Acta Polytechnica CTU Proceedings **56**:16–22, 2026
`https://doi.org/10.14311/APP.2026.56.0016`

Published by the `Czech Technical University in Prague`

EFFECT OF TANGENT AND SECANT ELASTIC CONSTANTS ON CCBO STRESS EVALUATION IN TRANSVERSELY ISOTROPIC ROCK

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Abstract. The Compact Conical Borehole Over-coring (CCBO) method is employed for the determination of the three-dimensional stress state in rock environments. The method utilises a strain gauge cell to quantify the deformation of over-cored rock, the deformation characteristics of which are evaluated in the laboratory. It is assumed that the in situ rock material is homogeneous, elastic and transversely isotropic and it is, therefore, imperative to ascertain the deformation parameters of the transversely isotropic material present in situ. The tangent and secant deformation parameters were taken from previous research and then employed throughout the stress determination process. This paper outlines the fundamental principles of the method and presents results from practical measurements carried out at the Grimsel Underground Research Laboratory in Switzerland. The stress results vary depending on whether alternative deformation characteristics (i.e. tangent or secant) are taken into account during the evaluation process.

Keywords: 3D stress state, stress state in rock mass, CCBO method, over-coring method, in situ stress, determination of stress, transversely isotropic rock.

1. Introduction

Knowledge of the stress state in a rock mass is one of the keys to designing underground works and rock structures in fields such as tunnelling, mining, geothermal energy extraction and the underground disposal of nuclear waste [1, 2]. The full stress tensor can be determined by using over-coring methods based on the discontinuation of a specific rock volume from its inherited stress field. This is accomplished through a process of over-coring, which involves the removal of the specified rock volume from its in situ position. This results in the relaxation of stress within the tested volume, which subsequently gives rise to a quantifiable deformation. The application of over-coring techniques is limited by the magnitudes of in situ stress, which must not exceed the strength of the rock. The deformations observed in the over-cored core should be within the elastic field of deformation. Hooke's law is employed as a constitutive law between stress and strain. The deformation of the over-cored core is monitored using strain gauges positioned at varying locations on the surface of the over-cored rock volume [3, 4].

Over-coring methods are indirect methods that measure the deformation of over-cored core through the employment of strain gauges. In order to ascertain the stresses from the measured strains, it is necessary to first determine the deformation parameters of the rock material. This can be achieved through various laboratory tests, with particular attention being paid to the determination of deformation parameters for anisotropic materials in oriented samples [5].

There are multiple methods for locating the strain gauges on the surface of over-cored rock core. The first strain gauge probe, called a 'Doorstopper', was employed in 1932 for the measurement of stress within a tunnel situated beneath the Hoover Dam in the United States of America. The two perpendicular strain gauges were situated at the end of the borehole, with the wellhead subsequently being over-cored [6]. In order to determine the full stress tensor, a greater number of boreholes were required. Subsequently, further development was focused on the placement of strain gauges on the longitudinal walls of the borehole, with the objective of determining the full stress tensor using a single borehole.

Further probes were cylindrical in shape, with the strain rosettes situated at the surface of the probe and glued or pressed towards the wall of the borehole. 'The C.S.I.R. Triaxial Strain cell' was developed by the South African Council for Scientific and Industrial Research [6]. Australian CSIRO (or CSIRO Hollow Inclusion – (CSIRO HI)) was developed by the Commonwealth Scientific and Industrial Research Organization and is commercially available and officially recommended by ISRM committees for in situ stress determination [7, 8]. The Swedish 'Borre Probe' is also recommended by the International Society for Rock Mechanics and Rock Engineering (ISRM) committee [9]. The 'USBM' probe was developed by the U.S. Bureau of Mines [10], and the other is

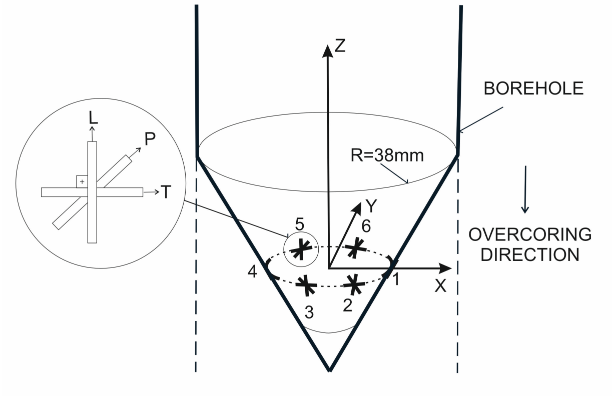


Figure 1. CCBO probe situated at the end of a borehole and then over-cored (ε_{ij} – measured strains in directions belonging to individual strain gauges; i – position around the circumference of the probe (i = 1–6); j – direction of individual strain at the position (direction T, L or P)). Obtained from the source [5].

Finnish 'LVDT' (Linear Variable Differential Transducer cell) [11]. Cylindrical probes allow the use of the analytical theory of elasticity proposed by Lekhnitski [12]. The advantage of this method is that it is a known analytical solution for the transformation between rectangular and cylindrical coordinates in isotropic and transversely isotropic or orthotropic material models [13]. The disadvantage when using this method is the necessity to drill a pilot borehole into which the probe is placed, with the drilling extending across the width of the main borehole.

The Compact Conical Borehole Over-coring probes (CCBO), originally developed in Japan, are compact probes of elastic material that are fixed to the borehole head. The probes are designed with a specific conical shape that allows direct installation into the wellhead, thus eliminating the need for a pilot hole. However, the strain gauge configuration is designed with directional variability, to ensure accurate data collection (Figure 1). The CCBO method is officially recommended by the ISRM committees for in situ stress determination [3, 4].

This conical shaped probe has an advantage in reducing the time, effort and cost of a series of rock stress measurements, combining compact over-coring, the diameter of which is equal to that of the pilot borehole. The method was developed for horizontal (or upper hemisphere) boring in underground work, and thus the disadvantage of the method is that the probe is not expected to be used for a submerged borehole bottom. A further disadvantage of this methodology is that, due to the absence of a known analytical solution, a numerical model is needed to ascertain the necessary relationships between stress and strain.

2. THEORETICAL OVERVIEW OF THE CCBO METHOD

Equation (1) introduces a constitutive law between measured strains and the sought stress tensor:

$$\varepsilon_{ij} = (D) \cdot \sigma, \tag{1}$$

where

ε_{ij} – vector of measured strains [–] (i – position of the strain gauge around the circumference of the probe, i = (1–6), j – direction of the strain gauge at the i-th position (direction T, L or P) (see Figure 1);

σ – vector of unknown parameters of the stress tensor, where $\sigma = (\sigma_x, \sigma_y, \sigma_z, \sigma_{xy}, \sigma_{yz}, \sigma_{xz})$ [MPa];

(D) – distribution matrix (where the number of rows is equal to the number of components of the vector ε_{ij}) [GPa^{-1}].

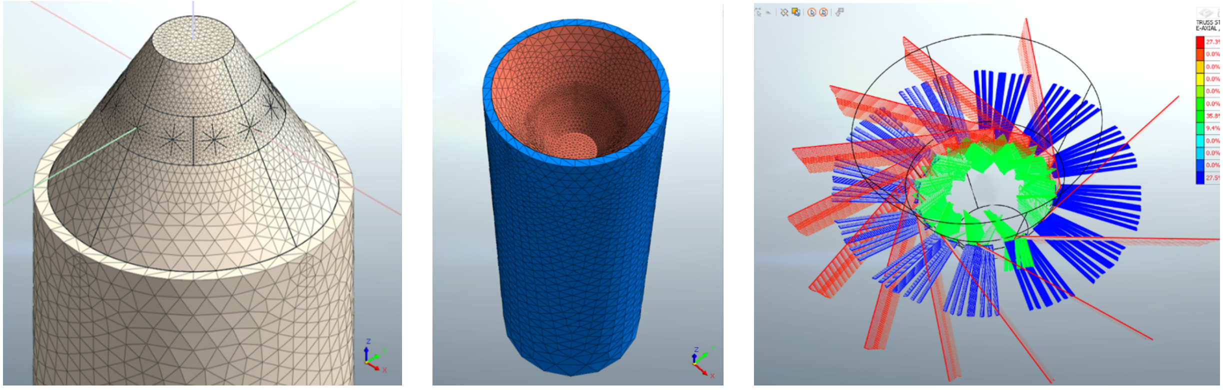
The distribution matrix captures information about the stiffness of the rock material, the transformations between the rectangular coordinate system and the system of directions of measured strains, through strain gauges on the conical probe and the redistribution of stresses resulting from the over-coring process in the immediate vicinity of the conical probe. The distribution matrix is established through a parametric analysis employing numerical modelling using the Finite Element Method. The parametric analysis is based on the principle of the superposition law, where the individual unit components of the stress tensor are applied to the numerical mesh (Figure 2).

The distribution matrix consists of distribution coefficients:

$$D = \begin{pmatrix} k_{1(\varepsilon_T,\sigma_a)} & k_{1(\varepsilon_T,\sigma_b)} & k_{1(\varepsilon_T,\sigma_c)} & k_{1(\varepsilon_T,\sigma_d)} & k_{1(\varepsilon_T,\sigma_e)} & k_{1(\varepsilon_T,\sigma_f)} \\ k_{1(\varepsilon_L,\sigma_a)} & k_{1(\varepsilon_L,\sigma_b)} & k_{1(\varepsilon_L,\sigma_c)} & k_{1(\varepsilon_L,\sigma_d)} & k_{1(\varepsilon_L,\sigma_e)} & k_{1(\varepsilon_L,\sigma_f)} \\ k_{1(\varepsilon_P,\sigma_a)} & k_{1(\varepsilon_P,\sigma_b)} & k_{1(\varepsilon_P,\sigma_c)} & k_{1(\varepsilon_P,\sigma_d)} & k_{1(\varepsilon_P,\sigma_e)} & k_{1(\varepsilon_P,\sigma_f)} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ k_{n(\varepsilon_T,\sigma_a)} & k_{n(\varepsilon_T,\sigma_b)} & k_{n(\varepsilon_T,\sigma_c)} & k_{n(\varepsilon_T,\sigma_d)} & k_{n(\varepsilon_T,\sigma_e)} & k_{n(\varepsilon_T,\sigma_f)} \\ k_{n(\varepsilon_L,\sigma_a)} & k_{n(\varepsilon_L,\sigma_b)} & k_{n(\varepsilon_L,\sigma_c)} & k_{n(\varepsilon_L,\sigma_d)} & k_{n(\varepsilon_L,\sigma_e)} & k_{n(\varepsilon_L,\sigma_f)} \\ k_{n(\varepsilon_P,\sigma_a)} & k_{n(\varepsilon_P,\sigma_b)} & k_{n(\varepsilon_P,\sigma_c)} & k_{n(\varepsilon_P,\sigma_d)} & k_{n(\varepsilon_P,\sigma_e)} & k_{n(\varepsilon_P,\sigma_f)} \end{pmatrix} \tag{2}$$

where the individual coefficients k_i of the matrix D are denoted by their azimuthal position around the probe ($i = 1 \ldots n$) and the characteristic orientation of the individual strain gauge T, L, P (see Figure 1), and are different for each superposition state applied to the model simulation (σ_a–σ_f) [5].

In the case of anisotropic material, the exact position of the principal axes of the material constants, in relation to the position of the measuring probe, must also be known. It is necessary to construct an original distribution matrix for each measurement. This is because each measurement is positioned in a specific relation to the principle axes of the material characteristics of anisotropic material. All rotations of the tensors throughout the evaluation process are adapted to the position of the principal axes of the material constants of the anisotropic material.



(a). Numerical mesh of the CCBO probe.

(b). Numerical mesh of the overcored rock surrounding the probe.

(c). Example of strain responses to stress acting along the borehole axis.

Figure 2. Numerical model.

The number of measured strain gauges exceeds the number of unknown components of the stress tensor; this problem is, therefore, overdetermined and is typically solved using the least squares method, which yields the following solution:

$$\tilde{\sigma} = (D^T \cdot D)^{-1} \cdot D^T \cdot \varepsilon_{ij}, \tag{3}$$

where

$\tilde{\sigma}$ – vector of unknown parameters of the stress tensor,

where $\tilde{\sigma} = (\tilde{\sigma}_x, \tilde{\sigma}_y, \tilde{\sigma}_z, \tilde{\sigma}_{xy}, \tilde{\sigma}_{yz}, \tilde{\sigma}_{xz})^T$ [MPa];

D^T – transposed distribution matrix [GPa^{-1}].

3. LABORATORY TESTING OF ROCK DEFORMATION PARAMETERS

The uniaxial compression test represents the simplest and most widely used method for evaluating the strength and deformation characteristics of rock material. In order to ascertain the deformation and strength characteristics of isotropic material, the ISRM methodology is employed [14], which pertains to the uniaxial compression test procedure and allows for the undertaking of multiple procedures for the determination of deformation characteristics, particularly with regard to the selection of the range of values from which the elastic modulus is to be evaluated. In accordance with the methodology, it is feasible to utilise the linear portion of the curve; alternatively, the tangent or secant of the curve may be employed. Nevertheless, there is no established standard for determining the elastic modulus of an anisotropic material. No standard exists that specifies the manner in which the deformation characteristics of a rock material should be determined under the assumption of an anisotropic material model.

A number of authors have addressed the determination of deformation characteristics of transversely isotropic rock material [14–22]. An alternative approach involves the use of ultrasonic wave-velocity measurements acquired in multiple propagation directions to determine the dynamic elastic constants of anisotropic rock. This method can be used to reconstruct the material's complete elastic stiffness tensor [16].

4. IN SITU CASE

4.1. SITE INTRODUCTION

For this research, experiments were conducted at the Grimsel Testing Site (GTS; see Figure 3), an underground research laboratory located in Switzerland. The measurements were conducted in the corridor designated as W073 on the CCBO1 probe. This paper presents the impact of incorporating two distinct stiffnesses of transversely isotropic material, i.e. material that has an axis of symmetry of rotation and exhibits isotropic behaviour in the plane normal to that axis, into the stress evaluation process.

From a geological perspective, the GTS is situated within the southern region of the Aar Massif, which is characterised by the presence of leucocratic granite and Grimsel granodiorite as the host rock [24]. From a geotechnical point of view, it can be described as a compact rock mass, predominantly composed of granite, which appears to be homogeneous and isotropic on the scale of the underground works. In some areas, the rock mass exhibits permeable discontinuities, through which water flows, but there are no such discontinuities at the site where the measurements were taken. In the scale of rock core, the rock may indicate the presence of micro-cracks within the formation and mineral clustering may suggest that the material could be characterised as anisotropic.

4.2. PREVIOUS AND RECENT RESEARCH

In previous research [25], the effect of introducing a transversely isotropic constitutive model into the evaluation workflow was examined, and isotropic results were compared with those obtained for a transversely isotropic material identified by ultrasonic wave

FIGURE 3. The Grimsel Test Site (GTS) is situated within the subterranean section of the Aar Massif, situated between Grimsel Lake (on the left) and Raeterichsboden (on the right). Figure 3 depicts an aerial view of the underground research laboratory, marked with 1, taken from the east. This image is sourced from reference [24].

	$\boldsymbol{\frac{1}{E}}$	$\boldsymbol{\frac{1}{E'}}$	$\boldsymbol{\frac{-\nu}{E}}$	$\boldsymbol{\frac{-\nu'}{E'}}$	$\boldsymbol{\frac{1}{G}}$	$\boldsymbol{\frac{1}{G'}}$
Tangent $K_E = 3.9$	$\frac{1}{27.2}$	$\frac{1}{6.9}$	$\frac{0.17}{27.2}$	$\frac{0.01}{6.9}$	$\frac{1}{11.7}$	$\frac{1}{7.9}$
Secant $K_E = 1.9$	$\frac{1}{28.7}$	$\frac{1}{15}$	$\frac{0.24}{28.7}$	$\frac{0.07}{15}$	$\frac{1}{11.5}$	$\frac{1}{9.1}$

TABLE 1. Normalised elastic properties for the transversely isotropic material [GPa^{-1}]. Obtained and edited from the source [21].

measurements [16]. The present paper focuses on a transversely isotropic rock and adopts material constants reported by a different laboratory [21, 22]. These constants were derived from a series of uniaxial compression tests with strain-gauge measurements on rock samples from the GTS. This paper demonstrates that, even for the same set of rock specimens, applying the two standard linearisations – tangent versus secant – throughout the stress determination process leads to marked discrepancies in the recovered stress tensors.

4.3. DEFORMATION PARAMETERS OF GRIMSEL GRANITE

The results of the uniaxial test performed on the rock specimens from the GTS were obtained from the source [21]. The authors present the results of using the tangent and secant method to evaluate the stiffness of the transversely isotropic rock material from the GTS. The tangent values of the elastic constants were determined for the purpose of analysing the load-dependency of the elastic constants. The secant values of the elastic constants were obtained to analyse the average deformational behaviour of the rock [21]. The secant deformation parameters of the rock material were normalised by reducing the magnitudes of Young's and shear elastic moduli, while maintaining the ratios between the eponymous parameters in two principle perpendicular directions. The objective was to reduce the secant stiffness to a level comparable to that of the tangent one, thereby ensuring that the resulting stress tensors were comparable with each other. These normalised tangent and secant deformation parameters are presented in Table 1. The degree of anisotropy K_E is defined as the ratio between the Young's modulus of elasticity in the plane of isotropy (E) and the Young's modulus of elasticity perpendicular to the planes of isotropy (E'). Accordingly, the degree of anisotropy for the tangent method is $K_E = 3.9$; whereas, for the secant method it is $K_E = 1.9$.

4.4. IN SITU CCBO MEASUREMENT OF STRAINS

In this case, a CCBO probe was used with only 12 strain gauges on its surface, 6 in the L and 6 in

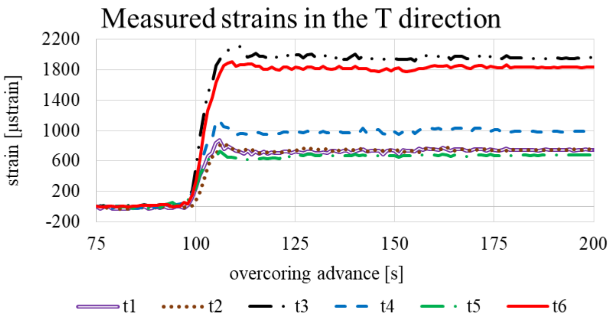


FIGURE 4. Strains measured during over-coring at six positions around the circumference of the probe in the T (t1–t6) directions.

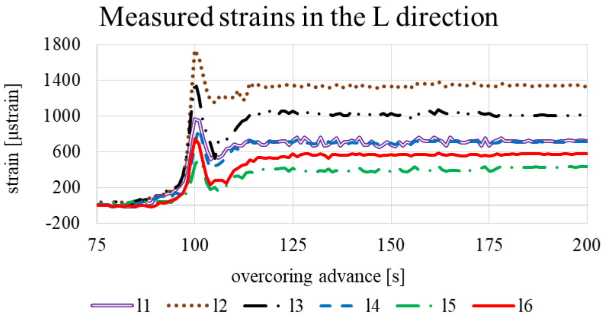


FIGURE 5. Strains measured during over-coring at six positions around the circumference of the probe in the L (l1–l6) directions.

the T-direction (Figure 1). The results of these measurements are shown in Figure 4 (for the T-direction) and Figure 5 (for the L-direction). All of the strain responses exhibit a smooth pattern, marked by the appearance of characteristic inflection points, followed by stabilisation of the strain response. Subtracting the steady-state strain values ε_{ij} (neglecting frequency noise) allows the resulting values of strains to be employed in Equation (3). In this case, stabilisation occurs at a time within 150 seconds.

4.5. EVALUATION PROCESS

Based on the known deformation characteristics, two individual distribution matrices were constructed through a parametric study using numerical modelling according to Equation (2). These were fitted to Equation (1), together with the steady-state strain values ε_{ij} subtracted from measured strains from Figures 4 and 5. The least squares method was employed to ascertain the full stress tensor, from which the principal stresses and their directions were subsequently determined using Equation (3).

5. RESULTS

The solution to Equation (3) is illustrated in Figure 6. The resulting 3D stress states are represented by projections of the principal stresses into the upper hemisphere. These results are based on the normalised stiffness of the two cases of input deformation characteristics.

Besides directional dependencies, the Figure 6 also represents the magnitudes of the resulting principal stresses. It is important to note that the most interesting parameter is not the magnitudes of the resulting stresses themselves but, rather, the ratios between the principal stresses resulting from each approach. These ratios indicate whether the resulting stresses are more anisotropic in character or if the resulting stress state is more uniform in character. By employing tangential deformation characteristics with a relatively high degree of anisotropy, the following was deduced:

- The resulting stress tensor is transversely isotropic in character, exhibiting a maximum principal stress that is approximately three times higher than the other two.
- The maximum principal stress is oriented between the first and second strain gauges, with an angle of dip of 35 degrees. The minimum principal stress is in close approximation to the XY plane, intersecting with the sixth strain gauge.

The following evaluation is based on the secant deformation characteristics, which were normalised with respect to the tangent characteristics.

- The resulting stress tensor is found to be orthotropic in character. The application of a reduced degree of anisotropy resulted in a redistribution of stresses in all three directions.
- The minimum principal stress was observed to shift towards the third strain gauge, with a dip angle of 35 degrees. Accordingly, the total maximum deviation from the tangential solution is 40 degrees.

6. DISCUSSION

The CCBO method is founded upon the disturbance of naturally occurring rock through over-coring of the rock core, with the objective of relaxing the in situ stress through the deformative reaction. In essence, this process is the inverse of that which is tested via uniaxial compression testing. The secant elastic moduli adopted from [21] were obtained for the purpose of analysing the average deformational behaviour and the range of stress, which is more familiar and, therefore, more readily comparable to the magnitudes of the in situ stress. In contrast, the tangent elastic moduli were determined for the purpose of analysing the load dependency of the material, which displays a stronger nonlinear deformational behaviour at low stress [21]. The strain gauges situated at the surface of the CCBO cell were utilised to quantify strains resulting from in situ stresses, which ultimately lead to zero stress conditions. In essence, the strain gauges located within the cell were employed to monitor the full spectrum of stress-strain behaviour during the over-coring process.

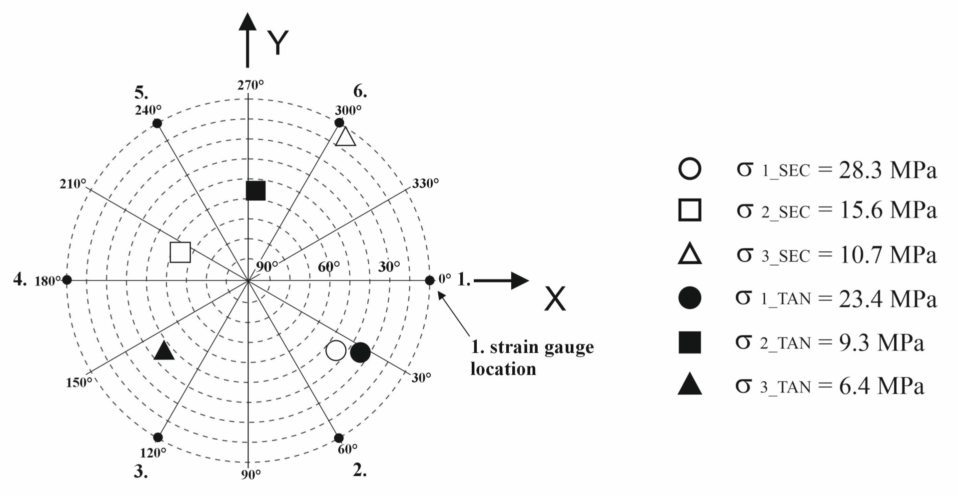


Figure 6. Resulting principal stress magnitudes and their directions – stereographic projection of the principal stress directions; projection into the upper hemisphere; conical probe coordinate system – top view of the probe ($\sigma_{1\ SEC}$, $\sigma_{2\ SEC}$, $\sigma_{3\ SEC}$ – maximum, mean and minimum principal stresses of the solution using secant deformation characteristic; $\sigma_{1\ TAN}$, $\sigma_{2\ TAN}$, $\sigma_{3\ TAN}$ – maximum, mean and minimum principal stresses of the solution using tangent deformation characteristics).

In future work, it would be appropriate to consider a division of the strains measured on the CCBO probe into several segments, whereby multiple distribution matrices would also be used in the stress-evaluation process (see Equations (1)–(3)). The entire computational procedure would thus consist of parts, each yielding a segment-specific full stress tensor as an intermediate result. The individual parts would be formed by intervals in which crack opening–closure is assumed; in this part the tangent modulus of elasticity would be used together with the measured strains that exhibit extreme values during overcoring (strains recorded around the 100th second in Figures 4 and 5); and further into intervals where the suitable use of the secant modulus of elasticity and the standard stabilised strains measured on the conical probe would be applied for evaluating the corresponding segment-specific full stress tensor (strains recorded around the 150th second). The final full stress tensor would then be obtained by superposition of the segment-specific full stress tensors, each computed from the corresponding distribution matrix and recorded strains.

7. Conclusion

Results from two different approaches for determining the deformation characteristics were employed throughout the stress determination process, for the purpose of comparing the resulting stresses. In light of the above, it is not possible to determine which of these results is more accurate. It is proposed that the utilisation of the secant deformation characteristics during the stress evaluation will facilitate the assessment of the secant modulus for pressures that are proximate to the in situ pressures. Conversely, the tangential strain characteristics are thought to elucidate the deformation behaviour of the rock at low pressures, which are actually encountered during overcoring due to the presence of micro-cracks, thereby leading to a nonlinear strain response in the material.

When evaluating the state of stress in a rock mass, it is necessary to consider that the deformation characteristics which are determined, based on the results of laboratory tests, are dependent on the methodologies employed, the boundary conditions applied, and the initial theoretical assumptions made. As a consequence, the resulting data may vary considerably, even when the samples themselves are identical. This paper presents evidence that the resulting stress tensor is highly sensitive to the input deformation parameters. In the absence of laboratory test outputs for transversely isotropic material, the resulting stress tensor should be evaluated based on laboratory test outputs for isotropic material, at the very least. Furthermore, it is appropriate to utilise hypothetical variants of the deformation characteristics of the transversely isotropic material, derived from the laboratory test results for the isotropic variant.

Acknowledgements

The authors would like to thank Dr. Mohammad Nejati, Dr. Mauro L. T. Dambly, and Prof. Martin O. Saar for their valuable scientific contribution and for the published data used in this study, cited in the present work as reference [21].

The research was co-funded by the European Union under the project INODIN, no. CZ.02.01.01/00/23_020/0008487.

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