DETERMINATION OF STRESS TENSOR BY THE CCBO(M) METHOD THEORY OVERWIEV AND PRACTICAL USE EXAMPLE

STANOVENÍ TENZORU NAPJATOSTI CCBO(M) METODOU TEORETICKÝ PŘEHLED A PŘÍKLAD PRAKTICKÉHO VYUŽITÍ

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Abstract

CCBO (Compact Conical Borehole Overcoring) or CCBM (Compact Conical Borehole Monitoring) is the method of in situ stress measurement and observation of stress changes in the rock mass. Since 1998 "ISRM suggested methods" have provided guidance on the use of a Japanese borehole overcoring technique in which only one borehole is required to determine the full stress tensor. This method and its monitoring promotion are widely used in the Institute of Geonics of the CAS, v.v.i. (hereinafter the Institute). This article presents problematic issues associated with theory requirements, modelling errors and problems associated with the differences between theory and reality, as well as introducing a practical example of use.

Abstrakt

CCBO (kompaktní kuželově-zakončená sonda obvrtaná) nebo CCBM (kompaktní kuželově-zakončená sonda monitorovací) se nazývá metoda pro měření napětí respektive metoda pro zjišťování napěťových změn v horninovém prostředí. Od roku 1998 "ISRM doporučené metody" poskytují pokyny pro použití této japonské obvrtávací techniky, při které je zapotřebí pouze jediný vrt pro stanovení úplného tenzoru napjatosti. Tato metoda i s její monitorovací nadstavbou je již široce používaná Ústavem Geoniky AV, v.v.i.. Článek představuje problematické záležitosti spojené s teoretickými předpoklady, chybami modelování a s rozdíly mezi teorií a realitou, dále jepředstaven praktický příklad využití metody.

Keywords

stress tensor, CCBO, CCBM, conical probe, measurement of in situ stress, monitoring of stress

Klíčová slova

tenzor napjatosti, CCBO, CCBM, kuželová sonda, měření napětí in situ, monitorování napětí

1 Introduction

Since human beings use rock strength to build underground works the need for knowledge of the rock environment is growing. In situ stress measurement is one of the basic needs on entering the rock mass. There are many methods to determine in situ stress. One of them is the CCBO (compact conical borehole overcoring) method which falls within the relief type of method and which can offer full stress tensor determination from only one borehole.

The theory of full stress tensor determination using the CCBO method has been developed in Japan and since 1999 it has become one of the ISRM suggested methods for rock stress determination (Sugawara and Obara, 1999; Kang, 2000). The Institute has been using this method for stress tensor determination (Staš at al., 2005; Knejzlik et al., 2008) and also for monitoring stress tensor changes using the CCBM (compact conical borehole monitoring) method (Staš et al., 2007; Staš et al., 2008; Kaláb et al., 2011; Staš et al., 2011; Soucek et al., 2013). This method of stress tensor determination depends on the theory of elasticity and is subjected to the laws of homogeneity and isotropy. Practical experience shows that these conditions of the surroundings do not meet the theoretical requirements, hence the Institute is trying to develop an advanced theory solution to fulfil the conditions of inhomogeneous, anisotropic but still elastic-responding surrounding media.

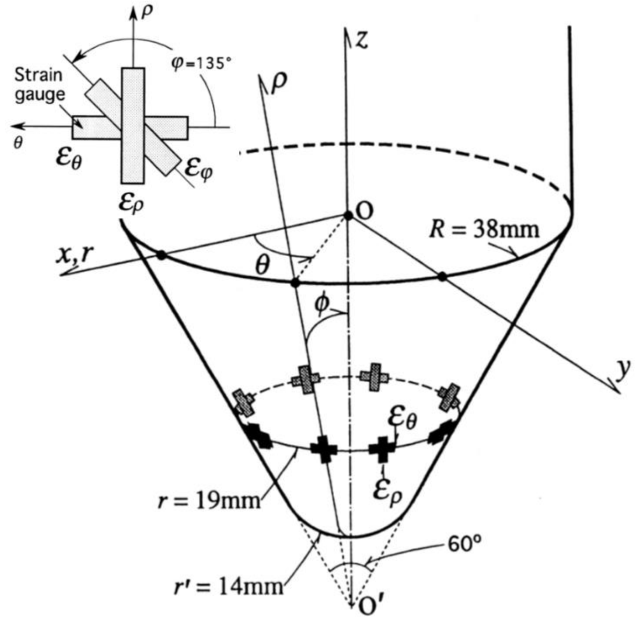

***Figure 1** Definition of the cylindrical, the spherical and the Cartesian coordinates, the left picture shows the additional strain gauge in the φ direction (Sugawara and Obara, 1999)*

2 CCBO method

CCBO is a method of in situ stress measurement in the rock mass using the inherent behaviour of releasing rock from the initial stress field. Overcoring itself causes the release of stress which manifests with a deformation response of the rock mass. Relations between strains along the perimeter of the probe give insight into the stress state in which the rock was initially placed.

2.1 CCBO theory

Figure 1 represents a measuring device with eight measuring points with two strain gauges at each point measuring strains in the radial ρ and the tangential θ direction. The triple gauge method can also be used but an additional strain gauge is required at each point to measure strain in the φ direction. The strains $\{\varepsilon_\theta, \varepsilon_\rho\}^T$ at each strain measuring point of a tangential angle θ for the double gauge method can be given, in the isotropic case, as follows:

$$\begin{Bmatrix} \varepsilon_\theta \\ \varepsilon_\rho \end{Bmatrix} = \begin{bmatrix} A_{11} + A_{12}\cos 2\theta, & A_{11} - A_{12}\cos 2\theta, & C_{11}, & D_{11}\sin\theta, & D_{11}\cos\theta, & 2A_{12}\sin 2\theta \\ A_{21} + A_{22}\cos 2\theta, & A_{21} - A_{22}\cos 2\theta, & C_{21}, & D_{21}\sin\theta, & D_{21}\cos\theta, & 2A_{22}\sin 2\theta \end{bmatrix} \cdot \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{zx} \\ \tau_{xy} \end{Bmatrix} \cdot \frac{1}{E}, \qquad (1)$$

where A_{11}, A_{12},..., D_{21} are the redistribution strain coefficients (Sugawara and Obara, 1999; Kang, 2000).

From an analytical point of view, the equation gives the relations between the measured tangential or radial strains $\{\varepsilon_\theta, \varepsilon_\rho\}^T$ and the stress tensor in the Cartesian coordinates **{σ}**. The inside trigonometric relationships are given by Hooke´s law and the Kirsch solution representing strains around the hollow cylinder. The conical shape has no analytical solution, hence strain redistribution coefficients have to be evaluated by numerical analysis. Their values can be determined from the amplitudes of the responding goniometric functions of the strains around the perimeter of the conical probe to the applied superposition states.

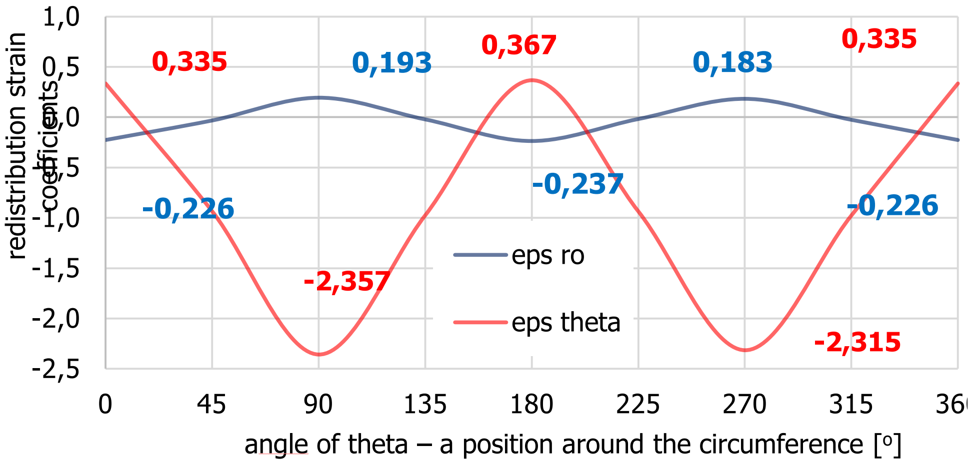

Figure 2 Responding goniometric function of the strain in the radial and tangential directions to the applied superposition state of σ_x =1 [Pa]

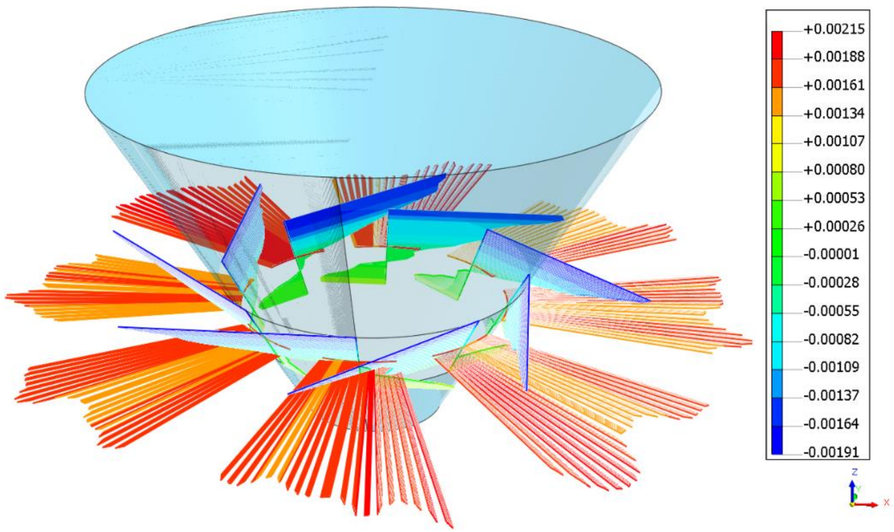

Figure 3 Modelled responding strains in the radial and tangential directions to the applied superposition state of σ_z =1 [Pa]

Each superposition state is given by the unit stress tensor (for example the superposition state for σ_x=1[Pa] is given by the following stress tensor: {1,0,0,0,0,0}) and the responding strains are investigated. Figure 2 shows an example of the responding function of the strain in the radial and tangential directions to the applied unit stress tensor {1,0,0,0,0,0}. Figure 3 shows the responding courses of the strains along the modelled gauges in the radial and tangential directions for the superposition state of {0,0,1,0,0,0} (σ_z=1[Pa]).

2.2 Model tuning

From Figure 2 it can be seen that the deviations of the responding strain values in the radial and tangential directions appear. The maximum deviation reaches the value 0.042; hence the error of the model can be represented by the value of 4.2 per cent. Its value can be reduced by finding the ideal number of element divisions as well as by renumbering the mesh elements. Figure 3 presents the results of strains to the superposition state {0,0,1,0,0,0} after this treatment. Due to the assumption that the strain responses to the stress σ_z (stress acting in the direction of the rotation axis of the probe) should be identical, the strain responses coursing along the modelled gauges to this superposition state are expected to be of the lowest deviation values. Deviations of applied σ_z meet the requirement of deviation values in thousandths. Assuming this critical value of the model error, it can be stated that detailed geometry of the strain gauge may be replaced by simple line elements, because differences between the strain results of the modelled gauges of the precise shape and strain results of the modelled gauge idealized by the 1D element are rich values of up to 1 thousandth.

2.3 Determination of stress tensor

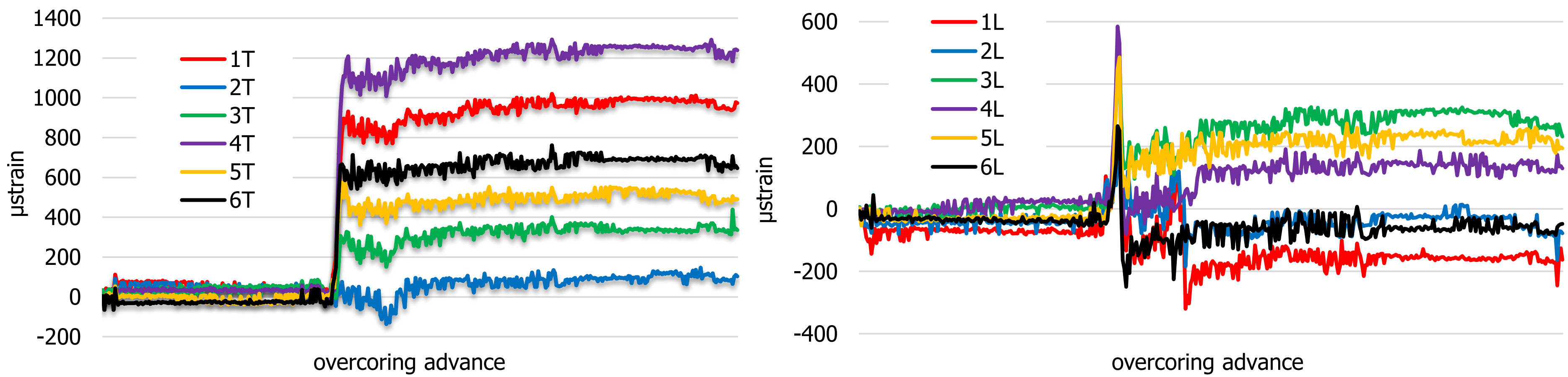

Figure 4 Strain response due to the overcoring advance left – tangential direction, right – radial (longitudinal) direction

Figure 4 represents example responses of strains in the tangential and radial directions due to overcoring advances. At the beginning of the measurement, the strains are set to zero; during the overcoring, inflection peaks can be detected and after complete overcoring a certain kind of stabilization occurs and values of these stabilised relief strains (post overcored strains) are read and considered as essential data for following stress tensor determination.

These stabilised relief strains can be denoted by

$$\{\beta\} = \{\beta_1, \beta_2, \beta_3, \ldots\ldots, \beta_n\}^T, \qquad (2)$$

where n is the number of strain gauges. For this example n=12 (6 for the tangential direction and 6 for the radial). Additional wording of Equation 1 is as follows:

$$[A]\{\sigma\} = E\{\beta\}, \qquad (3)$$

where elements of [A] are the inside trigonometric relations explained in the section 2.1., {σ} is the search stress tensor. (Note that this equation is an identical equation to Equation 1 with the only difference being that the stress tensor is the unknown in this case). Sugawara and Obara (1999) recommend that the most probable values of the stress tensor are determined by the least square method.

3 CCBM method

After the CCBO probe has been overcored and pulled out of the borehole, additional drilling takes place and another monitoring probe can be installed. This CCBM probe may give an overview of the natural stress changes or stress changes induced by human impact. The results of the CCBM are stress tensor changes from which principle stress changes and their direction can be determined.

The total stress field is represented by its tensor {σ} as the superposition of the basic stress tensor measured at the time of the probe installation (σ_0 – obtained from the CCBO method) and supplementary stress changes monitored by the CCBM method {S} (Kukutsch et al., 2015) as follows:

$$\{\sigma\} = \{\sigma_0\} + \{S\} \qquad (4)$$

4 Practical use example

The CCBO(M) methods can be used in mining to determine the initial stress tensor and its changes during the longwall face advance. One of the areas of interest was also modelled in the software Midas GTS using FEM (Finite Element Method) to picture the

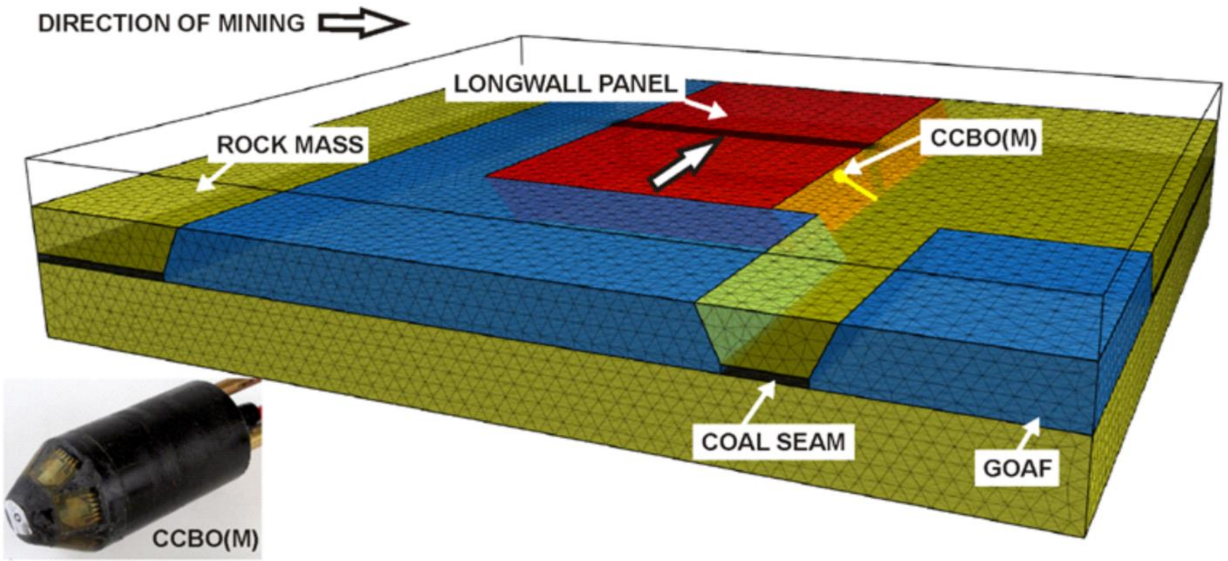

Figure 5 Basic geometry of the model

courses of principal stress changes during the longwall face advance. Basic linear static analysis was performed with together almost 239 000 tetrahedron elements with edges mostly 10 m long. The nearby area mesh of the probe observation elements is refined to the edge size of 2 metres and the edges of the probe observation elements are 0.2 metres long.

The CCBO probe is installed from the gate to the overburden of the longwall panel. The initial stress tensor is estimated. The CCBM probe follows and the stress tensor changes are monitored during the longwall face advance (Figure 5). Figure 6 represents the characteristics of the trend of the relative principle components of the stress tensor change, based on numerical model results and the results of in situ monitoring by CCBM. For a better interpretation of the results of the principle components of the stress tensor changes $S_{IS(j)}$ and $S_{M(j)}$ determined from the stress tensor change in situ $\{S_{IS}\}$ and from the stress tensor change based on the results of numerical modelling $\{S_M\}$ respectively, relative principle components $S_{(j)}$ – *in situ* and $S_{(j)}$ – *model* are standardized by their maximum value of the course of the major principle stresses $S_{IS(1)max}$ and $S_{M(1)max}$.

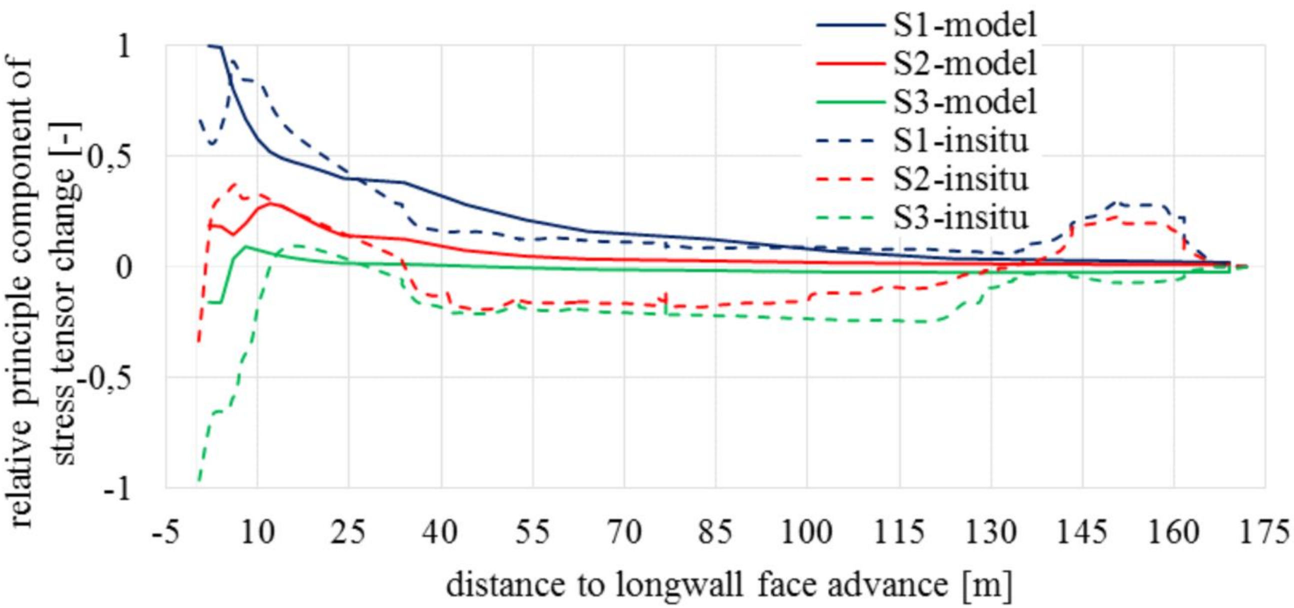

Figure 6 Interrelation of principle component of stress tensor changes model versus in situ measurement

Hence:

$$S_{(j)} - \text{in situ} = S_{IS(j)} / S_{is(1)\max} \qquad S_{(j)} - \text{model} = S_{M(j)} / S_{M(1)\max} \tag{5}$$

where:

$j = 1,2,3$ = adequate to three normalized principal components,
$\{S_{IS}\}$ = stress tensor change determined from in situ data [MPa],
$\{S_M\}$ = stress tensor change determined from data of numerical modelling [MPa],
$S_{IS(j)}$ = principle component of stress tensor change determined from $\{S_{IS}\}$ [MPa] (3 principle stresses),
$S_{M(j)}$ = principle component of stress tensor change determined from $\{S_M\}$ [MPa] (3 principle stresses),
$S_{IS(1)max}$ = maximum value of course of $S_{IS(1)}$ [MPa] (course of major principle stress),
$S_{M(1)max}$ = maximum value of course of $S_{M(1)}$ [MPa] (course of major principle stress),
$S_{(j)}$ – *in situ* = relative principle component evaluated from $S_{IS(j)} / S_{IS(1)max}$ [-],
$S_{(j)}$ – *model* = relative principle component evaluated from $S_{M(1)} / S_{M(1)max}$ [-].

Courses of modelled and in situ relative principle components of stress tensor changes fulfil the assumption of the process of longwall face advance. As soon as the longwall face approaches the monitoring site, the principle stress components increase. There are noticeable inflection points in the graph which indicate decreasing stress. The in situ data was read even behind the longwall face so certain courses of stress behind the advance can be noted.

The directions of the principle stress components in Figure 7 may suggest that the site is originally under a different stress field, meaning that certain model calibrations must be undertaken. Nonlinear static analysis as well as well-chosen type of the solver might be the solution to get the results closer to measured data.

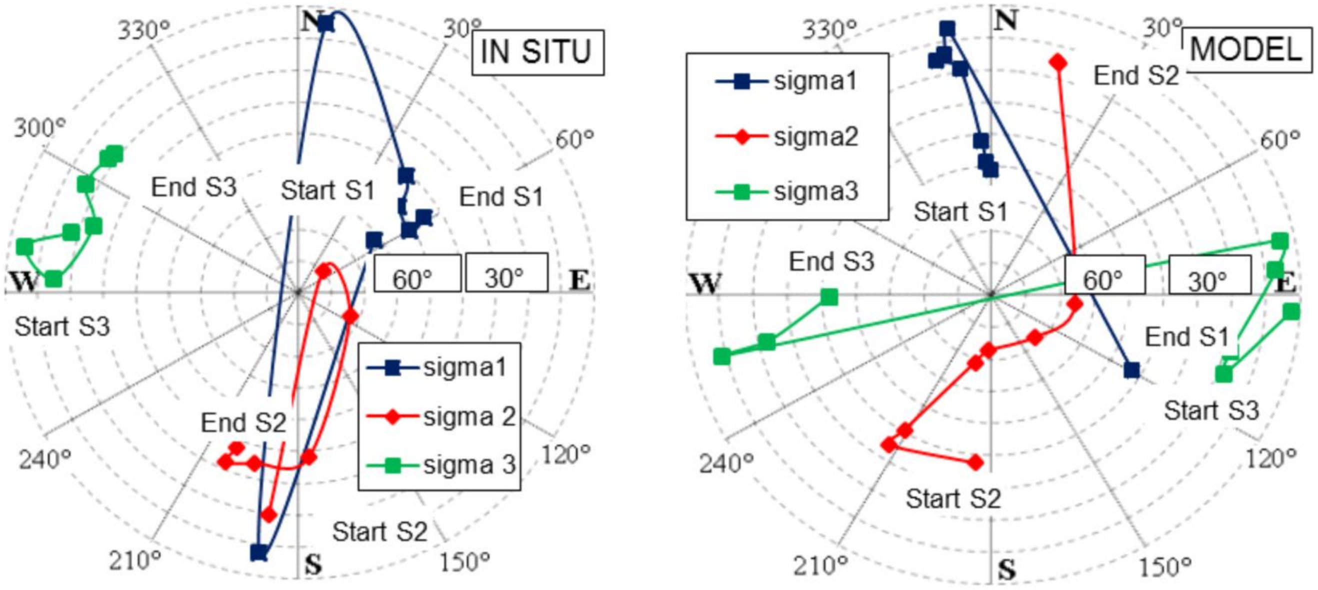

Figure 7 Directions of principle stresses and their changes along the longwall face advance

5 Conclusion

The Institute of Geonics has been using the CCBO method for more than ten years. Monitoring promotion CCBM has been used for stress tensor changes in coal mines (Staš at al., 2008; Kukutsch at al., 2015) in the Rožná uranium mine and in underground laboratories.

From experience, it can be stated that certain analysis should be undertaken in the future. First, strain redistribution coefficients should be estimated having regard to the numerical modelling error. In the case of the recent theory assumptions of homogenous and isotropic rock surroundings, certain sensitivity analysis should follow. In particular, the sensitivity of the final stress tensor matrix to the input data, such as Poisson ratio as reflected in strain redistribution coefficients, should be analysed. The same procedure should follow for the anisotropic case. Hence, different strain coefficients estimated for different cases of anisotropy should be evaluated. When the CCBO(M) method is used in hard rock such as granite, inhomogeneity more than anisotropy poses problems for the processing of the results. This issue is more dependent on laboratory results than on numerical modelling and is time consuming, but an investigation should be carried out.

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