Excavation Support for TBM Retrieval Shaft using Deep Soil Mixing Technique, Kuala Lumpur

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ABSTRACT: As part of the construction for the Klang Valley Mass Rapid Transit (KVMRT) Line 1, the South Portal structure at Taman Maluri acted as the shaft to retrieve the Tunnel Boring Machine (TBM) from Cochrane Station. An earth retaining system was required to retain the 15m deep shaft. Deep soil mixing (DSM) columns were used to provide excavation support instead of conventional secant bored pile walls in limestone. The DSM columns were constructed to form a gravity block which has no steel reinforcements and allowed excavation to be carried out without lateral supports. This enabled the TBM to be driven through and retrieved without the need to cut through reinforcing bars or having to design complex placement of struts.

KEYWORDS: Deep Soil Mixing, Limestone, Excavation, Cement

1. INTRODUCTION

The Klang Valley Mass Rapid Transit (KVMRT) Project when completed will cover a distance of 51km and comprise of 31 passenger stations. The South Portal structure at Taman Maluri, Kuala Lumpur (KL) acted as the transition point between the elevated and underground sections of the Sungai Buloh - Kajang line and also, as the shaft for retrieval of the Tunnel Boring Machines (TBM) from Cochrane Station. The rail level is about 15m below the existing ground level. The ensuing 15m deep excavation required an earth support system. Conventional secant pile retaining walls in limestone have to be designed to resist bending moments and minimise lateral deflection. This is normally done using steel reinforcing bars and steel struts (or anchors). These steel elements do not provide convenient exit for the TBM and hence, an alternative retention system had to be devised.

Deep Soil Mixing (DSM) walls have been used with increasing regularity in Kuala Lumpur (Yee & Chua, 2008), especially over KL limestone formation. The advantages stem not only from the omission of steel reinforcement and lateral bracings, but when designed as a gravity structure, the DSM wall does not need to be socketed into limestone rock. However, there is no prior record of use of this type of wall for mass-transit station boxes and TBM retrieval shafts.

This paper explains the design philosophy adopted for the DSM retention system. The ensuing construction technique, including quality control and safeguards, are also explained. Subsequent performance, during and after TBM break-out, is assessed, together with suggested improvements for future application.

2. SITE LOCATION

The site is located within a commercial hub and beside a very busy Jalan Cheras, in Taman Maluri, Kuala Lumpur (see Figure 1). The site was a former petrol station. 3-storey commercial buildings are found just off the south of the site. Construction logistics issues included limited movement of construction vehicle during traffic peak hours and tight space constraint.

3. SUBSOIL CONDITION

Based on Geological Map of Selangor, Sheet 94 Kuala Lumpur 1976 and 1993, published by the Mineral and Geoscience Department, Malaysia, the proposed site is located over Kuala Lumpur limestone formation. Ground conditions in limestone areas are known to be exceptionally challenging (Chan, 1986). Due to the inherent karstic feature of limestone bedrock, depth of the limestone bedrock is highly irregular. Adding to the natural complexity of the ground, the site was a former tin mining area and hence, highly variable soil composition is to be expected.

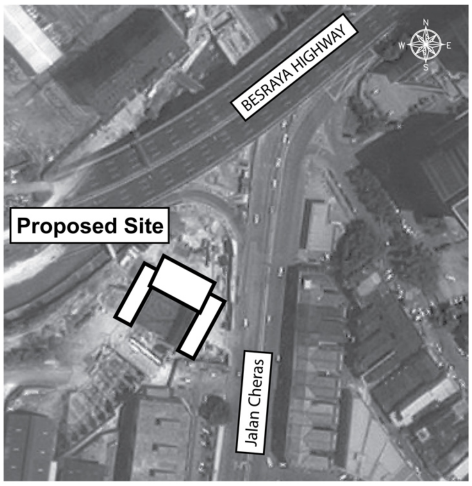


Figure 1a Location Plan (aerial view)

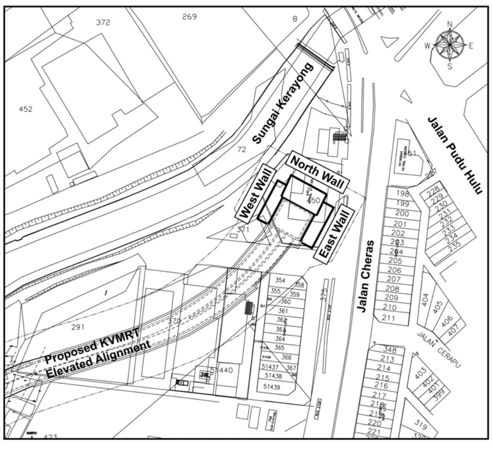


Figure 1b Location Plan (drawing)

Seven (7) boreholes were conducted on the site during the design stage. These showed that thickness of overburden soil varied between 7m and 10m below existing ground level. The soil generally comprised of sandy silt with interbedded layers of soft clay. This is typical of former tin mining soil. The soil was of soft to stiff consistency with SPT blow-counts typically in the range from 2 to 12 blows/ft.

Before commencement of site work, further information on the rock head profile was gathered by conducting a series of probes along the perimeter of the wall and also, perpendicular to the excavation. This enabled a profile of the rock head to be generated for the purpose of design (see Figure 2).

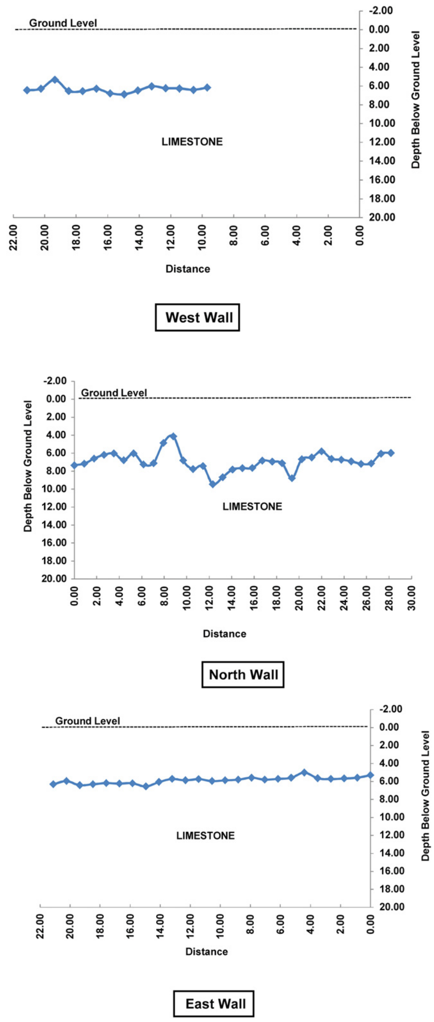


Figure 2 Rock Profile along Wall Perimeter

4. PROPOSED STRUCTURE

At the Maluri South Portal, two numbers of TBM crossed beneath the ground (invert level about 15m below ground surface). At the end of the tunnelling route, a retrieval shaft was required to retrieve the two TBMs. The retrieval shaft was to be formed by vertical excavation retained by an earth support system. As shown in Figure 3, three faces of the wall need to be retained, the most critical being the TBM drive exit. The retaining wall was not only required to resist active earth (and water) pressures but also the TBM thrust pressures at the drive face induced as the TBM daylights into the shaft. Figure 4 shows the cross section of the TBM drive exit face.

Conventional station boxes for the KVMRT were formed using secant bored piles and braced by horizontal struts (or anchors where space permits). Secant piles have advantages in the limestone geology as (i) each pile element can be terminated at different depth (depending on the rock head) after adequate rock socket is achieved, (ii) the interlocking pile elements minimise groundwater ingress into the excavation shaft. However, secant pile retaining walls have to be designed to resist bending moments and minimise lateral deflection. This is usually achieved by means of dense steel reinforcing bars and steel struts (or anchors). When it comes to TBM exit point, these steel elements do not provide a convenient passage. Hence, an alternative retention system was devised for this retrieval shaft.

Deep Soil Mixing (DSM) walls are becoming more common in Kuala Lumpur (Yee & Chua, 2008), especially for excavation over KL limestone formation. When designed as a gravity block, steel reinforcements and lateral steel bracings are not required; and rock socketing is also not needed. DSM walls have not been used for KVMRT station boxes mainly due to lack of case history for such application. There was concern of medium term durability of the unreinforced wall elements (as the excavation may be kept opened for more than 2 years.

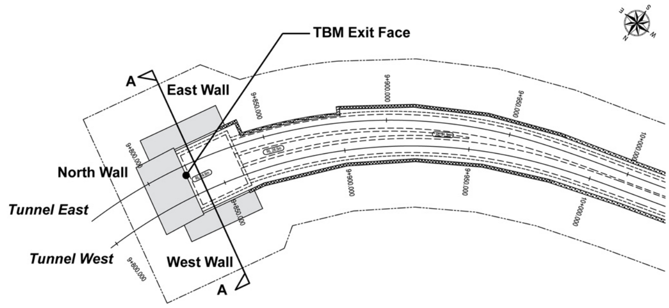


Figure 3 Layout Plan of Shaft

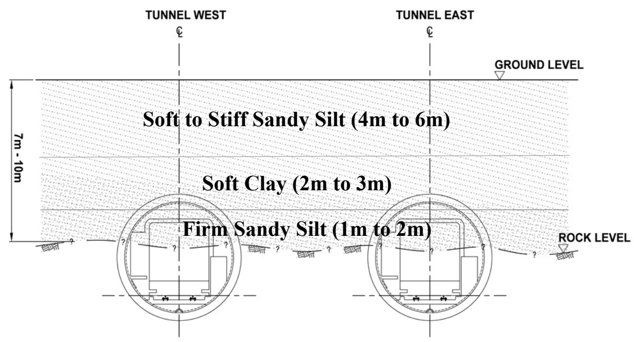


Figure 4 Cross Section of Shaft (Section A-A)

5. DESIGN CONSIDERATIONS FOR A DSM WALL

DSM technique involves the process of mixing soil with cement slurry by using a mechanical tool, which is drilled into the ground. The mixing tool has cutting blades which are rotated as the tool is pushed into the ground. Pre-mixed cement grout is pumped at high pressures through the mixing tool and injected into the soil during penetration and withdrawal, such that the cement paste and in-situ soil are well blended. Through this process, the in-situ soil is improved by cement hydration hardening, bonding of soil particles and filling of voids by pozzolanic hardening (CDIT, 2002). The end product will have greatly enhanced strength, low permeability and low compressibility compared to the original soil. Typical mixing tool is shown in Figure 5.

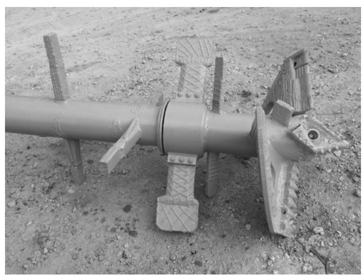


Figure 5 DSM Mixing Tool

For application at the Maluri Retrieval Shaft, the design requirements for the composite wall were reviewed from past projects and literature. Various column configurations were considered.

5.1 Discrete Columns Arrangement

Individual DSM discrete columns have been shown to perform well to support vertical load for say, railway embankments (Raju and Abdullah, 2005) and even foundation rafts (Tolponicki, 2002). However, such discrete columns are not suitable when required to resists lateral forces and cases of failure have been documented. Topolnicki (2004) reported that tensile strength may be as low as 8% of UCS and unlikely to be higher than 200 kPa. Since the material is rather brittle, lateral shear forces, uneven movements, or bending stresses may result in failure of the column; and if a series of discrete columns are lined up together, progressive failure may ensue (see Figure 6). Hence, the design has to ensure that compressive stress acting on the columns should not be exceeded and tensile stress avoided.

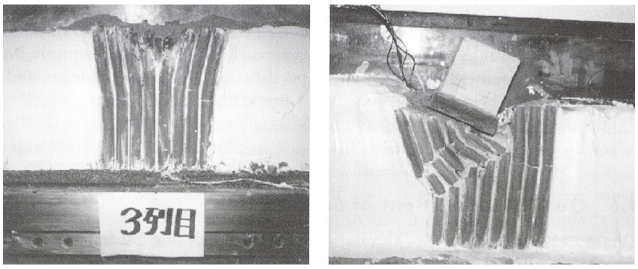


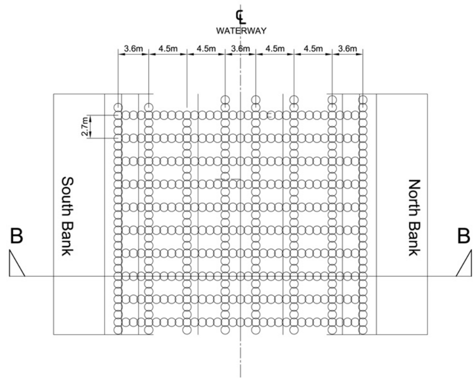
Figure 6 Typical Modes of Failure Observed in Centrifuge Tests (Kitazume et al, 2000)

5.2 Column Grids Arrangement

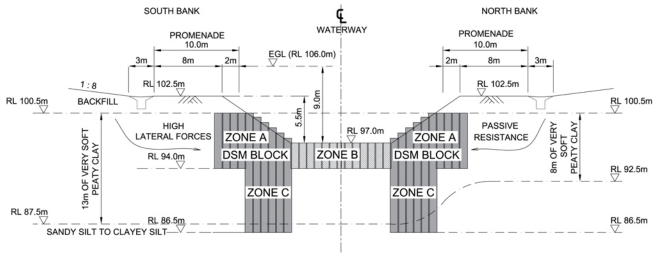
Topolnicki (2004) describes applications where grids of columns are constructed and tied together, primarily, to increase rigidity and reduce risks of progressive failure. Since the risks of subjecting the DSM wall to bending forces and movements are increased, detailed analyses using finite element need to be carried out. Strain compatibility between the soil (to mobilise peak shear strength), the structure being supported and the DSM elements would need to be assessed carefully. For example, the failure strain of soft clay is generally 2% to 5%, whilst the DSM column is less than 1% as reported by Topolnicki (2004). Leong W.K. et al (2012) describe such detailed considerations for a slope stabilisation application in soft soils in Singapore. 3D FE analyses were carried out to derive a DSM wall configuration (about 50% replacement ratio) that not only fully utilises the advantages of the composite wall but also isolates the development of tensile stresses (Figure 7). The constructed wall performed efficiently with only 6mm deflection. It should be noted that the Mohr-Coulomb soil model should be used with caution for DSM wall design. At high stress levels, large volumetric change or strain softening may occur, which cannot be captured in the model (Lee, 2011).

5.3 Block Arrangement

The Maluri Shaft was designed to retain a vertical cut face up to 10m high. Together with rock excavation beneath, the total excavated shaft was 15m deep. The consequences of failure were severe and such risks had to be minimised. As such, the design intent was to mix the entire block of soil (100% replacement) using interlocking columns rather than a more economical grid pattern. Having said that, this DSM wall type was still found to be less expensive than conventional secant pile wall. The DSM block was formed by 1m diameter columns overlapping each other by 0.12m thickness in a honeycomb pattern (see Figure 8). Such a configuration ensures that the columns experience less stress; minimises uneven movements; and there is less concern of the effect of non-uniformity within the block.

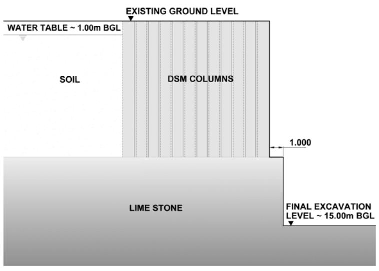


Plan View

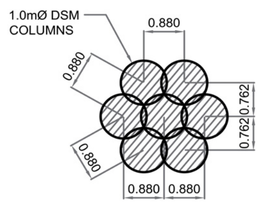


Section B-B

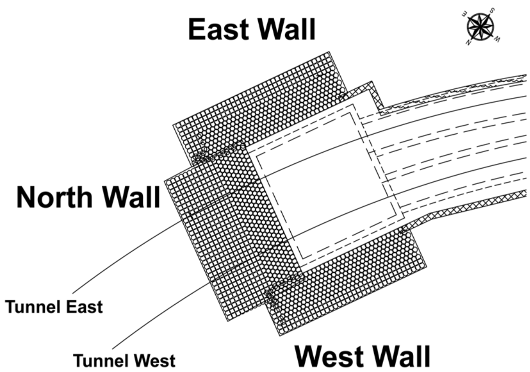
Figure 7 DSM Configuration for Slope Stabilisation (Leong W.K. et al. 2012)



(a) Cross Section



(b) Column Pattern



(c) Wall Layout

Figure 8 (a) Cross Section of DSM Block at the Maluri Shaft (b) Column Pattern (c) Wall Layout

6. DSM WALL ANALYSES

The DSM block design was checked against the following failure modes:

6.1 Wall overturning stability

The wall had to be sufficiently wide to ensure that it will act like a gravity block. No element of the wall will be subjected to tension or bending forces. Although not an issue on this project site, construction of the wall requires sufficient space (width) behind the excavation face. Generally, if the depth of soil face is H, then a block width of 0.6H to 0.8H would be required. A factor of safety against overturning of 3.0 was established (see Figure 9).

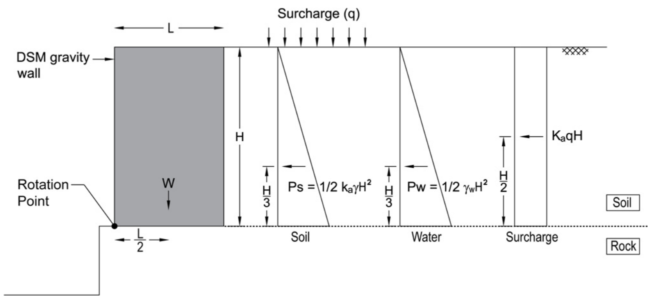


Figure 9 Check for Wall overturning

6.2 Wall sliding resistance

Once again, the wall has to be wide enough to provide resisting surface against lateral forces. In the limestone, the uneven rock surface provides excellent interface friction against lateral movement. However, it should be checked that the rock head profile does not incline toward the excavation, which may result in lower resistance than assumed. Sliding check assumed a safety factor of 2.0 (see Figure 10). A check was also made for reduced resistance should the interface be poorly mixed and portions of soils remain.

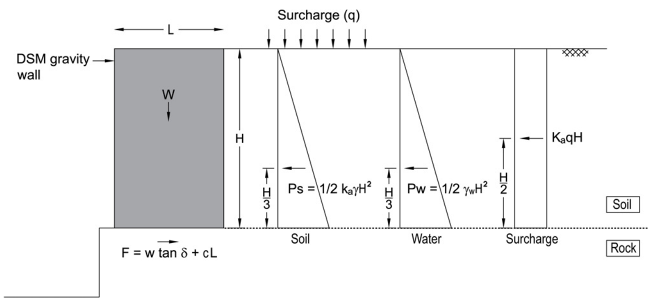


Figure 10 Check for Sliding along Rock Interface

6.3 Vertical load support

The block will be carrying temporary construction load. Since the block is supported on limestone rock, bearing capacity to support the load was not an issue. A temporary reinforced concrete slab was cast on the block to spread the load, and avoid any concentrated point load. Short anchor bars were drilled into the DSM block at certain designed grids to tie the slab onto the DSM block. A surcharge load of 20 kPa was assumed.

6.4 Inter-locking bond between column elements

The design relies on the effective distribution of soil, water and surcharge loads from the back of the wall into the entire block. For this to happen, load has to be transferred from one element to another via their contact bond (by shear). During construction, it was ensured that “cold joints” were avoided and each column was constructed within 48 hours of the preceding column.

6.5 Toe stability

The wall needs to be taken to a sufficient depth to prevent toe “kick out” and basal heave. However, for this project, the rock head is found at a higher level than the excavation level and hence, this check was not relevant.

6.6 Groundwater cut-off

The wall has to be effective in reducing water inflow into the excavation, both across the wall and also, the interface between the DSM and rock. Construction of the block was very effective in excluding water, as the size of the block and also, the jagged rock head decreased permeability manifold. The bigger concern of water infiltration stemmed from the untreated rock below the DSM block, with natural fissures and cavities (see Figure 11). It is common to treat the rock by grouting to reduce water infiltration (see Raju and Yee, 2006). Rock fissure grouting was carried out before construction of DSM block at 4m intervals along the excavation perimeter.

Figure 11 Rock Fissures where Water may Ingress into Excavation

6.7 Bedrock stability

Pre-construction soil investigation would need to establish that the rock is stable after excavation (against block failure). This is established indirectly, by means of examining the rock quality designation and core recovery ratio. Advice from a geologist is normally sought. During mining of the rock, the exposed rock face was examined at each excavation stage. Rock bolts were installed where there were localised defects found in the rock. Contingency measures to underpin the block using micropiles were planned but not found to be necessary for this project.

6.8 Movements (lateral strain)

The DSM block was not designed to withstand high levels of strain. The design had to minimize risks of uneven wall movement.

6.9 Blasting force during rock excavation

Mining of the rock within the excavation block is mainly done by controlled blasting. Adjacent to the wall, less invasive mechanical breakers were used. Past work in DSM wall has found that the cement-soil composite structure can tolerate peak particle velocity as high as 50 mm/sec without suffering damage. As a general guide, blasting was not carried out within 3m of the wall face.

6.10 TBM thrust pressure

The North DSM wall block had to be wide enough to resist the thrust forces from the TBM. Besides this, TBM operational requirements necessitated extended treatment. Hence, this block was eventually designed to be wider than the others.

Table 1 Dimensions of the DSM Walls

Wall Location	Depth to Rock (m)	Width of DSM Block (m)	Column Dia (m)	Column Interlock (m)	Remarks
North (TBM drive)	4.0 to 10.0	16.7	1.0	0.12	Design governed by TBM operation requirements. As-built DSM column depth varies between 3.5 to 10.5m
East	5.0 to 7.0	9.7	1.0	0.12	Design assumed worst case of 10m soil depth. As-built DSM column depth varies between 3.5 to 7.5m
West	5.0 to 7.0	8.8	1.0	0.12	Design assumed worst case of 10m soil depth. As-built DSM column depth varies between 3.0 to 10.0m

From the above considerations, it is clear that the design of the DSM wall has to consider many practical factors; has to be robust; and with allowance for a fair amount of redundancies. The installed DSM columns were required to have a shear strength of 0.75MPa (UCS = 1.5MPa). The final design dimensions of the wall are summarised in Table 1.

7. CONSTRUCTION

Construction of the wall began with site trials to determine the required cement content and mixing parameters. Based on work by Topolnicki (2004) and previous experience in KL, a design cement content between 300 and 350 kg/m^3 was adopted. The operating parameters (e.g. rotation speed, rate of penetration & withdrawal, blade rotation number, flow rate, grout pressure, binder content, etc.) were monitored using real-time computerised recording systems to ensure adequate and uniform mixing of the soil (see Figure 12). Blade rotation number T, defined as the total number of mixing blade passing during 1m of single shaft movement through the soil, was kept above 700 [$T = \Sigma M \times (R/V)$, where M = total number of mixing blades per m depth; R = rotational speed of mixing tool; V = penetration or withdrawal rate m/min]. Most practitioners recommend T > 400 for adequate mixing in normal application.

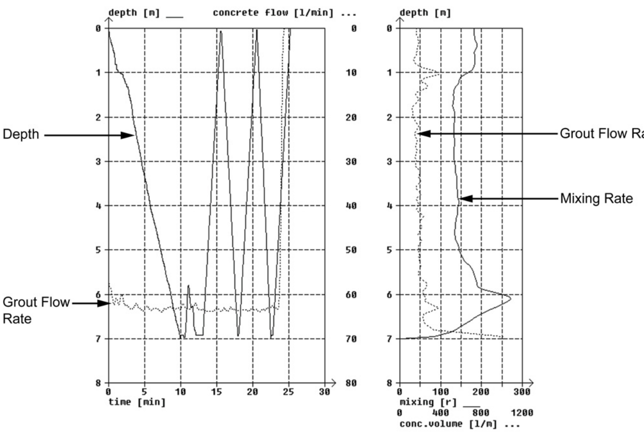


Figure 12 Typical Operation Parameters Monitored by Computer in Real Time during Installation

Figure 13 shows the exposed DSM column and the interface between the column and rock head. Good contact was achieved by keeping the tool at the deepest penetration level for at least 0.5 min whilst jetting and rotating.

There are layers of clay within the soil mass. To avoid formation of soil "bulb", which impedes thorough soil-cement mixing, a free blade was introduced (see Figure 14).

It was imperative that the columns were interlocked such that the individual columns combined to act as a single block. The formation of "cold joints" had to be avoided. It was ensured that corresponding columns were constructed within 48 hours of preceding columns. Where it was anticipated that this was not possible or there were ground complications, jet grouting was used to form larger columns. For example, in one localized areas, old timber pile foundations were encountered during installation, which required jet grouting to be instituted.

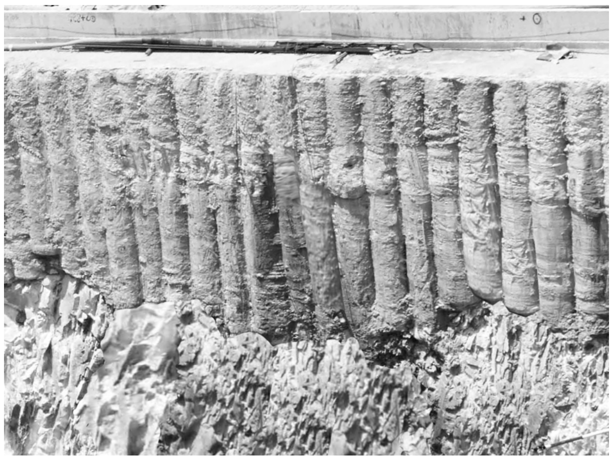


Figure 13 Exposed DSM Columns

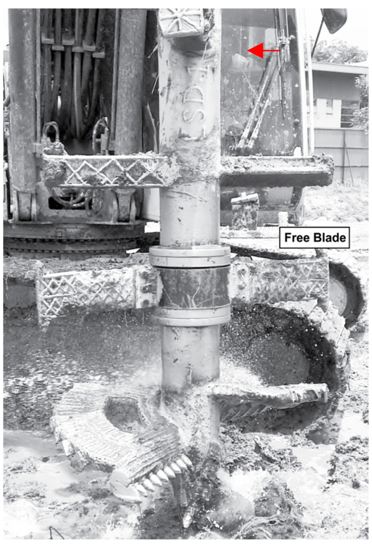


Figure 14 Free Blade in Mixing Tool to Avoid Formation of Soil Bulb

The advancement of DSM technology has resulted in the availability of machines using multiple shafts. Recently, the advent of cutter-soil mixing has also been met with optimism. However, such multiple shaft mixing is not suitable for use in limestone given the pinnacle nature of rock. "Gaps" would result in the soil-rock interface as the blades will be stopped at the highest peak in the limestone. Hence, to ensure proper mixing down to limestone rock head level, a single shaft mixing tool is preferred.

8. QUALITY CONTROL

The execution practice and quality control of DSM works follow the British Standard BS EN 14679:2005. A quality plan was drawn up, which included the methods and frequency of checks to be made during construction.

As mentioned before, the operating parameters were monitored using real-time computerised recording systems. Verification process included daily review of these computer records and any deviations were investigated and rectified to the satisfaction of the supervisory team.

Core samples were collected to examine consistency of the columns and to recover sections for unconfined compressive strength (UCS) tests. Cores were done in both the centre and the edge of the columns (where the columns intercept). As shown in Figure 15, test results show UCS strength consistently above 1.5 MPa after 28 days.

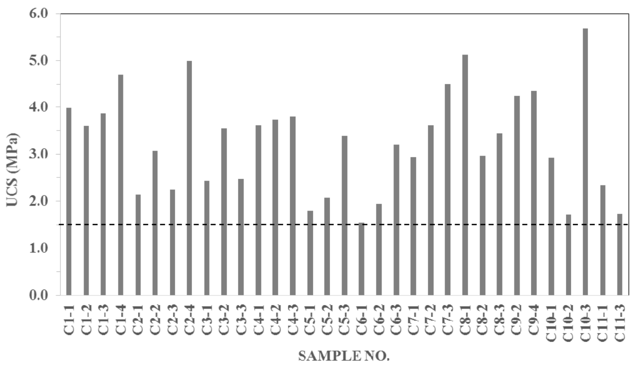


Figure 15 DSM Core Sample UCS Strength Test Results

9. PERFORMANCE

Excavation was carried out after completion of the DSM block (subsequent to a curing period exceeding 28 days). Bedrock was mined beneath the block using hydraulic breakers. Rock blasting was carried out nearby and the wall was monitored to ensure that the vibrations induced did not do any damage.

Wall movement was monitored during excavation works using both inclinometers and settlement markers. Three inclinometers were installed, one on each wall face, and twenty-one settlement markers on the ground surface (see Figure 16). Maximum wall movement was observed at East wall, showing a reading of 10 to 15mm (less than 0.15% wall height). The shape of the deflection implied that there was some sliding movement, albeit small. This is well within widely accepted wall defection criterion of 0.5%. The maximum ground subsidence of 2mm to 6mm was observed behind West wall, and this was probably caused by construction load. Back-analyses imply a stiffness modulus of the block between 35 and 100 x UCS.

Safety precautions were taken during tunnel break-out. This included reducing the TBM slurry pressure to very low levels from usual pressure. The speed of boring was slowed to 30% to 40% of normal speed. In addition to the above, 2 layers of temporary soil nails were installed to strengthen the front face of the DSM block during TBM break-out. The actual TBM break-out occurred on April 8, 2014 (West Tunnel) and April 24, 2014 (East Tunnel). It was reported by the TBM Operators that both break-outs occurred smoothly without incident. There were many spectators viewing the emerging TBMs and they were requested to stand behind barricades 20m away from the TBM wall face. A video of the break-out is available for view at http://mymrt-underground.com.my/videos/breakthrough. Figure 17 shows the wall during and after TBM exit.

With regards to wall durability, the DSM wall has been standing for 2 years (at the time of writing). Visual examination has found no signs of distress or degradation. For longer term application, weathering resistance can be enhanced with higher cement content (and higher strength of end product). Additional surface protection measures such as applying a gunite surface (with or without steel mesh) may also be implemented. In the permanent stage, structural walls and slabs will be constructed in front of the wall for long term serviceability requirements.

In future, for such applications, the designer could consider economising the design by reviewing the wall width, blade rotation number and other TBM-related parameters.

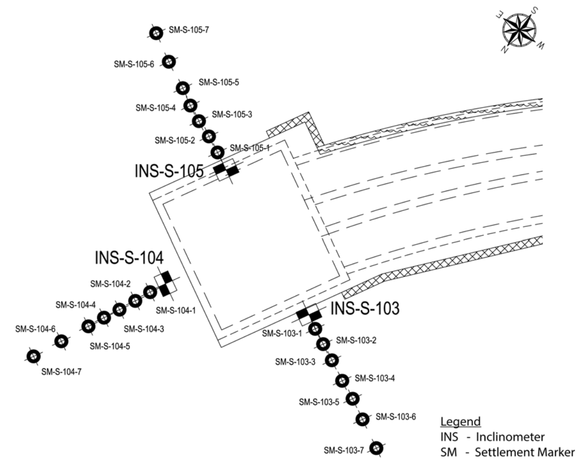


Figure 16 Location of Inclinometers and Settlement Markers

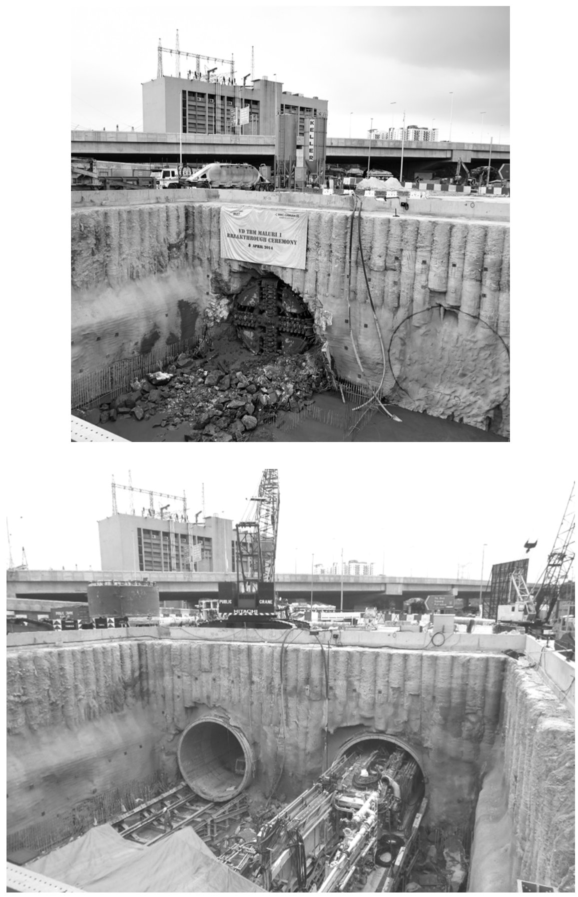


Figure 17 DSM Wall during and after TBM exit

10. CONCLUSION

The Maluri TBM Retrieval Shaft required an excavation of 15m deep. DSM walls comprising 1m diameter columns interlocked with each other were constructed to form a gravity block over three faces of the excavation pit. The DSM block was formed over soil up to 10m high and seated on limestone bedrock beneath. The design was approached with caution given the severe consequences of failure. Besides ensuring high safety factors in various wall stability and sliding checks, the block was designed to be fully treated with cement (100%) to avoid any risk of occurrence of tensile and bending stresses. Strains were kept to a minimum. Construction was carried out with high level of supervision and control, especially in ensuring thorough mixing and avoidance of cold joints between columns. Based on previous experience in similar soils in Kuala Lumpur, the mix design ensured that cement content up to 350 kg per m^3 and blade rotation number above 700 were achieved. The DSM block was excavated with maximum 15mm movement and did not display any duress during the further 5m deep rock excavation afterwards. The DSM wall performed well as the TBM break-out events occurred without incident. The DSM wall stood for 2 years before structural walls were constructed as permanent finish.

11. ACKNOWLEDGEMENTS

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