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Influence of physico-mechanical properties of tuff on penetration rate – a case study in Southern Johor Bahru, Malaysia

The relationship between physico-mechanical properties of tuff and penetration rate of air percussion drilling was investigated during an exploratory well drilling work at Southern Johor Bahru. The rocks were tested for weathering grade, average grain size, porosity, quartz content and point load strength test. The penetration rate was found to increase linearly with an increase in weathering rate, average grain size and porosity. Meanwhile, it decreases dlinearly with an increase in quartz content and point load strength index. The coefficient of determination, R^2 between weathering grade, average grain size, porosity, quartz, point load strength index and penetration rate were found to be 0.4875, 0.1838, 0.0186, 0.0863 and 0.6324 respectively in simple linear regression analysis. The findings from a multivariate regression analysis showed good correlation (R^2=0.79) between the tested parameters and penetration rate of tuff.

Keywords: *Tuff, weathering grade, average grain size, porosity, quartz, point load strength index, penetration rate.*

1.0 Introduction

The drillability of rock has always been a great interest for engineers. It is defined as control of a set of parameters on penetration rate and bit wear of the drilling rig (Altindag, 2004). The factors controlling the drillability is classified into three as in Fig.1. In general, a combination of parameters was correlated to penetration rate to evaluate the drillability. Many researches have evaluated the relationship of physico-mechanical parameters and penetration rate (Grattan-Bellew and Vijay, 1986; Kahraman, 2003; Bilim, 2011; Shaabani et al., 2016).This study focuses on the relationship between physio-mechanical properties of rock such as weathering grade, average grain size, porosity, quartz content and point load strength index with penetration rate.

Sugawara et al. (2003) has studied on relationship between weathering grade and penetration rate. The penetration rate increases with increasing weathering grade. Next, the penetration rate increases with increasing average grain size in general. A linear relationship is determined by Grattan-Bellew and Vijay (1986) while Altindag (2003) found an exponential relation. In addition, a linear relationship exists between the regression of average grain size to penetration rate (Adebayo and Akande, 2011). Next, porosity has a good correlation with the penetration rate (Demirdag et al., 2014). The penetration rate increased with an increase in porosity (Bilim, 2011; Thuro, 1997). Also, according to Adebayo and Akande (2011), a linear relationship exists between the regression of porosity and penetration rate.

Hassan et al. (2019) studied the relationship between mineral composition, uniaxial compressive strength and penetration rate. It was found that penetration rate reduces with increasing uniaxial compressive strength which is directly proportional to quartz content. It must be noted that the quartz showed a great relationship with uniaxial compressive strength compared to kaolinite and feldspar. Hence, quartz content is a significant parameter to predict drillability. Jethro et al. (2014) found an inverse linear relationship between quartz equivalent content and penetration rate. Correspondingly, Adebayo and Akande (2011) determined a linear correlation between the regression of quartz proportion and penetration rate.

Furthermore, the point load strength test has shown great correlation with penetration in previous studies. Jethro et al.(2014) found a linear relation while Bilim(2011) and Adebayo and Mukoya (2019) found regression of power. The relation between these parameters and the penetration rate has been summarised in Table 1. It can be seen vividly that these five parameters such as weathering grade, average grain size, porosity, quartz content and point load strength test have significant control on penetration rate. A case study was

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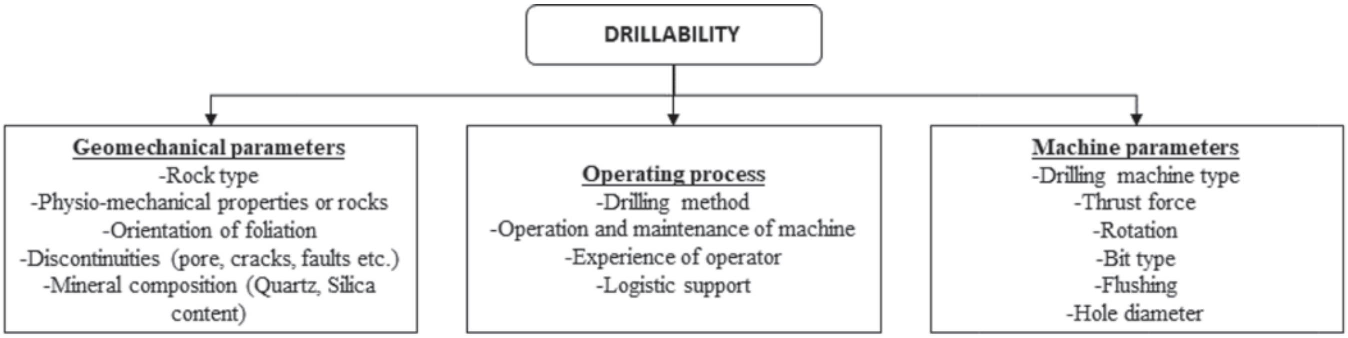

Fig.1. Classification of parameters controlling drillability (modified from Altindag (2003))

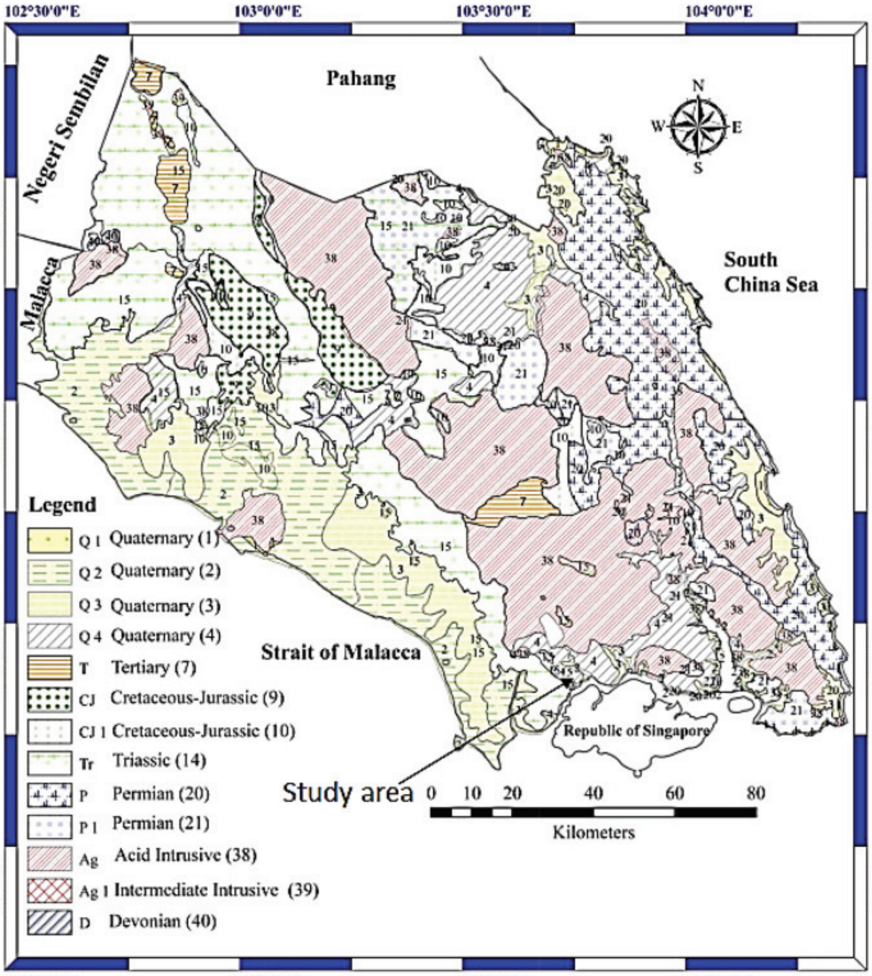

Fig.2. Geology of study area (Saleh et al., 2015)

conducted in Southern Johor Bahru to understand the relationship of these parameters and penetration rate of tuff using air percussion drilling.

2.0 Methodology

This study includes field and laboratory works. The penetration rate was monitored at the study area for air percussion drilling. Besides, the weathering grade of drilled fragments were determined at site. Then, the collected samples were brought to laboratory for further testing such as petrography, porosity, point load test.

2.1 Study area

Fig. 2 shows the location of study area. It is underlain by Jurong formation which consists of two members such as Bukit Resam Clastic Member and Gunung Pulai Volcanic Member (Burton, 1973). The Bukit Resam Clastic Member consists of interbedded sandstone and shale with subordinate conglomerate. Meanwhile, the Gunung Pulai volcanic member consists mainly of tuff. Older alluvium, a partly consolidated flat-lying formation overlays Jurong formation towards south. This study focuses on tuff foundin Gunung Pulai volcanic member.

2.2 Weathering grade (Table 2)

The weathering grade of drilled fragments were determined at field based on weathering classification of International Society of Rock Mechanics (ISRM) (1981).

2.3 Petrography

The drill fragments collected from the field were sent to the laboratory for preparation of thin section. Upon preparation, the thin section for tuff was viewed under the polarizing microscope. Few photomicrographs were taken. They were used to measure the average grain size. Then, the mineral composition was estimated.

2.4 Porosity

The porosity is determined using saturation and buoyancy technique as the rock sample was irregular in shape. The rock samples were saturated by water immersion in vacuum of approximately 800 Pa for an hour. Then, the

Table 1. Summary of relationship between weathering grade, average grain size, porosity and quartz content, point load strength test and penetration rate

Parameter	Author (Year)	Rock type	Equation	R^2
Weathering grade	Sugawara et al. (2003)	Soil and rock	Penetration rate increases with increasing weathering grade	-
Average grain size	Grattan-Bellew and Vijay (1986)	Granite, Quartz Diorite Amphibolite Norite Sandstone	$D = 0.8166 + 0.02222L$ where, D = Penetration rate; L= Grain size	0.74
	Altindag (2003)	Limestone	$PR = 0.9185e^{0.2795d}$ where, PR = Penetration rate; d = Mean particle size	0.81
	Adebayo and Akande (2011)	Granite	$PR = 3.52 – 1.004AVG1 - 1.129AVG2 - 1.554AVG3$ where, PR= Penetration rate; AVG1 = Average grain size for feldspar granite; AVG2 = Average grain size for biotite hornblende granite; AVG3 = Average grain size for coarse biotite granite	0.84
Porosity	Thuro (1997)	Sandstone	$y= 1.83 + 0.12x$ where, y = Penetration rate; x = Porosity	0.98
	Bilim (2011)	Andesite Marble Tuff Limestone Travertine	$y = 4.8693x^{0.5889}$ where, y = Porosity; x = Penetration rate	0.537
	Adebayo and Akande (2011)	Granite	$PR = 16.620 – 8.159n1 + 1.004n2 – 11.876n3$ where, PR= Penetration rate; n1 = Porosity of feldspar granite; n2 = Porosity of biotite hornblende granite; n3 = Porosity of coarse biotite granite	0.90
	Demirdag et al. (2014)	Marble	For vertical drilling: $y = 16.365e^{0.0431x}$; For horizontal drilling: $y = 13.066e^{0.0443x}$ where, y = Penetration rate; x= Porosity	For vertical drilling: r = 0.98; for horizontal drilling: r = 0.96
Quartz content	Adebayo and Akande (2011)	Granite	$PR=–211.163+0.657QZ1+0.937QZ2+2.380$ Where, PR= Penetration rate; QZ1= Quartz content of feldspar granite; QZ2= Quartz content of biotite hornblende granite; QZ3 = Quartz content of coarse biotite granite	0.83
	Jethro et al. (2014)	Migmatite Gneiss	$PR= –0.029QEC + 3.167$, where, PR = Penetration rate; QEC=Quartz equivalent content	0.767
Point load strength index	Jethro et al. (2014)	Migmatite Gneiss	$PR = 0.409PLS - 0.881$, where, PR= Penetration rate; PLS= Point load strength index	0.824
	Bilim (2011)	Andesite marble tuff limestone travertine	$y = 2.4836x^{–0.3373}$, where, y = Penetration rate; x = Point load strength index	0.844
	Adebayo and Mukoya(2019)	Gneiss Marble Interbedded marble and quartzite	$PR = 180.7PLI^{-0.60}$ where, PR= Penetration rate; PLI = Point load strength index	0.724

TABLE 2 WEATHERING GRADE CLASSIFICATION (INTERNATIONAL SOCIETY OF ROCK MECHANICS (ISRM), 1981)

Grade	Grade	Diagnostic Features
Fresh	I	No visible sign of decomposition or discoloration. Rings under hammer impact.
Slightly Weathered	II	Slight discoloration inwards from open fractures. Otherwise similar to F.
Moderately Weathered	III	Discolored throughout. Weaker minerals such as feldspar discomposed. Strength somewhat less than fresh rock but cores cannot be broken by hand or scraped by knife. Texture preserved.
Highly Weathered	IV	Most minerals somewhat decomposed. Specimens can be broken by hand with effort or shaved with knife. Core stones present in rock mass. Texture becoming indistinct but fabric preserved.
Completely Weathered	V	Mineral decomposed to soil but fabric and structure preserved (Saprolite). Specimens easily crumbled or penetrated.
Residual Soil	VI	Advanced state of decomposition resulting in plastic soils. Rock fabric and structure completely destroyed. Large volume change.

sample was immersed in the beaker. The saturated-submerged mass, M_{sub} was determined using equation 1. Later, a small container with lid was washed and air-dried. The mass of the container with lid, M_A was measured. The sample was removed from beaker and surface-dried. The sample was placed in the container. The mass of the container with lid and sample, M_B in it was measured. The lid was removed and the container with lid and sample was kept in oven at 105°C for 24 hours. Finally, the mass of container with lid and air-dried sample, M_C was measured after the sample cooled down to room temperature. The porosity, n (%) shall be determined using the equations 2-6.

Saturated-submerged mass, M_{sub} (g)= $M_{beaker+sample} - M_{beaker}$ ... (1)

where,

$M_{beaker+sample}$ (g) = Mass of beaker with sample

M_{beaker} (g) = Mass of beaker

Saturated-surface dry mass, M_{sat} (g)= $M_B - M_A$ ... (2)

where,

M_B (g) = Mass of the container with lid and sample

M_A (g) = Mass of the container with lid

Grain weight, M_s (g) = $M_C - M_A$ ... (3)

where,

M_C (g) = Mass of container with lid and air-dried sample

Bulk volume,V (cm^3)= $M_{sat} - M_{sub} / \rho w$ ... (4)

Pore volume, V_v (cm^3)= $M_{sat} - M_s / \rho w$ ... (5)

Porosity, n (%) = $100V_v/V$ ... (6)

2.5 Point load test

The point load test was carried out on collected lump samples of tuff. The samples were checked for suitability based on Franklin (1985). The specimen was inserted into the testing machine. The platens were closed to make contact with the smallest dimension of sample. Distance, D between platen contact points and the smallest specimen width, W perpendicular to the loading direction were measured. The load was steadily increased until failure occurs. The failure load, P was recorded. Then, Point Load Strength Index, $I_{s(50)}$ was calculated using the Equation 7-10.

Uncorrected poin load strength, $I_s = P/D_e^2$ ... (7)

where,

$D_e^2 = 4WD/\pi$ (for lump samples) ..(8)

$I_{s(50)} = F \times I_s$ ... (9)

where,

$F = (D_e/50)^{0.45}$ ... (10)

3.0 Results and discussion

Firstly, borelog and photomicrographs are discussed. Then, simple linear regression analysis for weathering grade, average grain size, quartz content, porosity and point load strength to penetration rate was carried out. Later, multivariate regression analysis was carried out.

3.1 Borelog

The borehole logs are shown in Fig.3. The thickness of clay is from 12m to 28m. Two types of tuff such as greyish crystal tuff and reddish rhyolitic were encountered at 28m and 88m-112m respectively. Quartzite was encountered in borehole 2. The distance between both boreholes are approximately 1.6km.

As the study focuses on physio-mechanical properties of tuff, only its photomicrographs are shown in Figs.4 (a) and (b). Fig.4(a) shows almost all phenocryst within sample are composed to quartz crystal. The embayment texture indicated rock of volcanic origin. Quartz is surrounded by very fine grain microcrystalline groundmass and the feldspar has been fully altered by secondary mica in Fig.4(b).

3.2 Simple linear regression analysis

The penetration rates were correlated to weathering grade, average grain size, quartz content, porosity and point load strength index by using simple linear regression analysis. The equation for best-fit line and correlation coefficient (R^2) were determined for each parameter. First of all, the relationship between weathering grade and penetration rate was examined. The weathering grade ranges from Grade II to Grade III. It shows that the penetration rate increases linearly with increasing weathering grade as in Fig.5. The trend is similar to Sugawara et al. (2003) and the relation can be expressed as in equation 11.

$PR = 1.6512(WG) - 0.2035, R^2 = 0.4875$ ... (11)

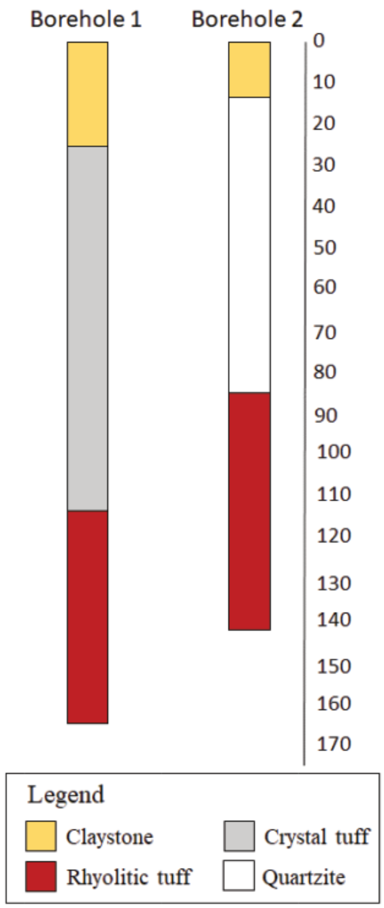

Fig.3. Borehole logs

where,

PR = Penetration rate

WG = Weathering grade

The average grain size of tuff ranged from 0.4mm to 2mm. The penetration rate increases with increasing average grain size. A linear relationship can be seen between average grain size and penetration rate with R^2 of 0.1838 as in Fig.6. It shows that this parameter has weak relation unlike other researchers such as Altindag (2003) (R^2= 0.81) and Adebayo and Akande(2011) (R^2= 0.84). The relation can be expressed as in equation 12.

$$PR = 0.3282(AVG) + 2.798, R^2 = 0.1838 \quad \text{... (12)}$$

where,

AVG = Average grain size (mm)

The quartz content is ranged between 10% and 35% for tuff. The penetration rate decreases linearly with increasing quartz content as in Fig.7. The correlation is weak with R^2 of 0.0186 compared to Jethro, et al. (2014) (R^2 = 0.767) and Adebayo and Akande (2011) (R^2 = 0.83). The relation can be expressed as in equation 13.

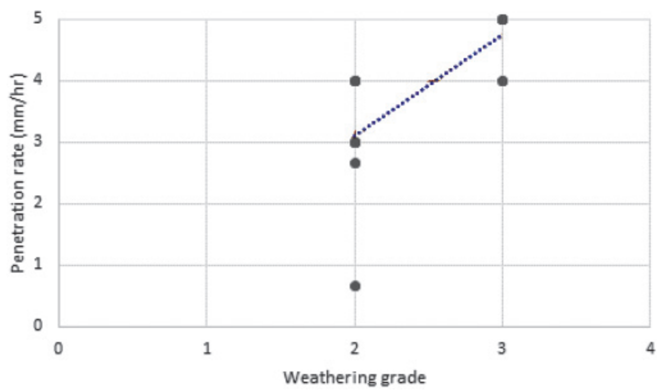

Fig.5. Graph of weathering grade vs penetration rate

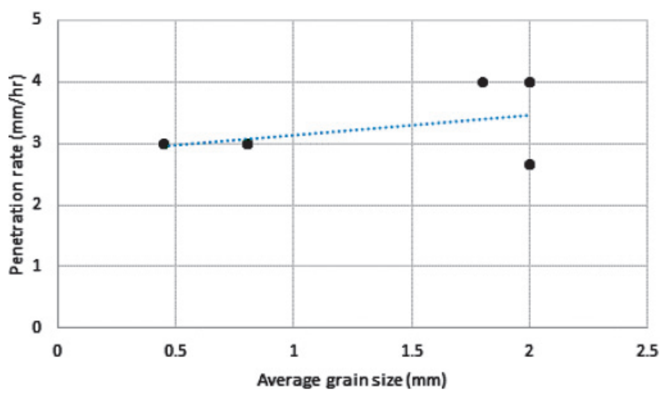

Fig.6. Graph of average grain size vs penetration rate

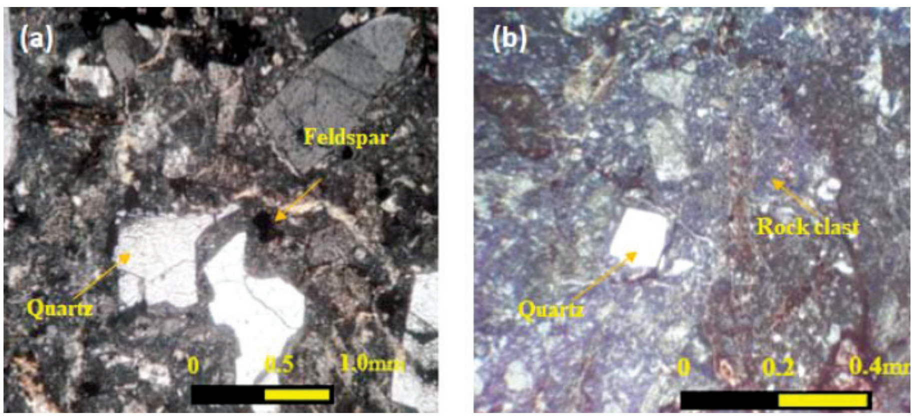

Fig.4 Photomicrograph of (a) rhyolitic tuff; (b) crystal tuff

$$PR = -0.0167(QC) + 4.1399, R^2 = 0.0186 \quad \text{... (13)}$$

where,

QC = Quartz content (%)

Next, relation between porosity and penetration rate was examined. The porosity of tuff ranged from 2.82% to 4.37%. It was found that the penetration rate increases with increasing porosity as in Fig.8. A poor linear relationship (R^2 = 0.0863) was seen between porosity and penetration rate. The correlation is

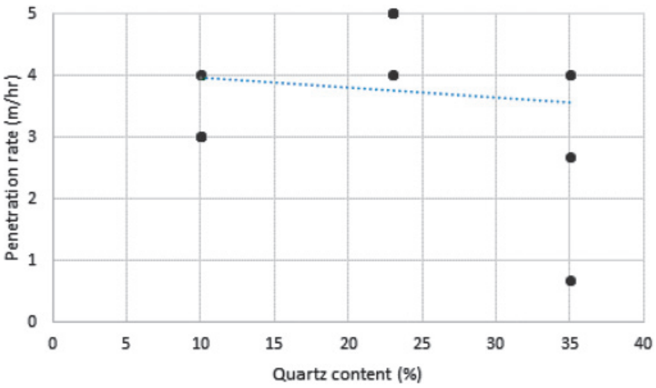

Fig.7. Graph of quartz content vs penetration rate

weaker compared to study carried out on tuff by Bilim (2011) ($R^2 = 0.537$) as well as other rock types (Adebayo and Akande, 2011($R^2 = 0.90$); Demirdag et al., 2014 (R^2 = 096-0.98)).

$$PR = 0.2848(P) + 2.8325, R^2 = 0.0863 \quad \text{... (14)}$$

where,

P = Porosity (%)

The penetration rate decreases with point load strength index with R^2 of 0.6324 as in Fig.9. The point load strength index ranged from 0.9kN/m^2 to 2.55kN/m^2. It shows that this parameter has the best correlation with penetration rate when compared to other tested parameters in this study. The trend is linear and follows Jethro et al.(2014). However, there are also some studies with other trend but the correlation is good as well Bilim (2011) ($R^2 = 0.844$) and Adebayo and Mukoya (2019) ($R^2 = 0.724$).The relation can be expressed as in equation 15.

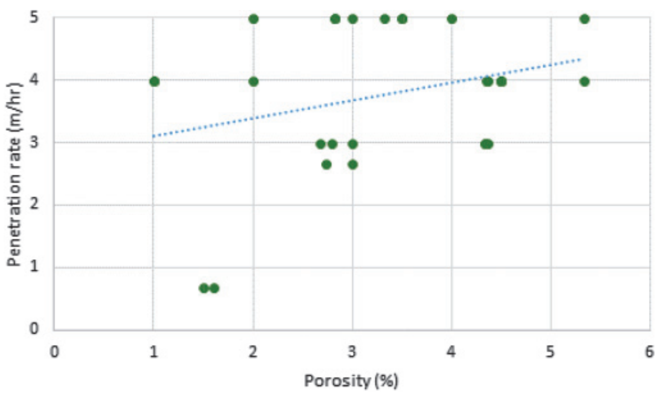

Fig.8. Graph of porosity vs penetration rate

$$PR = -1.4032(PLSI) + 6.3554, R^2 = 0.6324 \quad \text{... (15)}$$

where,

PLSI = Point Load Strength Index, $I_{s(50)}$ (kN/m^2)

In general, it was found that the relationship of tested parameters and penetration rate is in line with previous studied. However, unlike previous studies, the correlation coefficient of all parameters determined in this study is low to moderate only except for point load strength index. Hence, multivariate regression analysis was carried out in next section.

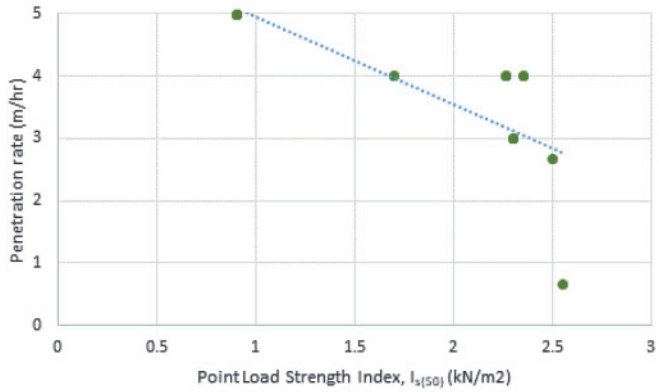

Fig.9. Graph of point load strength index vs penetration rate

3.3 Multivariate regression analysis

Figs.10 and 11 show relationship between all tested parameters and penetration rate along the boreholes 1 and 2 respectively. The increase in rock strength, reduction of porosity and grain size caused reduction of penetration rate at 90m in borehole 1. Next, the change in weathering grade from grades III to II, reduction in grain size and porosity seemed to further reduce the penetration rate at 138m in the same borehole. Meanwhile, in borehole 2, the reduction of

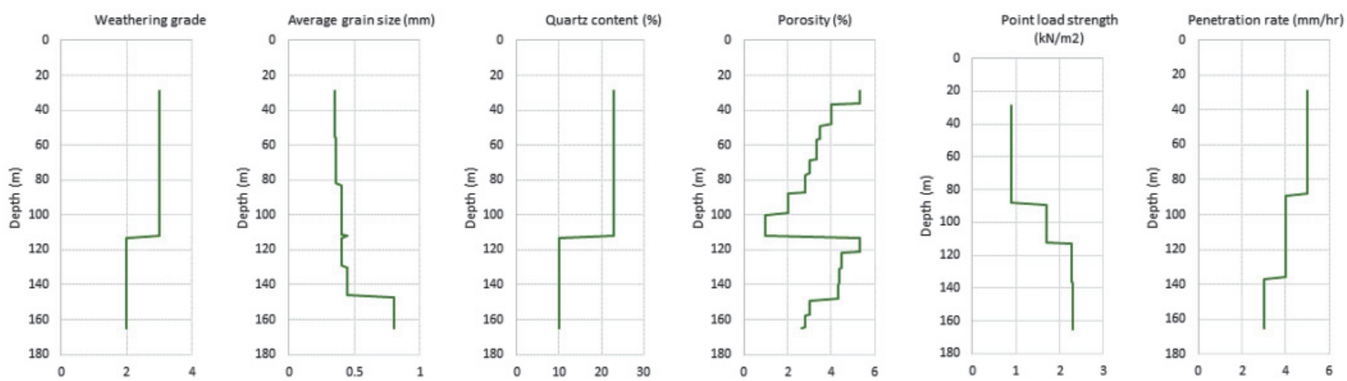

Fig.10. Relationship between all parameters and penetration rate of tuff along borehole 1

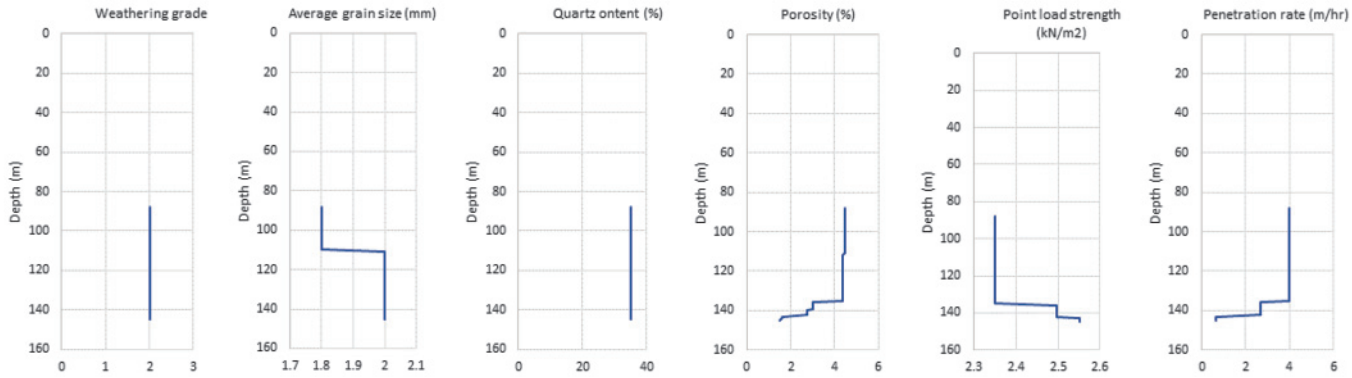

Fig.11.Relationship between all parameters and penetration rate of tuff along borehole 2

porosity and increase in strength of rock showed slight reduction in penetration rate at 138m and 142m. Hence, in general, all the tested parameters showed control on penetrate rate at different magnitude. A multivariate regression analysis was carried to determine the control of multiple physico-mechanical properties of tuff on penetration rate. The relation can be expressed as in equation 16. This analysis showed a great correlation ($R^2 = 0.79$) between the parameters and penetration rate as in Fig.12.

$$PR = 1.279114WG - 0.277192AGS + 0.004945QC + 0.475353P - 0.416997PLIS \quad ... (16)$$

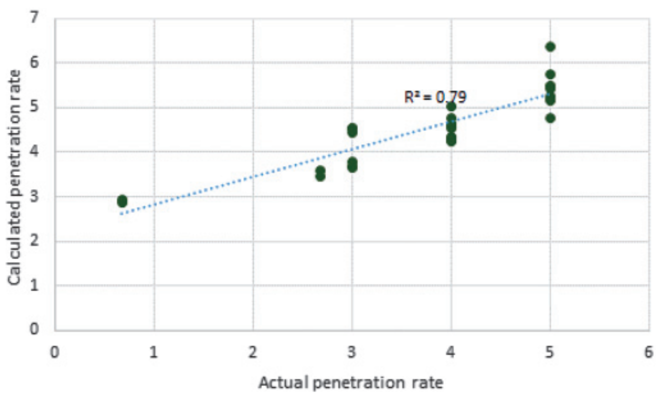

Fig.12. Graph of actual penetration rate vs calculated penetration rate of tuff

Conclusion

There are correlations between physico-mechanical properties of tuff such as weathering grade, average grain size, porosity, quartz content and point load strength index on the penetration rate. However, the simple linear regression analysis showed weak correlations compared to previous studies by other authors although the trend was similar. The penetration rate increases linearly with increasing weathering grade, average grain size and porosity. The penetration rate decreases linearly with increasing quartz content and point load strength index. Then, multivariate regression analysis was carried out. The findings showed better correlation among tested parameters and penetration rate ($R^2 = 0.79$). Further study is needed to improve the predictability of penetration rate of tuff.

Acknowledgement

The authors would like to express their appreciation for scholarship support of Zamalah Scholarship of Universiti Teknologi Malaysia and financial support of Vot No. 04G15 of UTM – COE grant.

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2.	Periodicity of its publication	... Bi-monthly
3.	Printer's Name	... Pradip Kumar Chanda
	Whether citizen of India ?	... Indian Citizen
	Address	... 62 Lenin Sarani, Kolkata 700 013
4.	Publisher's Name	... Pradip Kumar Chanda
	Whether citizen of India ?	... Indian Citizen
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