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The use of large-scale 3D numerical modelling to identify areas of increased seismic risk in Polish underground copper mines

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ABSTRACT

Seismic activity and related rockbursts are currently one of the most dangerous threats negatively affecting work safety and continuity of operation in Polish underground copper mines. Taking into account the experience to date, it can be clearly stated that current technical and organizational tools do not make it possible to eliminate mining tremors, however, by taking appropriate actions, it is possible to minimize the threat and partially control it, e.g. by active de-stressing the rock mass. However, developing an appropriate schedule of preventive activities is still a burning issue. This is due to the random nature of mining-induced seismic phenomena which makes it impossible to accurately predict the place, energy and time of the seismic event. A breakthrough could be the use of stage-based large-scale numerical modelling based on which it would be possible to track stress changes with ongoing exploitation and locate areas of increased seismic risk. This study presents the results of large-scale three-dimensional FEM-based numerical modelling enabling tracking of changes in stress distribution with the progress of exploitation. Then stress distribution and areas identified as prone to instability occurrence were correlated with the areas of high-energy seismic tremors manifestation. Models were prepared at monthly intervals, and validated with the use of measurements obtained with underground geomechanical monitoring systems. As preliminary analyses show, well-validated numerical models can be the basis for estimating seismic risk and may be useful at the stage of designing methods for preventing active rockbursts and seismicity prevention.

Keywords: numerical simulations; mining-induced seismicity; seismic wave velocities.

1. Introduction

The exploitation of copper deposits in the Lower Silesian Copper Basin (LSCB), Poland has been carried out for over 60 years. The stratoidal deposit, lying almost horizontally (slope up to 3 degrees), is mined using room-and-pillar systems. Over the years, as mining progressed, an intensification of seismic activity induced by mining operations was observed. The main causes of tremors include favourable geological conditions, a large depth of exploitation, the presence of faults above the level of the deposit, and an increasingly larger area of exploitation affecting stress disturbances in the rock mass.

Despite the implementation of increasingly advanced preventive measures over recent years, no significant improvement in the minimization of seismic activity has been achieved (Fig. 1).

The reason for this may be the lack of sufficient knowledge about the nature of the induced seismicity, which makes it currently impossible to determine the place and time of the earthquake. As a result, the implementation and planning of preventive actions are most often based on the experience of the mine crew and a possible qualitative risk assessment. A certain breakthrough may be numerical simulations, which, provided that the model is properly validated and the input data are of good quality, theoretically may enable tracking the nature of the hazard in a quantitative manner and may enable the assessment of changes in the seismic hazard level along with the progress of mining works (Li, 2022; Augarde et al., 2021).

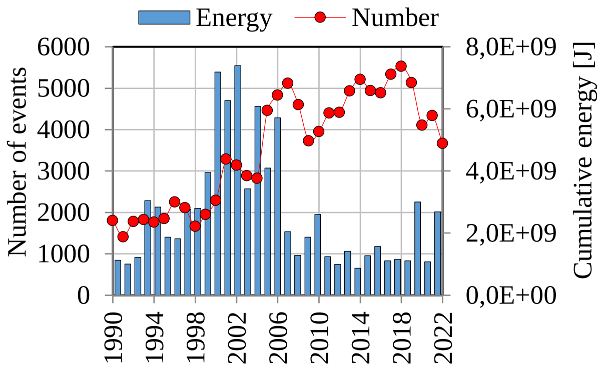

Figure 1. Seismic activity in LSCB between 1990-2022

This study presents a method for estimating seismic risk hazards based on large-scale 3-dimensional numerical modelling in the FEM environment. To increase the reliability of results model was validated with underground convergence measurement, and rock strength parameters were redefined to achieve comparable results of floor and roof stratum displacement. Then the results of the calculation were compared with seismic activity distribution in the analysed mining panel.

2. Current SoTA in numerical prediction of seismic hazard in underground mines.

The latest research clearly shows the importance of numerical modelling in geomechanical analyses. For instance, calculations in a static load system make it possible, to determine the roof fall risk (Napa-García et al., 2019; Fuławka et al., 2021) and the stability of pillars under different load conditions (Mallı et al., 2017; Masny et al., 2017; Adach-Pawelus & Szyry, 2022). In turn analyses in dynamic systems may be used for the determination of support behaviour under seismic load (Pytel et al., 2019; Pytel et al., 2021) or working stability in areas of high energy tremors occurrence (Cieślik et al., 2017). Moreover, many recent paper shows that FEM-based calculation plays a significant role also in the determination of optimal destressing approach in underground mines (Baranowski et al., 2019; Miao et al., 2022, Fuławka et al., 2022). Therefore, it can be assumed that a numerical model based on good quality data and prepared with an appropriate level of accuracy could be successfully used to determine the seismic hazard based on, among others, stress distribution analysis.

3. Material and Methods

In this study, numerical simulation was performed using GTS NX software in nonlinear static conditions. To verify the change in stress characteristics as the mining front advances, the analysis was carried out in stages, at one-month time intervals.

3.1. Site description

In Polish copper mines, the deposit is mined using room and pillar systems with a roof deflection. As mining progresses, the deposit is cut into pillars, which are intended to support the roof layers and ensure the stability of the mining excavations. As the front advances, the pillars are cut to remnant dimensions, which makes them yield and causes a slow deflection of the roof layers (Fig. 2)

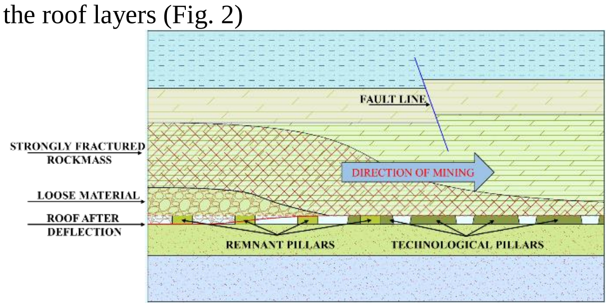

Figure 2. Simplified diagram of the room-and-pillar system used in Polish copper mines

Unfortunately, geological conditions in the analyzed area favour the occurrence of high-intensity seismic activity. In the direct roof of analysed area, strong dolomite layers with a thickness of over 30 meters and UCS reaching 160 MPa are present. Above, stiff strata of dolomite, limestone and anhydrite with a thickness of over 150 m are present. In turn, floor layers consist of strata of red sandstone with average strength (UCS up to 80 MPa) (Fig. 3). Strong roof layers with the simultaneous presence of medium-strength layers in the floor generate conditions which favors the rapid softening and yielding of the floor and pillars what often lead to accumulation of elastic energy above the mining area and seismic activity occurrence.

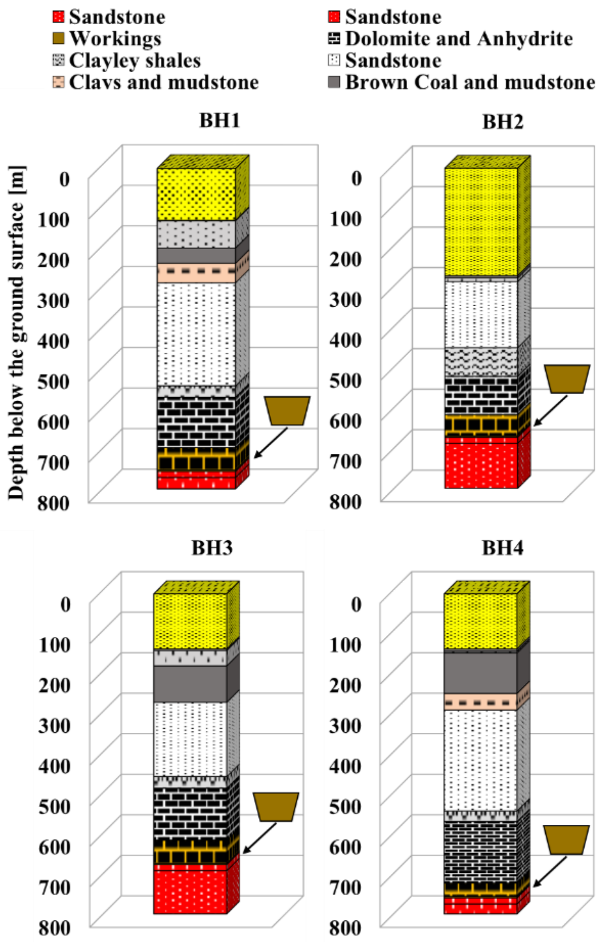

Figure 3. Geological profiles in the surroundings of the analyzed mining panel

3.2. Numerical simulations

Numerical simulations were performed for the G-2 mining panel, which is one of several dozen active mining divisions in Polish copper mines. This mining panel is operated in restricted conditions, i.e. in the vicinity of other mining fields and liquidation zones (Fig. 3).

The dimension of the developed model was 1 km × 1 km × 1.2 km. To achieve adequate accuracy, the maximum size of the element within the pillars and layers of the direct roof did not exceed 1 m. The model discretisation was carried out using the Hybrid-Mesh Algorithm, which enabled the achievement of an optimal combination of hexahedral and tetrahedral elements. Properties of rock were determined depending on the analysed structure. The backfilling area was filled with sand and clays and was described using Mohr-Coulomb failure criteria. At the same time intact rock mass, technological pillars, residual pillars and other rock layers in the roof and floor were described with the use of the Generalized Hoek-Brown (GH-B) criterion.

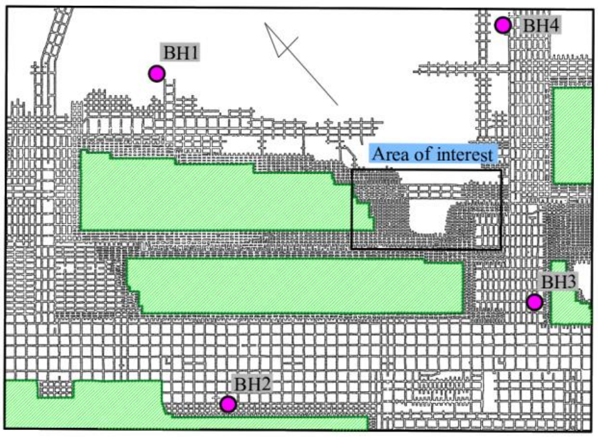

Figure 4. Top view of area surrounding G-2 mining pannel and location of boreholes which were used to determine geological profiles

The Generalized Hoek-Brown approach is a non-linear criterion which relates the major and minor effective principal stresses according to the following equation:

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

Where: σ_1 and σ_3 = major and minor effective principal stresses at failure; σ_{ci} = uniaxial compressive strength of the intact rock material; and *m* and *s* = material constants, where s = 1 for intact rock. Parameters m_b, *s*, and *a* are the rock mass material constants, given by equations 2-4:

$$m_b = m_i exp\left(\frac{GSI-100}{28-14D}\right) \quad (2)$$

$$s = \exp(\frac{GSI-100}{9-3D}) \quad (3)$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-GSI/15} - e^{-20/3}\right) \quad (4)$$

where GSI = Geological Strength Index; D = disturbance factor; m_i is a material constant for the intact rock. Parameter m_i was selected based on new edition of catalogs of physical and mechanical characteristics of deposit rocks in LSCB mine areas (KGHM, 2023).

The assumptions of the GH-B criterion are discussed in detail in the work (Hoek & Brown, 2019).

As part of this analysis, three scenarios for reducing rock strength parameters were analysed using the GSI scale. The variable parameters in the numerical models are presented in Tab. 1. At the same time it has to be highlighted that in all 3 scenarios, m_i parameter was 12.36.

Table 1. GSI parameters used during the calculation of different scenarios

Type of structure	Scenario I		Scenario II		Scenario III	
	GSI	D	GSI	D	GSI	D
Intact rock mass	95	0	90	0	80	0
Technological pillars	95	0	75	0.25	60	0.25
Residual pillars	95	0	60	0.5	40	0.50
Backfilling	Sand and clays (M-C criterion)					

In GTS NX software safety results are based on Mohr-Coulomb failure criteria which allows for the calculation of factor of safety of certain locations in the rock with the availability of major and minor principal stress at that location. The technique to calculate safety factor using this failure criterion was presented in papers (Kwon et al., 2013; Mao et al., 2020)

In general factor of safety is determined for each element of the model.

3.3. Seismic activity monitoring in the analysed mining panel

In the surrounding of the analysed area two types of seismic monitoring systems have been installed. First is managed by a mining operator and consists of number of uniaxial Willmore MK III seismometers, manufactured by Sensonics. These devices are adjustable-period velocity-sensing devices adapted for in-situ applications characterized by bandwidth of 0.1-150 Hz with set up recording rate of 500 Hz. The first system is used for the determination of tremors' energy, and their epicentral and hypocentral location. The second system consists of 14 triaxial MEMS-based accelerometers and was developed for monitoring of destress blasting efficacy and continuous, active profiling of seismic wave velocities. The recording rate in the accelerometric system was set to 1 kHz, while the clipping level of the accelerometers was ±2 g. Data from seismic activity monitoring was used for the evaluation of the reliability of numerical simulations.

3.4. Convergence analysis

The only direct parameter with is measured continuously and may be calculated with the use of numerical models is convergence within underground workings. Convergence monitoring most common method of monitoring the underground workings deformations in Polish underground copper mines. Within the subjected mining area number of convergometers were installed, and their location has been constantly changing along with the progress of the mining front (Fig 5.)

Figure 5. Progress of the mining front and location of convergometers in the subsequent months.

Each of the convergometers consists of two tubes of different diameters, connected by a spring. One of them has a vernier (range 0-250 mm). Convergometers work in a stretched position, i.e. zero is visible when stretched. Both ends of the convergometer are connected to the roof and the floor with the use of special ropes or steel lines. The upper cable is attached to an rock bolt (mounting plate), while the lower cable is attached to a repper stuck in the floor or load weighing at least 2 kg.

The convergence of workings H_{con} in the numerical model was calculated according to formula:

$$H_{con} = H_p - (S_f + |S_r|) \quad (5)$$

Where: H_p - height of workings; S_r - the sum of the values of roof settlement, S_f - floor uplift. Since the roof settlement has a negative direction in the model, the absolute value of this parameter

4. Results

4.1. Convergence analysis

Based on 30 numerical simulations (3 scenarios × 10 monthly time intervals), it was determined which computational variant is closest to the convergence measurements recorded in situ. Ultimately, it was found that scenario 3 is the option closest to reality. Generally, the measurement curves almost coincide with the calculated curve within 1-7 months. Differences were observed in the last 3 months due to the lack of direct convergometers. It should be noted that the characteristics of convergence recorded in real conditions are close to linear and, in general, it can be stated that the vertical convergence of workings is in the range of 0.09-0.1 m per month. At the same time, the simulation results indicate the logarithmic nature of the roof deflection, i.e. in the first phase of excavation, convergence is at its highest level, but over time the deflection curve flattens, tending to a zero increase in convergence. This situation is most likely due to the limitations of the developed numerical models, which do not take into account the plasticization of the pillars over time. As a result, the model only takes into account displacements resulting from changes in the stress state near the excavated workings, while omitting the process of pillars yielding over time. The result of analysis has been presented in Fig. 6.

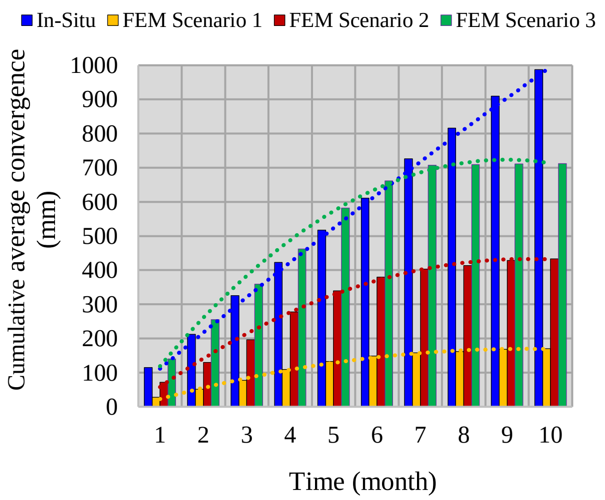

Figure 6. Comparison of average measured convergence with results of numerical simulations

4.2. Model validation

Figure 7 shows the seismic activity recorded in the G-2 mining panel during the analyzed period. As it may be observed, the months with the highest seismicity in terms of energy were January, June and October. Therefore, in order to verify whether numerical models can be used as a tool for predicting seismic hazard, the maps of the distribution of the safety factor (SF) were compared with the results of recorded seismic activity from these months.

From the point of view of seismic hazard evaluation, as a result of numerical simulations it should possible to determine the location of overstressed areas. However, the interpretation of the results may be problematic because it is not known exactly what stress level may be acceptable and what is close to critical in particular mining conditions.

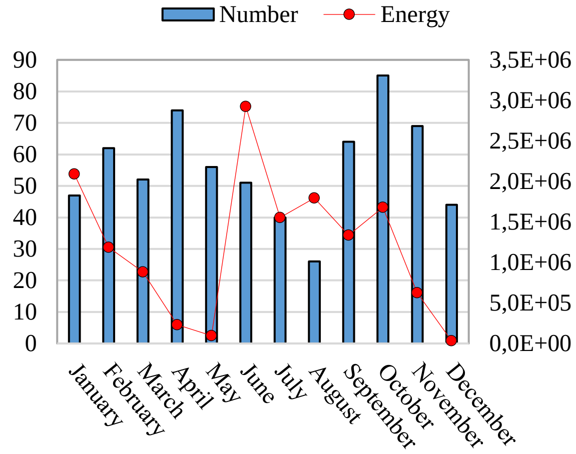

Figure 7. Seismicity in G-2 mining panel

A more intuitive parameter is the safety factor SF, whose values below 1.0 may indicate the risk of instability (Fig. 8). To check whether the results of numerical modelling can be the basis for predicting seismic activity caused by mining activities, a detailed 3D analysis of the distribution of the safety factor in the roof layers was performed for the three months characterized by the highest total seismic energy, i.e. January, June and October. Then the results were compared with hypocentral location of mining recorded in these particular months.

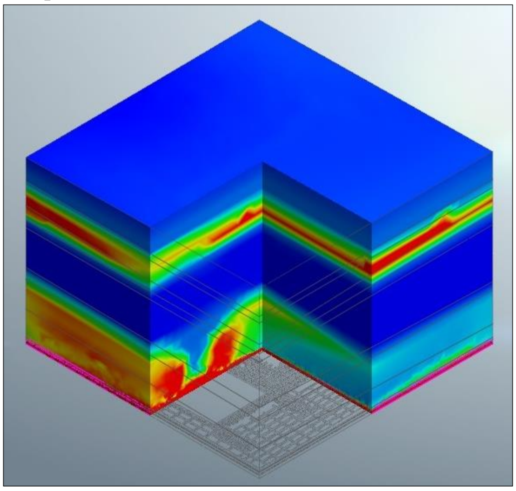

Figure 8. 3D results of numerical simulations – Safety factor distribution

Fig. 9 shows the results of the analysis for January 2023. The analysis shows that the zone of stress concentration and reduced SF values is located in the area bordered on two sides by goaf zone (Fig. 9 - top). The vertical cross-section through the numerical model indicates the concentration of stresses in the roof layers made of strong dolomites and anhydrite located approximately 100-150 meters from the level of the workings (Fig. 9. – bottom). Also, the influence of the backfilling zone (goafs) on the nature of the stress state before the mining front may be clearly indicated. What is important is the fact that the location of mining tremors coincides with the stress zone determined using numerical models in both horizontal and vertical directions.

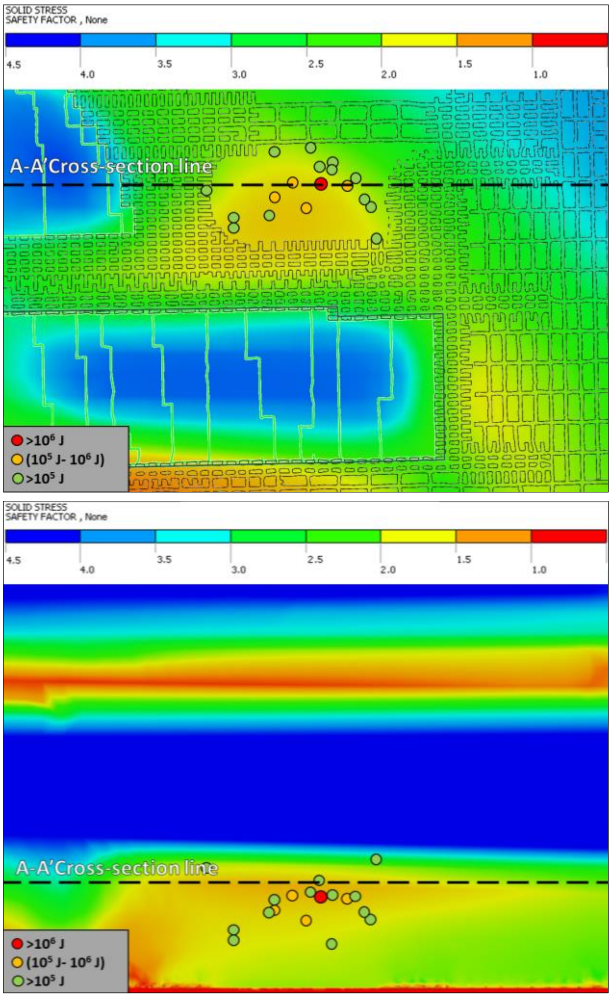

Figure 9. Horizontal cross-section representing safety factor distribution within the analysed area (top), vertical A-A' cross-section representing safety factor distribution (bottom) – January 2023

As can be observed in the vertical section (Fig. 8-bottom), there is a zone of low SF index values in the upper part of the model. This is a clay layer with low-strength parameters. However, due to the small depth of deposition and the plasticity of the material, layers of this type do not generate seismic activity.

Fig. 10 shows the results of the analysis for June 2023. In June, as mining progressed, a shift of the stress zone towards the exploited deposit was observed. At the mining front line, during this period, there was one high-energy tremor with energy $>10^6$ J and several moderate tremors with lower energies. Generally, the calculated zone of reduced SF coincides with the location of the tremors. In the case of vertical distribution, similarly to January, the areas most at risk of instability were the dolomite and anhydrite layers. Additionally, a stress relaxation zone can be seen above the goafs, which affects the distribution of the SF index in this area.

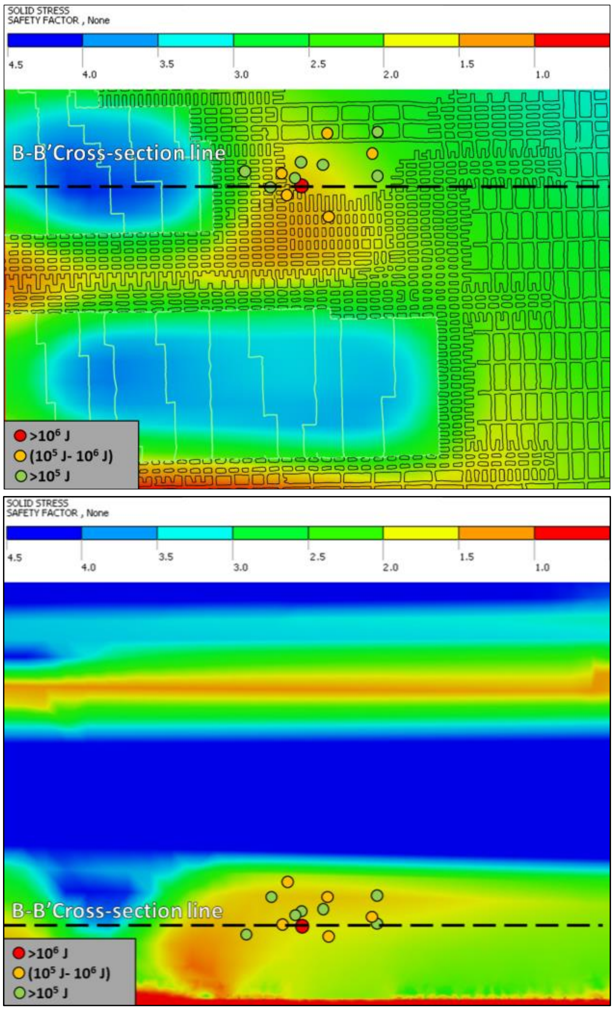

Figure 10. Horizontal cross-section representing safety factor distribution within analysed area (top), vertical B-B' cross-section representing safety factor distribution (bottom) – June 2023

Fig. 11 shows the simulation results for October 2023. In October, the exploitation of the deposit in the analysed section almost came to an end. The development of the workings zone influenced the state of stresses above the workings level and on the border of the mining front. Fig. 10 - bottom shows a clear development of the instability zone above the goafs. As in the case of the analyses for January and June, the designated zone of increased stress coincides satisfactorily with the location of seismic events recorded in the G-2 mining panel in October 2023.

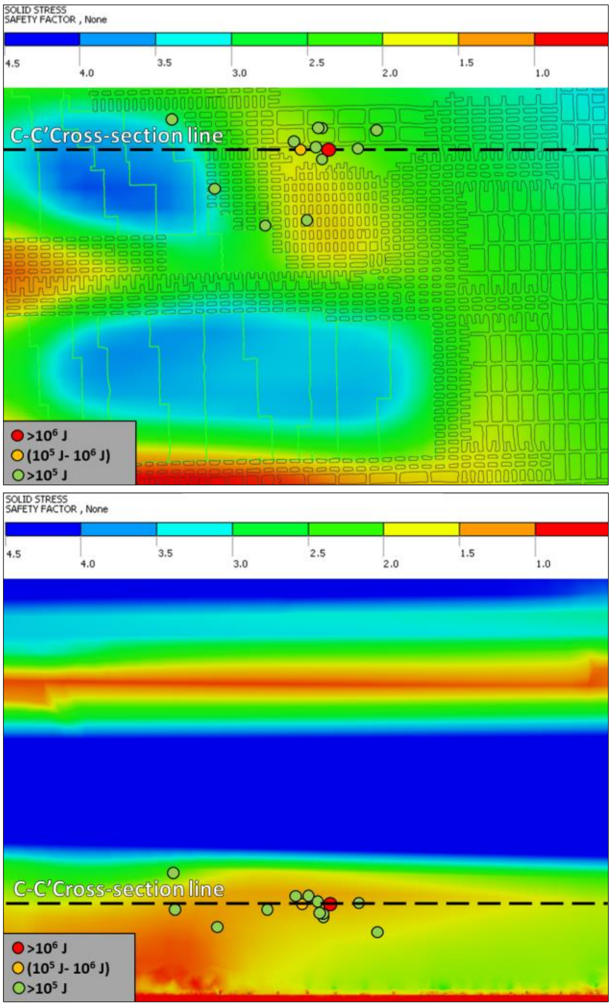

Figure 11. Horizontal cross-section representing safety factor distribution within the analysed area (top), vertical C-C' cross-section representing safety factor distribution (bottom) – October 2023

5. Conclusions

In this study, the possibility of using FEM-based 3D large scale numerical modelling for the purposes of predicting mining-induced seismicity was analysed. The G-2 mining panel of the Lubin underground copper mine was chosen as the experimental site, within which the deposit was lying horizontally, and no faults that could affect the results of the analysis were identified in the immediate vicinity of the mining operations. As shown by the conducted research, the convergence of workings may be a useful parameter at the stage of validation of the numerical model.

Due to the scale effect, validation of results with measurements recorded in real operational conditions may lead to more reliable results from numerical simulations than in the case of validation based on laboratory tests. It was found that by reducing the rock strength parameters of individual model elements, a satisfactory degree of correlation between the convergence resulting from calculations and the convergence resulting from underground measurements may be achieved.

Ultimately, the validated models were used to designate zones at risk of seismic activity. The analysis results were compared with actual data recorded by the mine's seismological network. The calculation results clearly indicate the usefulness of the proposed method and the possibility of estimating areas potentially prone to seismicity occurrence. Of course, this issue is highly complicated and further work aimed at better selection of rock strength parameters should be carried out. Nevertheless, already at this stage, knowledge regarding the location of zones of potential instability can be used, among others, to design mining works and develop the most efficient destress activities for particular mining and geology conditions.

Acknowledgements

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