Evaluation of rock stresses measured in a long water tunnel at deep depth

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ABSTRACT: Three different methods were used to measure stress in a deep tunnel under excavation, and the obtained values were compared. At two locations at a depth around 200m, the stress relief method (CCBO) and the hydraulic fracturing method (HF) were used. The stress states measured at these points have large horizontal stress components, and the maximum principal stresses were greater than the overburden stress. The stress states measured by CCBO and HF agreed well with each other. At a depth of location of 1,130m, CCBO and the Borehole Wall Strain method (BWS) were used. Assuming that the tunnel itself is a large borehole, stress measurements by BWS were obtained by gluing strain gauges directly to the tunnel wall and releasing stress only in that part. This BWS is a very unique and challenging method. Interestingly, the stress states measured by two different methods were in good agreement with each other.

Keywords: Rock stress. Stress relief method (CCBO). Hydraulic fracturing method (HF). Borehole wall strain method (BWS).

1 INTRODUCTION

In this study, rock stresses were measured during excavation of the Pahang-Selangor raw water transform tunnel in Malaysia. About 80% of 44.6 km was excavated by three tunnel-boring machines (TBMs) at the same time. This tunnel is very long and has an overburden of 1,246 m. To tunnel both safely and efficiently, it is extremely important to ensure the stability of the rock mass during excavation. Therefore, it was considered necessary to confirm the rock stresses that greatly affect the stability of the tunnel. The tunnel route consists mostly of granite. A schematic cross-section of the tunnel and the three measurement locations are shown in Figure 1.

The rock stresses were measured at three locations: two at the start of different TBM excavations at a depth of 200 m (shallow depth locations), and one at the middle of TBM excavation at a depth of 1,130 m (deep depth location). At the shallow depth locations, boreholes were drilled in three directions, at 90 degrees to the other. Two of these boreholes were horizontal and one was vertical. For the Compact Conical ended Borehole Overcoring method (CCBO), the horizontal borehole in the axial direction of the tunnel was used, and for the Hydraulic Fracturing method (HF), all three holes were used. CCBO used only one borehole because it is possible to measure a three- dimensional stress state in a single measurement. On the other hand, HF only measures a two-dimensional stress state in a single borehole, so the stress state in three dimensions was calculated by combining the data from the three boreholes.

At the deep depth location, both CCBO and the Borehole Wall Strain (BWS) method, which is a stress relief method, were used. In CCBO, the strain gages are required to be firmly glued on the bottom of the borehole to accurately record the strain changes during stress relief. However, because the rock temperature was as high as 52°C at this location, we had to make a trial-and-error approach to cooling the temperature at the bottom of the borehole. Therefore, BWS was also used to confirm the reliability of the values obtained by CCBO. The BWS used here is different from the standard method of measurement in boreholes, such as the CSIRO technique. Assuming that the tunnel itself is a large borehole, in the BWS method, stress measurements are obtained by gluing strain gauges directly to the tunnel wall and releasing stress only in that part. The data measured by the CCBO and BWS methods which were performed separately, were analyzed and the stress states obtained at both were compared and discussed.

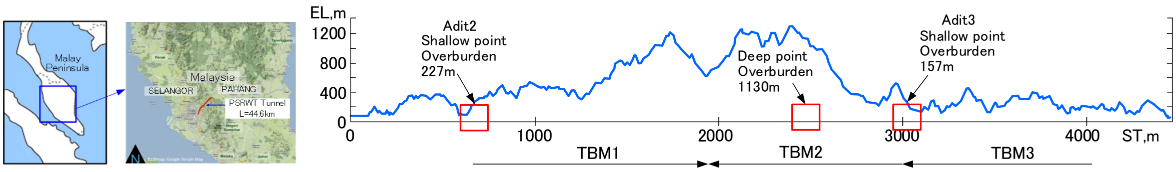

Figure 1. Pahang Selangor Raw Water Transfer (PSRWT) tunnel.
Tunnel location, topographic section, TBM excavation divisions, stress measurement locations.

2 MEASUREMENT METHODS

2.1 HF (Hydraulic Fracturing)

The HF method is a technique for determining rock stresses in two dimensions based on the relationship between the observed water pressure and the flow volume when artificial fractures open and close in the borehole wall (Ito et al., 1999 and JGS 3761-2017). Water is pumped into a section of the borehole separated by two packers, and when the pressure exceeds the tensile strength of the rock, a pair of artificial fractures are created in the borehole wall. In the re-opening test, the pressure at which the artificial fractures created by the initial hydraulic fracturing re-open is defined as "re-opening pressure". Thereafter, water is continued to be pumped, and the pumping is stopped after confirming that the water pressure has become almost constant. When the water supply is stopped, the water pressure drops rapidly, and the pressure at the moment the crack tip begins to close is defined as "shut-in pressure". After hydraulic fracturing, replicas of the artificial fractures in the test section are taken to determine the direction of the maximum principal stress.

2.2 CCBO (Compact Conical-ended Borehole Overcoring)

The CCBO method is a technique for determining rock stress in three dimensions based on elastic theory using strains measured in stress relief by overcoring (Sugawara & Obara, 1999 and JGS 3751-2012). The rock stress in three dimensions is determined from an observation equation based on the elasticity theory using the measured strains, Young's modulus, and Poisson's ratio. The most important features of this measurement technique are that the gluing of strain gauges and overcoring can be performed in one small borehole and that the three-dimensional stress state can be determined by a single overcoring operation. Also, continuous strain monitoring is possible in overcoring for stress relief. This technique has been applied to many sites worldwide because the tools are more compact than those used in other techniques and the measurement operation is easier and faster.

2.3 BWS (Borehole Wall Strain)

The BWS method is a technique for determining rock stress in three dimensions based on elastic theory using strain measured by stress release by overcoring, as in CCBO (Hiramatsu & Oka, 1968). The unique feature of this measurement technique is that three sets of three-component strain gauges are glued to the borehole wall of a pilot hole at equal intervals, and the stress is released by overcoring with a larger borehole diameter. In addition, stress analysis is easy because there is a theoretical solution to obtain the stress tensor in three dimensions with a single measurement. In this case, the tunnel itself was assumed to be a borehole, and stress was released around a three-component strain gauge glued to the wall of the same cross-section of the tunnel. In the stress relief, a core drilling machine with a diameter of 100 mm was used to drill to a depth of 100 mm. The strain was measured at this time, and stress analysis was conducted using the theoretical solution of BWS.

3 STRESS STATES AT A SHALLOW DEPTH

In the shallow tunnel, stress measurements were taken at two locations (Adit2, Adit3). Both of these locations are where the TBM starts, and the measurement points are near the face on the opposite side of the excavation direction (Adit2) shown in Figure 2(a). The boreholes used for the measurements were in the three directions shown in Figure 2(b). The rocks consist of very hard granite with few fractures.

The data obtained by CCBO were considered to be of good quality because both strains were well stabilized after the stresses were completely released. In the HF method applied in this study, the re-opening pressure is given a theoretical analysis of the fracture-opening process. In addition, the stiffness of the measurement system was increased to improve the reliability of the magnitude of the maximum principal stress of the rock stress obtained (Yokoyama & Ogawa, 2016).

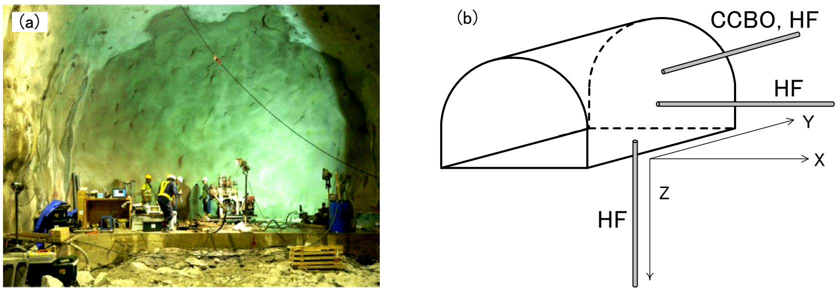

Figure 2. Stress measurement site, (a): Adit2 at shallow depth location, (b): layout of boreholes.

The rock stresses obtained by the CCBO and HF methods performed at two shallow locations are shown in Table 1 with the six stress components. A schematic diagram that is presented in terms of three-dimensional principal stress vectors due to CCBO is shown in Figure 3. In the stress state obtained, at Adit2, the ratio of the maximum principal stress to the minimum stress exceeds three times. At Adit3, the ratio of the maximum principal stress to the minimum stress is 7.2 times. The reason for the large stress state in the lateral stress ratio obtained in at Adit3 is considered to be due to the fact that the crustal stresses in this area generate large horizontal forces in the very hard and sound rock mass. In other words, this phenomenon is most likely due to the fact that there are few fractures in the rock mass.

Table 1. 6 stress components of rock stress by the CCBO and HF methods at shallow depths.

Method	σ_x	σ_y	σ_z	τ_{xy}	τ_{yz}	τ_{zx}
CCBO (Adit2)	4.95	4.12	4.67	1.54	1.69	1.08
HF (Adit2)	4.02	4.91	5.84	0.84	0.85	0.47
CCBO (Adit3)	10.34	1.65	3.60	0.64	-0.59	-1.79
HF (Adit3)	-	2.81	3.59	-	-0.31	-

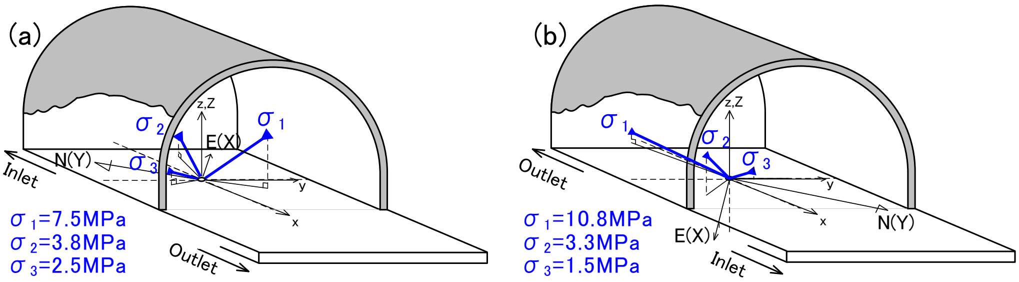

Figure 3. Stress states measured by the CCBO method at shallow depths: (a): Adit2, (b): Adit3.

4 STRESS STATES AT A DEEP DEPTH

Stress measurements were conducted in a tunnel under excavation with an overburden of 1,130 m. The CCBO method, which was also used at a shallow depth, was selected as the measurement method. However, the rock temperature around the measurement area was 52°C, so there was some concern about whether the strain gauges could be properly glued to the end of the borehole. To cool the end of the borehole, cooling water was circulated by pumping it into the borehole after the borehole was drilled. The strain gauges were glued after cooling, and measurements were conducted with constant cooling from the curing of the adhesive to overcoring.

In this case, three stress measurements were conducted. In the first measurement, the adhesive strength of the strain gauges was low; most of the strain values dropped during the overcoring process, and only some of the strains could be measured properly. Based on this experience, cooling by water circulation was performed for one day and night after conical shaping of the pilot borehole bottom to further reduce the temperature. As a result, the rock temperature near the bottom of the borehole was reduced from 36.5 to 34 °C. However, a second measurement could not obtain normal relief strain data due to the core breaking caused by discing. In the third measurement, we finally obtained a normal strain change curve and were able to evaluate the rock stress at this site.

To assure the reliability of CCBO under particular conditions, we tested a new and unique measurement method by applying BWS. This method is based on the measurement principle of the borehole wall strain method like CSIRO, as described previously, but can only be applied to monolithic, extremely good Class A rock such as in this study. A schematic diagram of BWS applied in this study is shown in Figure 4. After a fracture-free area around the same tunnel cross-section is selected, three-component strain gauges are glued at 120-degree intervals around the same circumference as shown in Figures 4(a) and (b). After the adhesive cures, overcoring is conducted around each strain gauge with a portable drill machine as shown in Figures 4(c) and (d). The results of the stress analysis for the CCBO described previously and this BWS are shown in Figure 5 as each two-dimensional stress state on the tunnel cross-section. The maximum principal stress in 2-dimensions on the tunnel cross-section is 33-35MPa. This stress corresponds to an overburden of 1,130m.

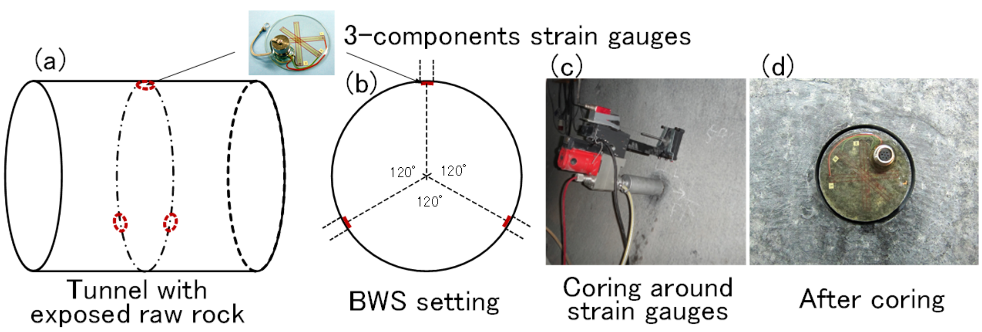

Figure 4. Schematic diagram of BWS, (a): Strain gauges glued on a tunnel wall, (b): Strain gauges on a tunnel cross-section, (c): Coring by using a drill machine, (d): Strain cell on rock surface after coring.

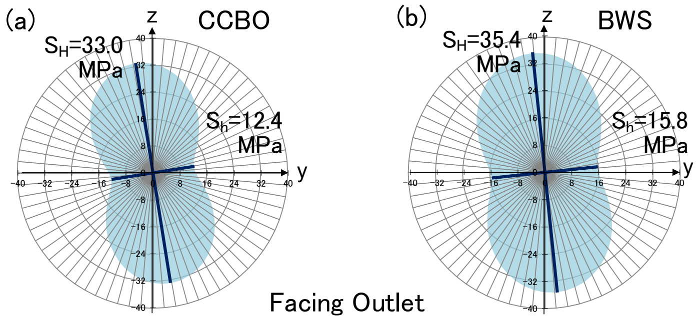

Figure 5. 2-dimensional stress states facing the outlet at a deep depth, (a): by CCBO, (b): by BWS.

5 DISCUSSION

To assure the reliability of the evaluated rock stress state, different measurement methods were used at the same location. CCBO and HF, which are based on different measurement principles, were used in the shallow part of the tunnel. CCBO can evaluate the stress state in three dimensions by measuring in a one-directional borehole.

On the other hand, HF can only evaluate 2-dimensional stresses with a one-directional borehole. Therefore, in this study, three perpendicular boreholes were used to analyze the 3-dimensional stress states by combining the stress vectors obtained separately.

A comparison of the 3-dimensional stress states obtained by the different methods is shown in Figure 6. The magnitude and direction of the principal stresses in the stress states obtained by the CCBO and HF methods are in very good agreement. The reason for the good agreement between the two measurements is considered to be the fact that the rock mass constituting the measurement area (a sound, hard Class A granite) exhibited fairly ideal elastic behavior.

For measurements at a deep depth, different measurement techniques with the same stress relief measurement principle were used. CCBO, which involves a small borehole, was compared with the BWS, which uses a tunnel approximately 5.2 m in diameter as a borehole. Remarkably, these measurements resulted in nearly equal stress states on the tunnel cross-section in two dimensions. The fact that the stress state was almost the same even when measured by different methods supports the high reliability of the respective measurement methods.

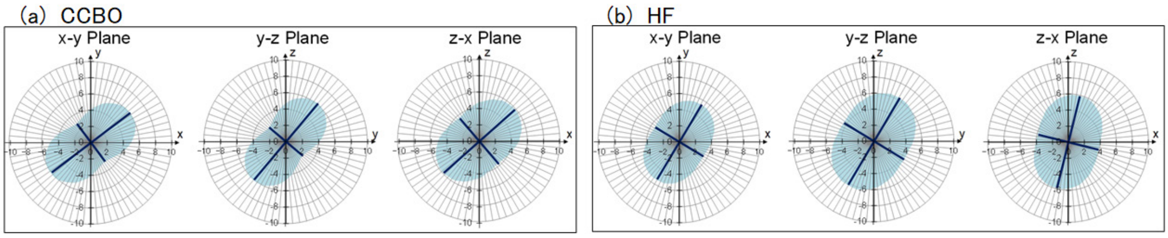

Figure 6. Two-dimensional stress states of shallow location in Adit2, (a): by CCBO, (b): by HF.

6 CONCLUSIONS

To efficiently and safely excavate a long tunnel at great depth with TBMs, the rock stresses around the tunnel had to be evaluated. We proposed a measurement method mainly based on CCBO, a stress relief method. In this case, to assure the reliability of CCBO, HF was also applied at the same time in a shallow area with an overburden of around 200 m, and the results of each measurement were evaluated. As a consequence, the rock stress states obtained by CCBO and HF, were in good agreement, supporting the reliability of CCBO.

Stress measurements using CCBO were also conducted at a greater with an overburden of 1,130 m. However, the rock temperature in this area was 52°C, and we were concerned about the reliable adhesion of the strain gauges used to measure the rock strain. CCBO was performed three times, and in two of the three measurements a few strain changes indicated anomalies in the obtained data due to insufficient adhesion or core breakage during the overcoring process. In the field measurements, efforts were made to lower the temperature of the rock where strain gauges were to be glued, and the results of only one measurement were considered to be successful.

To assure the reliability of the CCBO data, we tried to apply the stress relief method to the BWS technique, which is applicable only to this site, to measure rock stresses. As a result, the rock stress states evaluated by CCBO and BWS measured at the same location agreed well, which confirmed the reliability of the stress state obtained by CCBO. The stress state measured at a greater depth was evaluated to be within the range that would ensure the stability of the tunnel, but there was a possibility of a small-scale rock burst on some of the tunnel walls.

This is the first stress measurement result in the Malay Peninsula (Figure 7), which makes it extremely valuable data.

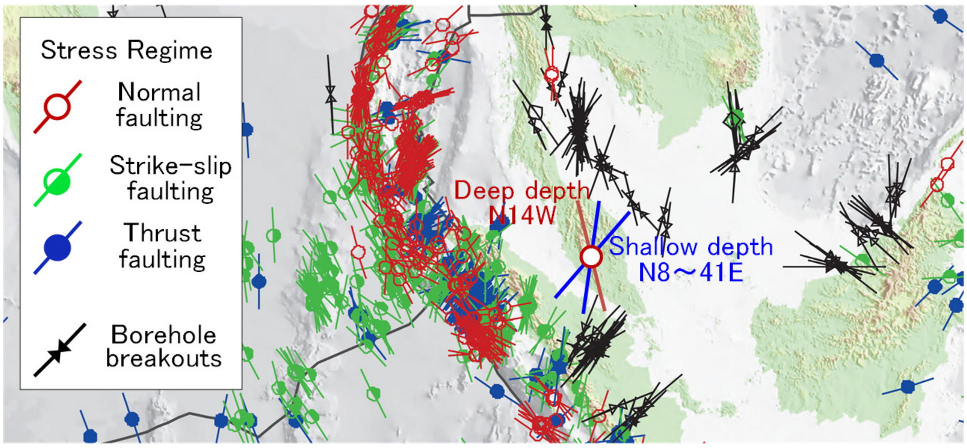

Figure 7. Stress states in Malaysia on the world stress map 2016. (https://www.world-stress-map.org)

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