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STRESS MEASUREMENT IN COAL SEAM AHEAD OF LONGWALL FACE – CASE STUDY

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ABSTRACT: Stress measurement and stress monitoring is an important task in mining geomechanics, because knowledge of the stress-strain state in a rock mass is the determining factor for the proper planning of roadway support and for the correct design of underground mining. This strategy is useful for ensuring mining safety, because increasing depth causes several issues, especially in areas with rockburst hazard, when roadways are loaded by the pressure ahead of an advanced longwall or by the stresses induced by destress blasting in overlying rock. Besides, mining is influenced by stress induced by previous excavations, mining edges in the overburden or abandoned workings in the same seam. The paper presents experiments with Compact Conical-endedBorehole Monitoring (CCBM) probes, which were used for stress monitoring in the area of a high-capacity coal face at Karvina Mine at the Lazy site (Czech Republic). This longwall panel is influenced by all the factors mentioned above. Monitoring of stress changes was carried out by using conical probes (CCBM) glued into a special cement body, which was installed directly into the coal seam. The basic description of the probe installed in the coal, the method of installation and the measurement results are the subject of this contribution. Another aim of the paper is to compare the measured values with the theoretical assumptions and mathematical model results.

INTRODUCTION

Knowledge, that is as accurate as possible, of the stress-strain state in the rock mass is the determining factor for the proper planning of roadway support and for the correct design of underground mining. That is why monitoring of the changes in stress induced by longwall mining was included within this experiment.

The problems of rock stress and its determination have been under investigation at the Institute of Geonics for a long time. For the determination of all the components of the stress state, a Compact Conical-ended Borehole Overcoring (CCBO) system was used, which was first used by K. Sugawara and Y. Obara from Kumamoto University (Sugawara and Obara 1999; Obara and Sugawara 2003). The conical shape of the CCBO probe provides a sufficient number of strain measurements in independent directions in one probe position in the borehole, so that all the values of the stress tensor can be determined. Two variants of the CCBO probe were developed and used at the Institute of Geonics. The latter, called a Compact Conical ended Borehole mMonitoring (CCBM) method device, was used for long-term monitoring of stress tensor changes (Stas *et al.,* 2005, 2011). Several measurements of stress tensor changes by the CCBM were performed (Soucek *et al*., 2013, Konicek *et al*., 2014). However, all the probes were installed in compact rocks, into the overburden of the coal seam. The flat conical shape of the borehole bottom is necessary for these types of probes in order to obtain relevant monitored data. In order to monitor the stress changes in the coal seam, a CCBM conical probe was glued into a special cement body. The body containing the CCBM probe was installed into a borehole in a selected longwall panel in the Karvina Sub-basin (see Figure 1) in the Upper Silesian Coal Basin (USCB). The system of the embedded cement body with the conical probe was implemented due to the impossibility of directly installing the conical probe into the coal due to the properties of coal (a brittle material that fails easily).

MINING AND GEOMECHANICAL CONDITIONS

The longwall t explored was the second panel in seam No. 4, which has a thickness of 3 to 8 m; the average seam thickness is 6.2 m. The seam lies about 800 m below the surface. The bed dip ranges from +10° to –17° (differing in the eastern and western limbs of the anticline). The longwall face length was 191 m. The explored area is documented in Figure 2. The hard coal seam is covered by solid and competent sandstone and sandy siltstone layers in this area.

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Figure 1: Location of the Karvina Sub-basin in the Upper Silesian Coal Basin (USCB)

In addition, seams No. 1, 2, and 3 have been irregularly mined out in the overburden. This causes irregular stress distribution in the rock mass and consequently a high risk of rockburst in the course of longwall mining. Seam No. 4 lies in the lower part of the Sedlove Member of the Namurian age. The main tectonic structures are obvious from Figure 2. A very flat anticline (maximum dip up to 20°) divides the geological block into two different parts, and three faults A, B and C. The influence of the mine edges of seams No. 2 and 3 in the overburden is evident from Figure 2 as well. For stress distribution in the area of the explored longwall, it is necessary to consider the mining in seams No. 2 and No. 3 in the next colliery B (east and north east of the explored area – see Figure 2). The first panel in seam. No. 4 was already mined out south of the explored long wall. Additional stress caused by this goaf caused a stress concentration in the south part of the explored panel. It was necessary toconsider the additional stresses caused by residual pillars in seams No. 2 and No. 3 too. These were left in the overburden at a distance of about 50 m and 80 m respectively. The location of experimental stress measurement in seam No. 4 (see CCBM 21 in Figure 2) was in the area of the border of the shaft protective pillar, where the additional stress concentration produced by the edges of seams No. 2 and 3 was considered.

Figure 2: Geological and mining condition of explored area

DESTRESS BLASTING

Destress blasting in the area of the longwall termination was adopted (see Figure 3). The main goal of the destress blasting was to weaken the strength/massiveness of the overlying competent rock strata before the underground mining began in the area of additional stress from previous mining in the overburden seams (seams No. 2 and 3 in Figure 2). First, the horizon of the competent overlying strata was identified through the procured core samples. Then, different sets of predefined, long boreholes were drilled from the gate-roads, targeting these competent strata and the existing mining activity in and around the panel.

A schematic diagram of the adopted design for the long borehole drilling for the destress rock blasting in the termination part of the panel is shown in Figure 3. Boreholes for the first main goal of destress blasting were drilled upwards at angles between 15^o and 35^o from both of the longwall gate-roads (boreholes perpendicular to gates and inclined boreholes towards the north from the maingate, all in Figure 3). The borehole lengths varied from 50 m (boreholes north from the maingate) to 100 m (boreholes perpendicular to gates). In view of the calculated amount of explosive required for the destress rock blasting, the diameter of these boreholes was 93 mm and the spacing of the boreholes was 10 m (boreholes perpendicular to gates). With suitable length and angle combinations for these boreholes, the bottoms (ends) of all of the boreholes were situated at a similar horizon inside the roof, nearly 25 m above coal seam No. 4.

All of these upward-drilled boreholes were charged pneumatically by the gelatine-type explosive Perunit 28E (heat of explosion 4100 kJ.kg^{-1}), and sand was used for the stemming. The length and amount of explosive in each borehole varied according to the surrounding geo-mining conditions. According to the condition of explored panel No. 140 704, the lengths of the charge in the different holes varied from 32 m to 80 m, and the length of the sand stemming varied from 18 m to 46 m. An individual group of loaded boreholes, typically ranging from 4 to 5 boreholes, was fired in advance according to the predefined firing order. All of the charged boreholes in a certain group were fired simultaneously, without any delay. The weight of the explosive charged in different holes varied according to the adopted length of the borehole. The amount of the explosive charged in a hole of the panel varied from 250 kg to 700 kg. The total amount of explosive (for the 4 to 5 boreholes in a group) blasted at a time in the panel varied from 1275 kg to 3050 kg.

According to the site conditions, boreholes Nos. 41–46, 61–64, and 161–164 (Figure 3) were adopted to dilute the influence of the edges between the mined and the un-mined parts of the seams in the overburden. Blasting in boreholes Nos. 71–75 and 171–175 were used to isolate the mining in the longwall panel and the protection shaft pillar. These borehole blastings were designed to develop continuous fractures in the rock mass, which is likely to be responsible for the generation and the accumulation of stress concentrations due to the mining. The competent overlying rock strata, which are continuously fractured due to these blastings, were also observed to be caving friendly. The decision to blast different individual groups of boreholes at different stages was made according to the surrounding workings and the strata, the development of seismic activity during mining and the advancement of the longwall face. As per the geo-mechanical properties of the overlying rock strata and existing legislation, the positions of the fired boreholes were kept in the range of 30 m to 100 m ahead of the longwall face (stages 21–23) and at a distance more than 100 m ahead of the longwall face (stages 19 and 20). The amount of explosive to be charged in each borehole is derived from the dimensions of the selected boreholes for firing. Finally, the selection of boreholes depends on the existing mining conditions, natural conditions and agreement of the registered seismic activity with the legislation.

The efficiency of the adopted destress blasting at the different mining stages is evaluated in terms of seismic effect (SE), which is calculated through the available seismic monitoring data and the weight of the explosive charged (Konicek 2013). These technical evaluation methods provided satisfactory results for the destress blasting design process. Results as well as destress blasting parameters are shown in Table 1. In spite of the fact that the main goal of the destress blasting was different (see text above), the seismic effect, which represents the effect of stress release in the rock mass, was very high (see Table 1). For the first three stages of destress blasting (stages No. 19, 20 and 21 in Table 1), the stress release effect of destress blasting was evaluated as Excellent (SE= 24.8, 44.6 and 14.9), while in the last stages it was extremely good and very good. This corresponds to previous knowledge of destress blasting in similar conditions (e.g. Konicek *et al.,* 2013).

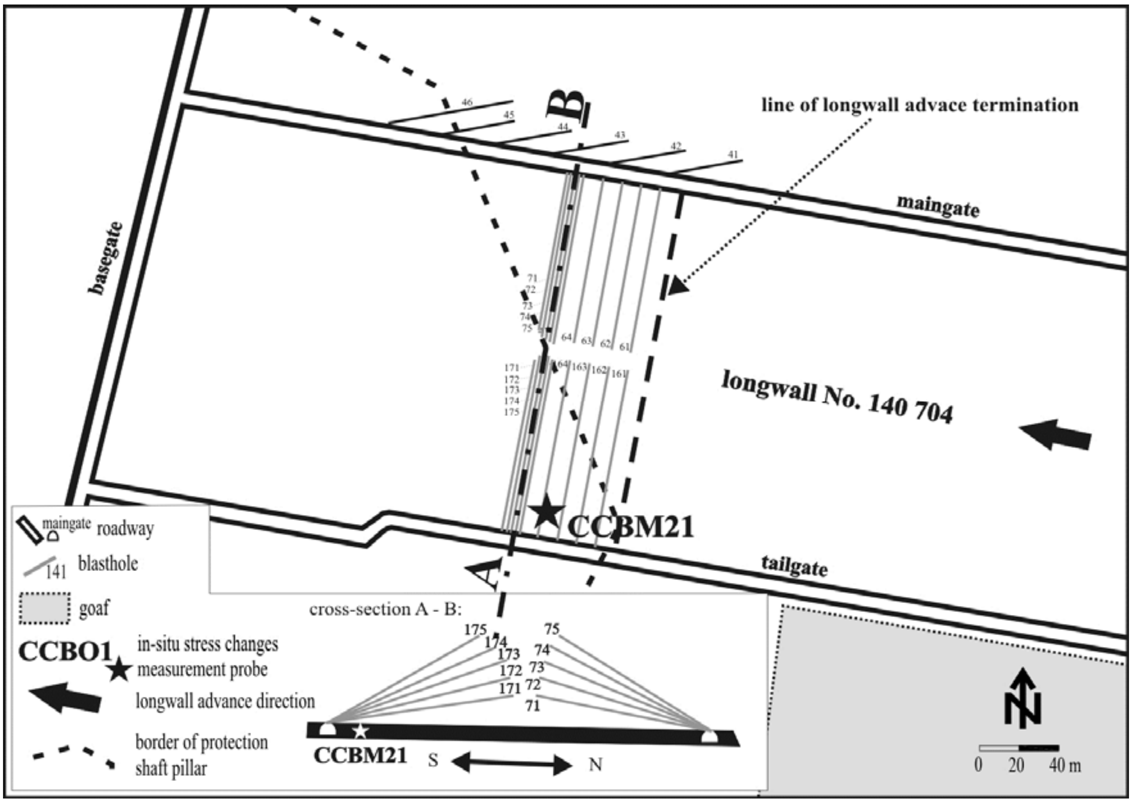

Figure 3: Destress blasting design in area of longwall termination

Table 1: Destress rock blasting parameters conducted in explored longwall

Stage	Numbers of boreholes	Explosive charge [kg]	Released seismic energy [J]	Seismic effect By Konicek 2013 [J.kg^{-1}]	Seismic effect evaluation
19	71, 72, 73, 74, 75	2 900	1.5E+05	24.8	Excellent
20	171, 172, 173, 174, 175	2 975	2.8E+05	44.6	Excellent
21	61, 62, 41, 161, 162	3 050	9.8E+04	14.9	Excellent
22	63, 64, 42, 163, 164	3 050	5.8E+04	8.7	Extremely good
23	43, 44, 45, 46	1 275	1.3E+04	5.0	Very good

EXPERIMENT DESCRIPTION

The objective of the experiment was to determine the stress-strain changes in the coal seam. As noted, the location of the experiment was chosen in an area where an additional stress concentration was contributed by the edges of seams in the overburden near the protective shaft pillar. Because the probe was not installed in the overlying rocks, where installation is relatively easy, it was necessary before installation in the coal seam to solve several problems.

These consisted of two main technical aspects:

- coal is a brittle material and close contact between the conical probe and coal is problematic,
- suitable consistency of grouting mixture.

The approach to these issues and the solution of these problems is the subject of the followingsections.

Parameters of filling material for fixing probe in the borehole in the coal seam

The basic input requirements for the composition and properties of the cementitious filling (grouting) mixture applied to a borehole in the coal seam, which had to be taken into account when designing the recipe, were:

1. The mixture in the fresh state has to exhibit a very high degree of plasticity so that it is able to spontaneously (by gravity) fill the space of a borehole with a very low inclination (10-15°);
2. Aggregates with grain sizes as small as possible must be used as filler in the mixture, with regard to the maximum homogeneity of the hardened mixture and the minimum porosity;
3. During the process of the setting and hardening of the mixture, shrinkage must not occur, so that the maximum possible contact between the cement filler and surrounding coal can be maintained during subsequent stress measurement.

The grouting compounds in fresh state were prepared and tested in the laboratory, showing properties comparable with the cast self-compacting and self-levelling materials that are commonly applied in the construction industry (e.g. as floor screeds). These are characterised by a high degree of spill (260-280 mm according to EN 13454-2: 2008), a relatively high flow rate (approximately 100 mm.s^{-1}) even in a low tilt test in PVC pipe (15°), and a low content of air pores (max. 2%).

During setting and hardening, the mixture exhibited moderate expansion of its volume. After 28 days of hydration of the mixture, the total value of the length change was approximately +0.3 mm.m^{-1}. The resulting mechanical and deformation properties of the hardened mixture are characterised by unconfined compressive strength in the range of 35-40 MPa, tensile bending from 5.0 to 6.0 MPa, indirect tensile strength from 3.0 to 4.0 MPa, static tensile modulus of 12-15 GPa and Poisson number from 0.15 to 0.22.

Installtion

The installation procedure in a coal seam is different from the installation in the overlying rocks. Since the probe would not stick to the coal and close contact between the probe and rock would not be possible, it was decided to put theprobe into a concrete body and then install this "container" in the borehole. The problem of inserting the probe into the concrete was solved by sticking the probe into a concrete body 75 mm in diameter (Figure 4). After solidification, this body was inserted into the casting vessel and secured with concrete, which increased the body dimensions of the probe to 280x100 mm. In order to approach a condition similar to that of the inserted probe in the body when it was sealed in the borehole, a free space was created behind the probe. Subsequently, centralisers with the same diameter as the borehole were mounted in front of and behind the probe in order to centre the body in the borehole. The orientation of the probe in the borehole was solved by using a pointer on the centraliser. Due to the dimensions of the probe, it was necessary to adjust the borehole diameter to the final proportions of the concrete container including the centralisers.

The experimental data shows how the coal will behave at the cave front. Under low confining stress, cleating has a dominant role and results in a weakening effect on the coal (this effect is similar to rib spall). Further into the coal mass, confining stresses are higher and shearing is more predominant. The caving model needs to be able to mimic the expansionary effect of coal at low confining stress, whilst adequately reflecting the effect of scale on strength.

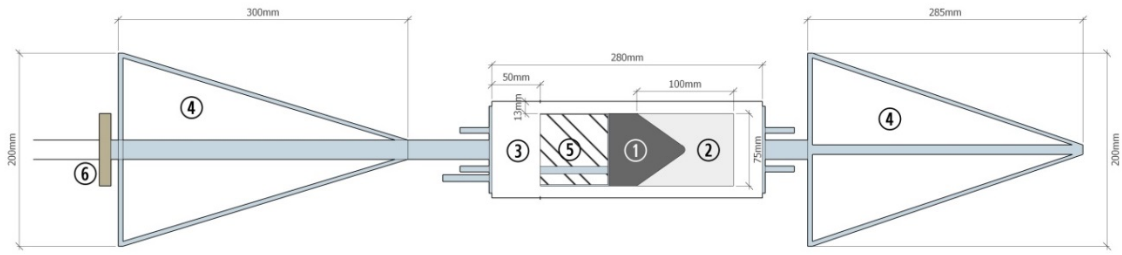

Figure 4: Cement body probe scheme: (1) CCBM probe (2) Inner cement body (3) Outer cement body (4) Centralizers (5) Free space (6) Pointer

Installation of the CCBM probe in front of the longwall No. 140 704 was done on the tailgate at the 128 m station. A borehole 10 m in length and 200 mm in diameter was drilled. The borehole was made perpendicular to the gate side at an inclination of 10° so that the end of the borehole was located in the coal (Figure 5).

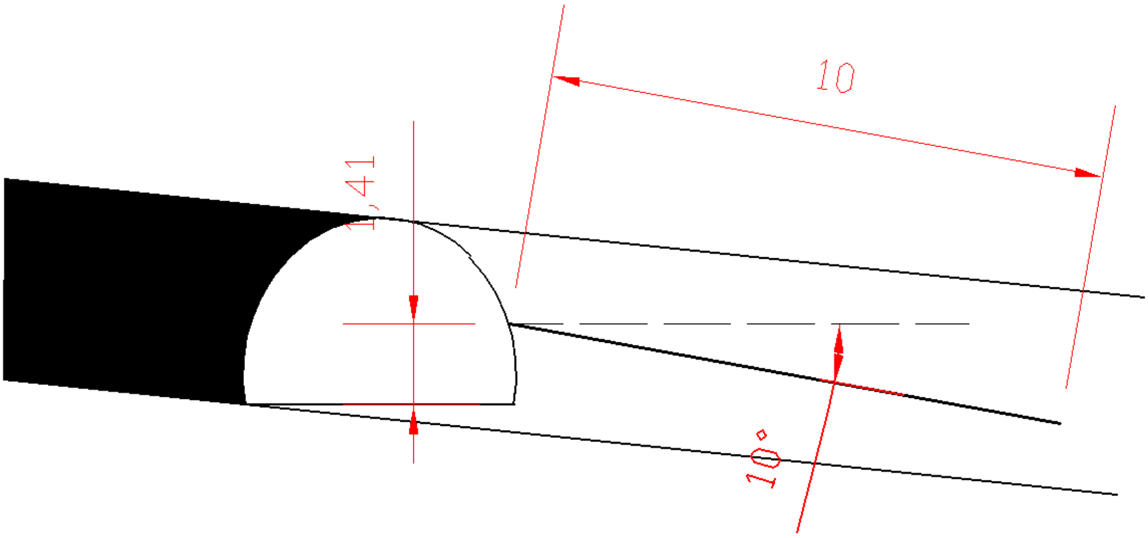

Figure 5: Cross-cut at tailgate 40 703

After drilling and cleaning the borehole, a video inspection of the borehole was performed. After a positive result (the borehole was accessible over its entire length), installation proceeded. This consisted of inserting the concrete container with the CCBM probe into the borehole using the installation rods and grouting the cement mixture. The dry, bagged mixture was mixed with the predetermined quantity of water and other additives. To transport the mixture to the end of the borehole, a PVC pipe was used to ensure that the mixture reached the bottom of the borehole and not elsewhere. The last step was to verify communication of the probe with a data logger.

24 hours after installation, the borehole was inspected using a video camera to verify successful solidification of the mixture. Subsequently, readings from the probe were taken and regular daily monitoring started. Mine employees took values from the probe and recorded the real daily advance and stationing of the coalface at the tailgate. The last step was to fill the mouth of the borehole with fitting foam.

STRESS CHANGES MONITORING AND MODELLING

The stress field induced ahead of a longwall face is affected by many factors, especially by:

- speed of advance of longwall,
- influence of previous mining activities (pillars and mining edges in the overburden),
- additional stress from the goaf of the previous longwall panel,
- occurrence of rigid strata between thick coal seams, and
- destress blasting and other rockburst prevention measures.

For the appropriate and correct interpretation, it is desirable to analyse all factors and to search for mutual relations. As it turns out, each of these factors play an important role in the development and change of the stress field. It should be pointed out that the longwall advance was irregular (from 0.5 m to 4.2 m per day) in the monitored period. Geological and geomechanical conditions were the main causes of it. Local coal seam erosion as well as tectonic faults caused fractures in the overburden and consequently rockfall in the longwall space. It took numerous drilling and blasting works to strengthen the longwall face.

Experiments of principal stress monitoring during longwall advance were modelled using the finite element method via Midas GTS 3D software. The linear elastic material model was used to obtain trends of principal stress changes during longwall face advance. The lengths of longwall advances in the model were chosen as 50 m. The final 50 m advance interval was separated into 5 m long sequences. Together, 17 stages were defined in the construction wizard – the primary stage and 16 advance stages defined by two phases. The first phase of each advance stage was ″excavation of the working unit" and the following phase was "caving" of the working unit, including roof units. Finally, goaf areas were connected from the left side and front of the longwall panel and on the right side the original rock massif remained. Total volume of the model was 0.05 km^3.

The total stress field represented by its tensor (σ) was considered as the superposition of the basic stress tensor measured at the time of the probe installation (σ_0 – start of monitoring) and supplementary stress changes monitored in the course of longwall advance (S) (Figure 6).

$$\sigma = \sigma_0 + S$$

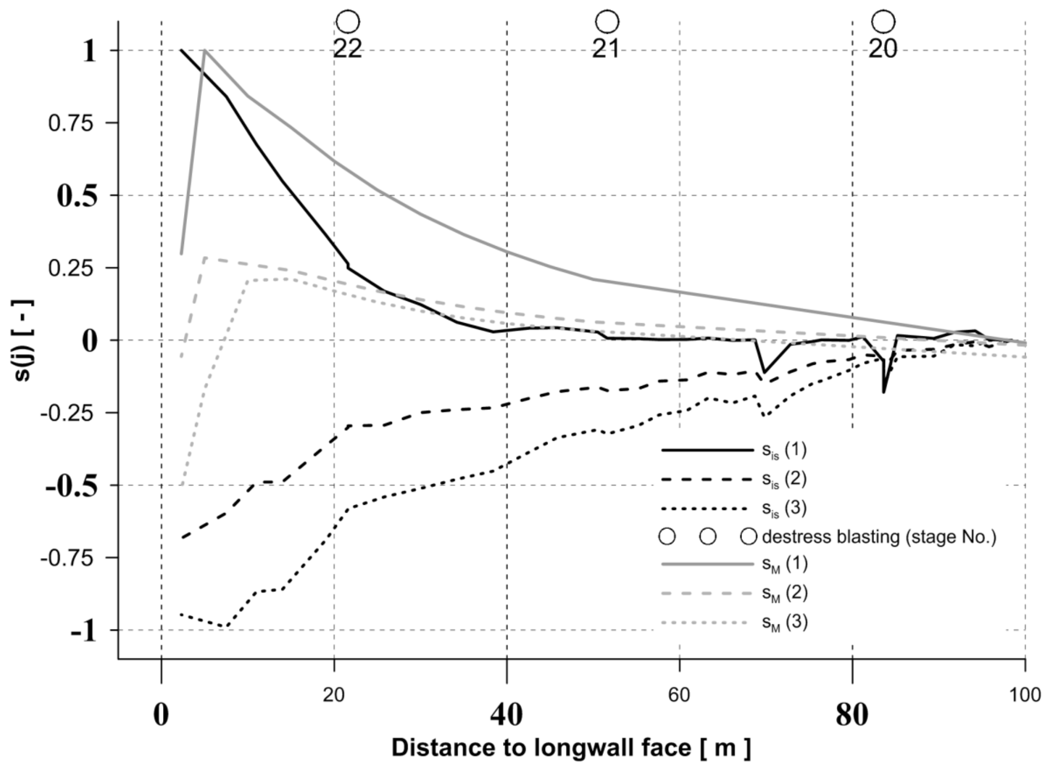

Figure 6: Relative principle components s(j) of tensor {S} ahead of longwall face

Supplementary stress change monitoring as well as mathematical modelling were done at a distance of 200 m before the CCBM probe. But only a 100 m section was selected for presentation (Figure 6). To better distinguish the shape of the graphs, the *in situ* monitored tensor (S_{is}) and modelled tensor (S_M) were normalised by their maximal achieved value using the following relations:

$$s_{is}(j) = S_{is}(j)/S_{is}(1)_{max} \text{ – for } \textit{in situ} \text{ monitoring}$$
$$s_M(j) = S_M(j)/S_M(1)_{max} \text{ – for model}$$

where (j) is adequate three normalised principal components.

The trend in this case is more important than the stress change magnitude (strong, different elastic modulus of coal and elastic modulus of concrete material of cylinder). In Figure 6 the trend of the normalised principal component monitored by CCBM $s_{is}(1)$ illustrates that values monitored by the probe in the concrete body are in compliance with normalised principal components calculated by the mathematical model $s_M(1)$. Different trends are evident from comparison of both of the other components: $s_{is}(2,3)$ and $s_M(2,3)$. This could be caused by simplification of the mathematical model against real conditions.

CONCLUSION

The article describes an experiment of measuring the stress changes induced by longwall face advance in a coal mine and presents results of the induced stress changes determined by the CCBM method. The CCBM probe itself was situated in the coal seam and was embedded in a concrete body. The results of the experiment show that it is possible to measure induced stress change by this method as the trends of the 3D model are in agreement with the results of the ones *in situ*. The next step of this research will be to determine the stress surrounding the concrete body (in the coal seam) and to determine the relationship between stress within the concrete body and outside of the concrete body in the coal seam. Mathematical model calibration according to the measured data must follow as well. Other variants of the placement of the probe in the concrete body will also be the topic of future work.

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