Bukit Timah Granite Formation Engineering Properties and Construction Challenges

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ABSTRACT: The Bukit Timah Granite Formation is one of the oldest geological formations in Singapore and is found mostly in the central and northern parts of Singapore. A major section of Singapore's underground metro construction passes through the Bukit Timah formation soils, and extensive field and laboratory testing has been carried out on the rock samples. Uniaxial Compressive Strength (UCS) tests have been carried out on hundreds of samples, test results have shown wide variation in the strength and the maximum strength is found to be much higher compared to the previously published data by Zhao et al 1995. This paper presents a review of UCS strength of the Bukit Timah Formation, Point Load index tests and correlations which were developed for site specific locations. This paper also reviews the abrasivity of Bukit Timah Granite and factors affecting it. Influence of UCS and other factors on the drilling, coring and excavation rates in Bukit Timah Granite are also presented

KEYWORDS: Bukit Timah Formation, Uniaxial Compressive Strength, Point Load Index Tests, Excavation rates

1. INTRODUCTION

Intrusion of the Bukit Timah Granite is believed to have taken place during the early Triassic period (230 million years ago). The rock in the formation varies from granite to grandiorite and various dykes are included in the formation. Top portions of the Bukit Timah Granite is generally weathered and decomposed into residual soils. As the water seeps through fractures of granite mass below the weathered soil, chemical processes take place and as a result, the subsurface of the rock is eroded, leaving numerous boulders in place. The engineering geology and rock mass properties of Bukit Timah granite were reviewed by Zhou (2001) and Zhao et al (1994) who had studied the weathering of Bukit Timah Formation. Deep tropical weathering and variability in bedrock level of the Bukit Timah Granite Formation is well established (Shirlaw et al 2000) and these inherent complexities of Bukit Timah Granite Formation pose challenges to excavations and tunnelling works. The Bukit Timah Granite occupies approximately one-third of the area of Singapore, it mainly covers the central area of Singapore extending 7-8 km in northerly and westerly directions. A major section of recent LTA projects such as Downtown Line Stage 2 (DTL2) and Thomson-East Cost Line (TEL) are located in the Bukit Timah Granite Formation. The DTL2 is 16.6km long and most of its sections from Gali Batu to Central Express Way (after Newton station) run through the Bukit Timah Granite Formation and Goh et al (2014) have presented the performance of different types of retaining walls in this formation. The TEL's Thomson line section is 30 km long running from Woodlands in the north to Marina South. A major section from Woodlands to Havelock is in the Bukit Timah Granite Formation. The construction of DTL2 has been completed, while the construction of TEL is still ongoing and the site investigation works for these sections have been completed. In this paper, a large of amount of available test data and some site specific data in the Bukit Timah Granite Formation are reviewed and presented. The various features of Bukit Timah Granite Formation encountered during the construction work are also reviewed. The UCS strength of Bukit Timah Granite Formation and Point Load index tests results are analysed and correlations which were developed for site specific locations. This paper also reviews the abrasivity of the Bukit Timah Granite and factors affecting it. Influence of UCS and other factors on the drilling, coring and excavation rates in the Bukit Timah Granite Formation are also presented.

2. WEATHERING OF BUKIT TIMAH GRANITE FORMATION

Bukit Timah Granite has undergone weathering processes over time and the degree of weathering decreases with depth, the upper portion of the BuKit Timah Granite Formation is mostly weathered and comprises completely weathered granite to residual soil, slightly weathered and fresh granite is found at deeper depth of the Formation(Figure 1).

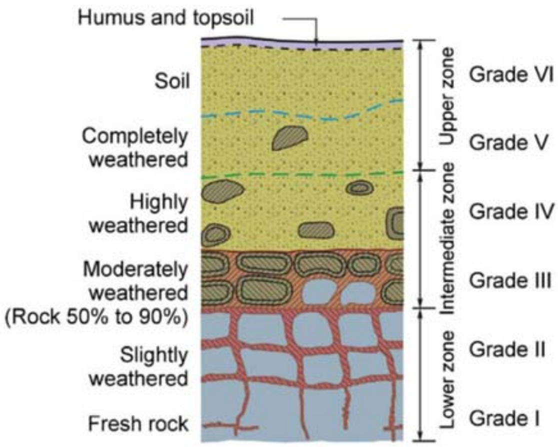

Figure 1 Weathering profile of igneous rock (Little 1969)

The weathering of the Bukit Timah Granite is gradational with stratified layers and sharp boundary between completely weathered layer (GV) and moderately weathered granite (GIII) is often observed. The rock head level is generally undulating with frequent valleys and commonly follows the topography. Because of the intrusive nature of the formation, variation in depth of granite rock is significant, based on the data of more than 700 boreholes drilled, the deepest depth of Bukit Timah Granite is located at 62m below the ground surface at 'Fourth Avenue' along Bukit Timah Road and the shallowest depth is located at 3m below the ground level at Jalan Gali Batu along the Woodlands Road.

From several deep excavations carried out in this formation, the most common feature observed is the presence of boulders which are frequently found near to the soil-rock interface and are also occasionally found within the residual soils. Boulders of various sizes were found during the excavation for cut and cover tunnels and during bored tunneling works (Figure 2). Sometimes the sizes of these boulders can range more than 6m.

Figure 2 Boulders of Bukit Timah Formation

3. STRENGTH AND ABRASIVITY OF BUKIT TIMAH GRANITE.

3.1 Uniaxial Compressive Strength (UCS)

Uniaxial Compressive Strength (UCS) is widely used by engineers in the design and construction of underground structures and tunneling works in rock formation. For Bukit Timah Granite, there is limited published data to represent the actual USC strength range. Zhao et al (1995) has shown that UCS of Bukit Timah Granite is 180 MPa and McChesney (2011) reported UCS of up to 280 MPa from Circle Line project. The UCS test data obtained from DTL2 and Thomson section of TEL show significant variation in the strength of the Bukit Timah Granite with a maximum value of 376 MPa measured from the Newton area.

Generally a higher range of UCS values are obtained in the southern areas of the Bukit Timah Formation such as Newton and Stevens areas compared to the Western and Northern parts such as Woodlands and Upper Bukit Timah areas (Figure 3 and 4). From the test data, the number of data points that show UCS of more than 250MPa from northern areas is limited compared to the southern areas where more data points show UCS of more than 250 MPa, most of the samples from northern areas appears to be light greyish in colour, whereas for southern areas it varies from light grey to strong greenish grey in colour.

However no detailed assessment has been made with regards to rock forming minerals of Granite from these two areas. There appears to be some relationship of these differences in strength with two distinct groups such as the Central Singapore Granite and Pulau Ubin Granite as discussed in Singapore Geology (1976). Further detailed studies are necessary to confirm these differences

3.2 Point Load Index

The procedure to conduct the UCS test is time consuming and requires a cylindrical core sample to be tested in a laboratory whereas Point Load Index tests (PLT) can be carried out on smaller pieces of rock. These tests can be carried out in the field to get quick results. PLT is an alternative method to estimate the UCS of rock speedily.

The International Society of Rock Mechanics (ISRM, 1985) has established the procedure for PLT testing.

The UCS of the rock is estimated from the PLT using the following relationship.

$$UCS = f * I_s \quad \text{…. (1)}$$

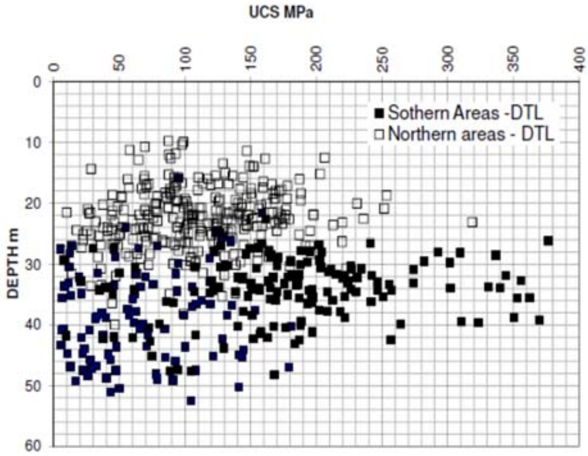

Figure 3 Variation of UCS with depth from DTL data

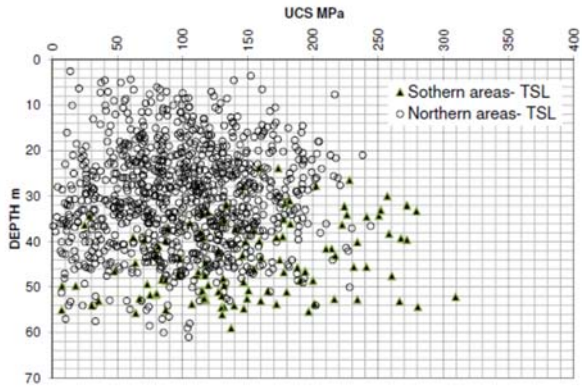

Figure 4 Variation of UCS with depth from TEL data

Where I_s = Point Load Index for 50mm diameter core and 'f' is the correlation factor. ISRM commission on Standardization of Laboratory and Field Test has reported correlation factor of 20-25 and based on several published data Rusnak and Mark (2000) have summarized correlation factor for sedimentary rocks which is in the range of 8-24. PLT is essentially a tensile test; however there is a relationship between the compressive strength and tensile strength of rock and hence a site specific correlation factor needs to be developed between PLT and UCS if PLT is to be used for determining excavation of rock. The correlation between PLT with UCS depends on the types of rock and it may vary for the same rock at different sites. In this paper, correlations for Bukit Timah Granite have been developed based on the several test results obtained from DTL and TEL projects.

The tests results of the correlation between UCS and PLT (Figures 5 to 8) have shown that, the correlation factor for Bukit Timah Granite varies across the sites in the range of 8-18 with distinct trend. Data from the Northern areas of Singapore shows a correlation factor of 8-10 whereas data from Southern areas shows the correlation factor in the range of 15-18. Based on these values, it is recommended that for the selection of construction equipment, a correlation factor of 10 for northern areas and 18 for southern areas to be used for UCS values measured from Point Load Index tests for Bukit Timah Granite rock

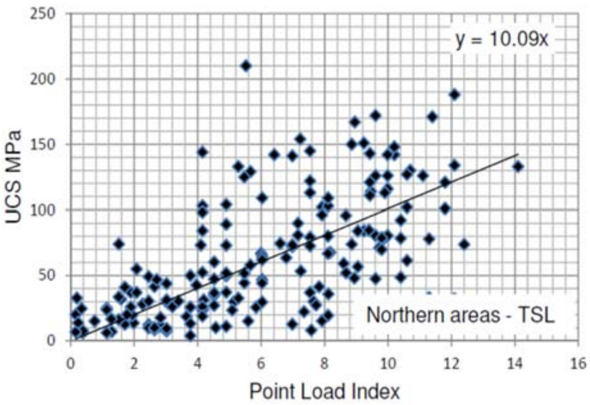

Figure 5 UCS Vs Point Load Index (TSL – Northern areas)

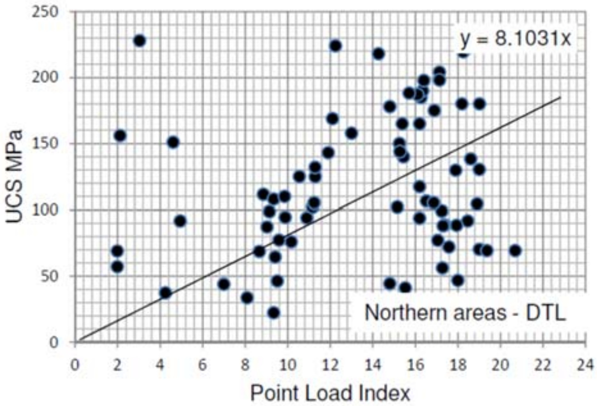

Figure 6 UCS Vs Point Load Index (DTL – Northern areas)

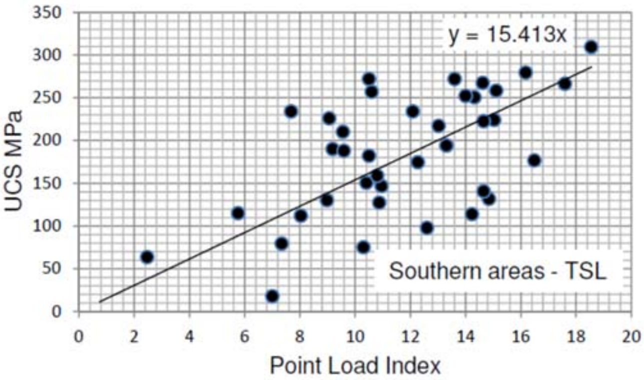

Figure 7 UCS Vs Point Load Index(TSL – Southern areas)

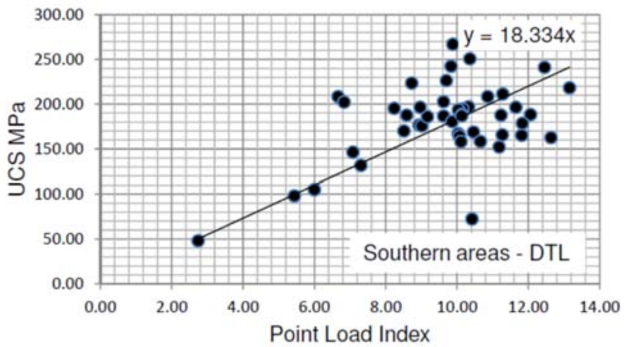

Figure 8 UCS Vs Point Load Index (DTL - Southern areas)

3.3 CERCHAR Abrasivity

CERCHAR Abrasivity Index (CAI) is commonly used to assess the abrasivity of rock in order to determine the cutting wear rate. From several test results analyzed, the general range of CAI for granite rock is found to be between 3 and 6. The CAI tests conducted from several bore holes at different areas of study give an average CAI of 4.6; the maximum value being 6.88 measured at 19m below the ground level from the bore holes at the northern areas of Singapore (Figure 9). Abrasiveness of Bukit Timah Granite can be classified as extremely abrasive as per the classification by Centre d' Estudes et de Recherches des Charbonnages (CERCHAR) de France. In order to study the variation of CAI with UCS of rock, samples are tested within 1m of CAI samples from the same bore holes. From these test results, it is found that the same abrasivity values are measured for rocks with different UCS values (Figure 10). Based on this, it can be concluded that there is no specific relationship between the abrasivity and UCS values for Bukit Timah Granite.

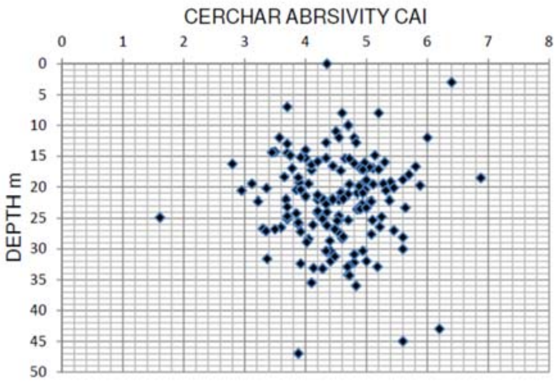

Figure 9 Variation of Cerchar Abrsasivity with Depth

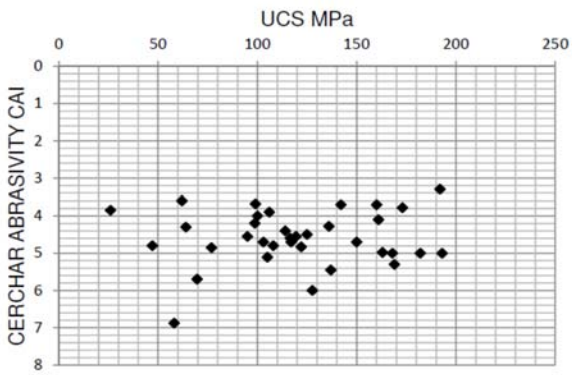

Figure 10 Variation of Cerchar Abrsasivity with UCS

West (1989) identified quartz content being the main parameter influences the CAI value, based on 29 data sets. Kasling (2000) carried out further research with more than 100 samples of different CAI ranges and found that the quartz content alone is not sufficient to confirm the relationship on the abrasion values. From the petrographic studies of granite samples from DTL2 in the northern areas, it is found that the major mineralogical content of granite is dominated by the presence of quartz and feldspar. The quartz content is found to be in the range of 30% to 40% and feldspar is found to be in the range of 5% to 58%. No definitive trend of CAI values is observed for the quartz content. More detailed studies may be required to establish the influence of various parameters on the CAI values for Singapore Bukit Timah Granite. The Rock Abrasivity Index (RAI) was introduced by Plinninger (2002) which uses UCS and equivalent quartz content was found to be useful in assessing the drill tool wear rate and 'life time'. Plinninger (2010) has reported the successful use of RAI values for drill tool consumption based on large diameter 1200mm bored piles. The author also reported the correlations between CAI and RAI values based on Schumacher (2004) studies.

4. CONSTRUCTION CHALLENGES

For deep excavation and tunneling works, the Bukit Timah Granite Formation can be considered as a complex formation due to the presence of boulders and undulating rock head level. The boulders of Bukit Timah Granite Formation vary in sizes, strength and grade of weathering. It is observed that the strength of these boulders can be as high as the parent rock. With such complexity, it is challenging for the installation of piles, diaphragm wall trenching and bored tunneling works. Some of the challenges encountered during bored pile wall, diaphragm wall and bored tunneling works from DTL project are presented in this section.

4.1 Bored pile drilling rates

Excavation rates generally depends on the type of drilling machine/drilling bit used, all else being equal, the stronger the rock the longer time it takes to bore or drill through. Theoretical and practical considerations on the penetration rates are discussed by Kahraman et al (2003). Based on the installation records of secant bored pile wall of size 800mm to 1180mm in Bukit Timah Granite using conventional hydraulic drilling rigs, the drilling rates are found to vary significantly. Figure 11 presents the variation between UCS and drilling rates for bored pile walls. In general, the trend indicates that the higher the rock strength, the longer it takes to core through the rock. The ability to core through rock is also dependent on the power and torque of the bored piling equipment used, including type of rock coring tools used for the bored pile operations. However the large scatter of the data appears to indicate that the drilling rates not only depend on rock strength but also on the quality of the rock mass. For rock which is highly fractured and heavily jointed, they can be excavated easily compared to less fractured rock of the same strength.

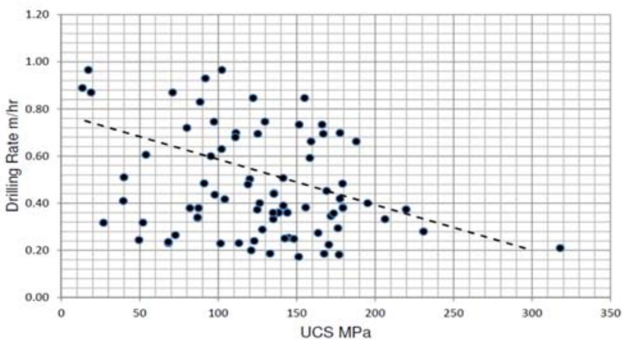

Figure 11 Bored pile drilling rates Vs UCS

The complexity of Bukit Timah Granite Formation, which can be highly abrasive and the prevalence of boulders can result in wearing of cutting tools more frequently and affect the drilling rates.

4.2 Diaphragm excavation rates

Tool wear problems are encountered for diaphragm wall installation through hard Bukit Timah Granite. For some of the panels at DTL Newton station, it took almost a day to penetrate only 100mm of rock using the rock cutter equipment. The rock level is generally very undulating (difference as much as 4m) between adjacent diaphragm wall panels and boulders were encountered frequently at various depths along the panels. Figure 12 shows excavation rates for the some of the panels and it shows similar trends as bored pile wall installation, only limited data is available for rocks of UCS more than 200 MPa.

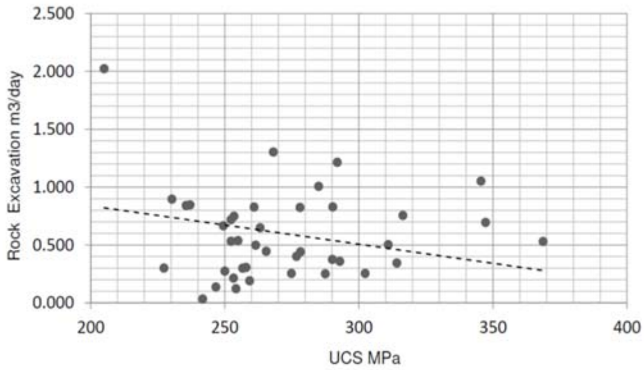

Figure 12 Diaphragm wall excavation rates Vs UCS

Just like bored piling operations, the type of d-wall machine used and wear of tools used in rock excavation influences the rock excavation progress and hence the project life cycle. It is important to note that when selecting the appropriate equipment for Bukit Timah Granite, other factors such as abrasively, rock mass quality, weathering and grain structure of the rock, presence of boulders, etc. need to be taken into account besides just looking at UCS values.

4.3 Installation of piles/diaphragm wall panels through boulders

Boulders are commonly encountered in Bukit Timah formation and sizes of boulders can vary significantly. In most of the boulder encounters, the boulders are embedded in soil which can be simply drilled through/break them. However in some instances, the boulders are loose and pushed to the side of the borehole by the drill bit and are difficult to cut through/break. In such cases, where boulders that do not offer any resistance underneath the drill bit, they are retrieved from the borehole/trench by a grab from surface. In some cases concrete is poured in the bottom-of-hole/trench at the boulder layer and after the concrete has hardened, it keeps the boulders firmly in place so that it can be continued to drill-through using normal procedure. Encountering of loose boulders was not observed frequently, but where they encountered has affected the drilling rates during the installation works.

4.4 Bulk Excavation

For bulk excavations where the rock head level is higher than the final formation level, excavation of the strong to very strong granite could only be achieved by controlled blasting. In an urban setting with sensitive buildings around the excavation site, vibration limits due to blasting has to be set within the allowable statutory limits. This meant that the charge rate to be used for the controlled blasting is limited to no more than 2kg per shot hole. Each blast is also limited to a depth of 3m, thereby slowing the bulk excavation works. The blasting work is also limited to no closer than 3m to 5m from kingposts. The rocks around the kingposts were removed using mechanical means. Shin et al (2011) have presented the application of deck blasting with electronic detonator as an alternative approach to conventional blasting. For TBM launching shaft along Upper Buki Timah Road where Granite rock to be excavated is more than 20m deep with UCS of 200MPa, use of conventional blasting would take a longer time as only two blasts are allowed per day due to proximity of buildings. Triple deck blasts with electronic detonators were used (Shin et al 2011) in place of conventional blasting. This method reduced the excavation time significantly. Excavations in the hard Bukit Timah Granite always pose a great challenge and the use of this new blasting technique increased the productivity of excavating in hard rock.

4.5 Groundwater ingress

Because of the undulating nature of the Bukit Timah Granite, one of the major construction challenges is controlling the ingress of groundwater and ground loss at the soil-rock interface. This is particularly problematic where the rock head is higher than the formation level. The supporting ERSS walls do not necessarily penetrate sufficiently deep enough to act as a cut-off wall. Fissure grouting was used to try to reduce the water flow through granite fractures. However, fissure grouting was not fully effective since the direction and penetration of grout could not be controlled. This resulted in water draw down extending to a wider area than originally predicted.

Another potential problem is that blasting during excavation could open up the fissures that were previously grouted up during the initial phase of fissure grouting. However, this effect could not been measured and observed, unless further studies are conducted.

4.6 Bored tunneling

During the bored tunneling along the stretch between Upper Bukit Timah Road and Bukit Timah Road, boulders were encountered within the residual soil and at the interface between soil and rock. The boulders encountered were of various shapes, sizes and strengths, some of the large pieces of boulders remained at the front of TBM and revolved with cutter head. This resulted in damage to the cutter discs and often clogging up the entrance of crusher chambers. TBM drives were slowed down due to these blockages and it required the stripping down of pipelines, pumps and crushers to unclog and remove the blockages, resulting in TBM downtime. Cutter head interventions had to be carried out to clear the blockages and repair the cutter head, including replacing slit control brackets and modifying slurry lines. From DTL2 tunneling experience it can be concluded that identification of boulders from borehole investigations data is not conclusive. It is difficult to quantify and identify boulders during soil investigation because the boreholes are small in size as compared to the boulders, so it is likely that they will be missed out from the soil investigations. Bored tunneling should therefore consider the likelihood of encountering of boulders when tunneling through Bukit Timah Formation. Some of these boulders were cored and UCS tests carried out indicated strengths as high as 177 MPa.

5. CONCLUSION

The Bukit Timah Granite Formation is one of the oldest geological formations in Singapore and is found mostly in the central and northern parts of Singapore. The weathering of the Bukit Timah Granite is gradational with stratified layers and sharp boundary between completely weathered layer (GV) and moderately weathered granite (GIII) is often observed. Based on the data of more than 700 boreholes drilled, the deepest depth of Bukit Timah Granite is located at 62m below the ground surface at 'Fourth Avenue' along Bukit Timah Road and the shallowest depth is located at 3m below the ground level at Jalan Gali Batu along the Woodlands Road.

From several deep excavations in Singapore Bukit Timah Granite formation, the most common feature observed is the encountering of boulders which are frequently found at the soil-rock interface. Occasionally these boulders are found within the residual soils. Boulders of various sizes were found during the excavation and bored tunneling through Bukit Timah Formation and boulders of more than 6m in size were found within the residual soils.

Generally higher UCS values are obtained in southern areas of Bukit Timah Granite Formation such as Newton and Stevens areas compared to the western and northern Parts such as Woodlands and Upper Bukit Timah. There appears to be some relationship of these differences in strength with two distinct groups such as Central Singapore Granite and Pulau Ubin Granite as discussed in Singapore Geology (1976). However, further detailed studies are necessary to confirm this difference.

Site specific correlations were developed between UCS and PLT, the correlation factor for Bukit Timah Granite varies across the sites in the range of 8-18. Based on the available results, it is recommended that for the selection of construction equipment, a correlation factor of 10 for northern areas and 18 for southern areas to be used for UCS values measured from Point Load Index tests.

Based on the drilling rates of bored piles and diaphragm walls, it was found that drilling rates not only depend on rock strength but on the quality of rock mass. For rock which is highly fractured and heavily jointed, they can be excavated easily compared to less fractured rock of the same strength. The type of machinery and equipment used including wear of tools in rock excavation influences the excavation process and hence the project life cycle. It is therefore essential to note that when selecting the appropriate drilling or excavation equipment for Bukit Timah Granite, other factors such as abrasivity, rock mass quality, weathering and grain structure of the rock, presence of boulders, etc. need to be taken into account besides just looking at UCS values. . Experiences of bored tunneling through Bukit Timah Granite indicated that boulders can be frequently expected and site investigation data alone is not sufficient to identify them.

6. REFERENCES

Goh, K.H., Lim, T.F., Chen, D.C and Wen, D. (2014) Excavation and temporary retaining wall systems for the stations and c/c tunnels of Downtown line.

ISRM Commision on Testing Methods. 1985. Suggested Method for Determining Point Load Strength. International Journal of Rock Mechanics, Mineral Sciences and Geo-mechanics. Abtract 22: 51-60.

Kahraman, S., Bilgin, N and Feridunoglu, C (2003). Dominant rock properties affecting the penetration rate of percussive drills. International Journal of Rock Mechanics & Mining Science Vol 40, pp 711-723.

Kasling, H. (2000). The Cerchar Scartch test: Value and possibilities for improvement of a index test fr rock abrasivity. 47p, diploma thesis TU Munich.

McChesney, S.A and Maw, M. (2011). Past experience on subsurface ground condition of Bukit Timah Granite formation in Circle Line Contract 854. Proceedings of the Underground Singapore Conference 2011. pp 189-195.

Plinninger, R.J. (2010). Hardrock abrasivity investigation using the Rock Abrasivity Index(RAI). Geologically Active-Williams et al (eds). Taylor & Francis Group, London.

Plinninger, R.J. (2002). Klassifizierung and Prognose von Werkzeugverschleib bei konventionellen Gabrigslosungsverfahern imFestgestein – Muncher GeologischeGefte. Reihe B: Angewandte Geologie B17, 146p.

Rusnak, J and Marck, C. (2000). Using the point load test to determine the uniaxial compressive strength of coal measure rock. Proceedings of 19th International Conference on Ground Control in Mining, Morgantown, West Virginia. Pp 362-371.

Shin,C.O., Ko, T.Y., Lee,S.C., Cho,M.S., Yoon,J.W., Lee,H.S., Hoblyn,S., and AW,E.M. (2011). Application of multiple – deck-charge blasting with electronic detonator at DTL2 Contract 915 in Singapore. Proceedings of the Underground Singapore Conference 2011, pp 208-214.

Shirlaw, J.N., Hencher, S.R & Zhao, J. (2000).Design and Construction issues for excavation and tunneling in some tropically weathered rocks and soils. Proceedings of International Symposiums on Geotechnical Aspect of Underground Construction in Soft Ground, London, 15-17 April 1996: 713-718. Rotterdam:Balkema.

Shumacher, L. (2004). Auslegung and Einsatzbedingungen von Tunnelvortriebsmaschinen im Hartgestein – Felsbau, 22, 3:21-28, Essen.

Singapore Geology (1976). The geology of the Republic of Singapore. Singapore Public Works Department, 1976.

West, G. (1989): Technical Note-Rock abrasiveness testing for Tunneling . International Journal of Rock Mechanics Mining Science & Geomech Abstract ., 26: 151-160.

Zhao, J., Lee, K.W and Chao, V (1995). Construction and utilization of rock caverns in Bukit Timah Granite of Singapore. Geotechnical Engineering monograph 1, NTU-PWD Geotechnical Research Centre.

Zhao, J., Broms,B,B., Zhou,Y., and Chao, V (1994). A Study of the Weathering of the Bukit Timah Granite part B: field and laboratory investigations. Bulletin of the International Association of Engineering Geology, Paris No. 50.

Zhou, Y (2001). Engineering Geology and Rock Mass Properties of the Bukit Timah Granite. Proceedings of the Underground Singapore Conference 2011. pp 308-314.