Stress Measurement in Weak Rock by Borehole Deformation Method
- A Case Study of Horonobe*

by Hem Nath GHIMIRE1, Yoji ISHIJIMA2, Takayuki SUGAWARA3, Hiroya MATSUI4 and Shigeo NAKAMA3

A vertical borehole of 50m depth was drilled in the diatomaceous mudstone, which is classified as weak rock, at Horonobe, Hokkaido and stress measurement by the borehole deformation method was carried out at different depths. The rock is massive with density as low as 1.48 g/cm³, reflecting high porosity of 45%. Mean value of the compressive strength is 3.21 MPa. Fresh water and bentonite was inevitably used as the drilling fluid to maintain the fragile borehole wall.

Stress measurements were tried at seven points along the borehole of 50m depth. At four measuring points, where the cores contained two types of fractures, longitudinal and cross, behaviors of the borehole deformations during overcoring deviated from the prediction based on the elastic theory. Results obtained at three measuring points, where cores contained little cracks, are judged to be reliable. Maximum principal stress directs EW and the stress is almost biaxial in the subsurface region of Horonobe district. This characteristic of stress condition is in harmony with the direction of the active folds distributed in the vicinity of this district.

The efficiency of measurement was highly dependent on the condition of borehole and three sets of measurements were taken within 8 hours working period, at sections where fewer cracks occurred. It has been proved that the stress meter is applicable in weak rock and that the measuring system adopted is practical, although the stress meter suffered some damages at sections where the core was highly fractured.

KEY WORDS: Stress Measurement, Weak Rock, Overcoring, Stress Meter

1. Introduction

The trend of measuring in-situ stresses has been increasing in recent years. But most of the data are from hard or moderately hard rock with very few data from the soft rock. Main cause of this tendency may possibly be that the rock stress measurements accompany more difficulties in soft rock compared to hard rock. Strata control problems occur more frequently in soft rock than in hard rock, since fracture and large deformation are easily induced in soft rock whose strength and stiffness are small in magnitude. Since the ratio of soft rock occupied in the whole rock mass in Japan is relatively high, development of the measuring technique of rock stress in the soft rock is awaiting.

In the previous paper1), we have proposed a new method, called borehole deformation method, to measure rock stresses based on the overcoring method, which is applicable not only to hard rock and moderately hard rock but also to soft rock. To test the utility of this method, we have conducted in-situ rock stress measurement works repeatedly along a vertical borehole 50m in depth driven in the soft rock. Experiments and results obtained in this work will be presented in the following manner in this paper.

In Sec.2, some physical properties of the soft rock together with the geology are described. In Sec.3, measuring techniques including drilling works, as well as the laboratory experiment to confirm the functioning of the stress meter in the soft rock, are explained. In Sec.4, some problems that affect the accuracy of the measurement are discussed. In Sec.5, measured results and features of the stress state in the measured area are shown. In Sec.6, interpretation of the phenomena obtained during the stress measurement is made.

2. Rock mass and geology of the site

The rock mass encountered was diatomaceous mudstone, which is classified as weak rock. It belongs to the Koetoi formation of the Neocene era, which extends from the surface to 360 m in depth at the site. The rock is massive, with low density of 1.48 g/cm³, reflecting high porosity of 45%. The means of compressive strength, tensile strength and Young's modulus are 3.21 MPa (0.61 MPa), 0.45 MPa (0.10 MPa), 0.53 GPa (0.097 GPa), respectively (the numbers in parentheses are standard deviation).

The measurement site is west of the Oomagari fault, whose strike is NNW and which has typical periglacial landforms with hilly view. A borehole was drilled from the top of a low hill.
3. Measuring operation and performance of the stress meter

3.1 Drilling

A spindle boring machine (D2-JS-58, Toho-Underground Excavation Machines Ltd.) with a maximum attainable depth of 200 m was used.

Since the highly fissured zone, which extends as deep as 24 m from the surface, covers the surface a 300-mm-diameter steel casing was inserted from the surface to a depth of 20 m, after completion of a 146-mm-diameter core boring and 300-mm-diameter non-core boring. The region deeper than 20 m was the object of the stress measurement operation.

Three different bits were used for stress measurements.

- A 146-mm-diameter core bit impregnated with diamond powder, for overcoring
- A 145-mm-diameter conical bit (cone angle of 70 degrees) for finishing the overcoring hole into a conical bottom
- A 40-mm-diameter non-core bit for drilling a pilot hole from the center of the conical bottom for insertion of the stress meter

Although the rock is weak, the core recovery using double core tubing system was fairly good and the stress meter was recovered within a thick cylindrical core protected by the thin vinyl tube (Figs.7(c) and 7(g)). A low rotational speed of 30 rpm was adopted to operate the boring machine. The drilling fluid was changed from fresh water to a mixture of fresh water and bentonite (100/7 kgf), when it became apparent that the maintenance of the hole wall was difficult using the former.

The borehole wall might be covered by the film of the weak mud-cake by the usage of the mud water. The pin-shaped head of the sensor on the stress meter (Fig.1) was expected to directly touch the borehole wall, thereby guaranteeing precise measurement of the borehole wall deformation.

3.2 Measuring techniques

The measuring operation used in the borehole deformation method is detailed in the reference 1).

Drilling of a 40-mm-diameter coaxial pilot hole downward from the center of the bottom of the overcoring hole was the most technically difficult operation. Hence, the following methods were devised: The overcoring hole was finished by using the conical bit to create a conical bottom, so that the tip of the 40-mm bit comes always at the center of the bottom surface of the overcoring hole. The boring rod was equipped with an appropriate number of centralizers to prevent its vibration during boring. The length of the pilot hole was limited to 50 cm to keep deviation of the hole to a minimum. The drill bit was mounted on a special rod that has a thin-walled open cylindrical tube with a bottom lid (Fig.2). During drilling of the pilot hole, most of the cuttings mixed into the drilling fluid were collected and gathered in this cylindrical tube and only a limited amount of cuttings accumulated at the bottom of the pilot hole, under normal conditions.

Operation to insert the stress meter into the desired position in the pilot hole was conducted using the drilling rod (each rod unit was composed of three 3-m-long rod components, for a total length of 9 m). This operation required a few minutes. Due to the conical shape of the bottom of the overcoring hole (Fig.1), the stress meter went smoothly into the pilot hole by sinking the rod equipped with a single centralizer beneath its tip.

When debris choked the pilot hole, which was presumably induced when the hole wall collapsed, efficiency of the work was interrupted, since such condition was an obstacle to insertion of the stress meter. In the worst case, the stress meter was damaged after it was pressed against the pile of the cuttings accumulated at the borehole bottom. When such situation was encountered, the measuring region was abandoned and a new pilot hole was drilled in a deeper section.

The core recovered from the shallow depth was frequently fractured into many rock pieces, which became entangled and mixed with the stress meter in the 150-mm-diameter core tube, resulting damage of the stress meter.

Parts of the damaged stress meter were the exposed regions outside of the cylindrical main part. Several hours were sufficient to repair the damaged portions by replacing them with new ones. During the whole process of the stress measurement made this time, three sets of stress meter were prepared, which proved to be sufficient to conduct smoothly the series of measurements.

The rock condition was relatively good at a portion from 38.80m to 46.25m in depth (Sec.5·1), and measurements at three different depths could be conducted within eight hours of measurement operation.

3.3 Performance of the stress meter

To confirm that the stress meter responds properly to the deformation of a borehole drilled in weak rock, the following laboratory experiment was conducted. A thick-walled cylindrical test piece (Fig.3(a)), \( l_f = 288 \text{mm}, d = 40.0 \text{mm}, D = 124.2 \text{mm} \) was prepared from the core obtained from the depth of 48.73m to 49.07m at the site, which had been preserved in water (Sec.5·3). This test piece was axially loaded, after the stress meter was inserted in the middle of the 40-mm-diameter. The stress meter, shown in Fig.1, can measure the following seven components of borehole deformation \( \{w\} \) at once.

\[
\{w\} = \{u_x, u_y, u_{20}, w_0, w_{30}, w_{60}, w_{270}\}^T
\]  

Fig. 1 Stress meter inside the pilot hole with major sections indicated. Refer to Ref(1) for the precise definition of the borehole deformation components \( u(\theta) \) and \( w(\theta) \).

Fig. 2 Special centralizer equipped with hollow tubing to keep the cuttings. ①: 40mm diameter non-coring bit, ②: centering metal rod, ③: drill rod.
Among the seven components, three are diametrical changes $u_i$ and four are axial elongations $w_i$ between two sections $z = z_F$ and $z = z_R$, where $i$ indicates the direction $i$ (Equation (6) of reference 1).

As can be seen from Figs.3(b) and 3(c), every component of borehole deformation $\{w\}$ responds well to the applied axial stress $q$. It is noted that irreversible shortening of the test piece was induced after loading (Fig.3(c)), reflecting the softness of the test piece material.

Taking into consideration that the object of this test is to confirm the ability of the stress meter to predict the axial load on the boundary (Fig.3(a)), under the following four assumptions:

A) The stress to be measured is uniform.

B) The rock behaves like homogeneous isotropic elastic material.

C) The tip of the overcoring hole is sufficiently far from the stress meter as if it is inserted in the infinitely long pilot hole.

However, since the actual situation does not completely satisfy these assumptions, appropriate corrections and/or evaluations are required, which will be discussed in this section.

4.1 Modifying the observation equation to take into account the real geometry

The stress meter sits in the pilot hole 10 cm to 15 cm above the bottom of the overcoring hole, since the length of the pilot hole is limited to 50 cm (Sec.3-2). This geometry violates the above-mentioned assumption C. For this reason, three-dimensional finite element stress analyses were conducted on the real geometry shown in Fig.4(a), under the following four different cases on the remote stress state $\{\sigma\} = (\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{xz}, \tau_{yz})^T$:

- case 1: $\{\sigma\} = (\sigma_x = 1, \sigma_y = 0, \sigma_z = 0, \tau_{xy} = 0, \tau_{xz} = 0, \tau_{yz} = 0)$
- case 2: $\{\sigma\} = (\sigma_x = 0, \sigma_y = 0, \sigma_z = 1, \tau_{xy} = 0, \tau_{xz} = 0, \tau_{yz} = 0)$
- case 3: $\{\sigma\} = (\sigma_x = 0, \sigma_y = 0, \sigma_z = 0, \tau_{xy} = 1, \tau_{xz} = 0, \tau_{yz} = 0)$
- case 4: $\{\sigma\} = (\sigma_x = 1, \sigma_y = 0, \sigma_z = 0, \tau_{xy} = 0, \tau_{xz} = 0, \tau_{yz} = 1)$

Based on the results, the original observation equation (Equation (9) of reference 3) that relates the observed borehole deformations $\{w\}$ to the rock stresses $\{\sigma\}$ was modified, as

$$\{w\} = (d/E)[A]\{\sigma\} \quad \text{acting on the boundary (Fig.3(a)).}$$

$$\{w\} = (-17.1, -16.8, -3.4, 133.3, 91.9, 79.3, 98.9)^T \, (\mu \text{m})$$

These graphs in Fig.3 show the borehole deformations $\{w\}$ accompanying the unloading process from $\sigma_z = 0.461 \text{ MPa}$ to the stress relief condition to be:

$$(d/E) [A] \{\sigma\} = \sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{xz}, \tau_{yz}^T$$
Expressed here in matrix form.

\[ \{w\} = (d/E)[A^*][\sigma] \]

\[
\begin{bmatrix}
    (3-2v^2) & (v^2-1) & -v & 0 & 0 & 0 \\
    v^2 & (2-v^2) & -v & 2\sqrt{3} & 0 & 0 \\
    v^2 & (2-v^2) & -v & 2\sqrt{3} & 0 & 0 \\
    -aLv & -aLv & L & 0 & 0 & -2\beta(1+v) \\
    -aLv & -aLv & L & 0 & -2\beta(1+v) & 0 \\
    -aLv & -aLv & L & 0 & 0 & 2\beta(1+v) \\
    -aLv & -aLv & L & 0 & 2\beta(1+v) & 0 \\
\end{bmatrix} \cdots (3) 
\]

where, \( \alpha = 0.918 \) and \( \beta = 0.910 \) are correction factors.

On comparing the original and modified equations, the characteristics of the latter may be summarized as follows.

A) The diametrical deformations are independent from the geometry.

B) The sensitivity of the axial deformations \( (w_0, w_{90}, w_{180}, w_{270}) \) becomes roughly 10% worse, for stress components such as \( \tau_{x\alpha}, \tau_{x\beta}, \tau_{y\gamma} \).

Changes of borehole deformations accompanying overcoring are shown in Fig.4(b) and 4(c). This is almost same as that of the original one. From the figures, the following characteristics of borehole deformation are recognized: Borehole deformation is generated when the overcoring bit reaches a position that is apart about D (D: diameter of the overcoring hole) from the measuring section. The sign of deformation reverses immediately after the bit passes the section, and the deformation converges to a certain value as the bit goes through the measuring section to a distance of D (Fig.4(b)). On the contrary, axial deformation increases monotonically with progression of overcoring, under axial stress (Fig.4(c)) and reaches near to a constant value after the bit passes a distance of about D over the section FS (Fig.4(a)).

4・2 Time-dependent behavior

Most soft rock shows time-dependent deformation under sustained load. Such deformation is not taken into account in the observation equation (see assumption B) in Sec.4・1, which brings another error into the evaluated stresses.

Here will introduce an example to estimate the magnitude of time-dependent deformation. The diametrical changes in the three different directions in the pilot borehole were monitored for 12.5 hours, in advance of the overcoring work, at a depth from 22.6m to 23.75m (Sec.5・1) at the site of stress measurement at Horonobe. Five minutes was adopted as the sampling interval (in the case of stress measurement, sampling interval was set as 70 seconds). Diametrical change with time is shown in Fig.5. The maximum change of diameter during the measurement period is 15 micrometers. The time required for overcoring work is 45 minutes, at most, which brings the error of borehole deformation due to time-dependent behaviors to 0.9 micrometers. This value is small enough to ignore.

The ability to monitor time-dependent borehole deformation is one of the merits of this stress meter.

5. Measured rock stresses and their features

5・1 Borehole deformations accompanying overcoring

Measurements of rock stress were conducted at seven different depths. Borehole deformations accompanying overcoring observed in each measuring point are shown in Fig.6.

First measurement was conducted when the depth of a hole reached to 22.60m. Since it was likely that the surface fractured zone reaches this depth, the main objective of the measurement was to monitor the time dependent deformation of the borehole. And the two-dimensional stress meter, which measures only the diametrical changes in three different directions, was set in the pilot hole for about 12.5 hours. Deformation during this period has been discussed in Sec.4・2. After this, overcoring started.

Every component of the borehole deformations continued even after overcoring advanced over the right-side arrow (Fig.6(a)). Similar behavior is also recognized in Fig.6(b). Dense fractures are recognized in the cores, as shown in Figs.7(a) and (b). Therefore, the above-mentioned inelastic behavior might be attributed to the heavily fractured condition of the rock. Diametrical change \( u_{-60} \) and every axial deformation continued to change even after overcoring passed over the right-side arrow, in case of Fig.6(f). The component of axial deformation \( w_{270} \) showed substantial change even after the overcoring bit passed over the right-side arrow, in case of Fig.6(g). However, the magnitudes of these deformations in case of Figs.6(f) and (g) are not so large compared with those observed in Figs.6 (a) and (b). In harmony with this behavior, densities of fractures shown in Figs.7(f) and (g) are lesser compared with those of Figs.7(a) and (b).

Changes of the borehole deformations accompanying overcoring are almost limited between the two arrows of both sides in case of Fig.6(c). Similar behaviors are recognized in Figs.6(d) and (e).

However, the diametrical deformation \( u_{0} \) started to change again after the suspension period in case of Fig.6(c). Behaviors of axial displacement are rather peculiar in case of Fig.6(d). First, the magnitude of each displacement is small. Second, displacement continues even after the overcoring bit passed over the arrow at the right-hand side.

5・2 Fractures observed on the core surface

The cores obtained accompanying the stress measuring work at seven different points are shown in Fig.7. Two different types of fracture, longitudinal (i.e., the fracture plane is parallel to the hole axis) and oblique (i.e., the fracture plane crosses the...
hole axis at an oblique angle), were observed on the surface of the core as shown in Fig. 7(b). One of the oblique fractures crosses the region $z_R \leq z \leq z_F$ (Fig. 4(a)). Although it is not known when these cracks developed (this will be addressed in Sec. 6·1), their existence could be a main cause of the abovementioned behaviors of borehole deformation, which are different from those predicted in Sec. 4·1.

Similarly, two groups of fractures are observed on the surface of the core, as shown in Fig. 7(f). Oblique fractures of the same orientation were distributed at equal intervals along
the region $z_R \leq z \leq z_F$ (Fig.4(a)). It was confirmed by visual inspection that the fracture surfaces are slightly curved in the shape of saddles. These are characteristic features of core disking$^4)$. Longitudinal fractures oriented EW developed between the neighboring oblique fractures.

The oblique fractures appeared in Fig.7(g) are identical to those of the neighboring core (Fig.7(f)). Therefore, the oblique fractures are considered to have the same cause. However, there are two differences between the two. One is that the interval between the oblique fractures of the former is greater than that of the latter. Another is that the longitudinal cracks of the former are more predominant and longer than those of the latter.

In case of Fig.7(c), no cracks were confirmed on the surface of the core. However, microscopic observation revealed existence of several micro-cracks, as shown in Fig.8, at the intersection between the hole periphery and the y-axis (Fig.11(a)). In case of Fig.7(d), no cracks were visible on the surface of the core upon inspection immediately after its withdrawal from the core barrel. However, a few minutes afterward, a few oblique cracks appeared on the core surface. The core has no cracks in case of Fig.7(e).

5・3 Evaluation of Young's modulus

Since the observation equation is a function of the Young's modulus and Poisson's ratio of the rock, their evaluation is important. The most reliable method to evaluate these material constants is to use the core in which the stress meter sits$^1)$. However, since most of the recovered cores contained many cracks, loading test using the core, which includes the stress meter, was difficult. Instead, elastic properties were evaluated by loading test using small cylindrical test pieces obtained by drilling the core. The loading tests were conducted at two places. One was the site of stress measurement, in which case...
the loading test (Fig.9) was completed within two hours after the cores were recovered from the hole. Therefore, weathering of the test piece was reduced to a minimum. The other place was the laboratory, where test pieces were prepared from the cores, which were kept in water. There was little difference between the results obtained in the field and in the laboratory. For example, the uniaxial compressive strength obtained in the field and in the laboratory are 3.27 MPa (1.25 MPa) and 3.21 MPa (0.61 MPa), respectively (the number in parentheses are standard deviation). Total numbers of the test pieces used to evaluate the Young's modulus are 10 (field test) and 140 (laboratory test), respectively. In the laboratory test, the test pieces were prepared from the cores that were collected from various locations along the hole. Therefore, the values obtained in the laboratory using the test pieces prepared from the core located nearest to the measuring point were used for stress evaluation.

5.4 Measured stresses and judgment of their accuracy

As stated in Sec.5.1, there are two types on the borehole deformations during overcoring. In one type, they are similar to those indicated in Sec.4.1, which means that the rock is behaving elastically. Accuracy of the rock stresses evaluated using the data belonging to this type is high.

If the cracks are newly induced in the core during the overcoring, then the attained borehole deformations are different from the ones without cracks. This difference causes the error of the measured stress. As shown in Sec.6.1, both longitudinal and oblique cracks appeared in the core are regarded to be induced by the overcoring. It will be needless to say that when the pre-existing cracks are distributed in the core, the evaluated stresses contain error, since the observation equation is induced under the assumption that it does not contain cracks.

Among seven measurements conducted at different depths along a hole, four of these measurements seem to be deficient in reliability due to two reasons: One is behavior of in-elastic borehole deformations (Sec.5.1). Another is fracture induced in the core (Sec.5.2). Only three cores obtained from depth of 38.80 to 46.25m do not contain visible cracks, at least, immediately after recovering of them and the measured borehole deformations behaved as explained in Sec.4.1 (Table 2). Therefore, the remaining three stresses evaluated by substituting the measured borehole deformations into Equation (2), which are shown in Table 1 and in Fig.10, are considered to be reliable. Stress state of the three are resembles to each other: It is almost biaxial and maximum principal stress $\sigma_{1}$ is oriented EW (Table 1).

It has been empirically recognized that the vertical stress component $\sigma_{z}$ coincides to the overburden pressure $\sigma_{v}$, irrespective
of the site and rock type. Overburden pressure $\sigma_v$ (MPa) in the site of the present rock stress measurement at a depth $Z$ (m) from surface is evaluated as follows.

1) $Z \leq Z_0$ ( = 24 m) (weight of unit volume of rock is 1.00 $gf/cm^3$)

$$\sigma_v = 0.0098Z \quad (MPa)$$

2) $Z_0 \leq Z$ (weight of unit volume of rock is 1.49 $gf/cm^3$)

$$\sigma_v = 0.0098Z_0 + 0.0145(Z - Z_0) \quad (MPa)$$

Vertical stress component $\sigma_z$ is 0.44 MPa of the data corresponding to the overcoring depth of 45.15 m to 46.25 m, which roughly agrees with the overburden pressure $\sigma_v = 0.55MPa$. Therefore, this gives seemingly most reliable state of stress.

6・5 Features of the state of rock stresses

One of the striking features of the measured stresses is that the absolute value of the minimum principal stress $\sigma_3$ is small compared to the maximum principal stress $\sigma_1$ for every measured result as shown in Table 1. Hence, the stress condition is close to the biaxial state. At the same time, stress $\sigma_3$ is negative (tensile) in every case. It is reasonable to interpret the occurrence of tensile stress as erroneous measurement, since it is highly improbable that the tensile stress is induced in the rock.

The maximum principal stress $\sigma_1$ is oriented EW and almost lie in the horizontal plane. This is in harmony with the following three events: First is the existence of small-scale active folds distributed around this district, whose strike orientation is NS$^5$. Second is the maximum principal stress, which is determined based on the mechanism of the earthquakes in this district whose centers are shallower than 10 km depth, directs EW$^6$. Third is the result of stress evaluation based on the analyses of break-out occurred along deep holes in the same area with the present site$^7$.

6. Discussion

6・1 Mechanism of development of two types of fractures observed in the cores

Two different types of fracture, one longitudinal and the other oblique, were observed in the cores. These cracks have the possibility to be induced accompanying overcoring. To confirm this, the mechanism of development of these fractures will be discussed.

For this purpose, elastic stress analyses were conducted for the geometry shown in Fig.11(a), which corresponds to such situation that the overcoring proceeds to the intermediate position of the pilot hole. Since inclination of the maximum and minimum principal stresses are both small (Table1), it is assumed here that the direction of the minimum principal stress $\sigma_3$ and the maximum principal stress $\sigma_1$ are parallel to x and

\[
\begin{array}{c|c|c|c|c|c}
\text{Measuring Depth (m)} & \text{Principal stress (MPa)} & \text{Principal direction (degree)*} \\
\hline
38.80 – 39.80 & 0.25 & 0.15 & -0.07 & 0/90/270 & 90/23/68 \\
39.90 – 40.90 & 0.30 & 0.21 & -0.04 & 31/160/284 & 61/42/63 \\
45.15 – 46.25 & 0.69 & 0.40 & -0.17 & 176/41/291 & 47/53/66 \\
\end{array}
\]

* $\phi$ is bearing measured from east to north and $\varphi$ is inclination measured from vertical to horizontal

\[
\begin{array}{c|c|c|c}
\text{Measuring Depth (m)} & \text{DSP} & \sigma_v/\sigma_v \\
\hline
38.80 – 39.80 & low similarity & 0.27 \\
39.90 – 40.90 & low similarity & 0.38 \\
45.15 – 46.25 & high similarity & 0.80 \\
\end{array}
\]

DSP = degree of similarity of profile of the borehole deformation-overcoring depth curve between the measurement and prediction

$\sigma_v$=normal stress in z-direction

$\sigma_v$=overburden pressure

Fig. 9 Uniaxial loading apparatus for usage in the site.

Fig. 10 Principal stresses plotted in Wulf net, which are shown in Table 1.
Stress Measurement in Weak Rock by Borehole Deformation Method – A Case Study of Horonobe

The stress analyses were conducted using the three-dimensional finite element method, under the following two cases on the remote stresses state:

case 1 (\(\sigma_x = \sigma_3 = 0, \sigma_y = \sigma_1 = 1, \sigma_z = \sigma_2 = 0\)),
case 2 (\(\sigma_x = \sigma_3 = 0, \sigma_y = \sigma_1 = 0, \sigma_z = \sigma_2 = 1\))

The stress distributions corresponding to case 1 are illustrated in Figs.11(b), (c) and (d). It is noticed that stresses \(\sigma_x\) and \(\sigma_z\) in the vicinity of the pilot hole are tensile. Based on these stress analyses, followings become clear.

Tangential stress \(\sigma_\theta\) and axial stress \(\sigma_z^*\), at an intersection of the periphery of the pilot hole and the y-axis on \(z = 0\) plane, becomes as follows under the remote stresses \(\{\sigma\} = (\sigma_x, \sigma_y, \sigma_z)^T\):

\[
\sigma_\theta = 0.029\sigma_x - 0.872\sigma_y - 0.015\sigma_z
\]

\[
\sigma_z^* = 0.208\sigma_x - 0.555\sigma_y + 0.913\sigma_z
\]

The stress component \(\sigma_\theta\) defined by Equation (5) becomes tensile (minus), for the rock stresses shown in Table 1. Under this stress state, there is high possibility that tensile fracture whose fracture plane is parallel to the plane \(x = 0\) is induced. This is in harmony with the longitudinal fractures oriented EW as observed in the cores. This estimation is supported by the following two phenomena. The first is that small-scale fractures oriented EW developed on the pilot hole wall at the measuring site where the overcoring depth was from 38.80 m to 39.80 m. In this case, the zone where fractures developed was limited to a small area, probably because this region has greater strength than other places. The second phenomenon is that the orientations of the longitudinal fracture and the maximum principal stress are the same.

There is also possibility that the axial stress \(\sigma_z^*\) defined by Equation (6) becomes tensile, when the rock stress \(\sigma_y (\sigma_1)\) is large compared to \(\sigma_x (\sigma_3)\) and \(\sigma_z (\sigma_2)\). Fracture plane of the tensile mode induced under this condition will be parallel to the plane \(z = 0\). This fracture must be identical to the oblique fracture observed in the core. There is possibility that the fracture plane of the latter tilted due to the strength anisotropy observed in the rock. Since core disking is tensile fracture, we can say that the oblique fracture has the same fracture mechanism with the core disking, which have common cause that they are induced accompanying overcoring.

6 - 2 Limit of depth attainable by the present measuring method

The present measuring operation using a borehole filled with water has made it known that the air pressure required to release the stress meter from the insertion tool increases with depth (Sec.4 - 2 of reference 1). The maximum air pressure that can be used safely and easily in the field is 1.0 MPa. Under this constraint, the measuring depth is limited to 70 m.

Sensors whose wire-resistance strain gauges are glued to the surface of a phosphor bronze plate work to a depth of 1000 m. Improvement of the present measuring system for use at this depth will be difficult due to the following reasons: First, the...
mechanism used to release the stress meter in the present measuring system must be modified. Second, the container to store the data recorder and battery must be stiffer to increase its pressure tolerance. Third, the measuring system must be made adaptable to a wire line drilling system, which is a standard core boring method for deep borehole.

Therefore, the recommended submersible limit is 70m or so. Even under this limitation, the system’s range of application is sufficiently wide. Particularly it is applicable to determine the precise stress distribution around the tunnel and/or the shaft.

7. Conclusions

The main results are as follows.

(1) The stress meter has been proven applicable for rock stress measurement based on borehole deformation method in weak rock.

(2) The efficiency of stress measurement operation is highly dependent on the borehole conditions. Cores with fewer fractures afford greater efficiency. Three sets of stress measurement at depths from 43m to 50m from the surface were achieved within eight hours.

(3) Maximum principal stress is oriented EW and the stress state is biaxial in the subsurface region of Horonobe district west of the Oomagari fault.

(4) The two types of fractures (longitudinal, and oblique) that frequently developed in the thick-walled cylindrical core could have been induced by overcoring under the conditions of rock stress stated in (3) combined with the low rock strength.

(5) The effect of these cracks induced during overcoring on the accuracy of the measured stresses was clarified.

(6) The depth of measurement is limited to about 70m.

References