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In-situ Stress Measurement by Overcoring and Hydraulic Fracturing of Pahang-Selangor Raw Water Transfer Project

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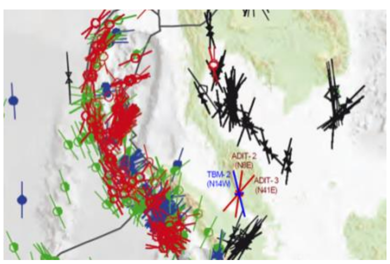
Graphical abstract



Abstract

Estimation of in-situ stress orientation and magnitude is necessary for assessing the excavation risks for Pahang-Selangor Raw Water Transfer (PSRWT) tunnel project. However, the in-situ stress state of the rock generally differs according to area and depth. Therefore, the in-situ stress measurements test in the tunnel are determined in three (3) locations, which are at Adit 2, TBM 2, and Adit 3, in which the overburdens are 227, 1130, and 570 m, respectively. The stress relief method of overcoring technique and hydraulic fracturing by high stiffness system were applied for this project. The results demonstrate that the existence of high vertical stress was estimated in particular in the TBM 2. The maximum principal stress is determined nearly along the vertical direction. Meanwhile, the stress in the horizontal plane is relatively small, and the horizontal to vertical stress ratio is less than one (1). The direction of the horizontal stress obtained is N8E, N14W, and N41E. Results indicate that this method is suitable for estimating in-situ stresses in deep tunnels. The above data and their interpretations enhance the stress database for Peninsular Malaysia.

Keywords: In-situ stress measurement; tunnel; overcoring; hydraulic fracturing

Abstrak

Penganggaran orientasi dan magnitud tegasan di-situ adalah perlu bagi menilai risiko penggalian terowong untuk projek Penyaluran Air Mentah Pahang-Selangor (PSRWT). Walau bagaimanapun, tegasan di-situ sesuatu batuan lazimnya adalah berbeza mengikut keadaan kawasan dan kedalaman tertentu. Oleh itu, ujian pengukuran tegasan di-situ telah dijalankan di tiga (3) lokasi iaitu Adit 2, TBM 2 dan Adit 3 dimana masing-masing mempunyai kedalaman 227 m, 1130 m dan 570 m. Kaedah legaan tegasan, teknik lampau terasan dan peretakan hidraulik dengan sistem kekakuan tinggi telah digunakan bagi projek ini. Keputusan ujian menunjukkan tegasan tegak yang tinggi terutamanya di TBM 2. Tegasan utama maksimum adalah selari dengan arah graviti. Manakala tegasan pada satah datar adalah kecil dan nisbah perbandinagn antara tegasan datar dan tegasan pugak adalah kurang daripada satu (1). Arah tegasan sisi yang diperolehi adalah N8E, N14W dan N41E. Keputusan menunjukkan kaedah ini adalah sesuai untuk penganggaran tegasan di-situ bagi terowong yang dalam. Data di atas dan tafsirannya dapat menambah data tegasan bagi Semenanjung Malaysia.

Kata kunci: Pengukuran tegasan di-situ; terowong; lampau terasan; peretakan hidraulik

1.0 INTRODUCTION

The estimations of in-situ stress magnitude and orientation, represents important engineering parameters required to accurately evaluate the behaviour of underground excavations. In-situ stress measurement refers to the techniques used for determining stress conditions with some kind of physical measurement collected in-situ. However, in-situ stresses are often not well defined because of the inadequate amount of the collected stress information. Therefore, many countries have compiled stress databases that are publicly accessible. For example, the World Stress Map (WSM) project is an online tool that allows quick access to a large database containing in-situ stress measurements collected around the world [1]. Initially, the majority of these measurements are located near the ground surface and only 1.9 % of the records are derived from hydraulic fracturing and overcoring [2]. Hence, applying database trends for predicting in-situ stresses at higher depths can be statistically challenging [3].

Numerous methods exist for in-situ stress measurement including mechanical, geophysical and geological method. Hudson *et al.* [4] proposed direct and indirect methods to solve the problem of in-situ stress in rock engineering. Although there are many indirect ways of analysing in-situ stress [5], the applications of those methods in deep tunnels are rather limited and require improvement. This is largely due to restriction of theoretical hypothesis and data integrity requirements.

The methods for stress measurements used in civil engineering applications are hydraulic fracturing, overcoring, borehole slotting and flat jack. Most common methods include hydraulic and relief methods. The ISRM has published suggested methods for estimating rock stress [6-10] for the basic principles of overcoring and hydraulic fracturing.

In this study, the In-situ stress orientation and magnitude had to be accurately estimated to determine and assess the excavation stability for a more efficient tunnel excavation in the Pahang-Selangor Raw Water Transfer Project. The estimation of the initial stress state along the planned route of the water transfer tunnel were carried out at the junctions of the water transfer tunnel in Adit 2 and Adit 3, prior to the commencement of TBM excavation. In order to assess the potential of rock burst and spalling failure particularly at the overburden depth more than 1000 m, the measurements test was conducted at TBM 2, at the middle stage of the tunnel excavation.

2.0 PROJECT BACKGROUND

2.1 Project background

The Pahang-Selangor Raw Water Transfer Tunnel Project is aimed to transfer raw water from the river in Pahang to Selangor State through a transfer tunnel, which is 5.2 m in diameter and 44.6 km in length. A tunnel boring machine (TBM) is primarily used for the excavation at about 35 km of the whole tunnel length. More than 40 % of the tunnel is at depth greater than 800 m. The tunnel traverses under the Main Range on the border between Pahang and Selangor States. The highest peak in the Main Range is at 2183 m, which is about 1350 m above sea level along the tunnel route.

2.2 Geological Description

Figure 1 shows the general geology along the tunnel consists of Karak Formation from the inlet to Chainage (Ch.) 4.0 km which is made up of metasediments such as schist, phyllite, and hornfels. From Ch. 4.0 km to the other end of the tunnel, the geology consists of granite with small sections of Hawthorndon Schist. The tunnel alignment is intersected by several faults with a strike essentially N-S, but with increasing occurrence of NW-SE along the western of the tunnel. The faults are generally indicating a general tensional state of stress in the central part of the range. There are also several lineaments that have been identified from regional topographic trends such as stream channels. The faults and lineament appear to be integral parts of the granite emplacement, uplift and alteration.

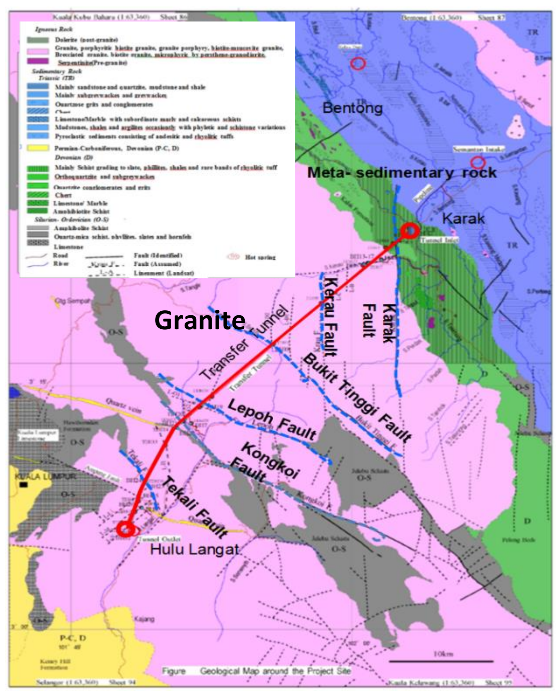


Figure 1 Geological condition along the tunnel alignment [11]

3.0 METHODOLOGY

The stress relief method of compact conical-ended borehole overcoring technique (CCBO) and hydraulic fracturing (HF) method by high stiffness system were applied for this project. The in-situ stress measurements in the tunnel are determined in three locations (Figure 2), which are at TBM 1 (Adit 2), TBM 2, and TBM 3 (Adit 2). The CCBO method was carried out at these locations. The CCBO and HF methods were conducted the same area of the end parts of Adit 2. Comparison between these methods was made for reliable result of the measurement.

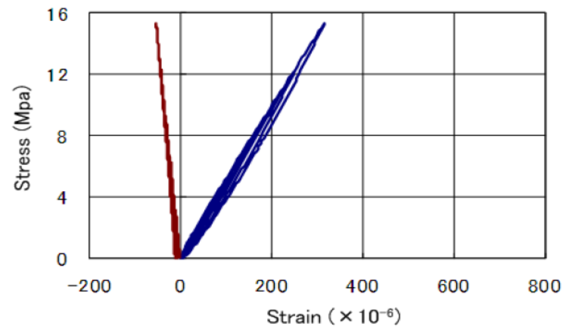


Figure 3 Example of stress-strain relation

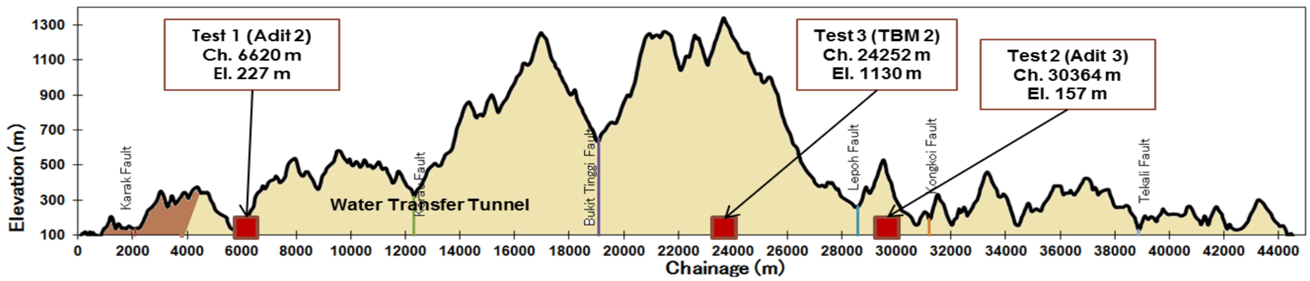


Figure 2 In-situ stress test locations

3.1 Uniaxial Compressive Test

In the stress measurement by CCBO, It is extremely important to evaluate elastic ratio of rock correctly as well as accuracy measurement of in-site released strain. This is because the calculated stress strongly depends on elastic constant such as Young's modulus, Poisson's ratio as strain at stress released is measured by the stress-relief method. The uniaxial compressive test is carried out for the evaluation of the elastic constant, nonlinearity and anisotropic of the rock. In addition, rock was treated as linear elastic mediums as long as estimated in-situ stress by check of response to cycle of loading and unloading on the rock. It is desirable that the specimen to use for laboratory test to be sampled from the core which is collected at every overcoring.

The test was carried out in 5 cycles of loading and unloading. The maximum loading stress at each cycle was raised, the each peak value of which was 3, 6, 9, 12, and 15 MPa. The maximum loading stress in the last cycle was taken from maximum strain measured at an overcoring in-situ as a guide. An axial strain and lateral strain were measured in the uniaxial compression test and a stress - strain curve as shown in Figure 3 is obtained, then Young's modulus and Poisson's ratio are determined.

3.2 Compact Conical-Ended Borehole Overcoring

The CCBO device for stress measurement was the subject of an ISRM suggested method published in 2003 [8]. It was carried out in 20m long with 76mm diameter borehole which is inclined 5° upwards. The strain cell was installed in bottom of borehole and overcored using a large diameter drill bit.

Overcoring releases sampled rock from the rock mass and in-situ stresses acting on it. Figure 4 shows the schematic drawing for CCBO.

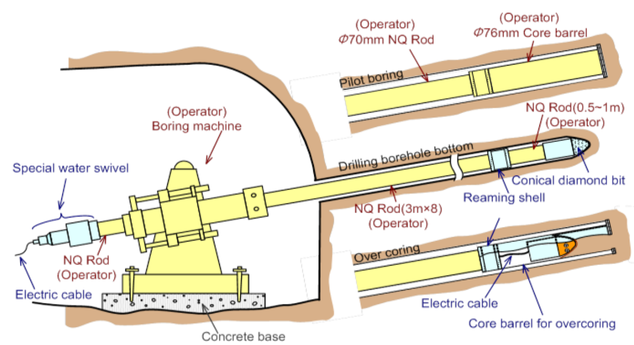


Figure 4 Schematic of detailed drilling tools for CCBO

The released strain is the value obtained from the relation of drilling depth and strain change during overcoring. The three-dimensional stresses σ_x, σ_y, σ_z, τ_{xy}, τ_{yz}, and τ_{zx} (Cartesian coordinates) were calculated based on elasticity theory, which were measured from recovered rock samples. The tangential, ε_θ, radial, ε_ρ, and oblique strains, $\varepsilon_\varnothing$, were measured at each strain measuring point, as shown in Figure 5.

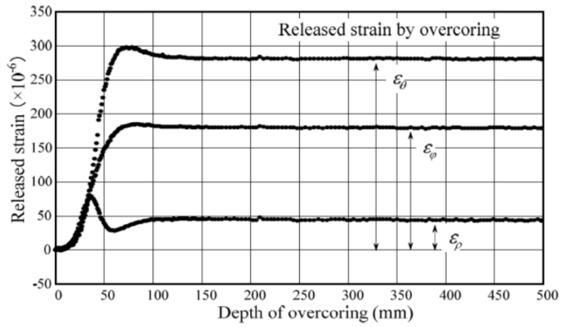


Figure 5 Example of strain change during overcoring

The relieved strains measured during overcoring are represented as $\{\varepsilon\}^T = \{\varepsilon_1, \varepsilon_2, ..., \varepsilon_n\}$ observation equation of the initial stress tensor is given as follows:

$$\{\varepsilon\} = \frac{1}{E}.[A].\{\sigma\} \quad (1)$$

where E is Young's modulus (measured from recovered rock samples) and the $[A]$ is an n by 6 elastic compliance matrix. The most probable values of the initial stress components are determined by the following equation:

$$\{\sigma\} = E \cdot [[A]^T \cdot [A]]^{-1} \cdot [A]^T \cdot \{\varepsilon\} \quad (2)$$

where the upper suffix -1 represents the inverse matrix.

The initial stress from the CCBO was calculated with the value of released strain and the values of Young's modulus and Poisson's ratio obtained from the laboratory test. The coordinate system used for analysing the data of stress measurement was a tunnel coordinate system. In this system, the outlet side of the tunnel was defined as plus on the x-axis, the horizontal left side of the tunnel toward the outlet was determined as plus on the y-axis, and the vertical upper part of the axis was interpreted as plus on the z-axis. In the relationship between the azimuth and this coordinate system, the direction rotating 135° clockwise from the positive side of the x-axis was *N* (true North).

3.3 Hydraulic Fracturing

The HF by high stiffness system is a method that has modified from conventional observation equation and measurement system ISRM Suggested Method 2003 [8]. Figure 6 shows the modified HF test system. The significant difference on this system from a conventional system is the stiffer stainless steel pipe for fluid circuit and a syringe pump for injection of fluid.

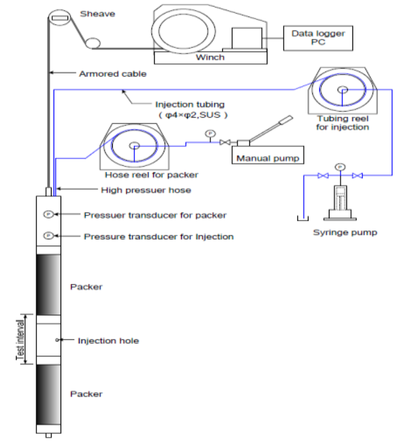


Figure 6 High stiffness system for HF test in deep boreholes

HF is a method to calculate an applied stress to open and close a new crack on rock from observed fluid pressure variation. When a borehole was drilled in a homogeneous isotropic elastic rock body, the distribution of stress on the two dimensional plane perpendiculars to the borehole axis will be shown as Figure 7.

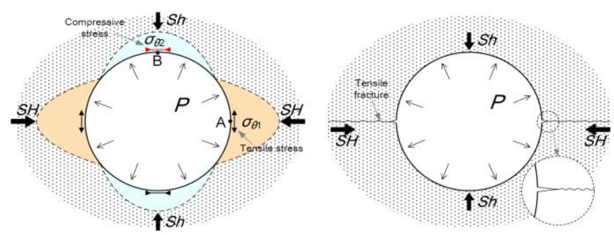


Figure 7 A schematic view of opening of the fractures around a borehole wall

Then, the stress $\sigma_{\theta 1}$ at point A that crosses to *SH* (σ_{Hmax}) axis and stress $\sigma_{\theta 2}$ that crosses *Sh* (σ_{Hmin}) axis will be described as follows:

$$\sigma_{\theta 1} = 3Sh - SH \quad (3)$$

$$\sigma_{\theta 2} = 3SH - Sh \quad (4)$$

Here, *SH* is the maximum initial principal stress and *Sh* is the minimum initial principal stress on the plane. Also, $\sigma_{\theta 1}$ will be smaller than $\sigma_{\theta 2}$ if the compressive stress is positive. Following the increasing of fluid pressure in the borehole, the tensile stress at point A will reach maximum, then a crack will form at a certain pressure. The breakdown pressure *Pb* will be described as equation below:

$$Pb = 3Sh - SH + T - Pp \quad (5)$$

where *T* for tensile stress of the rock, and Pp for the pore pressure of the rock. Next, re-opening pressure, *Pr*, is water pressure at the moment of fracture re-opening, that is caused by increasing water pressure again after a fracture closed by decreasing water pressure. *Pr* is expressed in equation below:

$$Pr = (3Sh - SH)/2 \quad (6)$$

at such time of re-opening, if tensile strength as $T = 0$, and pore pressure of the rock as *Pp* is equivalent to water pressure of fracture inside, *Pr*, that has opened once. In addition, it is assumed that the minimum principal stress *Sh* and water pressure are in equilibrium state in the process of a fracture closing slowly from tip at stopping the water injection suddenly after lengthened enough. The water pressure *Ps* (Shut-in pressure) at this time is expressed in Equation below:

$$Ps = Sh \quad (7)$$

These are the observed equation of hydraulic fracturing method based on the modified concept. The maximum principal stress SH and minimum principal stress Sh are obtained from two observed parameters *Pr* and *Ps*.

3.4 Estimation of In-Situ Stress

The gravitational vertical stress at a depth (z) is the product of the depth and the unit weight (γ) of the overlying rock mass. The vertical stress tends to be on average equal to the weight of the overburden. Thus, the vertical gravitational stress (σ_v) was estimated from the simple relationship of γz indicating that the overburden stress should increase linearly with depth. Hoek [12] summarized some measurement values of vertical stress at various mining and civil engineering sites around the world, show a simple linear expression (i.e. $\sigma_v = 0.027z$) which can be used to estimate the vertical stress.

The horizontal stresses, which receive considerable attention from civil engineers, are influenced by global factors (e.g., plate tectonics) and local topographic features [13]. Therefore, the ratio of horizontal stress to vertical stress ($K = \sigma_H/\sigma_v$) was used for indicating the local tectonic stress settings. For the estimation of the horizontal to vertical stress the theoretical relationships derived by Sheorey [14] ratio was applied. Shoerey [14] developed an elasto-static thermal stress model of the earth as a more useful basis for estimating horizontal in-situ stresses. A plot of the ratio of horizontal to vertical stress predicted by Shoerey [14] is extremely similar in appearance to that derived by Hoek and Brown [15] based on the measured in-situ stresses around the world [12].

4.0 RESULT AND DISCUSSION

4.1 Laboratory Test

The result obtained from the uniaxial compressive strength test was done in laboratory using the samples from in-situ stress test. Specimens for the test were taken from the recovered cores from each overcoring in three directions perpendicular to the borehole axis. The test was carried out to determine basic properties of the granite. Table 1 shows average results at each test location. Results of the Young's modulus and Poisson's ratio listed in the table were used for data analysis of initial stress measurement.

Table 1 Results of uniaxial compressive strength test

Location	Density P (g/cm^3)	Compressive strength (MPa)	Young's modulus E (MPa)	Poisson's ratio v
Adit 2	2.64	163	62533	0.21
Adit 3	2.65	156	54200	0.13
TBM 2	2.67	141	54450	0.20

4.2 In-situ Stress Measurement

The initial stress at each measurement point was calculated by the value of released strain. The results of stress analysis are summarized in Table 1 for both Adit 2 and Adit 3.

Table 2 Summary of stress measurement in Adit 2 and Adit 3

	Adit 2			Adit 3		
Average principal stress in 3 dimension						
	Stress (MPa)	**Azimuth (°)**	**Dip (°)**	**Stress (MPa)**	**Azimuth (°)**	**Dip (°)**
σ_1	7.45	268	35	10.86	230	14
σ_2	3.74	36	41	3.26	2	69
σ_3	2.55	155	29	1.48	136	15
Horizontal and vertical stress						
	Stress (MPa)	**Direction (°)**	**K**	**Stress (MPa)**	**Direction (°)**	**K**
σ_H	6.13	82.4	1.3	10.40	49.2	2.89
σ_h	2.94		0.6	1.60		0.45
σ_v	4.67			3.60		

The maximum principal stress is about 3 times of the minimum principal stress in Adit 2, a differential stress of in principal stresses is relatively large. The vertical stress is 4.7 MPa, which is slightly smaller than 5.8 MPa of overburden pressure. It is considered that it is because the actual density of rock is non-uniform and smaller than the assuming density 2.6 g/cm^3 used for the calculation of overburden pressure due to weathering of the rock on the ground surface.

The principal stress directions are plotted on the lower hemispherical stereographic projection displayed in Figure 8. In Adit 2, the maximum principal stress inclined from the south side (outlet of the tunnel) to the north. In this section, the maximum principal stress was about three times of the minimum principal stress, and the differential stress among the principal stresses was relatively large. The stress state measured at Adit 2 and Adit 3, which maximum principal stress axis is conformable to the axis of the tunnel, is beneficial to the stability of tunnel excavation.

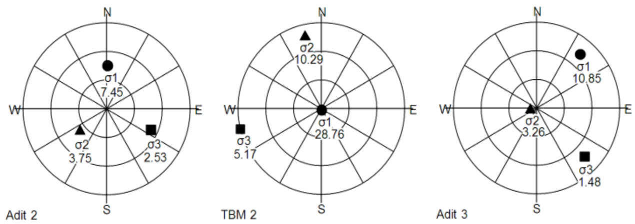


Figure 8 Projection of major stress (Lower hemisphere projection)

The in-situ stress measurement using CCBO was also carried out at Ch. 24,252 with the overburden of 1130 m when the excavation about the centre of mountain (TBM 2). The result of TBM 2 indicates that the direction of the maximum principal stress was nearly vertical with a value of 28.76 MPa, while the minimum principal stress was observed as 5.17 MPa. The measured value is close to the expected vertical stress of 29.6 MPa (1130 m x 2.67 g/cm^3 x 9.81 m/s^2 = 29.6 MPa). The K value (ratio of horizontal and vertical stress) was 0.315, which is very low for an area supposedly unaffected by active tectonic movement.

4.3 Result of Hydraulic Fracturing

HF tests were conducted in Adit 2 at the same time with the overcoring method. The holes were drilled in three directions to detect the three orthogonal stress components of north, east, and vertical directions. The direction of maximum principal stress was formed by the first water injection of HF test. Such pressure is called breakdown pressure, Pb that is read out as first and maximum pressure. The direction of formed fracture was detected by moulding packer test after measurement. Figure 9 shows an example of relationship between water pressure and elapsed time obtained by hydraulic fracturing test.

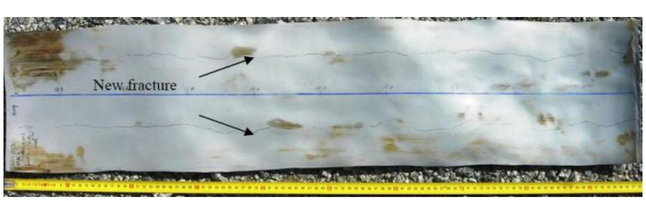


Figure 9 Image of interpreted fracture orientation recorded by moulding packer test

The data analysis of stress measurement was made with re-opening pressure, Pr, shut-in pressure, Ps and direction of fractures. The stress state is expressed by maximum principal stress, SH, and minimum principal stress, Sh, both of which are perpendicular to borehole axis, and direction of SH. The conversion method from two-dimensional stress to three-dimensional stress was conducted by using each three stress components in three planes. As previously mentioned, comparison of the measurement results by CCBO and hydraulic fracturing method Lists of measurement results by CCBO and hydraulic fracturing method are shown in Table 2.

Table 2 Results of hydraulic fracturing and overcoring

	Principal stresses (MPa)		Direction of SH (°)	Stress Components (MPa)		
	Sh	SH		σ_x	σ_y	σ_z
HF	3.2	4.9	N5W	3.9	4.2	4.57
CCBO	2.9	6.1	N8E	4.95	4.12	4.67

The comparison of the measurement results by CCBO and HF are almost consistent with each other. Figure 10 shows a schmit-net, the direction of the principal stress obtained by both methods are comparatively similar. As considered that the almost similarity in the measurement results by different measurement methods, it can be considered that the results of in-situ stress measurements have a credibility.

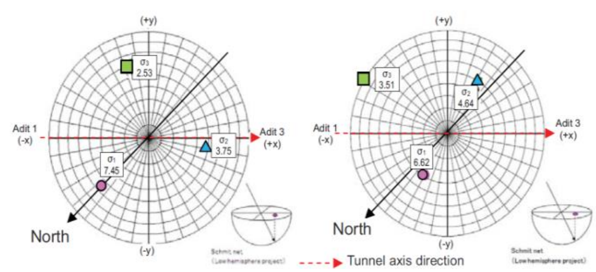


Figure 10 Correlation between CCBO (left) and HF (right)

4.4 Crustal Stress on Regional Scale

The directions of the horizontal stress component measured at Adit 2, TBM 2, and Adit 3 around the Pahang-Selangor tunnel were N8E, N14W, and N41E, respectively. This direction is consistent with the axes of crustal stress state around the Malay Peninsula as seen in World Stress Map of Figure11. Figure 12 shows an enlarged crustal strain distribution map of the area with the new stress from in-situ stress measurement plot on World Stress Map for East-South Asia [1] database. An overwriting of the results of the principal initial stress direction measurements indicates that the direction of the principal initial stress reasonably close to the direction of the crustal stress.

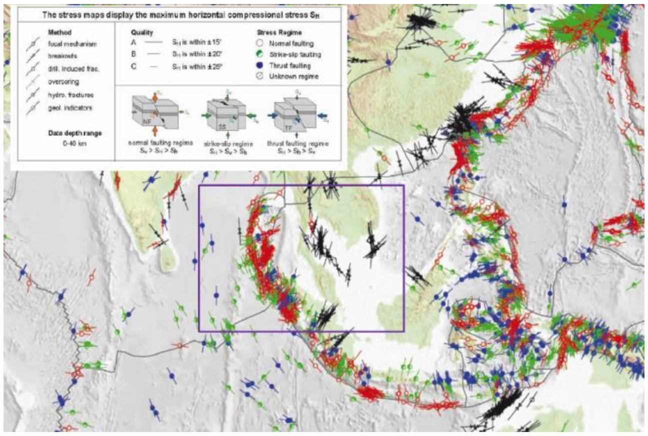


Figure 11 Distribution of stress directions for East-South Asia [1]

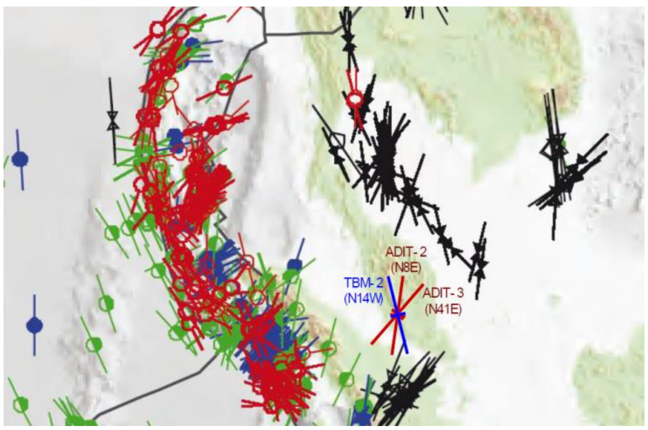


Figure 12 Stress directions measured in Pahang-Selangor Raw Water Transfer Tunnel

4.5 Relationship of In-Situ Stress with Depth

Vertical stress can be approximated with the product of the depth levels below surface and with the unit weight of rock mass. The graph in Fig. 13 reveals that the relationship between the *K* values and depths obtained from the Pahang-Selangor tunnel is similar to the theoretical relationships derived by Hoek and Brown [15]. The *K* values are relatively greater in shallow areas than in other areas, and they gradually decrease to a fixed value as depth increases. The granite data obtained by Kluth in 1964 from Cameron Highlands (Malaysia), which was mention in the Hoek and Brown [15] was also included. Cameron Highlands is about 140 km northwest north of the tunnel inlet in this project.

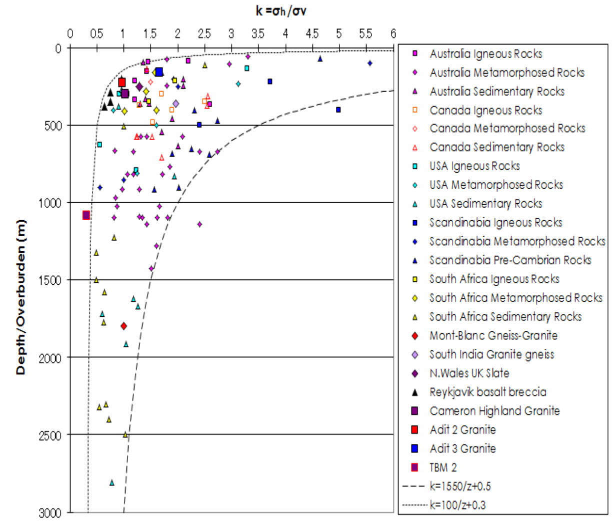


Figure 13 Plot of Variation of Average Horizontal Stress with depth below Surface (After Hoek and Brown [15])

5.0 CONCLUSION

CCBO and HF are considered the simplest, easiest, and most valued of the stress-relief and high stiffness methods. CCBO can possibly take measurements more effectively due to its 3D stress state that can be evaluated into only one measurement. Meanwhile, HF is a better approach for calculating the average initial stress states in comparatively wide ranges because its measurement results obtained from three boreholes of different directions at the same place are combined together and evaluated as an average 3D stress state.

In-situ stresses increase with depth. Contrarily, the rate of increase in horizontal stresses decreases with increasing depths. In shallow areas, the rate of increase in horizontal stresses with higher depths is greater than that of vertical stress. K value in cross section perpendicular to the tunnel axis and the maximum tangential stress at the wall is 76.8 MPa. Since the uniaxial compressive strength of rock is 144 MPa, the tunnel stability has been sufficiently secured. However, considering possible variation of rock strength and rock stress, there is a possibility locally to produce the rock burst or spalling phenomena. As the value of the estimated stress state had a wide range from maximum to minimum, it is necessary to check the stability of the tunnel by numerical analysis.

The direction of the principal stress along the route is similar to the direction of the crustal strain. These data and their interpretations enhance the rock stress database for Peninsular Malaysia. Nonetheless, further tests must be performed to establish whether the trend is regional or whether a more complex regional distribution of the principal stresses exists.

Acknowledgement

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