Stability Assessment of Headings Situated in a Field of High Horizontal Stress in Polish Copper Mines by Means of Numerical Methods

To cite this article: Daniel Pawelus 2019 IOP Conf. Ser.: Earth Environ. Sci. 221 012097

View the article online for updates and enhancements.
Stability Assessment of Headings Situated in a Field of High Horizontal Stress in Polish Copper Mines by Means of Numerical Methods

Daniel Pawelus 1

1 Wroclaw University of Science and Technology, Faculty of Geoengineering, Mining and Geology, 27 Wybrzeze Wyspianskiego St., 50-370 Wroclaw, Poland
daniel.pawelus@pwr.edu.pl

Abstract The tests on three-dimensional stress pattern in Polish copper mines made in 2012 confirmed the occurrence of high horizontal stress in the Legnica-Glogow Copper Belt (LGCB). No procedures (criteria) have been defined for proper selection of mining support for mining headings situated in a field of high horizontal stress. This is why, for a long time now, as mining works progress in deeper regions of the rock mass in the Legnica-Glogow Copper Belt, there is a need to identify the problem and define criteria (procedures) in order to ensure long-term and safe functioning of mining headings, particularly those being driven under unfavourable geological and mining conditions. These procedures should include, inter alia, values and directions of high horizontal stress. This article concerns the problem of access headings stability and preparatory headings stability driven in a field of high horizontal stress in Polish copper mines. This problem is very important due to the special safety requirements for mining headings that have been in use in mines for over a decade. The finite element method (FEM) was applied to assess the stability of mining headings under the conditions present in one of the copper mines in the Legnica-Glogow Copper Belt (the “Polkowice-Sieroszowice” copper mine). Rock parameters for numerical modelling were determined on the basis of the Hoek-Brown classification. The RocLab 1.0 computer application was used for this purpose. Stress field parameters were determined on the basis of underground tests performed in the “Polkowice-Sieroszowice” copper mine in 2012. Numerical modelling was performed by means of the Phase2 v. 8.0 application in a triaxial stress state and plane strain state. The Mohr-Coulomb failure criterion was applied in numerical analyses. An elastic-plastic model with softening was applied to describe the rock medium. The obtained results of numerical analyses served to provide an example of the application of a roof bolting system to protect headings located in the high horizontal stress field.

1. Introduction

Information gathered in mining operations worldwide suggests that the maximum component of horizontal stresses in rock mass is frequently even several times higher than the vertical component [1, 2, 3]. Based on numerous observations and measurements, a conclusion was made that the value of primary horizontal stresses is significantly greater than the values accepted to date, based solely on the Poisson's ratio \( v \) [4, 5, 6, 7]. Primary stresses in the rocks forming the Earth's crust have been observed to result from the accumulation of gravitational and tectonic stress fields [8], and the intensity of horizontal stresses is the function of:

...
• interaction of individual tectonic units,
• the terrain surface,
• tectonic features of the rock mass,
• depth of the rock mass,
• stiffness of rock material, expressed, among others through Poisson's ratio $\nu$ and the modulus of linear deformation (longitudinal modulus of elasticity) $E$.

Observations performed in underground mines worldwide (inter alia in Canada, the U.S., Australia and RSA) show that the loss of stability of mining excavations and the ensuing seismic events affecting the excavations may be attributed to high horizontal stresses (which are greater than the values due to gravity). The loss of stability was frequently observed for excavations (Figure 1) driven in the zone affected by high horizontal stresses. Such events included:
• roof collapse,
• floor uplift,
• loosening of side wall fragments,
• damage of the excavation support.

Figure 1. Cutter roofs into the excavations due to high horizontal stresses [6]

In Polish underground mines, the design of excavation layout and the selection of optimal support structure are not preceded by studies into the values and directions of primary horizontal stresses in the rock mass. Roof bolting is the most commonly used roof support system in Polish copper mines of the LGCB region. A particular design of the roof bolting system is selected in accordance with the “Regulations on the selection, construction and control of excavation support in the KGHM Polska Miedz S.A. mines.” [9]. The roofs in headings are protected with bolts at least 1.6 m long. The distance between the bolts (bolting mesh) is adjusted depending on the class of the roof and on the width of the heading below the roof. Roof class in a mining excavation (from class 1 – the worst, to class 5 – the best) is determined in accordance with the “Instructions on determining the geomechanical parameters of roof rocks with respect to roof classes in copper mines, as required in the selection of a roof bolting system design” [10]. Roof rocks are classified on the basis of such parameters as:
• roof bedding (vertical split),
• concentration of mineralized foigs,
• fault concentration,
• average fault throw,
• tensile strength of the roof rock beam.
Apart from roofs, reinforcement is also provided to excavation side walls in cases when:

- excavation height is greater than 4.5 m (regardless of the inclination angle of the side walls),
- excavation height is not greater than 4.5 m and moving the side walls outwards by approximately 10° is not possible.

The roof bolts have a length of at least 1.6 m and are spaced in the side walls at 1.5 x 1.5 m. The lower row of roof bolts is situated at a distance of approximately 1.8 m from the floor.

Numerical, FEM-based computer analyses of the stability of mining excavations demonstrated the influence of horizontal stress direction on the stability of excavations in the LGCB mines [11]. Therefore, further, extensive research was needed into the directions and values of main stresses in the KGHM Polska Miedz S.A. mining plants and into the influence of high horizontal stresses on the stability of mining excavations with roof bolting support.

2. The stress field in the “Polkowice-Sieroszowice” mine

Underground in-situ examinations of rock mass stresses in the “Polkowice-Sieroszowice” mine were conducted in 2012 as part of a research project entitled “Determination of the impact of the primary stress directions and magnitudes on the optimal geometry of mining fields” [12]. The measurements were performed by a team consisting of the employees of KGHM Cuprum Ltd. – R&D Center (CBR), “Rudna” mine and Golder Associates Ltd. The primary goal of the measurements performed in the geological and mining conditions of the “Polkowice-Sieroszowice” mine was to identify the distribution of primary stresses in the regions planned for operation within the “Deep Głogow” mining area. Based on the progress of the access and preparatory works, the location of the measurement stands was decided to be in the northern and north-western parts of the “Polkowice-Sieroszowice” mine. Three measuring stands were selected and agreed. Their detailed locations were determined after consultation with the Rock Mass Mechanics Engineers at the “Polkowice-Sieroszowice” mine, taking into account technical conditions, functions and dimensions of excavations in the selected locations.

Underground measurements in the “Polkowice-Sieroszowice” mine were performed with the overcoring method, which is a stress relief method. The overcoring method consists in cutting a rock sample from the existing stress field and in simultaneously measuring strain or displacement due to stress relief in the sample. The strain values measured during the process of relieving the sample in the vicinity of the measurement device serve to calculate stress tensor components in the rock mass [13].

The measurement device used in the “Polkowice-Sieroszowice” mine comprised a CSIRO HI test probe, which was glued in the measurement borehole with a special adhesive of known deformation parameters. It has 12 independent strain gauges glued in an arrangement of three “rosettes”, three gauge in each “rosette” and three gauges glued circumferentially. As a result, a single measurement provides a sufficient amount of data to fully determine the components of the stress tensor in the three-axis system. The disadvantages of the overcoring measurements with the use of the CSIRO HI probe include the sensitivity to loose rock fragments in the borehole which hinder correct insertion of the probe, as well as thermal effects generated during the drilling process and the presence of water in the borehole [7, 12, 13]. The obtained results allowed determining horizontal stress distribution in the rock mass for the “Polkowice-Sieroszowice” mine (Table 1). They also served to calculate main stress values in the x, y, z coordinate system and the azimuths of their directions.

| Parameter | SM12 | SM13 | Measurement test no. | SM14 | SM22 | SM32 | SM33 |
|-----------|------|------|---------------------|------|------|------|------|
| $\sigma_{H}$ [MPa] | 29.9 | 29.9 | 20.6 | 32.2 | 27.7 | 19.2 |
| $\alpha_{H}$ [°] | 160.0 | 157.0 | 158.0 | 6.0 | 156.0 | 139.0 |
| $\sigma_{h}$ [MPa] | 22.3 | 24.4 | 16.9 | 26.1 | 14.5 | 12.8 |
| $\alpha_{h}$ [°] | 70.0 | 67.0 | 68.0 | 96.0 | 66.0 | 49.0 |
| $\sigma_{v}$ [MPa] | 27.7 | 27.9 | 22.7 | 27.7 | 27.6 | 18.2 |
Symbols used in Table 1:
- $\sigma_H$ – maximum horizontal stress component,
- $\alpha_H$ – azimuth of the maximum horizontal stress component,
- $\sigma_h$ – minimum horizontal stress component,
- $\alpha_h$ – azimuth of the minimum horizontal stress component,
- $\sigma_v$ – vertical stress.

3. Prediction on the stability of headings in the “Polkowice-Sieroszowice” mine
The decrease or the loss of stability in headings located in the “Polkowice-Sieroszowice” mine, in the field of high horizontal stresses, were modelled using numerical simulations. Numerical calculations were performed in the Phase2 v. 8.0 application, which is based on the Finite Element Method (FEM), i.e. one of the most popular numerical methods. In FEM, a solution to a typical problem is searched for in the following stages:
- dividing an area into subareas,
- determining FEM equations for the elements,
- gluing (aggregating) the elements,
- allowing for boundary conditions,
- solving the equations,
- calculating additional values in other (than nodes) points of the area [11].

Table 2 contains rock parameters used in the numerical modelling of the stability of access and preparatory excavations (headings) in the conditions found in the “Polkowice-Sieroszowice” mine. The parameters were determined from the geomechanical tests of rock samples. The rock samples for laboratory tests were obtained from the Jm-06 To-1 borehole. The analysis of the data obtained from the Jm-06 To-1 borehole indicates that the rock mass represents a geological structure typical for the Fore Sudetic Monocline in which the access and preparatory excavations of the “Polkowice-Sieroszowice” mine are driven. The immediate roof is built of carbonate formations (calcareous dolomite II) which have high strength and strain parameters, as opposed to the rocks forming the mined deposit height and the formations in the floor.

Subsequently, the Hoek-Brown failure criterion, which is broadly used in geomechanical analyses of rock mass deformations and effort, was assumed for the rock mass. The generalized Hoek-Brown failure criterion for a fractured rock mass may be described with the following equation [14]:

$$\sigma_1 = \sigma_3 + \frac{1}{2} \frac{m_b}{\sigma_{ci}} \left( \frac{\sigma_i}{\sigma_{ci}} + s \right)^a,$$

where:
- $\sigma_1$ and $\sigma_3$ – values of the maximum and minimum principal effective stress at failure,
- $m_b$ – the Hoek-Brown constant for the rock mass,
- $s$ and $a$ – constants depending on the rock mass properties,
- $\sigma_{ci}$ – the uniaxial compressive strength of the rock sample.

When rock mass tensile strength $\sigma_{tm}$ is exceeded, the equation for $a = 0.5$ can be formulated as follows:

$$\sigma_{tm} = \frac{\sigma_{ci}}{2} \sqrt{m_b^2 + 4s},$$
Table 2. Mean strength and strain rock parameters, as determined in laboratory tests of uniaxial compression for the Jm-06 To-1 borehole.

| Location     | Rock type          | \( h \) [m] | \( \rho \) [kg/dm³] | \( R_c \) [MPa] | \( R_r \) [MPa] | \( E_i \) [GPa] | \( v \) [-] |
|--------------|--------------------|--------------|--------------------|----------------|----------------|----------------|------|
| Roof         | Anhydrite          | 16.00        | 2.94               | 92.16          | 6.69           | 53.22          | 0.26 |
|              | Calcareous dolomite II | 9.00        | 2.82               | 236.10         | 14.59          | 113.17         | 0.25 |
|              | Calcareous dolomite I | 0.50        | 2.47               | 98.43          | 6.04           | 38.77          | 0.26 |
|              | Streaky dolomite   | 0.90         | 2.77               | 140.57         | 9.33           | 40.73          | 0.24 |
|              | Clay dolomite      | 0.55         | 2.63               | 79.50          | 5.70           | 28.75          | 0.23 |
|              | Quartz sandstone IV | 0.25        | 2.40               | 39.97          | 2.78           | 16.53          | 0.19 |
|              | Quartz sandstone III | 0.30        | 2.25               | 16.57          | 0.80           | 7.23           | 0.13 |
| Excavation   | Quartz sandstone II | 3.90        | 2.07               | 20.67          | 1.22           | 8.63           | 0.14 |
|              | Quartz sandstone I | 1.10         | 2.02               | 16.95          | 0.75           | 6.65           | 0.12 |

After the failure criterion was assumed, the following rock mass parameters have been determined for each of the rock layers obtained from the Jm-06 To-1 borehole, using the RocLab 1.0 application and the Hoek-Brown classification [14, 15, 16, 17] (Table 3):

- cohesion \( c \),
- internal friction angle \( \phi \),
- uniaxial tensile strength of the rock mass \( \sigma_t \),
- rock mass modulus of elasticity \( E_{rm} \).

Numerical modelling was performed using the Phase2 v. 8.0 application, in a triaxial stress state and in plane strain state. Numerical calculations were performed for an isotropic and for a uniform medium. The rock medium was described with an elastic-plastic model with softening. The strength-strain parameters of the rocks in the model are shown in Table 4. The numerical modelling was performed on the basis of the Mohr-Coulomb failure criterion, which states that rock may reach threshold effort if the following condition is met:

\[
\sigma_1 = \sigma_3 \frac{1 + \sin \phi}{1 - \sin \phi} + \frac{2c \cdot \cos \phi}{1 - \sin \phi}
\]

or

\[
\sigma_3 = -\sigma_1
\]

where:

- \( \sigma_1 \) and \( \sigma_3 \) – effective maximum and minimum stress at failure,
- \( \phi \) – internal friction angle,
- \( c \) – cohesion,
- \( \sigma_t \) – uniaxial tensile strength of the rock mass.
### Table 3. Rock mass parameters determined with the RocLab 1.0 application – the Jm-06 To-1 measurement borehole.

| Location | Rock type               | $c$ [MPa] | $\varphi$ [$^\circ$] | $\sigma_t$ [MPa] | $E_{cm}$ [MPa] |
|----------|-------------------------|-----------|----------------------|------------------|---------------|
| Roof     | Anhydrite               | 6.896     | 38.66                | 0.738            | 39,000.37     |
|          | Calcareous dolomite II  | 21.535    | 39.00                | 5.226            | 99,628.96     |
|          | Calcareous dolomite I   | 7.853     | 37.69                | 1.495            | 31,649.89     |
|          | Streaky dolomite        | 12.821    | 39.00                | 3.112            | 35,856.57     |
|          | Clay dolomite           | 5.653     | 36.31                | 0.828            | 21,068.41     |
|          | Quartz sandstone IV     | 2.784     | 39.06                | 0.103            | 8,595.60      |
|          | Quartz sandstone III    | 1.154     | 39.06                | 0.043            | 3,759.60      |
| Excavation | Quartz sandstone II    | 1.439     | 39.06                | 0.053            | 4,487.60      |
|          | Quartz sandstone I      | 1.180     | 39.06                | 0.044            | 3,458.00      |
| Floor    |                         |           |                      |                  |               |

### Table 4. Rock mass parameters adopted for the elastic-plastic numerical model with softening, for the Mohr-Coulomb criterion – the Jm-06 To-1 borehole.

| Location       | Rock type                               | $h$ [m] | $E_s$ [MPa] | $\nu$ [-] | $\sigma_t$ [MPa] | $\varphi_{\text{peak}}$ [$^\circ$] | $c_{\text{peak}}$ [MPa] | $\varphi_{\text{dy}}$ [$^\circ$] | $c_{\text{dy}}$ [MPa] | $\varphi_{\text{resid}}$ [$^\circ$] | $c_{\text{resid}}$ [MPa] |
|----------------|-----------------------------------------|---------|-------------|-----------|------------------|-------------------------------------|--------------------------|----------------------------------|--------------------------|-------------------------------------|--------------------------|
| Roof           | Anhydrite                               | 16.00   | 39,000.37   | 0.26      | 0.738            | 38.66                               | 6.896                    | 2.00                            | 36.73                    | 1.379                                |                          |
|                | Calcareous dolomite II                  | 9.00    | 99,628.96   | 0.25      | 5.226            | 39.00                               | 21.535                   | 2.00                            | 37.05                    | 4.307                                |                          |
| Excavation (h = 3.5 m) | Deposit mined in dolomite-sandstone | 2.50    | 25,184.11   | 0.22      | 1.617            | 38.16                               | 7.847                    | 2.00                            | 36.25                    | 1.569                                |                          |
| Floor          | Quartz sandstone II                     | 3.90    | 4,487.60    | 0.14      | 0.053            | 39.06                               | 1.439                    | 2.00                            | 37.11                    | 0.288                                |                          |
|                | Quartz sandstone I                      | 1.10    | 3,458.00    | 0.12      | 0.044            | 39.06                               | 1.180                    | 2.00                            | 37.11                    | 0.236                                |                          |

The numerical analyses were performed for two headings. The excavations have a trapezoidal shape. The inclination angle of the side walls was assumed at 10º. Table 5 contains the dimensions of headings in the assumed cross-sections.

### Table 5. Dimensions of the analysed headings.

| Excavation height $h$ [m] | Excavation width below the roof $d_{sec}$ [m] | Excavation width at the floor $d_{top}$ [m] | Mean excavation width $d_{sec}$ [m] | Excavation surface area $S_e$ [m²] | Side wall inclination angle $\alpha$ [$^\circ$] |
|---------------------------|--------------------------------------------|---------------------------------------------|-------------------------------------|-----------------------------------|-------------------------------------------|
| 3.5                       | 6.0                                        | 4.8                                         | 5.4                                 | 18.9                              | 10.0                                      |


The primary stress of the rock mass for numerical modelling was determined on the basis of the results of measurements taken in the underground excavations of the “Polkowice-Sieroszowice” mine in 2012. Two variants of loads acting on the group of headings were assumed for the numerical calculations. The flat, rectangular plate with openings shaped to correspond to the shapes of the analysed excavations located inside was loaded on its edges:

- load variant 1 (maximum horizontal stress component $\sigma_H$ is in the direction perpendicular to the longer axis of the headings):
  - side edges: $p_x = 29.90$ MPa,
  - upper edge and bottom edge: $p_z = 27.70$ MPa,
  - direction perpendicular to plate surface: $p_y = 22.30$ MPa,

- load variant 2 (maximum horizontal stress component $\sigma_H$ is in the direction parallel to the longer axis of the headings):
  - side edges: $p_x = 22.30$ MPa,
  - upper edge and bottom edge: $p_z = 27.70$ MPa,
  - direction perpendicular to plate surface: $p_y = 29.90$ MPa.

The edges of the analysed plate were equipped with supports which do not slide either in the vertical or in the horizontal direction. The numerical analysis employed finite elements having three nodes and triangular shape. The plate edges were assumed to be at a 100 m distance from the extreme points on each side of the analysed headings (the roof, the floor and the side walls). In the middle of the plate, in the area where the headings were excavated, smaller size finite elements were used (finite element grid density region) in order to increase the accuracy of numerical calculations. Based on the numerical calculations of heading stability for each model (calculation variant), the following parameters were determined:

- stress distribution $\sigma_1$,
- stress distribution $\sigma_3$,
- horizontal stress distribution $\sigma_{xx}$,
- vertical stress distribution $\sigma_{yy}$,
- total displacements,
- yielded element area (yielded rock mass zone).

The analysis of the results indicated that the optimal measure of heading stability is the range of the yielded rock mass zone in the roof of the heading.

4. Results of the modelling and selection of a roof bolting system

Numerical modelling of the stability of headings located in the field of high horizontal stresses, in the geological and mining conditions assumed for the “Polkowice-Sieroszowice” mine, confirmed the results obtained in the publication titled “Influence of horizontal stress on the stability of underground excavations in copper mines” [11]. The numerical simulations also demonstrated that:

- The surface of the relaxed area around a heading increases together with the increase of the horizontal stress in the rock mass (high stress field in the rock mass).
- In the analysed headings, stress concentration occurs only in the corners of the roofs and side walls.
- The greatest total displacements occur in the floors of the analysed headings (sandstones having low strength and strain parameters); their intensity increases together with the increase of horizontal stresses in the rock mass.
- The maximum range of yielded rock in the roofs of the headings whose longer axis is perpendicular to the direction of the maximum horizontal stress component $\sigma_H$ (load variant 1) was 1.54 m (Figure 2). At the same time, the maximum range of yielded rock in the roofs of the headings whose longer axis is parallel to the direction of the maximum horizontal stress...
component $\sigma_H$ (load variant 2) was 1.36 m (Figure 3). This fact indicates that the direction in which headings are driven in a field of high horizontal stresses may be of key importance to the stability of headings in the LGCB mines. Problems with stability may occur when the yielded rock zone in the roof is larger than the bolted zone.

- The surface of the yielded rock area around headings driven in a group increases together with the influence of horizontal stresses in the rock mass (high horizontal stress field in the rock mass); this phenomenon negatively influences the stability of mining excavations and is strictly related to the stress and strain parameters of the rock layers surrounding the excavations.
- The results of the numerical simulations obtained for the plastic-elastic model with rock softening correspond most accurately to the observed cases of stability losses in the mining excavations of Polish copper mines.

![Figure 2. Yielded element zone, load variant 1](image1)

![Figure 3. Yielded element zone, load variant 2](image2)

The numerical modelling allowed an optimal selection of the roof bolting system design for headings driven in the field of high horizontal stresses in the conditions of the “Polkowice-Sieroszowice” mine. Due to security requirements, the roof bolting design was selected for the least advantageous geomechanical situation (headings are driven in perpendicular to the direction of the maximum horizontal stress component $\sigma_H$). The system consisted of resin-grouted bolts type RM-18, 2.2 m in
length and spaced at 1.5 x 1.5 m according to an assumption that the bolted zone in the roof must be larger by at least 0.5 m than the maximum range of the yielded zone.

5. Conclusions
Some observed cases of stability loss in excavations are caused by a lack of knowledge about the size and direction of horizontal stresses in the mined rock mass. According to the results of the research, the driving direction of a heading and the directions of horizontal stresses affect heading stability in the geological and mining conditions of the “Polkowice-Sieroszowice” mine.

The numerical modelling proved that heading stability is closely related to the shape of the heading, its cross-section surface area (heading width under the roof), heading depth (the value of stresses in the rock mass), and to the stress and strain parameters of the rocks surrounding the heading. Apparently, the position of the longer axis of the heading (the driving direction of the heading) in relation to the direction of the maximum horizontal stress component $\sigma_H$ in the rock mass is an additional factor which influences heading stability. These parameters should be considered in the selection of an optimal roof support system for a heading.

An accurately recognized stress field in the areas of mining works allows the development of optimal preventive methods. The principles of directional mining [2, 18], developed on the basis of observed relationships, may serve as an example. They consist in driving an excavation in the rock mass parallel to the direction of the largest component of high horizontal stresses. The in-situ observations of actual stability loss cases in the “Polkowice-Sieroszowice” mine, as well as numerical simulations of the stability of headings fully confirm the concept of directional mining.

Acknowledgment
This research has been performed as part of statutory activity 0401/0126/17 carried out at Wroclaw University of Science and Technology, Faculty of Geoengineering, Mining and Geology.

References
[1] C. Mark, “Horizontal stress and its effects on longwall ground control,” Mining Engineering 11, pp. 1356–1360, 1991.
[2] G. Daws, B. Hons, “Roofbolting in coal mining – design and implementation,” Wiadomosci Gornicze, No. 1, (in Polish), pp. 27-32, 1992.
[3] J. Agapito, L. Gilbride, “Horizontal stresses as indicators of roof stability,” Preprint 02-056, SME Annual Meeting, Phoenix, Arizona, Feb. pp. 25–27, 2002.
[4] C. Mark, T. P. Mucho, “Longwall mine design for control of horizontal stress,” New Technology for Longwall Ground Control, Proc.: U.S. Bureau of Mines Technology Transfer Seminar, Special Publication, pp. 53–73, 1994.
[5] C. Mark, T. P. Mucho, and D. Dolinar, “Horizontal stress and longwall headgate ground control,” Mining Engineering, Jan., pp. 61–68, 1998.
[6] C. Mark, “Focus on Ground Control: Horizontal Stress,” Coal Age, Mar. 1, pp. 47–50, 2001.
[7] S. Fabich et. al., “Calculation of stress in rock mass in various geological and mining conditions on the basis of in-situ measurements, Stage I: Development of technologies allowing the measurement of primary and exploitation stress tensor in the rock mass, and completing the first stage of measurements,” CBPM “Cuprum” OBR, (in Polish, unpublished), Wroclaw, 2003.
[8] A. Kidybiński, “Basics of mining geotechnology,” Wydawnictwo „Slask”, (in Polish), Katowice, 1982.
[9] Collaborative publication, “Regulations on the selection, construction and control of excavation support in the KGHM Polska Miedź S.A. mines,” (in Polish, unpublished), KGHM Polska Miedź S.A., 2017.
[10] Collaborative publication, “Instructions on determining the geomechanical parameters of roof rocks with respect to roof classes in copper mines, as required in the selection of a roof bolt
system design,” (in Polish, unpublished), *KGHM Polska Miedz S.A.*, 2017.
[11] D. Pawelus, “Influence of horizontal stress on the stability of underground excavations in copper mines,” (Doctoral dissertation, in Polish, unpublished), Wroclaw, 2010.
[12] J. Butra et al., “Magnitude and directions of primary stress in deep copper ore deposit,” *KGHM Cuprum sp. z o.o. CBR*, (in Polish, unpublished), Wroclaw, 2012.
[13] B. Amadei, O. Stephansson, “Rock stress and its measurement,” *Chapman & Hall*, London, 2009.
[14] E. Hoek, C. T. Carranza-Torres, and B. Corkum, “Hoek-Brown failure criterion – 2002 edition”, *Proc. North American Rock Mechanics Society meeting in Toronto in July*, 2002
[15] E. Hoek, “Strength of rock and rock masses,” *ISRM News Journal*, 2 (2), pp. 4-16, 1994.
[16] E. Hoek, E. T. Brown, “Practical estimates of rock mass strength,” *Inter. Journ. of Rock Mechanics and Min. Sc.*, v. 34, no 8, pp. 1165-1186, 1997.
[17] E. Hoek, P. Marinos, “GSI: a geologically friendly tool for rock mass strength estimation”, 2000.
[18] Ch. Reynolds, “The experiences and new directions of roofbolting in Australian coal mines,” *Proceedings of the School of Underground Mining 1994*, pp. 145-156, Krakow, 1994.