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3D STRESS DETERMINATION AROUND AN UNDERGROUND WALL USING STRAIN GAUGE CCBO FOR ISOTROPIC AND TRANSVERSELY ISOTROPIC SOLUTIONS

STANOVENÍ 3D NAPJATOSTI V OKOLÍ PODZEMNÍ CHODBY MĚŘENÉ POMOCÍ TENZOMETRICKÉ SONDY CCBO PRO IZOTROPNÍ A PŘÍČNĚ IZOTROPNÍ VARIANTU ŘEŠENÍ

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Abstract

The stress state in the rock mass can be determined through the measurement using a conical strain gauge, which is installed at the end of a borehole in the rock mass. A numerical model is constructed here based on knowledge of the stiffness of the rock material and the orientation of the principal axes of the material constants. This model is used to determine the distribution matrix, which represents the relationship between the measured strains and the desired 3D stress at the location of the measuring probe. The results vary depending on whether alternative theoretical material models (i.e. isotropic or transversely isotropic) are taken into account during the evaluation process. Using the example of the interpretation of measurements in the Grimsel location, some results are presented for the stress determined in 3D in the vicinity of the corridor of the Grimsel Testing Site – underground research laboratory in a massif of granitic rocks.

Abstrakt

Napjatost v horninovém masivu může být stanovena na základě měření pomocí kuželové tenzometrické sondy, která je instalována na konci vrtu v horninovém masivu. Na základě znalosti o tuhosti horninového materiálu a orientaci hlavních os materiálových konstant je pomocí numerického modelu stanovena distribuční matice, která je potřebným vztahem mezi měřenými přetvořeními a hledanou 3D napjatostí v místě měřicí sondy. Výsledky se odlišují, pokud jsou do procesu vyhodnocování použity jiné varianty teoretického materiálového modelu, tj. izotropní nebo příčně izotropní. Příspěvek, na příkladu interpretace měření v lokalitě Grimsel, představuje tyto rozdílné výsledné napjatosti stanovované ve 3D v okolí chodby podzemní výzkumné laboratoře – Grimsel Testing Site – v masivu granitických hornin.

Keywords

stress tensor, stress state in the rock mass, CCBO method, stiffness matrix, numerical modelling, GTS

Klíčová slova

tenzor napjatosti, napjatost v horninovém masivu, metoda CCBO, matice tuhosti, numerické modelování, GTS

1. Introduction

The determination of the stress in a rock mass is a fundamental task in the fields of geomechanics, tunnelling, mining and underground waste disposal. The design of underground structures requires the definition of boundary conditions, with the most important boundary condition for underground excavation analysis being in situ stress. Knowledge of the stress state provides valuable insight into the direction and scale in which the rock is likely to fail or in which direction significant convergences may occur. It is possible to ascertain the complete stress tensor via relief methods. Among these is the compact conical borehole overcoring (CCBO) method.

2. The CCBO method

The determination of the full stress tensor requires only one borehole. The method is using a special conical probe (see Fig. 1) that is installed at the end of the borehole. This strain probe is overcored, which results in relaxation of the stress originally acting at the location. Based on the strains measured by the strain gauges, which are positioned in specific directions on the surface of the probe, the full stress tensor at the idealised point can be determined (Sugawara et al., 1999; Knejzlík et al., 2008). This requires the use of a numerical model in conjunction with an understanding of the deformation parameters inherent to the rock environment. The rock environment is assumed to be homogene-

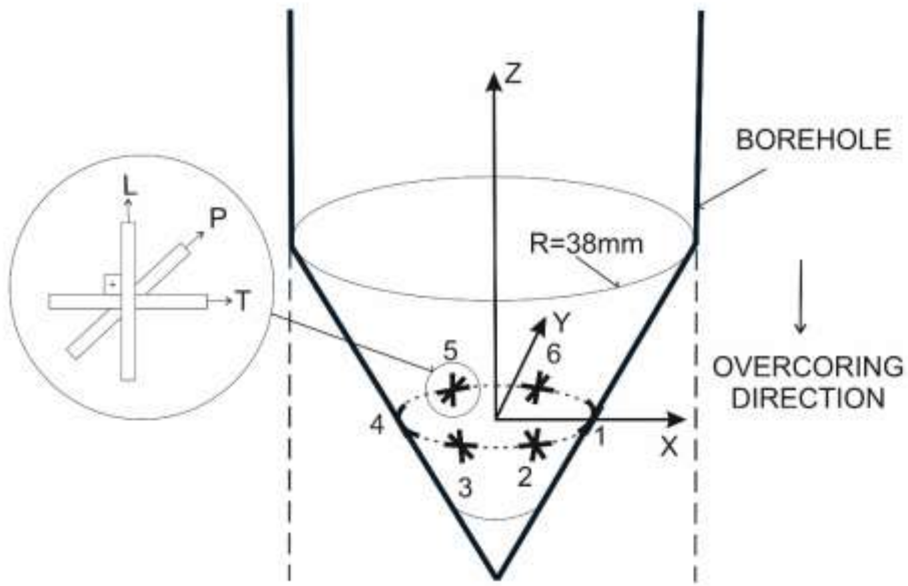

Fig. 1: CCBO probe situated at the end of a borehole and then overcored (ε_{ij} – measured strains in directions belonging to individual strain gauges; i – position around the circumference of the probe (i = 1–6); j – direction of individual strain at the position (direction T, L or P)).

ous, linearly elastic, isotropic or anisotropic.

The stiffness of the rock material is interpreted using the stiffness matrix, which is dependent on the theoretical material model in question. These models can be classified as isotropic, transversely isotropic, or orthotropic. The stiffness matrix is made up of the deformation parameters of the rock material, and is determined based on the results of laboratory tests. When the stiffness matrix for the surrounding rock is known, it is entered as input data to a numerical model that simulates the process of installing and drilling the strain gauge probe. By applying the superposition stress states to the numerical model and subtracting the reactive simulated strains, it is possible to construct a distribution matrix that represents the relationship between the strains measured with the strain gauges and the probable initial stress that was originally acting at the location of the measuring probe (Petrlíková 2024).

3. Mathematical solution for determination of the full stress tensor using the CCBO method

3.1. Stiffness or compliance matrix for the rock material

Equation (1) describes the relationship between stress and strain in the three-dimensional rectangular coordinates (x′, y′, z′) in which the transversely isotropic material is defined. In this case, the directions of the principal axes of the material constants coincide with the x′, y′ and z′ axes. Conversion between two quantities, strain and stress tensors, is accomplished through the use of the compliance matrix C, which is the inverse of the stiffness matrix. In Equation (1), the compliance matrix defined in terms of the principle axes, is presented for a transversely isotropic material model, which is distinguished by a single axis of rotation of the material constants around which the material constants are invariant, forming planes of isotropy that perpendicularly traverse the axis of rotation.

$$\boldsymbol{\varepsilon} = \begin{pmatrix} \varepsilon_{x'} \\ \varepsilon_{y'} \\ \varepsilon_{z'} \\ \varepsilon_{xy'} \\ \varepsilon_{yz'} \\ \varepsilon_{xz'} \end{pmatrix} = \boldsymbol{C} \cdot \boldsymbol{\sigma} = \begin{pmatrix} \frac{1}{E} & \frac{-\nu}{E} & \frac{-\nu'}{E'} & 0 & 0 & 0 \\ \frac{-\nu}{E} & \frac{1}{E} & \frac{-\nu'}{E'} & 0 & 0 & 0 \\ \frac{-\nu'}{E'} & \frac{-\nu'}{E'} & \frac{1}{E'} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G'} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G'} \end{pmatrix} \cdot \begin{pmatrix} \sigma_{x'} \\ \sigma_{y'} \\ \sigma_{z'} \\ \sigma_{xy'} \\ \sigma_{yz'} \\ \sigma_{xz'} \end{pmatrix} \tag{1}$$

where:

$\varepsilon_{x'}$, $\varepsilon_{y'}$, $\varepsilon_{z'}$, $\varepsilon_{xy'}$, $\varepsilon_{yz'}$, $\varepsilon_{xz'}$ – components of the strain tensor ε in a rectangular coordinate system [-],
$\sigma_{x'}$, $\sigma_{y'}$, $\sigma_{z'}$, $\sigma_{xy'}$, $\sigma_{yz'}$, $\sigma_{xz'}$ – components of the stress tensor σ in a rectangular coordinate system [MPa],
C – compliance matrix for a transversely isotropic material [GPa^{-1}], consisting of the following parameters:
E, E´ – Young´s modulus in the plane of isotropy and in the perpendicular direction, respectively [GPa],
ν, ν´ – Poisson´s ratio in the plane of isotropy and in the perpendicular direction, respectively [-],
G, G´ – shear modulus of elasticity in the plane of isotropy and in the direction perpendicular to it, respectively [GPa].

In order to ascertain the deformation characteristics of the isotropic material model, two parameters must be determined in the laboratory: Poisson's ratio ν, and Young's modulus E. In the case of a transversely isotropic material model, five independent linear constants must be determined: 1/E, -ν/E, -ν´/E´, 1/E´, and 1/G´. These can be obtained through a loading test, such as an uniaxial compression test with the assistance of multiple strain gauges (Amadei, 1983) or a compression test on a spherical specimen situated within a specialised pressure chamber. This allows for the determination of the dynamic elastic properties through the measurement of P-wave and S-wave velocities during an increase in medium pressure (Aminzadeh et al., 2022; Petružálek et al., 2023).

3.2. Compilation of the distribution matrix using numerical modelling

Since the coordinate system of the measuring probe (see Fig. 1) located in the rock mass may not correspond to the principle axes defining the transversely isotropic material (Equation 1), which describes the surrounding rock mass (i.e. the directions of the axes X, Y, Z and x´, y´, z´, may be different), and since there is still no known analytical solution for the redistribution of stress in 3D around the conical probe during the overcoring process, the distribution matrix must be determined using a numerical model. The distribution matrix captures information about the stiffness of the rock material (i.e. the compliance matrix from Equation 1), 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 overcoring process in the immediate vicinity of the conical probe. By applying the superposition of stress states to the numerical model of the overcored measuring probe situated in a transversely isotropic rock, and by subtracting the reactive simulated strains in the specified directions of the gauges, we can compile the distribution matrix, which represents the relationship between the measured strains and sought stress.

3.3. Calculation of stress from measured strain

The number of measured strains 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:

$$\boldsymbol{\tilde{\sigma}} = (\boldsymbol{D}^{\boldsymbol{T}} \cdot \boldsymbol{D})^{-1} \cdot \boldsymbol{D}^{\boldsymbol{T}} \cdot \boldsymbol{\varepsilon}_{\boldsymbol{ij}} \quad (2)$$

where:

$\widetilde{\sigma}$ – vector of unknown parameters of the stress tensor, where $\widetilde{\sigma} = \left(\widetilde{\sigma_x}, \widetilde{\sigma_y}, \widetilde{\sigma_z}, \widetilde{\sigma_{xy}}, \widetilde{\sigma_{yz}}, \widetilde{\sigma_{xz}}\right)^T$ [MPa],
D^T – transposed distribution matrix [GPa^{-1}],
D – distribution matrix (where the number of rows of D is equal to the number of components of the vector ε_{ij}) [GPa^{-1}],
ε_{ij}– vector of measured strains (where the vector components are in order according to the rows of D) [-],
i – position of the strain gauge around the circumference of the probe, i = (1–6) (Fig. 1),
j – direction of the strain gauge at the i-th position (direction T, L or P) (Fig. 1).

4. In-situ measurements

Experiments were carried out at the Grimsel underground research laboratory in Switzerland. Based on the 3D stress measurement system using CCBO probes in granitic rocks, we present some measurements here to illustrate how the introduction of transverse isotropy into the stress evaluation process affects the resulting 3D stress. We consider measurements from probe CCBO1, situated at the end of the 2 m long borehole of corridor W073.

4.1. Calculation input data

Fig. 2 depicts the strains measured during overcoring at the surface of the conical probe in specific directions. All of the strain responses from all strain gauges 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 (2). In the case presented in Fig. 2, stabilisation occurs in time before 150 seconds.

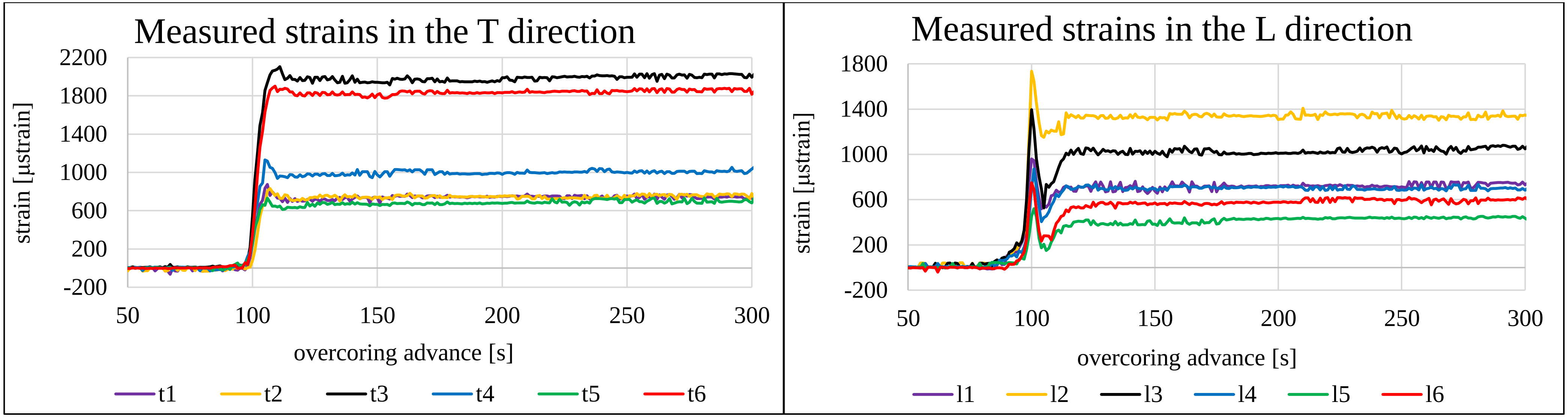

Fig. 2: Strains measured during overcoring at six positions around the circumference of the probe in the T (t1–t6) and L (l1–l6) directions.

For rock that was assumed to be isotropic, two deformation parameters were used: ν = 0.25 and E = 22 [GPa]. Based on the assumption of transverse isotropy, five components of the matrix of compliance were determined. These values were derived from experimental results reported by Aminzadeh et al. (2022), involving a compression test on a spherical specimen situated within a specialised pressure chamber (Petružálek et al., 2023). The values were calibrated so that the resulting stress values could be compared with the results for the isotropic variant, given that the stiffness values derived from the laboratory measurements are assumed to exceed those of the actual rock mass. The ratios were maintained for the pairs of deformation parameters in the plane of isotropy and across the plane of isotropy (E/E′, G/G′ and ν/ν′), and reduced amplitudes of the linear constants of the compliance matrix were used, as shown in Table 1.

Table 1 - Elastic properties for the transversely isotropic material [GPa^{-1}]

$\frac{1}{E}$	$\frac{1}{E'}$	$\frac{-\nu}{E}$	$\frac{-\nu'}{E'}$	$\frac{1}{G}$	$\frac{1}{G'}$
$\frac{1}{35.5}$	$\frac{1}{18}$	$\frac{0.33}{35.5}$	$\frac{0.18}{18}$	$\frac{1}{9.5}$	$\frac{1}{14}$

5. Stress results for the isotropic and transversely isotropic cases

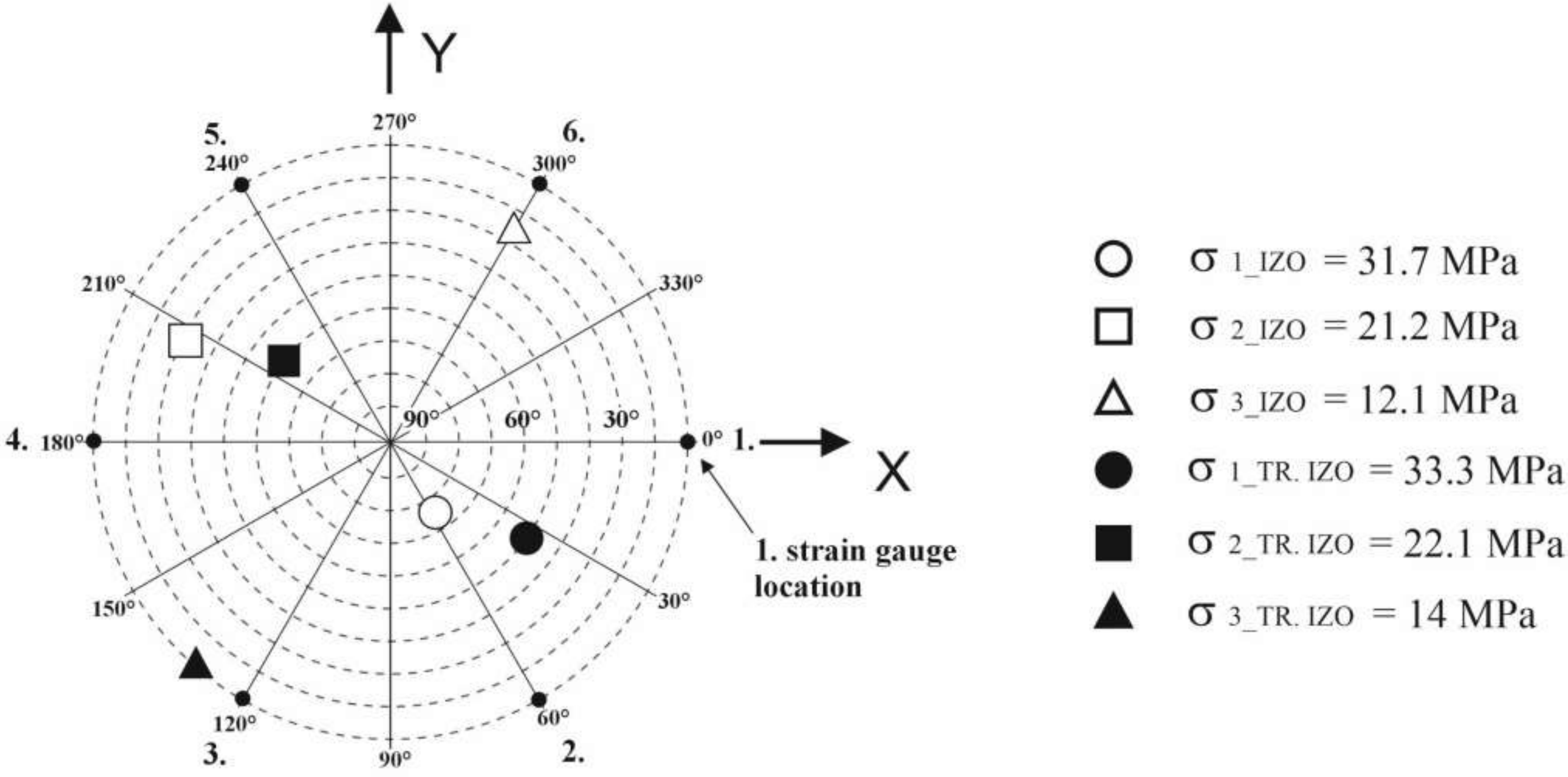

***Fig. 3:** Resulting principal stress amplitudes and their directions – stereographic projection of the principal stress directions; projection into the upper hemisphere; conical probe coordinate system – top view of the probe (σ_{1_IZO}, σ_{2_IZO}, σ_{3_IZO} - maximum, mean and minimum principal stresses of the isotropic solution; $\sigma_{1\_TR.\ IZO}$, $\sigma_{2\_TR.\ IZO}$, $\sigma_{3\_TR.\ IZO}$ - maximum, mean and minimum principal stresses for the transversely isotropic solution).*

Fig. 3 presents the resulting principal stresses for the isotropic solution and the transversely isotropic solution, and it can be seen that these are characterised by a degree of anisotropy of the rock material of approaching two. This input information, provided during the evaluation of the resulting stresses, caused a rotation of the axial cross of the principal stresses in such a way that the direction of the maximum principal stress deviated from the isotropic variant by 25°, the direction of the mean principal stress deviated by 32°, and the direction of the minimum principal stress deviated by 15°. The amplitudes of the resulting stresses for the isotropic and transversely isotropic variants represent differences in the range of 5–15%, with the ratios between the principal stresses remaining largely unaffected.

The rotations described here for the resulting axis of principal stresses indicate the manner in which the introduction of anisotropy into the evaluation process may affect the resulting 3D stress. If the orientation of the principal axes of the material constants relative to the orientation of the measurement probe had been specified differently throughout the stress determination process, larger changes in the principal stress amplitudes between the isotropic and transversely isotropic variants could have been observed. Furthermore, the deflection of the directions would also have been regulated by this effect.

6. Conclusion

The rate of change in the deflection of the principal stress directions and their amplitudes is contingent upon not only on the degree of anisotropy but also the orientation of the principal axes of the material constants relative to the measuring probe, which are equally important parameters affecting the resulting stress in an anisotropic rock environment. These two parameters are of great importance with regard to the resulting ratios of the three principal stresses and their directions (Petrlíková, 2024).

In the case where it is not feasible to ascertain the full stiffness matrix for the material through laboratory testing, it is advisable to determine the degree of anisotropy. It would be advantageous to consider at least hypothetical variations of the orientation of the principal axes of the material constants in relation to the measuring probe and to observe the hypothetical variations in the stress state that would result. Given that the rock material was evaluated by the laboratory test as transversely isotropic (Aminzadeh et al., 2022), it is assumed that the resulting stress tensor based on this solution is more realistic than the stress tensor determined for the isotropic variant.

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