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PHU MINH VUONG NGUYEN[1*], PIOTR LITWA[1], JANUSZ MAKÓWKA[1],
KRZYSZTOF SZCZERBIŃSKI[2], VAN VIET PHAN[3]

INVESTIGATION OF THE OCCURRENCE OF INTENSIVE SEISMIC ACTIVITY AT THE "POLKOWICE-SIEROSZOWICE" COPPER ORE MINE, POLAND

A series of intense seismic activities were unusually reported during the initial stage of room and pillar mining operations at the "Polkowice-Sieroszowice" copper ore mine, in Poland. In fact, high-energy tremors with energy of up to 10^7 J were observed in many mining fields from the beginning of the mining operation to the moment before reaching the critical space of the caved zone (goaf). Some of these tremors caused floor heave, sidewall squeezing, and spalling of the roof and sidewalls in the workings, leading to the stoppage of mining operations. This paper aims to identify the possible causes of these unexpected tremors. For this purpose, the geo-mining conditions and seismic activity data from the studied mining fields were reviewed and analysed. Additionally, a numerical analysis of rock mass behaviour was conducted, considering various geomechanical factors to better understand the mechanisms of seismic activity in these fields. All numerical calculations were performed using the finite difference method (FDM) code, FLAC3D. Based on the findings, the major causes of the high-energy tremors were determined as high primary stress, high-strength roof rocks, and the presence of a thick salt layer in the roof rocks. Consequently, practical recommendations for future mining operations were suggested to mitigate the impact of intense seismic activity. This research is expected to provide a valuable reference for copper mines prone to tremors and rockbursts, not only in Poland but worldwide.

Keywords: Seismic activity; numerical modelling; copper ore mine; room and pillar mining system

1. Introduction

Seismic and rockburst hazards are one of the most complex issues in Polish underground mines. Research and practice have indicated that geological and mining factors have a significant

[1] CENTRAL MINING INSTITUTE – NATIONAL RESEARCH INSTITUTE, KATOWICE, POLAND
[2] POLKOWICE-SIEROSZOWICE COPPER MINE, KGHM POLSKA MIEDZ S.A., KAŹMIERZÓW, POLAND
[3] VINACOMIN – INSTITUTE OF MINING SCIENCE AND TECHNOLOGY, HANOI, VIETNAM
* Corresponding author: pnguyen@gig.eu

impact on the seismic energy (magnitude) of tremors. The major factors are as follows: increased in-situ stress due to increasing mining depth [1-5], presence of discontinuities (such as active faults, fractured network) [6-8], presence of high-strength roof rocks (e.g. sandstone, lime, anhydrite, dolomite) [9-15], mining method, roof control method, mining face parameters etc. [16-27].

During the mining operation at the SI-XII mining field of the "Polkowice-Sieroszowice" copper ore mine, relatively high seismic activity was observed already at the initial stages, despite the small area of the caved zone (goaf). Since 2019, a total of 6 seismic events have been recorded, including 5 at the SI-XII/4 mining field (4 self-existent destresses in 2019-2020 and 1 triggered by distress blasting in 2021) and 1 self-existent destress at the SI-XII/5 mining field in 2022. Practically, from the beginning of the mining operation to the moment before the caved zone reached its critical space, high-energy tremors with energy of up to 10^7 J were observed. Previously, in other mining fields of the "Polkowice-Sieroszowice" copper ore mine located at lower depths and outside the salt deposit, no intensive seismic activity was observed in the initial stages. All self-existent and triggered destresses were associated with tremors energy of 10^6 J, i.e. relatively small values compared to other events that took place in all copper ore mines of KGHM Polska Miedź S.A. (TABLE 1).

TABLE 1

Parameters of seismic activity in individual mining fields of the Polkowice-Sieroszowice copper ore mine in the period January 2017-June 2022

Mining field	**Number of tremors with energy $E \geq 10^3$ J**	**$E \geq 10^6$ J**		**Sum of energy [$\times 10^6$ J]**	**With damages**	**Extracted surface [ha]**	**Expenditure [$\times 10^6$ J/ha]**
		Number of tremors	**In percentage [%]**				
PO-VI/4	124	4	3.23	17.75	0	31.522	0.563
PO-IV/4	4	0	0	0.15	0	4.308	0.030
PO-VI/1F	35	2	5.70	3.12	0	10.017	0.311
PO-V/5, /6, /7, /8	5	0	0	0.06	0	13.434	0.004
SI-IX/2	14	0	0	1.13	0	20.875	0.054
SI-IX/3	**145**	**5**	**3.50**	38.42	0	16.810	**2.286**
SI-IX/4	29	0	0	0.92	0	26.080	0.035
SI-V/5	66	1	1.51	3.30	0	14.570	0.226
SI-V/6	1	0	0	0.04	0	4.711	0.008
SI-VII/3	**194**	**4**	**2.06**	36.06	1	5.779	**6.240**
SI-XII/4	259	0	0	11.06	0	31.958	0.346
SI-XII/5	**166**	**4**	**2.40**	39.23	2	18.820	2.084
SI-II/3	33	0	0	0.73	0	8.902	0.082
SI-X/3	464	8	1.72	34.34	0	39.339	0.873
SI-X/5	3	0	0	0.065	0	2.431	0.027
SI-XI/3	91	0	0	3.49	0	35.968	0.097

In the last decades, numerical modelling has been increasingly applied as an auxiliary tool in solving geomechanical problems in underground mining. The major advantage of numerical modelling is the possibility of illustrating the behaviour and interaction of rock layers in the rock mass surrounding the mine openings, taking many geological and mining factors into consideration, which is impossible in analytical, statistical or empirical analyses. The results of numerical calculations become useful especially when it is supported and verified by the in-situ measurements. Then, the prediction of rock mass behaviour can be determined [28-36]. Several studies related to mining-induced seismicity and earthquakes have been conducted using numerical modelling [37-48].

Due to the described seismic situation at the "Polkowice-Sieroszowice" copper ore mine, the main aim of the research is to define the causes that lead to occurrence of the intensive seismic activity. For this purpose, numerical analysis was conducted using the finite difference method (FDM) code, FLAC3D [49], presenting the exact geological and mining conditions of the selected mining field to examine the behaviour of rock mass during the mining operation. Various geomechanical factors were taken into account to have a better understanding of the rock mass behaviour associated with the mechanism of the intensive seismic activity. Based on the outcomes, the possible causes of the intensive seismic activity were identified and discussed. As a result, some practical actions for further mining operations were suggested to limit the impact of seismic activity at the given mining fields.

2. Case study

The "Polkowice-Sieroszowice" mine is a large copper ore mine, located in the Polkowice district (West of Poland), operates in the following mining regions: Polkowice, East Radwanice and Sieroszowice (Fig. 1). This mine belongs to the Legnicko-Głogowski Copper District (LGCD).

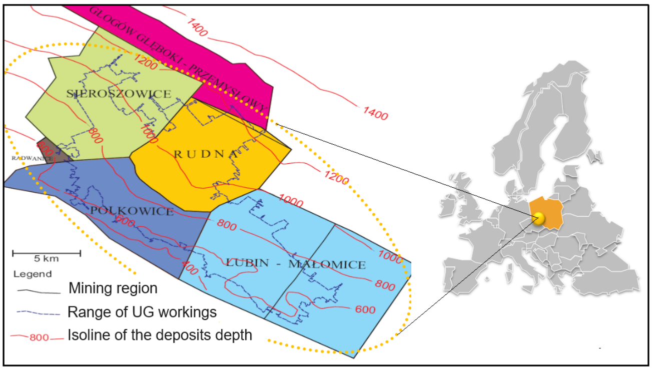
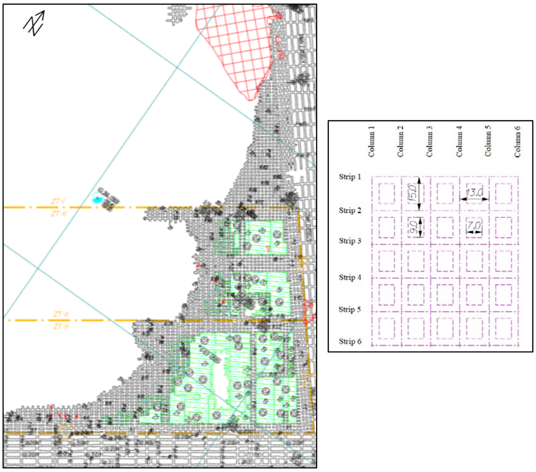


Fig. 1. Location of the "Polkowice-Sieroszowice" copper ore mine [50]

2.1. Description of mining operation in the SI-XII field

In the SI-XII mining field, exploitation has been carried out since 2018 with the room and pillar system with the roof layers deflection with a front of 460 m long, moving forward in the South-Western direction. The height of the mining extraction is approximately 2.5 m. The depth of the mining extraction is in the range of 1100÷1200 m b.g.l. The mining field is typically divided into columns and strips (Fig. 2). The opening front width (working zone) ranges from 4 to 7 strips. Behind the working zone, pillars will be collected to the final dimension of approximately 3×3 m. After that, roof rocks slowly deflect, forming a goaf.



a b

Fig. 2. The room and pillar system at the SI-XII mining field: a) Outline of the room and pillar system with the roof layers deflection; b) Dimension of rooms and pillars

2.2. Geological characteristics of the SI-XII field

In the SI-XII region, a typical copper deposit is built of dolomites, cupriferous shale and sandstone. The thickness of the deposit varies from 0.35 m to 3.30 m. A typical copper deposit structure is shown in Fig. 3.

Roof rocks consist of 7.2÷13.4 m dolomites, 26.6÷83.2 m anhydrites, and 29÷80.2 m fine and medium-crystal rock salt. Floor rocks are sandstones with various colours (white, grey and red) and grain sizes (up to several hundred metres). Roof rocks and floor rocks are strong, while cupriferous shale is brittle and strongly fractured. The lithology of rock mass at the "Polkowice-Sieroszowice" copper ore mine is shown in Fig. 4. Mechanical parameters of the intact rocks in the SI-XII field are shown in TABLE 2.

Fig. 3. An example of copper deposit structure in the SI-XII field, the "Polkowice-Sieroszowice" copper ore mine

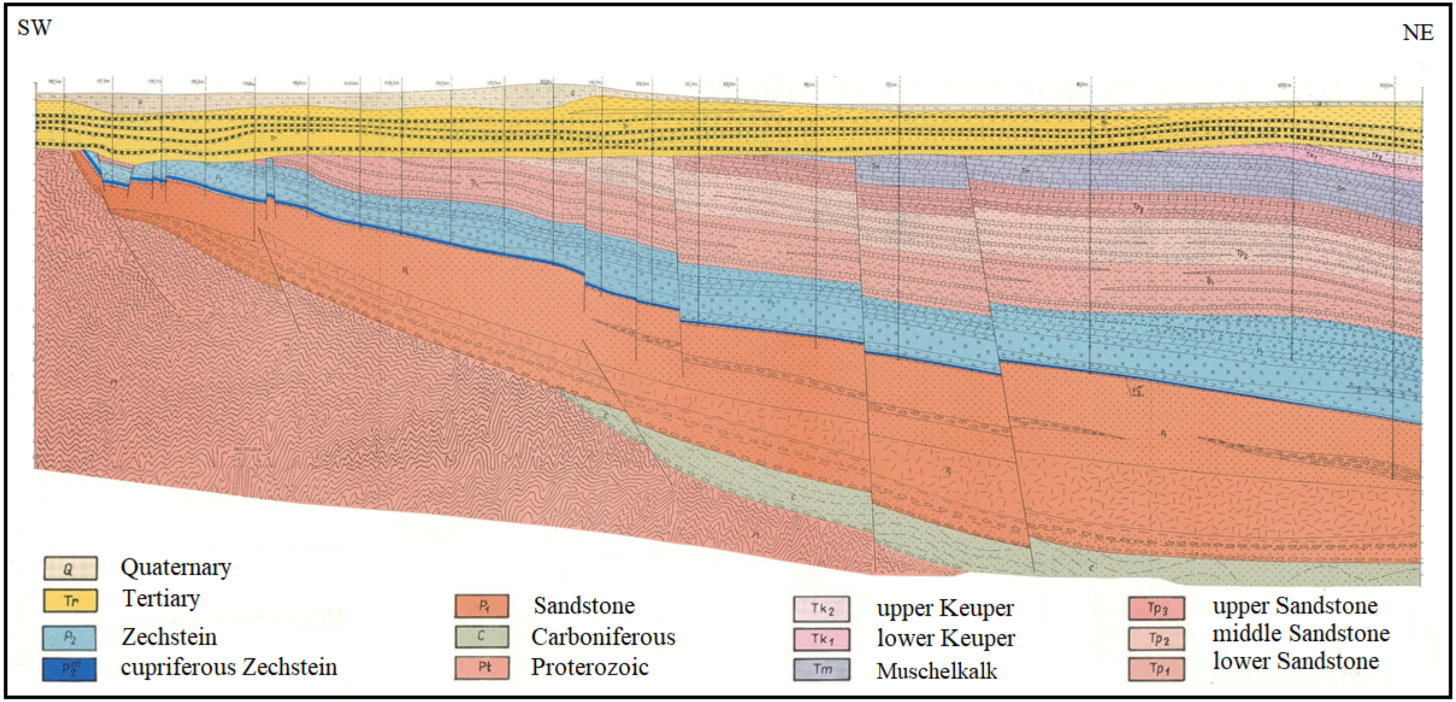


Fig. 4. An example of geological cross-section at the "Polkowice-Sieroszowice" copper ore mine

Tectonic: The copper deposit extends in the NW-SE direction, with a dip of 2÷40. The rock mass is weakly involved tectonically. In the studied area, three faults were found with throws from 1.0 m to 5.0 m. The strike line of faults is in the NW-SE direction.

TABLE 2

Mechanical parameters of intact rocks at the SI-XII field

	Young's modulus, E [GPa]	Poisson's ratio, υ [-]	Friction angle, θ [deg.]	Cohesion, c [MPa]	Tensile strength, R_t [MPa]	Compressive strength, R_c [MPa]	Density, γ [kg/m^3]
Anhydrite	37÷74	0.21÷0.31	63÷65	14÷19	4.4÷8.1	54÷144	2700÷3000
Dolomite	24÷100	0.17÷0.34	59÷68	12÷21	3.1÷12	45÷224	2200÷2700
Rock salt	4÷7	0.25÷0.31	56÷60	4÷6	1.2÷1.7	18÷41	2000÷2100
Cupriferous shale (copper deposit)	8÷19	0.16÷0.21	58÷63	5÷8	0.9÷2.5	20÷58	2100÷2800
Sandstone	5÷8	0.1÷0.18	45÷48	3÷5	0.6÷1.1	10÷22	1800÷2400

2.3. Description of the seismicity monitoring system at the mine site

To assess and predict the seismic and rock burst hazard at the "Polkowice-Sieroszowice" copper ore mine, a series of monitoring measures were routinely conducted as follows:

- measurements of the underground workings convergence in the opening front zone, at least 2 times a week;
- measurements of the induced seismoacoustic activity after blasting operations: once a day;
- continuous recording of seismic activity;
- visual observations of the rock mass condition at each operating shift, including floor uplift, excessive acoustic activity, fracturing or falling of the roof rocks, spalling from the sidewalls, signs of hardening of pillars or their delayed transformation to the post-failure state (roof fracturing, change of the goaf size by the sidewalls, the presence of an un-fractured "core" of pillar after front line advanced).

3. Numerical modelling of rock mass behaviour in the context of the occurrence of high-energy seismic events

3.1. Model description

Based on the available geological profiles in the SI-XII area of the "Polkowice-Sieroszowice" copper ore mine, a 3D model was built in the FLAC3D software [49]. Fig. 5 shows the dimensions of the 3D model and the location of rock layers. The numerical model was a rectangular cube fixed at the bottom, top and sidewalls in appropriate directions (perpendicular to individual planes). It was divided into approx. 770 thousand zones and had dimensions of 180×330×250 m. For this research, numerical calculations were performed using the plastic model group. Based on the characteristics of rock mass mentioned in Chapter 2, the Mohr-Coulomb model was adopted for roof and floor rocks, while the strain-softening model was considered as the material model for the copper deposit (cupriferous shale). The strain-softening model enables the representation of non-linear material softening behaviour based on prescribed variations of the Mohr-Coulomb model properties (shear strength) as functions of the deviatoric plastic strain [49,51].

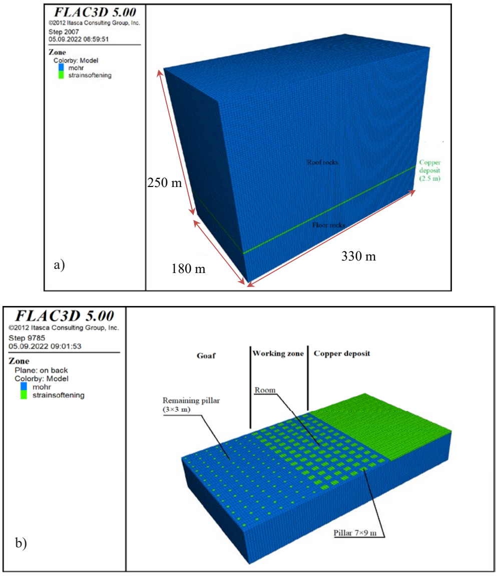


Fig. 5. Numerical model in FLAC3D: a) adopted constitutive models for rock mass,
b) actual geometry of the room and pillar system

The model was originally solved as elastic in order to reach the primary state of stress. Then the displacement and velocity vectors were zeroed. In the next step, the 'null' model was assigned to the zones corresponding to the extracted copper deposit, and the model was recalculated.

3.2. Model verification

A back-analysis was carried out, comparing the results of numerical modelling with the measurements of convergence around the excavation as a result of the installed monitoring systems. Fig. 6 shows a comparison of convergence values from numerical modelling and monitoring.

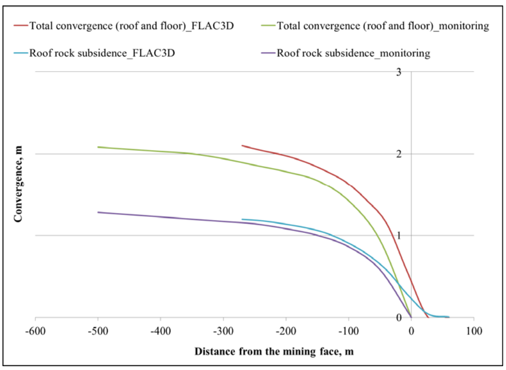


Fig. 6. Comparison of the convergence values along the mining direction with the room and pillar system

A similar trend of convergence along the mining direction was observed. Convergence values obtained from FLAC3D are in good agreement with the in-situ measurements. Thus, the modelling procedure, adopted rock mechanical parameters and material models can be considered appropriate for further numerical calculations.

3.3. Calculation variants

Numerical calculations were carried out for different geometric configurations of the salt layer (Fig. 7) and the width of the opening front (Fig. 8) to identify factors enabling the occurrence of seismic events (tremors) during the operation of the room and pillar system in the SI-XII/4 field.

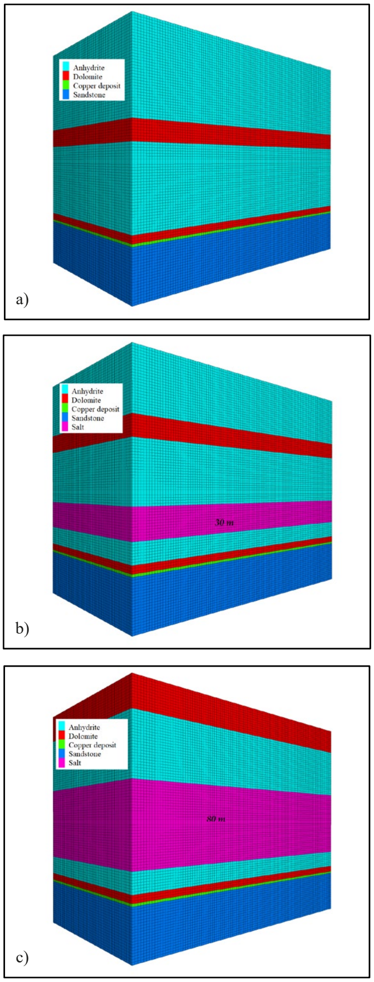


Fig. 7. Numerical model of the rock mass with the assumption related to the presence of salt in the roof: a) no salt, b) 30 m, c) 80 m

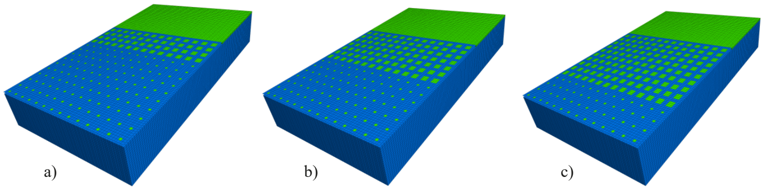


Fig. 8. Numerical model of the rock mass with different widths of the opening front:
a) 4 strips, b) 7 strips, c) 10 strips

3.4. Results analysis

The results were presented in the form of maps of vertical displacements, showing the roof subsidence and plasticity indicators and illustrating the possible failure (shear failure and tension failure) zones around mining excavations. Based on these results, an assessment of the behaviour of the rock mass around the mining excavations was discussed. As a consequence, the causes of seismic events (tremors) during the operation of the room and pillar system were determined.

Figs. 9 and 10 present the results with different geometrical configurations of the salt layer. The roof rock subsidence in the case of an 80-m salt layer is much greater than the case with a 30-m salt layer and the case without the presence of salt in the roof rocks (Fig. 9). The size of the fractured zone in the roof rock is also much larger in the case of 80 m salt than in the case of 30 m salt and no salt (Fig. 10). This is because the deformation and strength parameters of the salt are much lower than the same parameters of other roof rocks, such as dolomite or anhydrite, as shown in TABLE 2. It can also be noticed that in the case of no salt or 30-m salt layer, there was no such failure in the front of the mining face (Fig. 10a, b). However, in the case of the model with 80 m of salt layer, there was a fractured zone in front of the mining face (Fig. 10c).

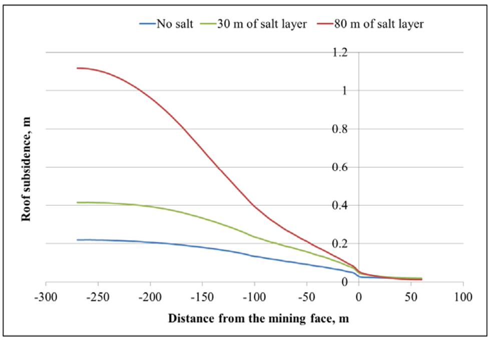


Fig. 9. Roof convergence along the mining direction with different thickness of the salt layer

Fracture propagation of rock mass in the case of an 80-m salt layer can be drawn in Fig. 11. At the initial stages (stage I and stage II), the vertical displacement (roof subsidence) was low, and no failure zone was observed. In the next stage (III), roof subsidence increased rapidly in a small range of calculation steps (less than 2000 steps). Shear and tensile failures were also observed in front of the mining face above the extraction working and enlarged in stage IV. Such

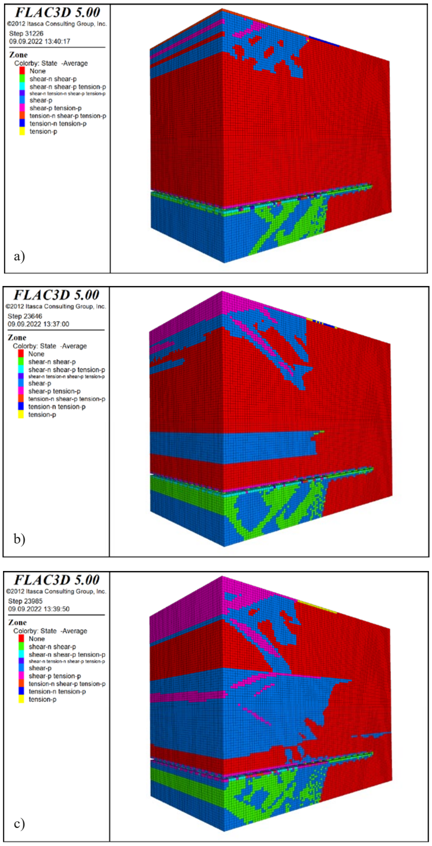


Fig. 10. Plasticity indicators around the mining excavations with different thickness of the salt layer: a) no salt, b) 30 m of salt, c) 80 m

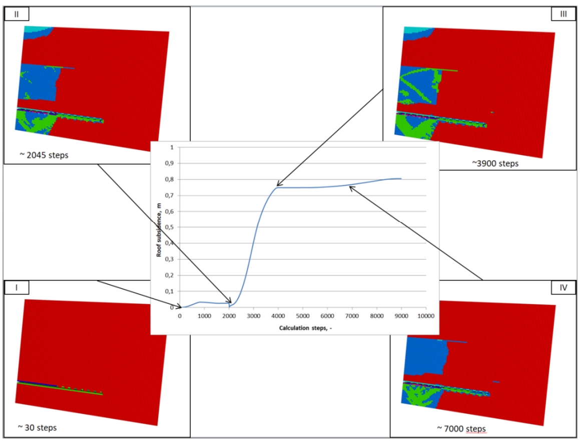


Fig. 11. Convergence and fracture propagation of rock mass in case of 80-m salt layer

intensive changes in roof rock convergence, associated with rock mass failure, led to seismic energy release and, consequently, intensive tremors. This mechanism of tremor occurrence related to roof convergence and rock mass failure was also described in other studies [52-56].

The results show such a tendency that the thicker the salt layer in the roof, the greater the roof subsidence and fractured zone in front of the mining face. This could unleash seismic energy and, consequently, lead to tremors occurring. Thus, it can be concluded that the presence of a thick layer of salt could be one of the factors that indirectly caused the occurrence of seismic events during the operation of the room and pillar system in the given mining field.

Fig. 12 presents the results with different widths of the opening front in the case of an 80 m thick salt layer. It can be noticed that the rood subsidence was smaller when the width of the opening front increased from 4 strips to 10 strips. The results indicate that a larger width of the opening front is more favourable in terms of reducing roof subsidence in the case of mining operations being carried out under a thick salt layer. Consequently, this could limit the possibility of seismic events occurring in both frequency and magnitude.

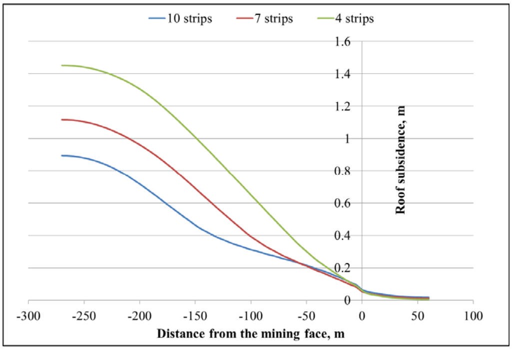


Fig. 12. Roof subsidence along the mining direction with a different width of the opening front (working zone)

4. Discussions

From the detailed description of the geo-mining conditions provided by the "Polkowice-Sieroszowice" copper ore mine, it can be noticed that the geological structure of the studied site plays a key role in the occurrence of all seismic events. The significant depth of the copper deposit, which reaches 1200 m, should be mentioned as the first possible factor of seismic activity occurrence. Measurements of the stress state carried out in 2012 showed that the max. horizontal stress is greater than the vertical stress, up to 32.2 MPa. The direction of the max. horizontal stress (from 139° to 160°) is parallel to the front line of the mining field SI-XII. This is why the stress concentration acts on the sidewall of the mining face during mining advance. Moreover, the complex roof rock structure consists of anhydrite and dolomite with variable thickness and high strength parameters (avg. 160 MPa) and a salt layer with variable thickness (from 30 to 80 m) and relatively low strength parameters (avg. 20 MPa). During the mining advance, when the mined space behind the mining face is large enough, the salt layer starts to subside, and the hanging wall phenomenon can be formed behind the mining face. At certain moments, these strong, thick roof rocks will break, unleashing seismic energy and consequently leading to tremors occurrence, as shown in Fig. 11.

Another factor that has a significant impact on the seismic activity observed is the method of mining with a specific geometry as shown in Fig. 2. In most of the mining fields, the room and pillar system is applied with an operating pillar that requires maintenance in the goaf zone. In this case, the mining system is implemented in the form of joint mining fronts in two or three mining fields. The analysis of the deformation state of the roof layers above the given mining field shows the occurrence of significant irregularities. This is due to the largely irregular distribution of the opening, liquidation and goaf. Additionally, operating pillars are maintained in the goaf areas. This causes the occurrence of zones with inhomogeneous, multi-directional deflection of the main roof rock. These zones are associated with an increased occurrence of tremors.

Based on the numerical analysis, it can be stated that a thick layer of salt and a small width of the opening front are unfavourable for exploitation with the room and pillar system. Under such conditions, exploitation with the room and pillar system causes high roof subsidence and large size of the fractured zones, as well as stress concentration in front of the mining face. This can lead to the release of accumulated elastic energy and, in consequence, lead to the occurrence of tremors. The high-energy tremors were noticeable at the advancing phases of exploitation in the given mining field. Some of these tremors caused damage in the underground workings when the mining face advanced closely to the deposit part located under the thick layer of salt.

5. Conclusions

A series of high-energy tremors were observed in many mining fields at the "Polkowice-Sieroszowice" copper ore mine during its room and pillar mining operation. This study aims to identify the causes of these seismic activities that occurred. For this purpose, the most crucial information regarding the geological, geomechanical and mining conditions and seismic data were gathered and analysed for the selected mining fields. Moreover, a 3D numerical analysis of the deformation-stress state was conducted using the finite difference method (FDM) code, FLAC3D, taking different geomechanical factors into account to have a better understanding of the roof rock behaviour. Based on the obtained results, the following conclusions can be drawn:

- Two natural factors have played an important role in seismic activity occurrence at the studied site. The first one is the high level of natural vertical primary stress due to the significant mining depth. The second one is the presence of high-strength roof rocks (anhydrite and dolomite with a compressive strength of avg. 160 MPa) with variable thickness in the complex geological structure.
- The presence of a thick layer of salt (with low strength parameters) has also played a significant role in intensive seismic activity occurrence. Such a mining operation under a thick layer of salt causes large roof subsidence and large size of the fractured zones, as well as a high-stress concentration in front of the mining face. These mining-induced events tend to unleash the seismic energy and, in consequence, lead to the occurrence of tremors.
- The adopted mining method (room and pillar system) with a specific geometry (connected mining fronts in two or three mining fields, operating pillars are maintained in the goaf, small width of the opening front) induces inhomogeneous, multi-directional deflection of the main roof rock, which is associated with an increased occurrence of tremors.

– The conducted analyses and calculations also allow to formulate certain suggestions for changes in the adopted mining method, which may have a beneficial effect on the scale of seismic and rockburst hazards in the given mining fields: (1) to maintain a straight line of mining face; (2) to reduce the number of workings maintained in goaf; (3) to separate the mining fronts to limit the maximum tremor energy; (4) to attempt further exploitation with the room and pillar system with a larger opening width (e.g. 10 strips) to limit the intensity and number of seismic event. The test results will allow to verify the results of numerical analyses, (5) to keep monitoring and analysing the causes of mining-induced seismic events. Understanding these factors can help control strong seismic events, ensuring a safer work environment for the crew.

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