DOI: https://doi.org/10.68732/d1ee5f9b68919af4

ISBN: 978-9989-2053-7-8

New Three-Dimensional Rock Stress Measurement Method in Vertically Downhole

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Abstract

A new three-dimensional rock stress measurement method for vertically downward-drilled boreholes has been developed. Although similar techniques focusing on hard rock have been proposed in the past, no method applicable across a wide range of rock types—from soft to hard—has been established. The principle of this technique is the stress relief method, in which a 24-element strain cell is bonded to a conical borehole wall and the in-situ stress is released through overcoring. This method is termed the *Conical Wall Borehole Overcoring* (CWBO) method. In this study, a new observation equation was formulated, and after resolving several issues through laboratory experiments, the method was finalized following field validation tests.

The study initially focused on sedimentary soft rocks. First, an adhesive was selected that enables reliable adhesion to rock surfaces underwater and allows measurements within approximately one day. Laboratory experiments were then conducted by preparing rock block specimens with hole walls shaped identically to those at the actual site. Strain sensitivity tests under true triaxial loading, overcoring tests under biaxial stress, and circumferential pressure sensitivity tests on the recovered cores were performed to confirm the reliability of the method.

Field experiments were conducted in sedimentary soft rock at depths of 30 m and 100 m. Subsequently, measurements were performed at a hard rock site under more favourable conditions at a depth of 15 m. Based on these results and previous studies, the CWBO method was recognized as a practical and reliable technique for three-dimensional stress measurement in vertical downward boreholes. Further improvements will be pursued, and the method will be applied to stress measurements at greater depths.

Keywords

Rock stress measurement, Three-dimensional, Vertically downhole, Stress relief, Soft and hard rock.

1 Introduction

Several in-situ rock stress measurement methods targeting hard rock have been developed to date. However, no method using vertical boreholes exceeding 100 m in length has been established that is applicable to a wide range of rock types, from soft to hard. In this study, we attempted a combined method incorporating the *Compact Conical-ended Borehole Overcoring* (CCBO) technique (Sugawara and Obara, 1999) and the *Borehole Wall Strain* (BWS) method (Leeman, 1968). Both methods are highly reliable and have well-established track records. This combined approach is termed the *Conical Wall Borehole Overcoring* (CWBO) method.

We first confirmed that the CWBO method provides higher theoretical measurement accuracy than the CCBO method. We also proposed a circumferential or confined pressure loading sensitivity test (hereafter, sensitivity test) that enables calibration of Young's modulus for each strain measurement point. By combining strain change data obtained during stress relief with strain data from the sensitivity test, we achieved stress analysis capable of correcting for non-negligible rock heterogeneity and anisotropy (Sakaguchi et al., 2024).

To make the method practical, the technique for bonding strain gauges underwater in boreholes is crucial. Through repeated bonding tests on sedimentary soft rock samples, we selected an optimal adhesive and established a reliable underwater bonding procedure. Furthermore, simulated conical-shaped hole drilling was conducted using large soft rock specimens, to which strain cells were bonded. Strain changes during overcoring under biaxial loading were measured, and sensitivity tests were performed on the recovered cores. Using the strain data obtained from these laboratory experiments, three-dimensional stress analysis was conducted using the newly formulated observation equation. The good agreement between the analysed stress state and the applied stress conditions confirmed the reliability of the method (Danjo et al., 2024).

Field validation tests were then conducted in sedimentary soft rock using a vertical borehole approximately 30 m deep within a tunnel with an overburden of 114 m. The strain data obtained during stress relief were generally satisfactory, and the analysed stress state was considered acceptable overall, although the vertical stress component was slightly smaller than expected (Yokoyama et al., 2024).

As described above, the measurement theory and methodology of the CWBO method have been established, and its feasibility and applicability to sedimentary soft rock have been confirmed through laboratory and field experiments. In this paper, we introduce the measurement equipment and procedures for applying the CWBO method to both soft and hard rock sites and discuss the characteristics of the obtained measurement data and the results of stress analysis.

2 Field Measurement Procedure

The measurement procedure for the CWBO method is shown in Fig. 1. A major feature of this method is that overcoring can be performed without cables, as the data logger is installed inside the borehole together with the strain cell. Installation of the strain gauges requires approximately 3 hours. After allowing the adhesive to cure for 20 hours, overcoring is performed the following day. Immediately afterward, sensitivity tests are conducted on the recovered rock cores, including the strain cell, at the site. For soft rock, a confining pressure test is performed, whereas for hard rock, a circumferential pressure test is used. Although the confining pressure test is the standard method, it is applied to soft rock because its low strength requires sufficient pressure to be applied. The entire sequence of operations is completed within two days.

Fig. 2shows the main equipment used for installing the strain cell. The three photographs show:(a) the conical bit used to shape the borehole wall, (b) the injection jig for collecting adhesive at the bottom of the borehole,and (c) the strain measurement instrument with the strain cell attached to the end of the data logger.

Fig. 3 presents photographs taken at the stress measurement site. The four photographs show: (a) the conical borehole wall captured by a borehole camera, (b) the strain cell used for measurement, (c) the rock core recovered by overcoring, and (d) the circumferential pressure sensitivity test.

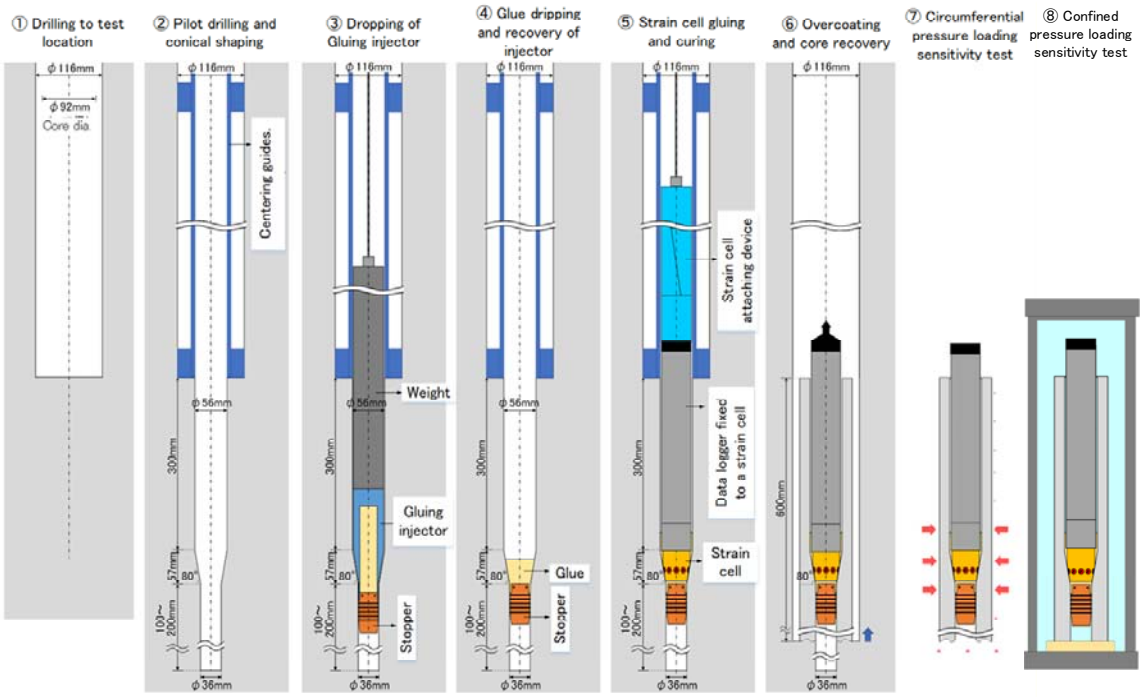


Fig. 1 CWBO in-situ measurement procedure. The detailed procedures are shown in steps from ①to⑧ in the diagram.

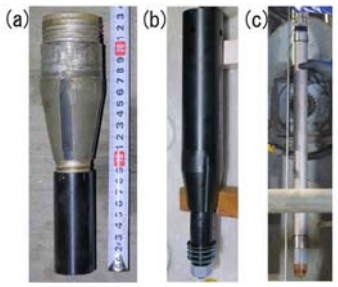


Fig. 2 Equipment for install the strain cell.

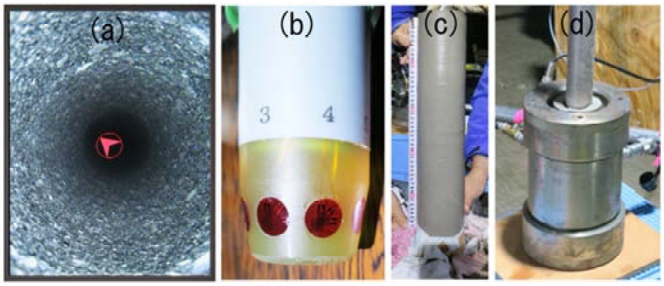


Fig. 3 photographs taken at the stress measurement site.

3 Field experiments at soft rock sites

Field experiments at the soft rock site were conducted inside a tunnel excavated in an area where late Cenozoic Miocene pumice tuff is distributed. The measurements were performed in a 100mdeep borehole drilled within a tunnel with an overburden of 110 m. The primary properties of the rock are a density of 1.8 g/cm³, a uniaxial compressive strength of 5 MPa, and a Young's modulus of 1 GPa.

Fig. 4 shows the relationship between drilling length and strain changes obtained during overcoring. The overall trend of the strain changes is as follows. After a significant response when the drilling reached the depth of the strain gauge, the strain appeared to peak and subsequently stabilize. The average drilling length was approximately 100 mm. A slight deviation was observed between 600 mm and 700 mm, likely due to noise associated with irregularities in the drilling operation.

Each strain cell contains 24 strain gauges, but the strain change characteristics were categorized into three components: axial (p), tangential (θ), and inclined (φ). The axial component p initially shifts significantly toward compression, then returns toward tension before stabilizing. Conversely, θ initially shifts significantly toward tension, then returns toward compression before stabilizing. The inclined component φ exhibits intermediate behavior between p and θ.

The pressure-strain relationships obtained from the confining pressure sensitivity test are shown in Fig. 5. All relationships generally exhibit linear behavior. The axial component p shows tensile behavior under confining pressure, although some data show little change. The tangential component θ shifts entirely toward compression due to the applied pressure. The inclined component φ exhibits both tensile and compressive behavior, representing an intermediate state between p and θ.

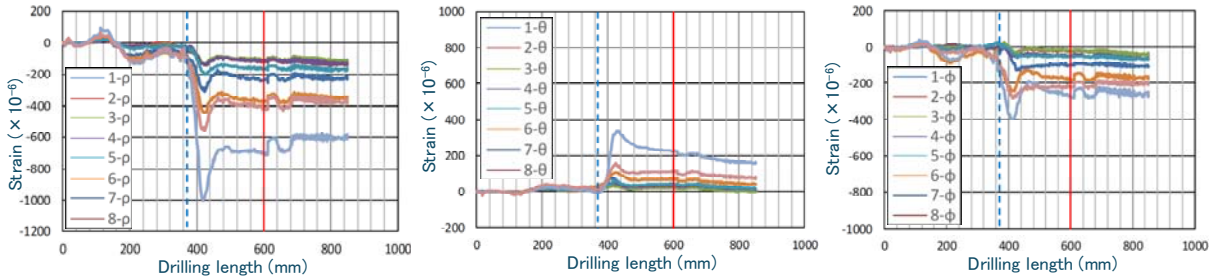


Fig. 4 Strain change data obtained by in-situ overcoring (Soft rock). The vertical dashed line indicates the strain gauge position.

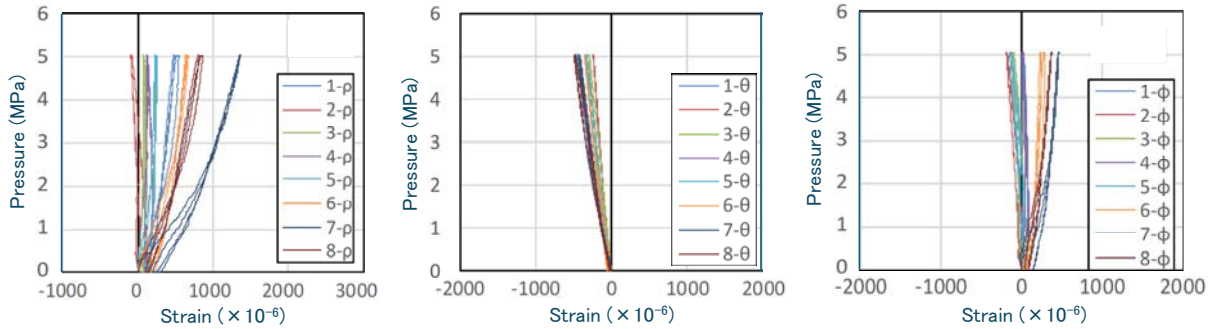


Fig. 5 Pressure-strain relationship data obtained by circumferential pressure loading test (Soft rock).

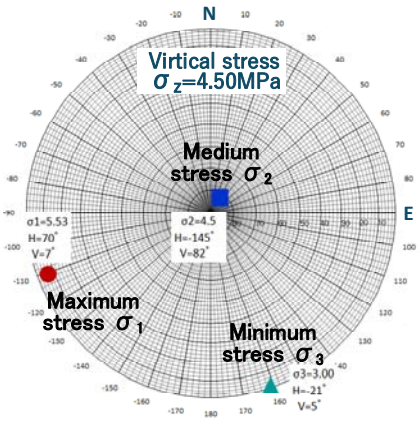


Fig. 6 Three-dimensional stress state obtained by in-situ experiments (Soft rock).

Figure 6 shows the three-dimensional stress state obtained from stress analysis using the strain data from both overcoring and the sensitivity test. The maximum principal stress was 5.53 MPa, the medium principal stress was 4.50 MPa, the minimum principal stress was 3.00 MPa, and the vertical stress was 4.50 MPa. The overburden at the measurement point is approximately 210 m. Assuming a rock density of 1.8 g/cm³, the overburden pressure is 3.70 MPa, indicating a measurement error of about 22%.

4 Field experiments at hard rock sites

Field tests at the hard rock site were conducted inside a tunnel excavated in an area where the Mesozoic Cretaceous Shimanto Group is distributed. The measurements were performed in a 12mdeep borehole drilled within a tunnel with an overburden of 200 m. The primary properties of the rock are a density of 2.7 g/cm³, a uniaxial compressive strength of 30 MPa, and a Young's modulus of 40 GPa.

Fig. 7 shows the relationship between drilling length and strain changes obtained during overcoring. The overall trend is similar to that observed in soft rock, but the behavior is more stable. The axial component ρ initially shifts significantly toward tension, then reverses toward compression and stabilizes in the compressive region. Conversely, the tangential component θ initially shifts slightly toward compression, then reverses significantly toward tension, stabilizing after passing through a small peak. The inclined component φ exhibits behavior characteristic of both p and θ.

The pressure–strain relationships obtained from the circumferential pressure sensitivity test are shown in Fig. 8. All relationships exhibit generally linear behavior. The axial component p shifts entirely toward tension due to the applied circumferential pressure. The tangential component θ shifts entirely toward compression. The inclined component φ also shifts toward compression, exhibiting behavior intermediate between p and θ.

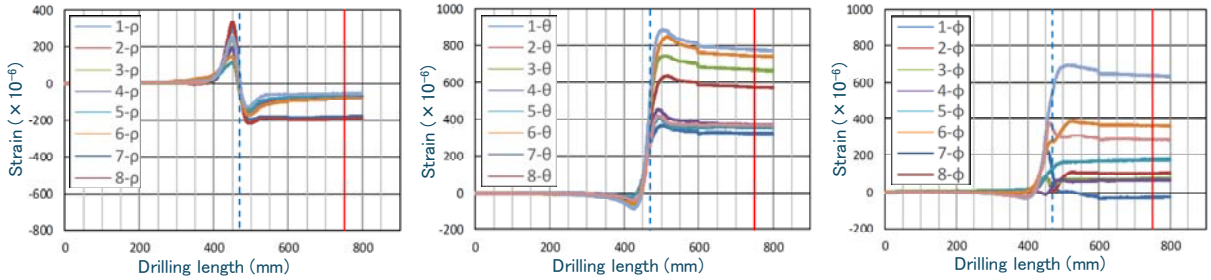


Fig. 7 Strain change data obtained by in-situ overcoring (Hard rock). The vertical dashed line indicates the strain gauge position.

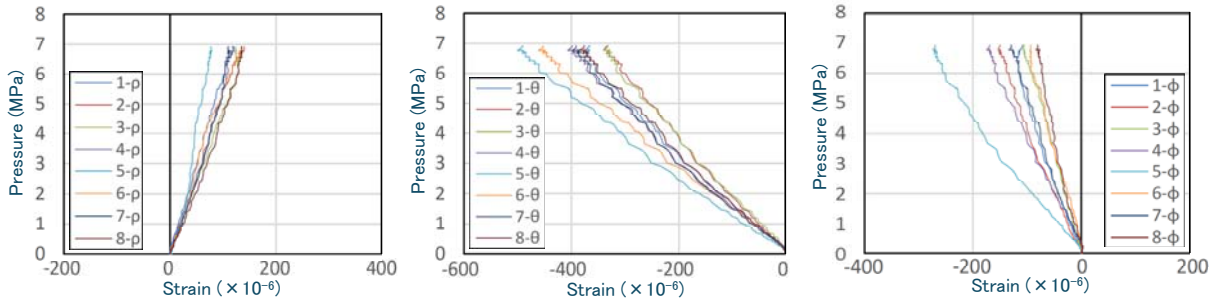


Fig. 8 Pressure-strain relationship data obtained by circumferential pressure loading test (Hard rock).

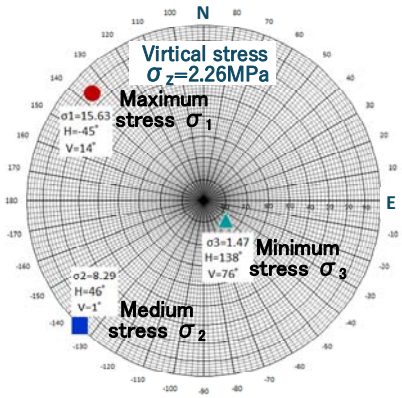


Fig. 9 Three-dimensional stress state obtained by in-situ experiments (Hard rock).

Fig. 9 shows the three-dimensional stress state obtained from stress analysis using the release strain and strain sensitivity data. The maximum principal stress was 15.63 MPa, the medium principal stress was 8.29 MPa, the minimum principal stress was 1.47 MPa, and the vertical stress was 2.26 MPa. The overburden at the measurement point is approximately 200 m. Assuming a rock density of 2.7 g/cm³, the overburden pressure is 5.30 MPa. The measured vertical stress was 43% of this overburden pressure.

5 Discussion

The reliability of the newly developed CWBO measurement method is evaluated from the following perspectives: a) the rationality of strain change behavior during stress relief, b)the rationality of strain change behavior during sensitivity tests, c) the rationality of the calculated stress state,and d)the adhesion condition of the strain cells.

a) The strain change behavior is similar to the standard strain change curve obtained during stress relief in typical CCBO measurements (JGS 3751, 2012). However, for soft rock, the final strain values for both ρ and φ fall on the compression side, and the magnitude of θ, which is normally the most sensitive parameter, is smaller than that of ρ and φ. For hard rock, the strain magnitude is greatest for θ, and the overall behavior resembles that of JGS 3751 data. However, ρ exhibits compressive strain, similar to the soft rock case.

b) The soft rock data exhibit generally linear behavior and are considered reasonable as strain change data under confining pressure. Specifically, ρ ranges from tensile to neutral, θ is compressive, and φ exhibits a mixture of tensile and compressive behavior, with no unreasonable trends observed. The hard rock data also exhibit generally linear behavior and are considered reasonable under circumferential pressure. Specifically, ρ is tensile, θ is compressive, and φ lies between ρ and θ.

c) For soft rock, the vertical stress, which is an important indicator of measurement accuracy, corresponds well to the overburden pressure, and the ratios of the three principal stresses fall within

the range of typical values. For hard rock, however, the vertical stress is less than half the equivalent overburden pressure, and the principal stress ratios are extremely large. Therefore, it is likely that the measured data do not accurately represent the true stress state at the measurement point.

d) Visual inspection of the recovered cores confirmed that all strain gauges were firmly adhered to the rock for both soft and hard rock tests.

Based on the above discussion, the data measured using the CWBO method are evaluated as follows. The strain change data obtained during stress relief and sensitivity testing appear to be close to the initially targeted quality. Although the quality of the strain change data in hard rock was satisfactory, the analysed stress state resulted in extremely large principal stress ratios. The cause of this discrepancy requires further investigation.

6 Conclusion

We have developed a new vertical downward stress relief method. We believe that the on-site stress measurement procedure has been largely established. However, inconsistencies were found in the stress state analysed from the obtained data, leaving issues to be addressed in future research. We intend to resolve these issues by re-examining the CWBO measurement conditions through detailed numerical analysis and additional field experiments.

Acknowledgements

The development of the methodology and the experimental results on soft rock present part of the results from a project commissioned by Ministry of Economy, Trade and Industry (METI), Japan, entitled “Research and development project for the disposal of low-level radioactive waste” (Grant Number: JPJ010897).Furthermore, the experimental results in hard rock present part of the findings of the “Fukada Laboratory Research Committee on Long-Term Changes in Crustal Stress,” funded by the Fukada Geological Research Institute.

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