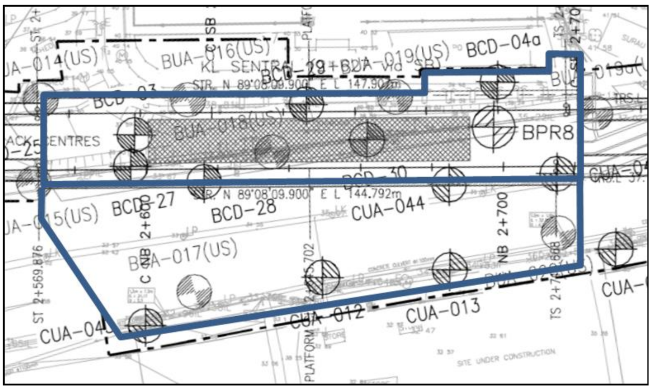

Figure 2A KL Sentral Station Borehole layout

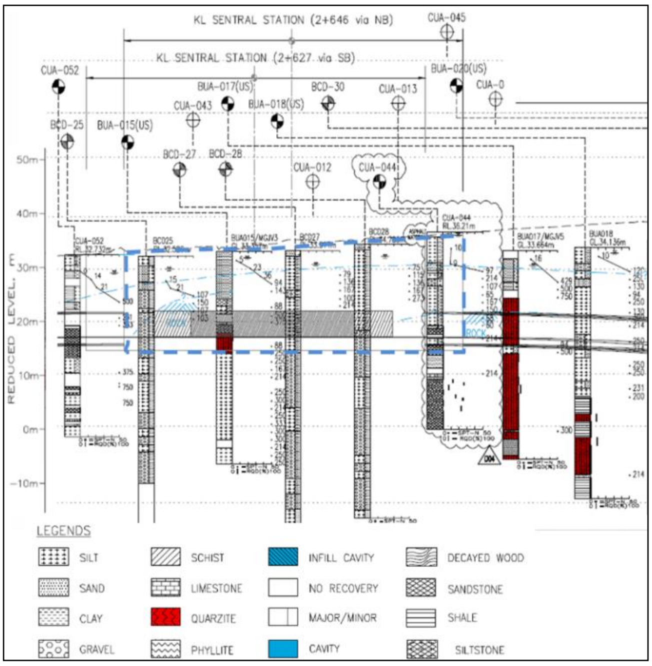

Figure 2B KL Sentral Station's simplified subsurface profile

2.4 Pasar Seni Station

Located just beside the Klang River bank, the Kenny Hill formation at this station consists of Soft to Medium Stiff overburden soil with SPT values of N between 2 to 8 within the first 6 m depth. Immediately underlying this soil layer was very hard material having SPT 'N' value greater than 100. Beyond 10m depth, highly fractured Grade III and Grade IV Siltstone with pockets of Schist with typical RQD of between 0 to 20% was encountered in some of the boreholes whilst the remaining boreholes have SPT 'N' values exceeding 250 respectively. The uniaxial compressive strength for the rock samples here range from 3.8 MPa to 28.7 MPa, with an average of 12.3 MPa.

Figures 3A and 3B are the respective Pasar Seni Station borehole layout and a section of the simplified subsurface profile.

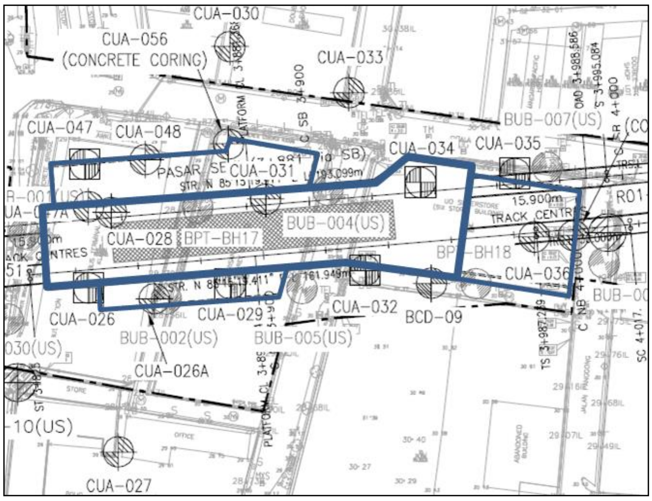

Figure 3A Pasar Seni Station Borehole layout

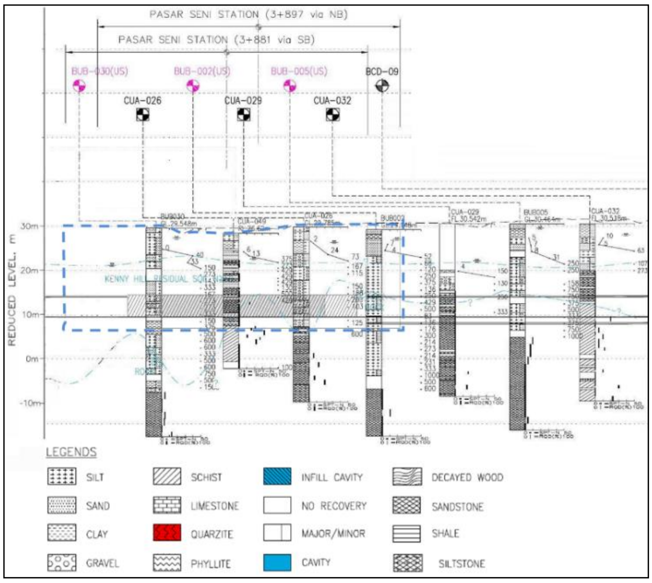

Figure 3B Pasar Seni Station's simplified subsurface profile

2.5 Merdeka Station

Located on a Hilly terrain, the top overburden soil here as expected mostly starts with Stiff to Very Stiff consistency with SPT 'N' between 8 to 20 within the first 7.5 m. The SPT 'N' values gradually increase to mostly between 20 to 50 from 7.5m to 20m depth. Beyond 20m depth, the soil becomes mostly hard having SPT 'N' values generally greater than 100.

Figure 4A and Figure 4B below are the Merdeka Station boreholes layout and a section of the station's simplified subsurface profile.

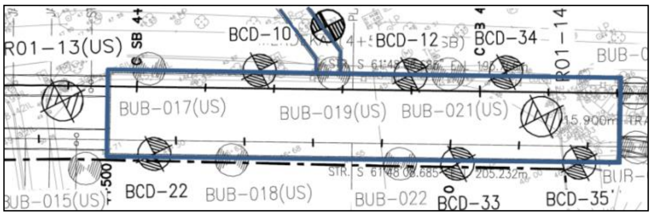

Figure 4A Merdeka Station Borehole layout

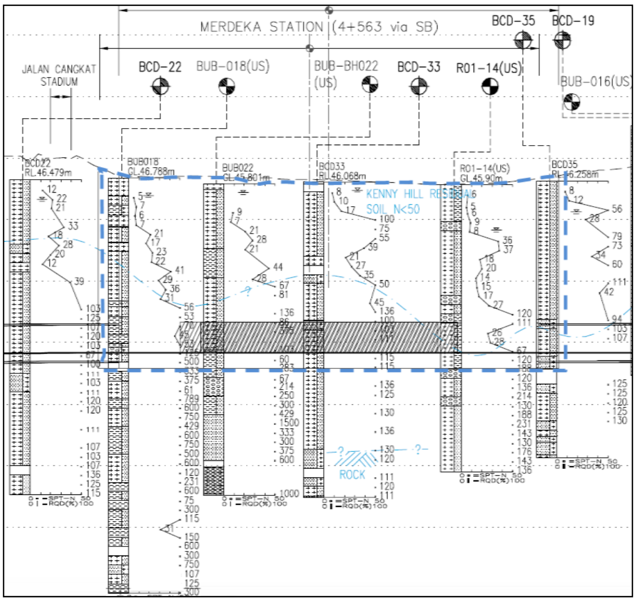

Figure 4B Merdeka Station's simplified subsurface profile

2.6 Bukit Bintang Station

Located approximately 250 m from the limestone geological boundary zone, the overburden Kenny Hill soil here has a lower SPT than the other stations at similar depth. The overburden soil SPT 'N' values are generally between 5 to 15 within the first 20 m depth. The SPT 'N' values gradually increases ranging between 15 to 25 up to 30 m depth. Beyond 30 m, the soil becomes mostly hard having SPT 'N' value greater than 100. Bedrock was not encountered within any of the boreholes.

Figures 5A and 5B are the respective Bukit Bintang Station borehole layout and a section of the station's simplified subsurface profile.

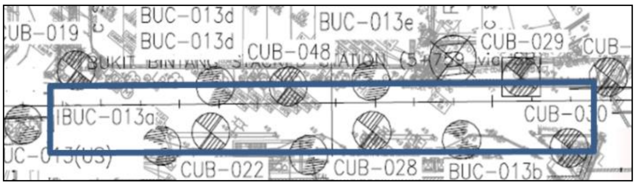

Figure 5A Bukit Bintang Station Borehole layout

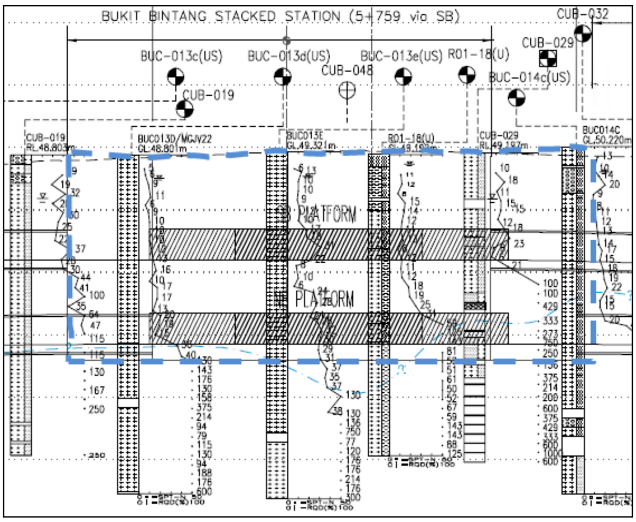

Figure 5B Bukit Bintang Station's simplified subsurface profile

2.7 Pasar Rakyat Station

Located after the geological interface boundary, the station is located in Kuala Lumpur Limestone formation. The limestone bedrock here is overlain by shallow overburden of approximately 5 m to 10 m with localised deeper solution feature at the centre (West wall) of the station. The upper 2 m are predominantly a sandy gravely silt or clay and may represent shallow made ground. Beyond 2 m, the overburden consist loose sandy ground. Locally within the solution feature, the depth to the valley of the limestone is in excess of 35 m below existing ground level.

It is expected there would be solution features trending from the North West to South East of the station as in the geology map there is a fault line is located nearby at CH7035 which is a sinistral strike-slip fault which trends in the NW-SE direction. The trend of the solution features means it will pass obliquely across the station box. These features may extend beyond the boundary of the station at the same bearing and will be present outside of the station. Solution affected rock including moderately weathered rock and smaller scale karstic features may be present for 20 m to 25 m adjacent to the main feature. Several of the boreholes have encountered cavities nearby this solution features. Rock overhangs, pinnacles, localised cavities and irregular rock head levels and variable infill material (including voids) are expected to be associated with solution feature.

Most of Limestone rock away from the solution features is typically in an unweathered state pale grey crystalline marble. The limestone is generally slightly weathered immediately below the overlying material. The UCS values of the limestone cores ranges between 48.35 to 107.1 MPa.

Figures 6A and 6B are the respective Pasar Rakyat Station boreholes layout and a section of the simplified subsurface profile.

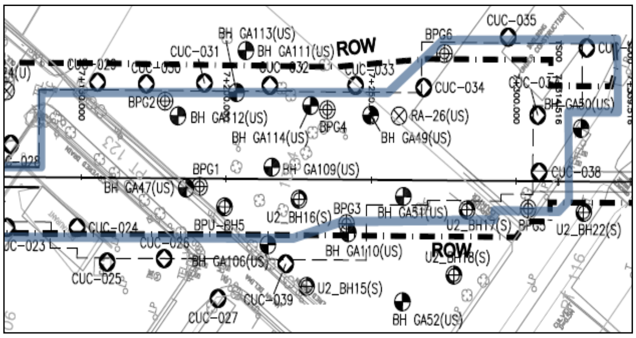

Figure 6A Pasar Rakyat Station Borehole layout

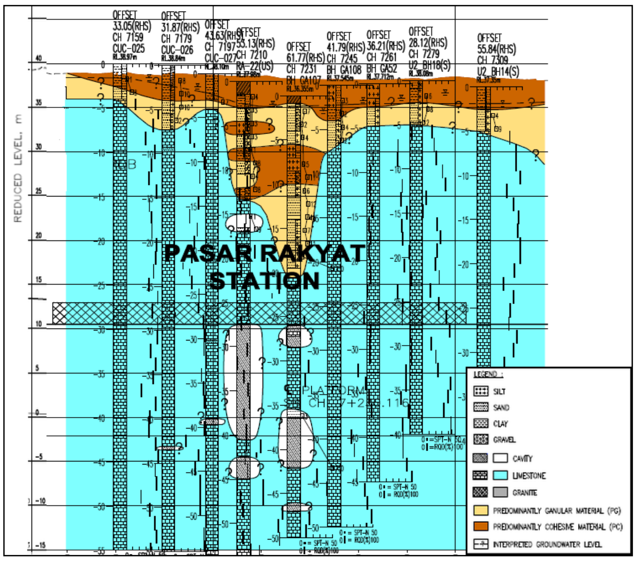

Figure 6B Pasar Rakyat Station's simplified subsurface profile

2.8 Cochrane Station

The Limestone bedrock here is very shallow, generally between 2 to 5 m and is overlain by loose sandy ground.

The station is located far from the known fault line and from geological interface zone. From the results of the boreholes carried out, the rock head here is less undulating suggesting the occurrence of less weathered Kuala Lumpur Limestone. Only few of boreholes have noticeable solution features. The UCS values of the limestone cores ranges between 11.3 to 104 MPa.

Figures 7A and 7B are the respective Cochrane Station borehole layout and a section of the simplified subsurface profile.

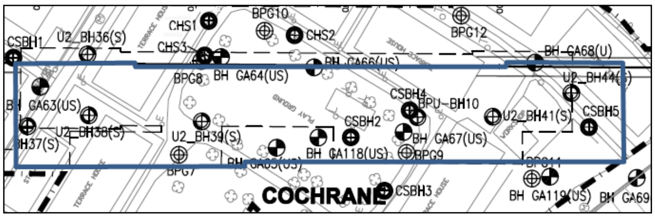

Figure 7A Cochrane Station Borehole layout

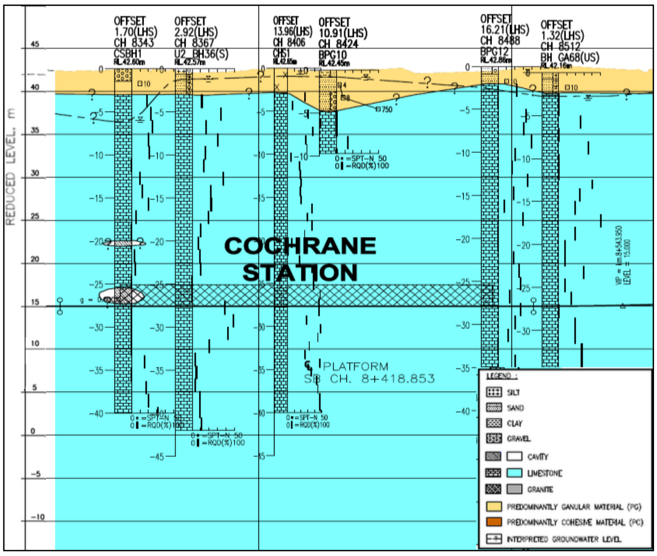

Figure 7B Cochrane Station's simplified subsurface profile

2.9 Maluri Station

Located in the KL Limestone Formation near to the Sg. Kerayong river channel and not too far away from the interface with the Granitic formation, the Limestone bedrock here is irregular, varying between 4 to 18 m and overlain by loose sandy ground.

There is no known fault line nearby here but a few granitic intrusions into the Limestone bedrock appear not too far away in the borehole carried out along the adjacent Peel Road north of the Site. Some of boreholes have noticeable solution features up to 5 to 8 m in size. Rock quality in the station box also appears to be quite variable. The UCS values of the limestone cores ranges between 31.6 to 96.1 MPa.

Figures 8A and 8B are the respective Maluri Station boreholes layout and a section of the simplified subsurface profile.

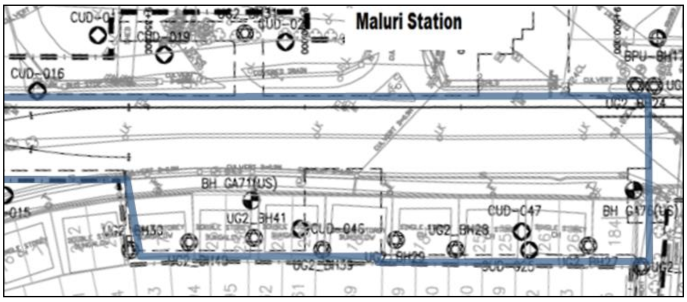

Figure 8A Maluri Station Borehole layout

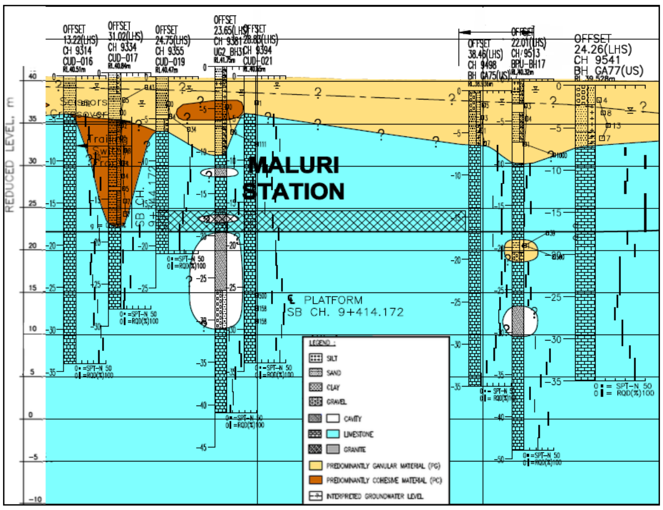

Figure 8B Maluri Simplified Subsurface profile

3. DESCRIPTION OF THE UNDERGROUND STATIONS

In addition to the subsurface conditions, the selection of types of retaining system and thicknesses depend on the dimension and excavation sequence of the stations. Briefly, below are description of each of the stations and the proposed sequences.

3.1 KL Sentral Station

The station box starts from Ch 2+536 to Ch 2+702 and is approximately 166 m long. This tiered two-level station will be excavated as a top-down construction. The existing ground level here varies from RL 33.9 to RL 40 m with an average level of RL 37.2 m. The design rail level for this station is RL +17.0 m and the base of excavation is RL +14.48 m. Figure 9 shows the schematic cross section of the station.

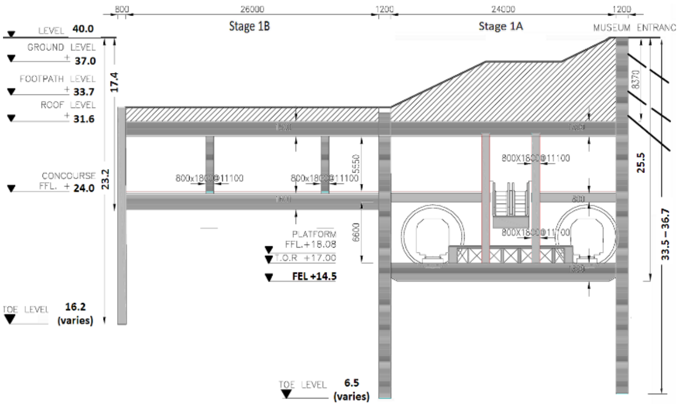

Figure 9 KL Sentral Station Cross Section

3.2 Pasar Seni Station

The station box starts from Ch 3+800 to Ch 3+961 and is approximately 161 m long. This three-level station will be excavated as a semi-top-down construction. I.e. Bottom up excavation sequence until the proposed concourse level at RL 21.6 m then Top-down until the base of excavation. The existing ground level at Pasar Seni Station is approximately RL 30 m. The design rail level for this station is RL 9.47 m and the base of excavation is at RL +6.535 m. Figure 10 shows the schematic cross section of the station.

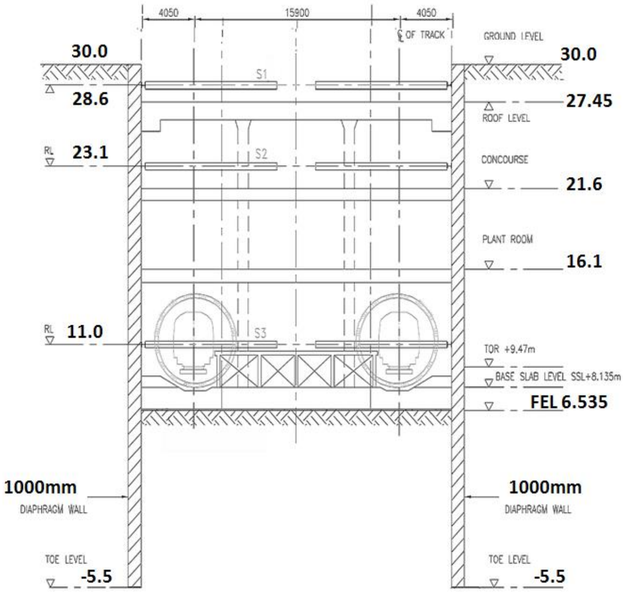

Figure 10 Pasar Seni Station Cross Section

3.3 Merdeka Station

The Merdeka station box starts from Ch 4+480 to Ch 4+628 and is approximately 148 m long. This four-level station will be excavated in a Bottom-Up sequence. The existing ground level at Merdeka Station is approximately at RL 46.5 m. The design rail level for this station is at RL 18.32 m and the base of excavation is at RL +15.385 m. Figure 11 shows the schematic cross section of the station.

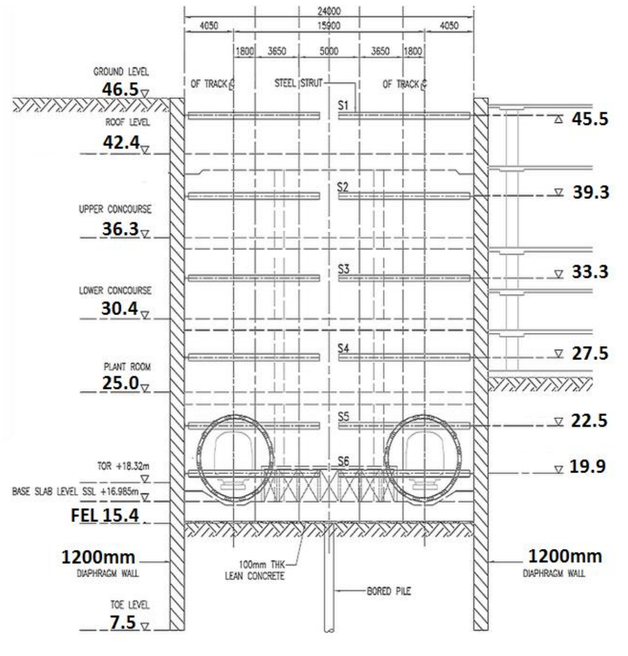

Figure 11 Merdeka Station Cross Section

3.4 Bukit Bintang Station

The station box starts from Ch 5+670 to Ch 5+820 and is approximately 150 m long. This four-level station will be excavated in a Top-Down sequence. The existing ground level at Bukit Bintang station is approximately RL 49.0 m. The design rail level for bottom north-bound line at this station is at RL 18.5 m whilst the base of excavation is RL +15.98 m. Figure 12 shows the schematic cross section of the station.

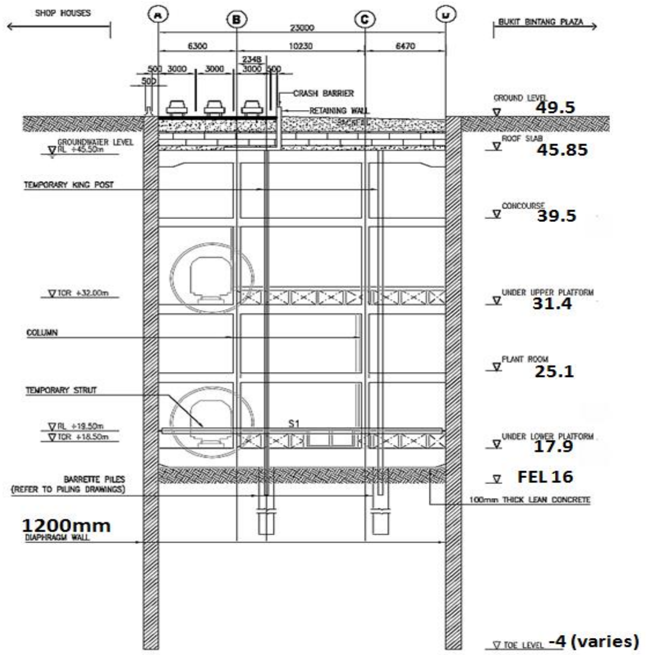

Figure 12 Bukit Bintang Cross Section

3.5 Pasar Rakyat Station

The station box starts from Ch 7+100 to Ch 7+293 and at approximately 193 m long, is the longest, largest and deepest of the underground station. This five-level station will be excavated in a Bottom-Up sequence. The existing ground level at Pasar Rakyat Station is approximately RL 38.0 m. The design rail levels for the southbound and northbound track are at RL 10.5 and RL -2.11 m and the base of excavation is RL -6.5 m. Figure 13 shows the schematic cross section of the station.

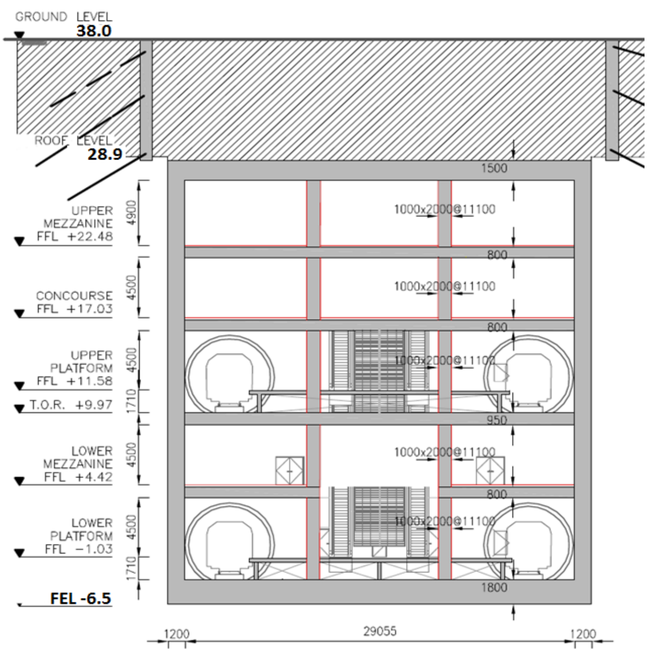

Figure 13 Pasar Rakyat Cross Section

3.6 Cochrane Station

The station box starts from Ch 8+342 to Ch 8+518 and is approximately 176 m long. This three-level station will be excavated in a Bottom-Up sequence and will be used as a launch shaft for the tunnel boring machines. The existing ground level at Cochrane Station is approximately at RL 42.5 m. The design rail level for the southbound and northbound track is RL 14.37 m and the base of excavation is RL 12.57 m. Figure 14 shows the schematic cross section of the station.

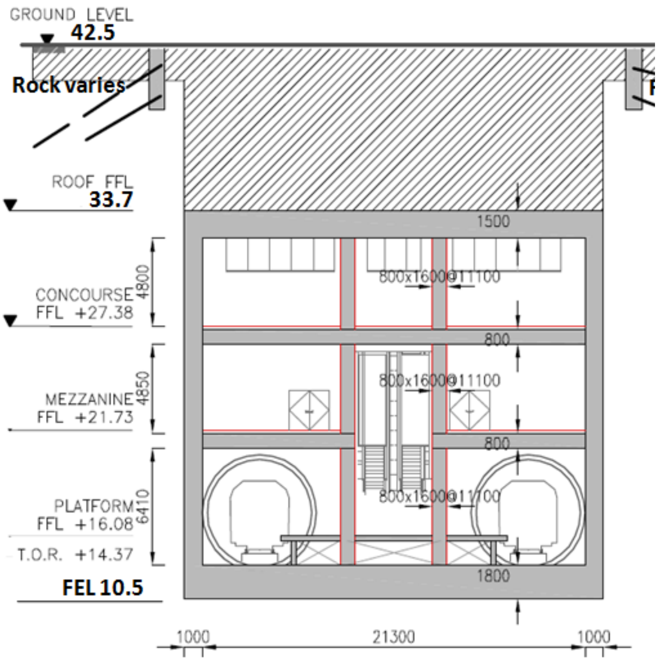

Figure 14 Cochrane Cross Section

3.7 Maluri Station

The station box starts from Ch 9+370 to Ch 9+523 and is approximately 153 m long. This three-level station will be excavated in a Bottom-Up sequence. The existing ground level at Maluri Station is approximately RL 42.5 m. The design rail level for the southbound and northbound track is RL 18.37 m and the base of excavation is RL 16.57 m. Figure 15 shows the schematic cross section of the station.

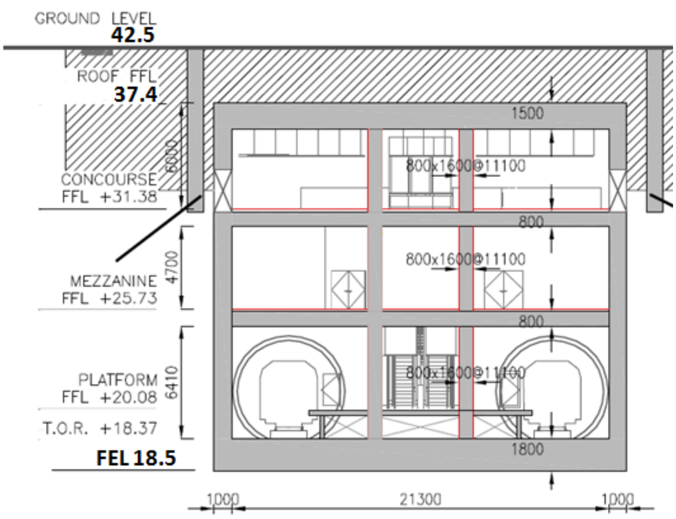

Figure 15 Maluri Cross Section

4. UNDERGROUND STATIONS RETAINING SYSTEM DESIGN CRITERIA AND OBJECTIVES

The KVMRT tender spelled out the underground temporary retaining design criteria in detail because the underground stations are constructed nearby to sensitive buildings in a densely populated urban environment. The objectives of the prescriptive design criteria are to reduce risks and ensure best practices are adhered to. Listed below are some of the salient design criteria.

1. Maximum ground water draw down allowed is limited to maximum of 1m below the baseline groundwater table and ground water recharging is to be considered whenever this limit is exceeded.
2. Settlement shall be limited such that any individual structure or building shall not suffer damage greater than "Slight" as defined by the Building and Structure Damage Classification, i.e. Max Tensile Strain between 0.075 to 0.15 (%) (After Burland et al, 1977 and Boscardin and Cording, 1989)
3. Factor of Safety against flotation, F.O.S > 1.10
4. Factor of Safety against Basal heave, F.O.S ≥ 1.2, if moderate conservative values of undrained shear strength are used and where the vertical shear resistance along retained ground shallower than the excavation is ignored.
5. For temporary works and excavation, the possibility of hydraulic uplift is to be assessed. The minimum factor of safety should, F.O.S ≥ 1.2.
6. To prevent failure by piping, the toe of the diaphragm wall is to penetrate to a sufficient depth or to a low permeable layer, such that the vertical seepage exit gradient at the base of the excavation is less than unity.
7. Toe in stability check using method given in the NAVFAC DM7.02 using BS8002 mobilization factors with an overall Factor of Safety of 1.0 shall be adopted. For effective stress parameters, c' and ϕ', the mobilization factor shall be 1.2, and for total stress parameters, cu the mobilization factor shall be 1.5.
8. Table 1 shows the load factors combination adopted for strut design under ultimate limit state condition.

Table 1 Load Factors Combination for Strut Design*

Load Combination	Load Factor				
	Excavation load (Soil+ Groundwater)	Dead load	Live load	Temperature load	Impact load
Normal working condition	1.4	1.4	1.6	1.2	-
One strut failure	1.05	1.05	0.5	-	-
Accidental impact	1.05	1.05	0.5	-	1.05

*Note: 1) Hydrostatic water level is adopted for design.
2) Change in temperature = 10 °C
3) Eccentricity, self-weight and unplanned excavations are to be considered.

Beside the design criteria, Table 2 shows some of the standards / codes of practice used, as applicable. In any other design and built project, other relevant codes of practice and analysis methods can be used subject to acceptance by the Employer's Representative.

Besides the design criteria and code of practices, a comprehensive instrumentation and monitoring scheme is required for all the deep excavation works to monitor the actual behaviour of excavation and to provide an early warning of impending failures, allowing time for safe evacuation of the excavations and time to implement preventive or remedial actions.

In addition, MGKT is expected to engage Contractor Independent Checking Engineer (CICE) to check and certify the design of all major temporary works.

Table 2 Standard / Codes of Practice

Codes/Standards	Descriptions
BS 8004:1986	Code of Practice for Foundations
BS 8002: 1994	Code of Practice for Earth Retaining Structures
BS 6031: 1981	Code of Practice for Earthworks
BS 8006: 1995	Code of Practice for Strengthened/Reinforced Soils & Other Fills
BS 8007: 1987	Design of Concrete Structures for Retaining Aqueous Liquids
BS 8081: 1989	Code of Practice for Ground Anchorages
BS 5930:1999	Code of Practice for Site Investigation
BS 1377:1990	Method of Test for Soils for Civil Engineering Purposes
CIRIA C580 (2003)	Embedded retaining walls - guidance for economic design
BS 6954	Tolerances for Building for the tolerances allowed for in the design of braced excavation works.

5. SELECTION AND CONSTRUCTION CONSIDERATION OF RETAINING AND STRUTTING SYSTEM

From the perspective of a design and built contractor, the criteria for selection of type of retaining system are contingent upon a number of factors such as; design requirement, ground condition, site constraints, environmental impacts, program, construction consideration and cost factors.

Below are listed several common temporary retaining systems for deep excavation in urban environment listed in increasing cost:

i) Open cut / Stabilised Slope (Nails, geotextile, etc.)
ii) Sheet pile walls
iii) Soldier piles and timber laggings
iv) Cement - Soil Mix Walls
v) Contiguous Bored Pile Wall
vi) Secant Pile Walls
vii) Diaphragm Walls

The selection process begin with listing all commonly available types of retaining systems in a matrix/table to check if it can meet the desired factors and requirements and then assessing the merits of the systems in the entirety.

Table 3 is a simplified list of the merit and demerit of each of the retaining system mentioned.

The selection of a suitable type of retaining system for each of the underground station is subjected to the system meeting the followings below:

a) Design requirement - Excavation depth, temporary and permanent loading, building damage categories, Water drawdown, Factor of Safety and etc.
b) Ground conditions - Geology (Formation type, soil type), water table and etc.
c) Site constraints – Site layout, working space limitations of plant and equipment layout, traffic movement and spoilt and material transport and etc. In this project, because of the limited space available; use of different type of retaining systems within the same station is kept to minimise the plants spacing requirements.
d) Environmental impacts – Noise and vibration constraint, water drawdown and settlement, proximity to buildings, working hours allowed and etc. For example, Silent Piler sheet piling has been used near sensitive building.
e) Time and program – The project has a short timeframe ie. 5 years (30/3/2012 to July 2017). Moreover, the time allowed for the retaining and excavation works is between 12 to 24 months. Selection of correct sequence of constructions, i.e. top down, bottom up and the type of strutting types (GA, steel, RC beam) are tied in closely with the project time planning requirements.
f) Construction consideration – Availability of specialist contractors within the planned program timing, availability of construction materials (e.g. D-wall, bored piles and strut sizes), market capacity and technological competency considerations.
g) Cost – The overall cost of retaining systems for this project are evaluated holistically including the impact on time, protection works, risks and public relation considerations and etc.

Table 3 Simplified List of the Merit and Demerit of Retaining System

Retention Type	Merits	Demerit	Remark
Open cut / Stabilised Slope	Cheap, fast and simple	Need additional R.O.W. setback, drawdown groundwater	Often limited excavation up to maximum 2 to 3m depth in urban environment
Sheet pile walls	Cheap, fast and simple. No setback required.	Limited depth due to Sheet pile length and penetration length (often cannot penetrate beyond SPT > 30 to 40 material), Vibration	Limited excavation depth of usually 6m to 8m depth in urban environment
Soldier piles and timber laggings	Fast and simple and relative cheap for deeper excavation. Minimum setback.	Non-water tight and limited depth due to pile and timber size constraints.	Suitable up to 10-12m of excavation when water table is low in cohesive soils.
Cement - Soil Mix Walls	Water tight, simple and fast.	Big machine and plant required, Often designed as gravity wall and need some setback.	Only efficient for approx. 3-6m of excavation. Deeper exaction will be costly.
Contiguous Bored Pile Wall (CBP)	Deeper excavation and can be installed into hard material/rock. Minimum setback.	Big machine and plant required, non-water tight	Suitable for deeper excavation when water table is low.
Secant Pile Wall (SBP)	Deeper excavation can be installed into hard material/rock and is water tight. Minimum setback.	High torque big machine and plant required, Need to overcut to ensure water tightness	Suitable for deeper excavation. Suitable up to maximum of 12-15 of excavation because of inefficiency of overcut at deeper depth.
Diaphragm Wall (D-wall)	Suitable for very deep excavation, can be installed into hard material/rock and is water tight. Minimum setback.	Big machines and plant required. Mobilisation expensive and slow setup.	Suitable for all depth and watertight but only economical in large scale job.

Based on the consideration above, for retaining system in Kenny Hill formation; where deep excavations are planned, with short time duration; Diaphragm wall were selected. However, for some of the Stations' Adits where the excavation depths are shallower and have multiple mobilisation and traffic diversion involved; secant bored piles were used as it more cost effective.

For retaining system within KL Limestone formations; where the retained overburdens are shallower and where wall toe depths are variable due to Karst conditions (i.e. cavity, overhangs, zone valleys) the flexible system of SBP wall were selected because the size and depth of the SBP can varied within short distance.

Table 4 lists down the summary of the seven underground stations and the type of temporary retaining system selected.

Table 4 Summary the Type of Retaining System Selected

Station	Wall Type/ Thickness (m)	Excavation Depth (m)	Wall Depth of Excavation (m bgl)	Remark
KL Sentral	D-wall 1.2 (Station box) 0.8 (Plant room)	21.5-25.2 10.2 (varies)	33.5-36.7 17.5 (varies)	Top-Down
Pasar Seni	D-wall 0.8 (Adit) 1.0 (Station box)	9.3 (varies) 22.8-24.5	19.2 (varies) 30.8-32.8	Semi Top Down
Merdeka	SBP (Adit) 0.88@1.36c/c 1.0@1.6c/c D-wall (Station) 1.2	8.1 (varies) 16.1 -17.5 31.1	11.4(varies) 20.1 - 28.6 39.0 -51.5	Bottom up
Bukit Bintang	D-wall 1.2	33.5	49 – 53.5	Top Down
Pasar Rakyat	SBP 0.88@1.5 c/c 1.18@ 1.8c/c 1.18 & 1.5@1.9 c/c	44.5	Rock levels bgl ≤ 8m ≤ 12m ≤23m	Bottom up
Cochrane	SBP 0.88@1.5 c/c 1.0@ 1.6 c/c	32	Rock levels bgl ≤ 8m to 10m ≤ 10m to 15m	Bottom up
Maluri	SBP 1.0@ 1.6 c/c 1.5@ 2.4c/c	24	Rock levels bgl ≤ 10m to 15m ≤ 16m	Bottom up

6. SOME OF THE CHALLENGES ENCOUNTERED IN DESIGN AND CONSTRUCTION

Some of the challenges encountered in the design and construction of the Diaphragm wall (D-wall) for the Kenny Hill formation and limestone formation are briefly discussed as follows:

For the design for the D-wall for the Kenny Hill formations, the following are planned with ease of construction in mind:

i. **Thickness of D-wall** - The thickness of the D-walls in this project varies from 0.8 to 1.2m. In addition depth of excavation; the thickness of the D-wall in the design is very much influenced by spacing selection and sequence of support used. A shorter support spacing can reduce the overall bending moment of the wall but require more supports level and limits the headroom available for bigger excavation machines. To reduce the thickness of the D-wall, a higher yield Type II deformed reinforcement steel with fy = 500 N/mm^2 was used in most of the wall design. Higher D-wall steel content; typically varying between 2.5 to 4.6% was used, keeping the wall thickness down. However, the higher use of steel content must be balance with the increasing likelihood of honeycombing.

   For example, for the bottom up Merdeka station, D-wall with 1.2m thickness was selected with 6 level of struts spaced at between 3.5m to 6m and steel content varying from 2.5% to 3%. While the top down Bukit Bintang station, D-wall with 1.2m thickness was used with higher steel content of between 3.7% to 4.6% because of the larger unsupported floors span required and poorer soil.

ii. **Panel Width -** D-wall panel width can varies from 2.8m to 6.7m. The consideration of the panel width is very much influence by the trench stability. For Kenny hill, in usually hard and stable soil, panel width can be selected to be wide. However, the width that can be selected is influenced by the steel cage weight that can be easily handled by the craneage at site. For example, for the Merdeka station, Panel size selected is 6.7m width.

iii. **D-wall excavation system -** There are numerous D-wall excavation systems that can be used depending on the time available and efficiency required. E.g. Wire rope grabs, hydraulics grabs and rotary cutters. For excavation efficiency over 25m depth in hard material over SPT 'N' > 50; 'Trench Cutter' or 'Hydrofraise' rotary cutters with reverse circulation are selected. These cutter machines minimise trenching noise, vibration and time in addition to having advantage of steering to maintain the desired verticality.

Some of the challenges encountered during the construction of the D-walls include –

i. Verticality – D-wall verticality is important especially in load bearing D-wall; or where it is located adjacent to tunnel (i.e. excessive deviation may cause it to encroach into the train kinematic envelope). For the Kenny hill formation at in hilly terrain, the verticality of the D-wall can be harder to be maintained especially for deeper excavation and in formation that have folding layers in certain direction. To ensure verticality; properly constructed Guide Wall and ultrasonic 'Koden' testings are employed during the D-wall installation to ensure the wall verticality meet the tolerance of 1(H):200(V) deviation as per the specification. For deeper depth beyond 20m, the use of Hydraulic Clamshell Grab machine should be minimised due to overbreak and verticality issue.

ii. **Trench Collapse** – D-wall Trench collapse although not common in Kenny Hill formation, can be minimised with the use of suitable Polymer and Bentonite mix and by shortening the trenching time. For Kenny Hills, the contractor can sometimes underestimated the amount of fine Silt content generated during trenching which exceed the capacity of a smaller hydrocyclone de-sanding machine and thus affecting the quality of the bentonite and increasing the risk of trench collapse.

iii. **Obstruction and planning** – During the project, there were numerous obstructions and challenges to D-walling works, for examples, limited headroom due to existing monorail rails; existing structures/piles/basement slabs, abandoned ground anchors, in situ utilities (e.g. 132kV TNB cables) and etc. Some of the D-walling machines used are so heavy; that they need proper foundation/temporary platform which was overlooked in some cases. It must be stressed that these challenges must be properly identified and planned in advanced so that the progress can meet the project deadline.

Figures 16 to 19 show some photos of the D-walling works for the KVMRT Underground Stations.

Figure 16 Low Headroom 'Hydrofraise' D-wall machine at Bukit Bintang Station

Figure 17 'Trench Cutter' D-wall machine at Pasar Seni Station sitting on temporary platform.

Figure 18 Pre-cutting of existing basement slab, to enable D-wall work to proceed at Pasar Seni Station

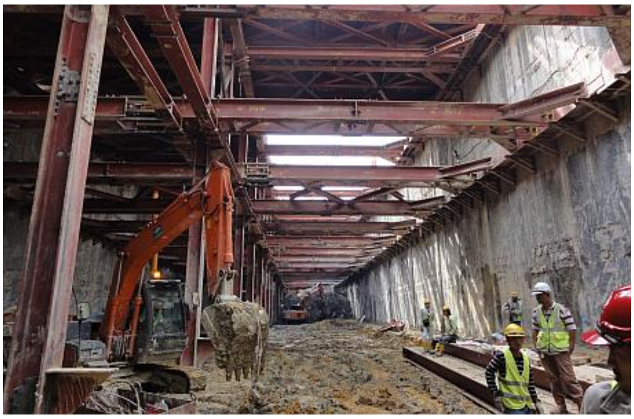

Figure 19 Bottom up excavation in Kenny Hill formation at the Merdeka Station.

For the Secant Bored Piled (SBP) wall in KL Limestone formations; the challenges in design and constructions are discussed below:

i. **Pile size** - The typical pile size selected for the SBP wall design varies from 0.9 to 1.5m. For construction ease, the design selects the common commercially available casing sizes.
ii. **Overcut** – The overcut needed is determined by the verticality tolerance of the pile. For this project a 1(H):100(V) tolerance is specified. Because it is designed as a temporary wall, overcut of 0.1 to 0.2m is generally sufficient for short wall of up to 12m depth.
iii. **Steel content**– Normally the amount of steel content for SBP is control by the spacing of the male piles and the ground anchors spacing. For stations like Pasar Rakyat, the typical steel content for the SBP male reinforced pile varies between 2.5-3%.
iv. **Ground anchors (GA)/struts** – Where space is available, use of temporary ground anchors is preferred to strutting with the objective to keep open spaces for the acceleration of excavation works. The spacing of the GA was designed to enable smooth progress of excavation. I.e. The spacing must not be too close that the excavation works have to wait for the GA installation. The GA spacing recommended ranges from 2.5m to 3.5m.

Some of the challenges encountered during the construction of the SBP include –

i. **Verticality & Overcut –** SBP walls in this project are constructed with guide walls and casings if possible to ensure the out of tolerance verticality and over break or collapse can minimised.
ii. **Rock socket –** The SBP piles are designed to be 'socketed in' certain amount of 'competent rock'. The competent rock is difficult quantified during the bored piling work. In the absence of any guidelines, the Point Load Index, $I_s > 5$ has been proposed for this project as definition of competent bedrock.
iii. **Karst conditions –** Localised solution channels and cavities are sometimes encountered during the drilling work. The bored piling contractors for the job are required to use high torque and fully cased drilling method to minimise the down time due to these Karst features. In addition, the sequences of drilling for these piles are arranged so that no adjacent piles are drilled side by side before the pile concrete is cured.

Figures 20 to 23 show photos of the SBP works for Stations with limestone formation.

Figure 20 SBP Guide wall being prepared prior to drilling works

Figure 21 Boring works for Secant Bored Piles wall

Figure 22 Installation of Temporary Ground Anchors for the SBP wall.

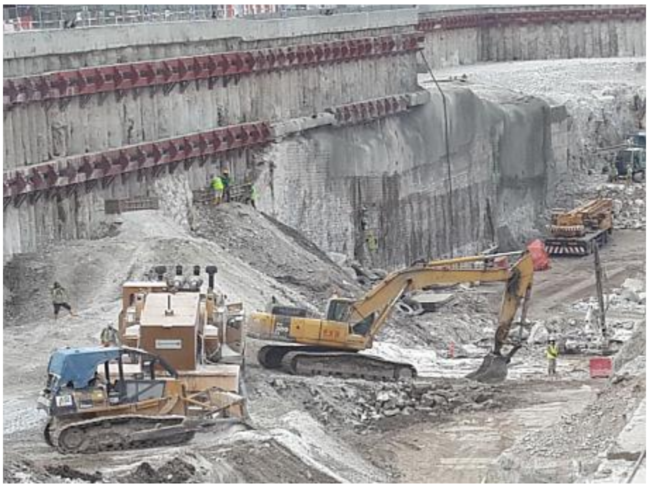

Figure 23 Excavation works at Pasar Rakyat in rock showing - Combination of Drill & Blasts method and Surface Miner

In addition to the SBP walls, Curtain Grouting cut-off similar to dam grouting is carried out along the perimeter of each Limestone station to try to cut off water seepage from solution channels. The Grout Curtain depth is extended to least 10m below the final excavation level or to a depth of 5 Lugeons. The spacing of the grout points for Primary, Secondary and Tertiary grouting are set at 4m, 2m and 1m center to center respectively with the grouting termination criteria set at 10m^3 volume or 2bar above hydrostatic and the acceptance criteria set at 5 Lugeons or lesser.

7. DISCUSSIONS AND CONCLUSIONS

At the time of writing, all the seven UG stations have reached the final excavation levels and some of stations are in the final process of completion of structural slabs and walls.

The selection of D-wall for Kenny Hills and SBP wall for Limestone formation have in general performed satisfactory and function as per designed, although there were some lessons to be learned.

One of the lesson learned, is not to undersize D-wall thickness to suite the market availability of smaller hydraulic clam machine. The D-wall under sizing created problematic congestion of steel, concrete honeycombing, trench over break and excessive trenching time due to machine limitation. It created numerous quality issues, like bulging, necking, honeycombing and leakages.

Another lesson learned, is not to take for granted the D-wall shaft friction capacity. The use of suitable type of stabilising fluid (Bentonite & polymer) and proper cleaning method of the D-wall are important construction factors to achieve the shaft friction as per design assumption. The D-wall barrettes at Bukit Bintang station assumed design shaft friction was downgraded after 3 numbers of instrumented pile tests showed that the barrettes achieved lower mobilised shaft friction than design assumption. Several remedial measures are then implemented to increase the shaft friction including adding brushes on the D-wall clamshell (Figure 24), using high capacity air-lift pumps to clean the D-wall base, shortening the concrete delivery time for the concrete placement after installation of reinforcement cage and to post grout the barrettes with tube-a-machete grout pipes.

Figure 24 D-wall Clamshell with brushes on side wall.

For the SBP walls Retaining system socketed into limestone located within shallow rock depth lesser than 25 m bgl; there was generally not much issues using this system. SBP wall can cope with the variability of the Karstic bedrock profile quite well for shallow bedrock. However, for SBP sections within bedrock depth beyond 25 m depth; beyond the commercially available pile casing depth of

25 m; the SBP quality of the uncased section of the piles becomes an issue. This SBP beyond 25m depth have numerous non-overlap and gaps thus leaking in the ground water and causing water drawdown behind the wall causing ground depression and subsidence. Figure 25 shows a section of SBP during excavation stage at approximately 25 m bgl where the difference in quality of the cased and uncased SBP can be clearly seen.

Figure 25 Section of SBP at approximately 25m bgl between cased and uncased SBP.

The performance of the retaining walls for the UG stations within Kenny Hill formation in terms of deflection and utilisation of struts capacity are generally satisfactory with the measured deflections and strut forces within the design prediction.

For example, the Merdeka Station located within Kenny Hill formation with one of the deepest D-wall retaining system of 51 m length and an excavation depth of 31 m bgl has performed satisfactory as has been confirmed by the station's 12 Inclinometers and 18 number of Strut's load cells. Figure 26 shows the measured Inclinometer INW2 displacement profile in the D-wall panel versus the Plaxis designed prediction at the final excavation level (FEL).

Table 5 shows the Merdeka Station measured strut loads versus the design values after the completion of excavation.

Table 5 Merdeka Stations Strut loadings

Struts at Level	Designed Strut Load (kN/m)	Maximum Measured Strut Load (kN/m)
S1	560	300 (53%)
S2	1250	879 (70%)
S3	1780	1419 (79%)
S4	2380	1513 (64%)
S5	1680	1315 (78%)
S6	1070	762 (68%)

While, the performance of retaining system for UG stations within the Limestone formation using SBP system and grout curtain cut off is generally acceptable but some improvements are needed. There were a few occasions where the ground water level was beyond the 1 m drawdown allowed and there were occasional depressions and sinkholes. However in general the SBP retaining system proved robust and flexible enough to cope with the KL Limestone extreme Karst condition to enable successful completion of the excavation works. Figure 27 shows the TRX Station box under construction with the SPB walls socketed into the undulating Limestone bedrock.

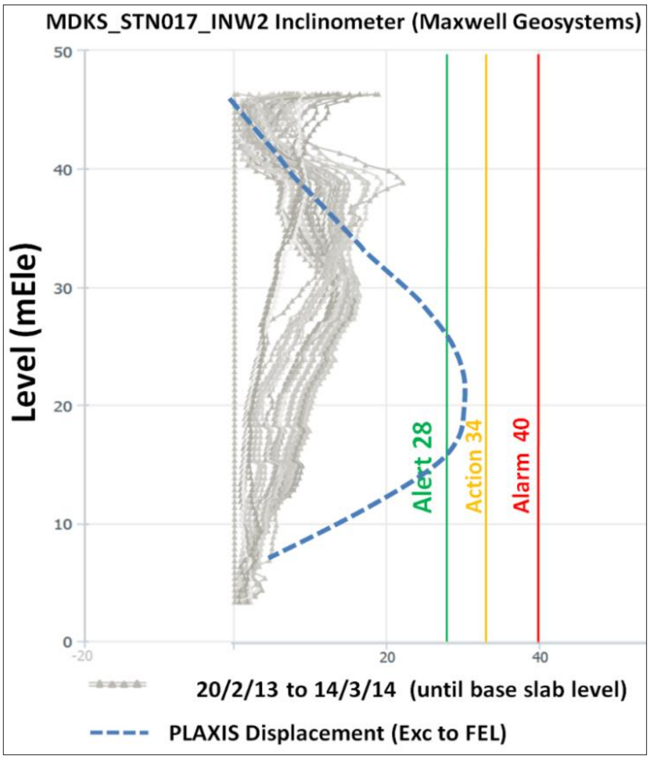

Figure 26 Inclinometer INW2 displacement profiles for Merdeka Station for the period up to excavation to FEL taken from the project online data management system; Maxwell Geosystems.

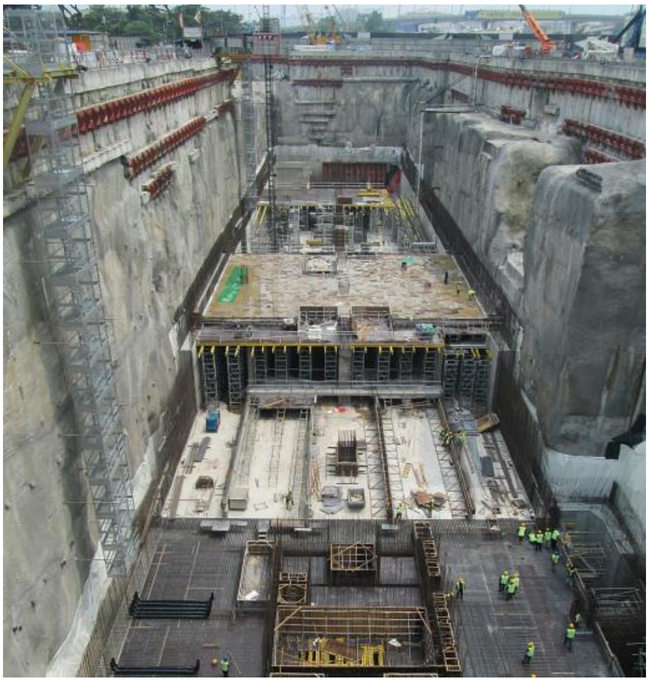

Figure 27 Pasar Rakyat (TRX) Station Box circa Mac 2015

The KVMRT MRT project has exposed the design and built contractor with unique challenges in the selections and considerations of retaining systems for deep excavation in a challenging urban environment. With the successful completion of the seven underground stations excavation works, many lessons were learnt; it is hopeful that with the instrumentation and monitoring data, SI test results, site observations and lesson learnt; further optimisation and cost saving from design and construction improvements for the next MRT Line can be passed on to the government and the general public.

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