DE GRUYTER OPEN
Studia Geotechnica et Mechanica, Vol. 39, No. 1, 2017
DOI: 10.1515/sgem-2017-0005

THE IMPACT OF MULTIPLE SEAM MINING EXPLOITATIONS ON SEISMIC ACTIVITY AND STATE OF STRESS

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Abstract: The paper presents an analysis of seismic activity for selected areas of hard coal mine executing exploitation in a rock mass with a variable degree of rock disturbance, i.e., also with a varied number of previous mined-out seams. A distribution of vertical stress and a value of vertical stress concentration coefficient were also determined in the strata of immediate roof of the seams planned for mining. In the analyzed case, despite the lack of thick and solid strata of sandstones in the roof, the rock mass emits seismic activity, where the energy largely depends upon an impact of exploitation edges and tectonic disturbance.

Key words: *mining, longwall system, seismic activity*

1. INTRODUCTION

Underground mining brings about some changes of the primary state of stress in a rock mass. The occurrence of the secondary state of balance causes the displacement of rock mass, which in many cases may cause a massive damage of rock and an emission of seismic energy (Haramy and McDonnel 1988, Majcherczyk et al. 1995). The volume of energy accumulated in a rock mass generally depends upon geological and mining factors. Most important geological factors embrace the primary state of stress, i.e., also the depth of mining exploitation, the occurrence of tectonic disturbance or the thickness of rock strata and their physical and mechanical properties (Marczak 2015).

In the case of hard coal deposits in many regions of the Upper Silesian Coal Basin, sandstones are most frequently treated as the strata capable of energy accumulation. They are characterized by large thickness and high values of strength and strain parameters. The remaining Carboniferous rocks, such as claystone and siltstone, usually form thin strata and are subject to damage without generating any seismic activity. As a rule, a seismic activity tends to increase in the areas of faults and in the rock mass with a tendency to accumulate energy (Majcherczyk et al. 1997).

The most important mining factors affecting the state of hazard with tremors and rock burst include: the mining system (e.g., room-and-pillar, shortwall or longwall mining), the method of roof management (caving or backfill), the velocity of mining front, the number of mined-out seams, the thickness of exploitation and the degree of rock disturbance. In the hard coal mines in Poland, the exploitation of seams is usually executed with the use of a longwall system with roof caving. Such a system causes that a massive volume of rock mass in the immediate roof suddenly becomes subject to displacement, which in the case of thick and solid rocks leads to their dynamic breakdown. The exploitation of subsequent seams causes a decompression of strata situated immediately above the mined-out zone and, in the case of tremors occurring in the overlying strata, the disturbed rock mass successfully suppresses elastic waves, thus not causing any hazard in mining excavations. On the other hand, the occurrence of exploitation edges of subsequent seams in one vertical plane causes a significant increase of stress and static loading in the support of headings, which in turn brings about a larger number of seismic phenomena (Majcherczyk et al. 2004). The headings situated in the area of such a concentration of edges are far more exposed to a possibility of rock burst. Therefore, planning exploitation in the seams situated below the mining zones requires a preparation of reliable predictions of possible occurrence of dangerous dynamic phenomena and their influence on the headings (Vacek et al. 2008, Dou et al. 2009, Kaiser and Cai 2012, Mutke et al. 2015, Zhang et al. 2015). In addition, it should also be kept in mind that the dynamic phenomena occurring in a rock mass are negative to surface objects (Boroń et al. 2011, Uszko et al. 2013).

The paper presents the characteristics of seismic activity in two zones of one coal mine. The exploitation of the seams in each part was analyzed with the use of the database of tremors recorded during the period of a decade, i.e., the years 2007–2016. In the analyzed zones, varied seismic activity was recorded despite similar geological conditions. The paper also discusses the distribution of vertical stress and vertical stress concentration coefficient for the planned exploitation of the seams situated below the past and current mining. Such an analysis provides sound arguments for formulating general conclusions on the impact of mining disturbance on seismic activity.

2. GEOLOGICAL AND MINING CONDITIONS

The analyzed mining area is part of a southern territory of the Upper Silesian Coal Basin. In the stratigraphic profile of the analyzed area, the layers of the Tertiary, Quaternary and Carboniferous rocks prevail. The Tertiary and Quaternary strata have a thickness of 150–800 m and mostly consist of sands, muds and silt. The Carboniferous rock mass consists of alternate layers of claystone and siltstone, with some layers of sandstones with the thickness of several meters.

Down to the depth of approximately 1,100 m, the occurrence of more than a dozen coal seams and strata was observed. Their thickness varied from only several centimeters to even 5.0 m. All the lithological layers often contain thin interlayers of other rock strata. The compression strength of rocks change considerably depending on the lithology, i.e., in the range from 10 MPa for coal, through 30–80 MPa for claystone, to approximately 60–100 MPa for sandstones and siltstone.

In the analyzed area there are faults with a throw ranging from a dozen to even three hundred meters, which divide the plane of the mine into several exploitation parts. Within those parts there are faults with a throw of usually up to 10 m.

Currently the coal mine executes the exploitation at a depth of 850–1000 m. Depending on an exploitation part, several to more than a dozen seams with the thickness ranging between 1.0 and 3.7 m were excavated. The height of panels was usually 1.6–2.4 m.

In the analyzed zone No. I, the exploitation was carried out in seam 401/1, situated at an average depth of 900 m, and in seam 404/1, situated at an average depth of 970 m. A lithological analysis in the area of both seams discussed indicates that in the range of total 130 m, i.e., 100 m above the seam and 30 m below the seam, the rock mass consists mostly of claystone strata. Depending on the seam, the total thickness of sandstone strata ranges between 16% for seam 404/1 to 31% for seam 404/1 (Fig. 1). Within the range of 130 m around the analyzed seams, the total number of rock strata ranged from 22 to 35, which indicates a varied thickness of rock strata.

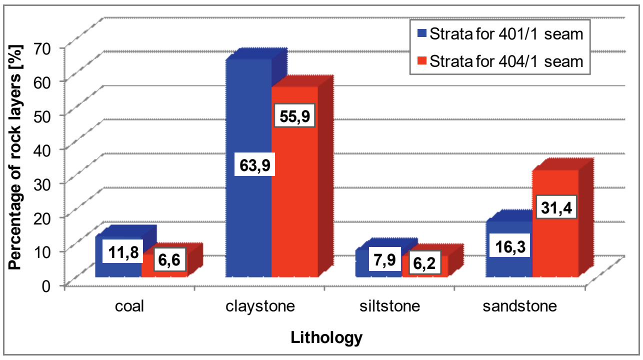

Fig. 1. Percentage of particular lithological layers in the construction of roof and floor in zone No. I

In zone No. II, the exploitation was carried out in seam 403/3 situated at an average depth of 780 m and in seam 404/1 situated at an average depth 805 m. A lithological analysis in the area of the seams discussed indicates that in the total range of 130 m the rock mass consists mostly of the claystone layer and, to a lower degree, sandstones. The total thickness of sandstone strata for both seams is the same and amounts to 36.5% (Fig. 2). In general, in the range of 130 m around the analyzed seams, the number of rock strata was 40 and 42, which indicates that the average thickness of an individual rock layer is insignificant and amounts to only about three meters.

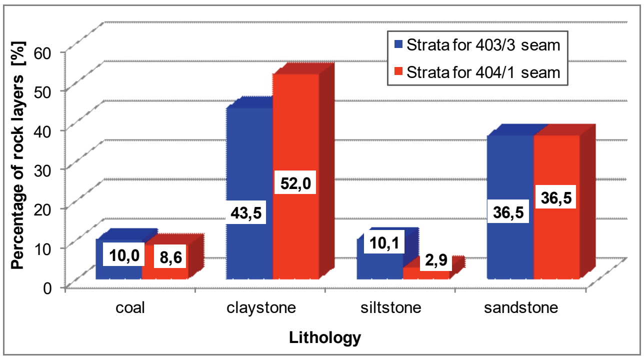

Fig. 2. Percentage of particular lithological layers in the construction of roof and floor in zone No. II

3. SEISMIC ACTIVITY RECORDED DURING EXPLOITATION

3.1. ZONE NO. I

In zone No. I of seam 401/1, five panels were mined out from the East to the West, whereas the subsequent panels were led from the South to the North. In the analyzed period, tremors were recorded with the energy at the level from 10^2 J to 10^5 J. The total number of tremors during excavation of particular panels was highly varied and ranged from 9 for the panel No. 3 to 175 for panel No. 5 (Table 1). It should be pointed out here that for the first three panels the activity was low and the tremors did not exceed the energy of about 10^3 J. As a result, the total energy emitted by the tremors was also low, which is, among other things, due to the exploitation of the seam 401/1 in the contour of the mined-out seam 363 at a distance of 25 m (Fig. 3). The situation changed during the exploitation of panels Nos. 4 and 5. Panel No. 4 of seam 401/1 commenced and completed its run before the edges of seam 363, whereas the entire panel No. 5 was situated outside the exploitation zone in the seam 363. In this area, the edges of the seam 361 were at a distance of 55 m and the edges of seam 360/1 were at a distance of 100 m. The facts specified above were the main reason for increasing a seismic activity and for the occurrence of tremors with the energy of about 10^4 J and two tremors with the energy at the level of even 10^5 J. The tremors with the highest energy took place in the area of the exploitation edges of seams 360/1 and 361. Due to the distribution of the seismic network, precise determination of the depth of tremors is not possible. In the immediate roof of the analyzed seam, there was a sandstone layer with the thickness of more than a dozen meters.

Table 1. Recorded tremors
during mining seam 401/1 in zone No. I

Panel No.	Number of tremors with a given energy				Tremors total	Total energy, J
	E2, J	E3, J	E4, J	E5, J		
1	14	5			19	2.32E+04
2	26	30			56	1.14E+05
3		9			9	2.38E+04
4	6	49	16		71	8.06E+05
5	12	91	70	2	175	3.95E+06
Total	58	184	86	2	330	4.92E+06

In zone No. I of seam 404/1, four panels had been hitherto excavated in the same way as in seam 401/1. In the analyzed period of time, the tremors with the energy ranging from the level of 10^2 J to the level of 10^5 J were recorded. The total number of tremors during the excavation of particular panels was slightly less varied than for seam 401/1 and ranged from 27 for panel No. 1 to 77 for panel No. 2 (Table 2). For the first three panels, the total emitted energy was approximate, i.e., $2.31*10^5$ J – $4.56*10^5$ J, similarly to

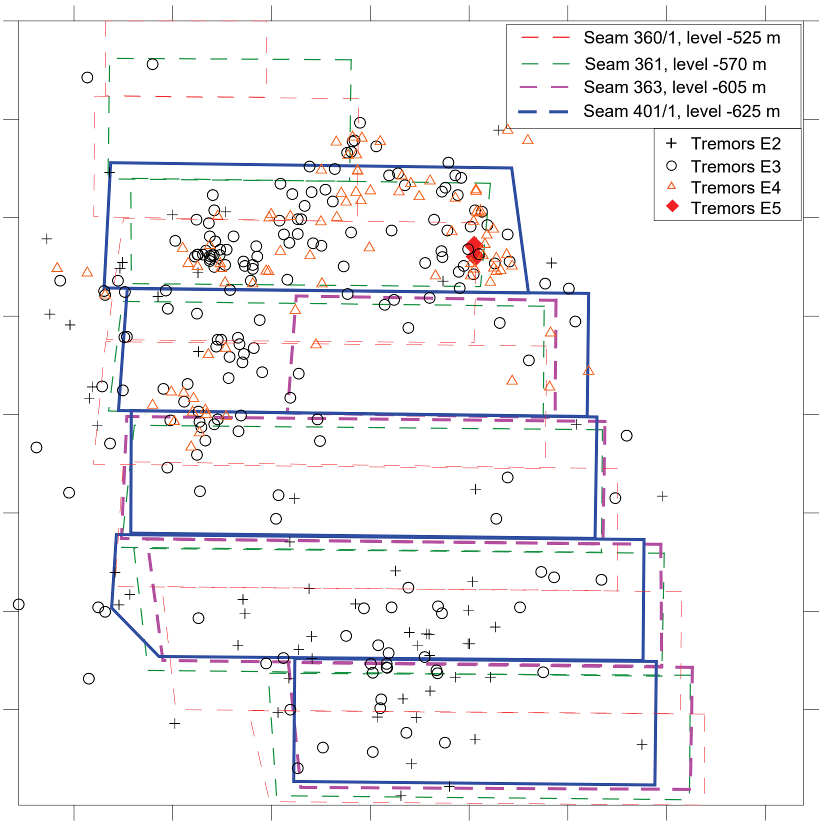

Fig. 3. Location of tremors in horizontal plane during mining seam 401/1 in zone No. I

the number of tremors with the energy of about 10^4 J. At the beginning of panel No. 4, which excavated the edges of seam 401/1 (Fig. 4), a larger number of tremors with the energy of about 10^4 J was recorded, as well as 3 tremors with the energy of about 10^5 J. In spite of the fact that around seam 404/1 the percentage of sandstone strata is twice as large as for seam 401/1, the number of recorded tremors and their total energy were lower. Such a situation is caused, among other things, by a serious disturbance of rock mass and an exploitation of the panels in the area of seam 401/1 excavated above. In the areas where seam 404/1 went beyond the contour of those edges, a seismic activity was usually higher.

Table 2. Recorded tremors during mining seam 404/1 in zone No. I

Panel No.	Number of tremors with a given energy				Tremors total	Total energy, J
	E2, J	E3, J	E4, J	E5, J		
1	3	17	7		27	2.31E+05
2	15	57	5		77	4.56E+05
3	28	40	5		73	3.16E+05
4	14	27	9	3	53	1.44E+06
Total	60	141	26	3	230	2.44E+06

3.2. ZONE NO. II

Within zone No. II of seam 403/3, a fragment of one panel and four other panels in a full range of exploitation were taken under consideration in an analysis of seismic activity. Three panels were mined out from the West to the East, whereas two of them were exploited from the South to the North (Fig. 5). In the period of exploitation, mostly the tremors with the energy of about 10^2 J and 10^3 J were recorded in the total number of 1,057. Taking the tremors embracing the exploitation of the entire panels (i.e., Nos. 3÷6) under consideration, it was observed that their number was varied: from 71 for panel No. 6 to 441 for panel No. 4 (Table 3).

The tremors with the highest energies of about 10^5 J were recorded during the exploitation of panels No. 3 and No. 4, and two of them were situated in the area of the edges of the overlying seams. Numerous tremors with the energy of about 10^4 J occurred particularly during the exploitation of panel No. 5, whose face was moving northbound (S-N). It resulted in the highest total energy amounting to $5.61*10^6$ J. The main reason for such a situation was apparently the excavation of the edge in seam 403/1, a considerable

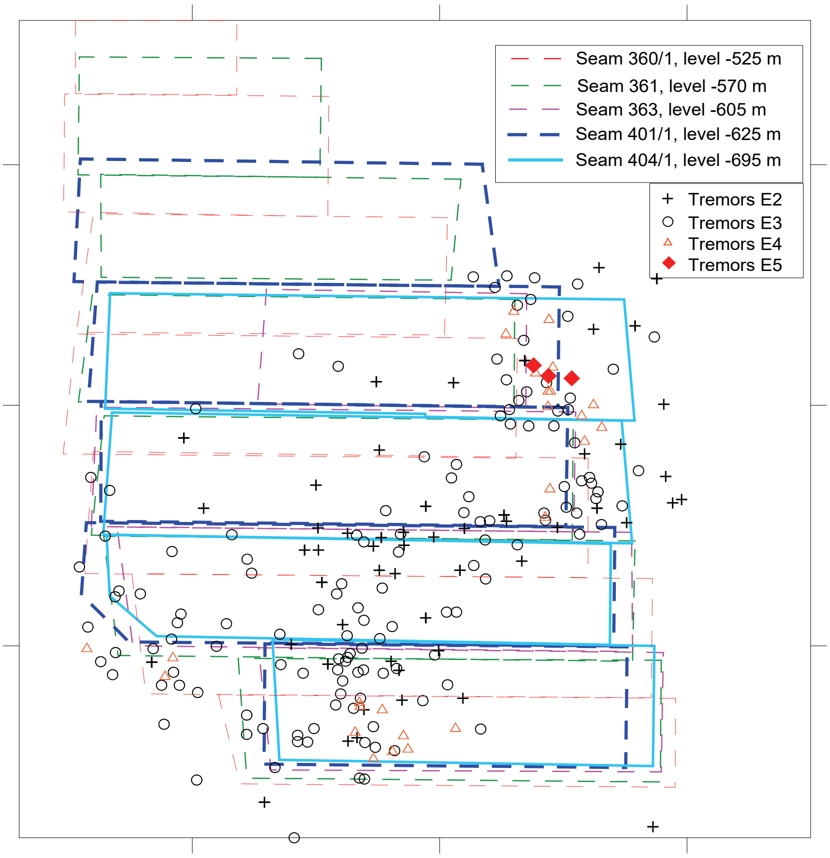

Fig. 4. Location of tremors in horizontal plane during mining seam 404/1 in zone No. I

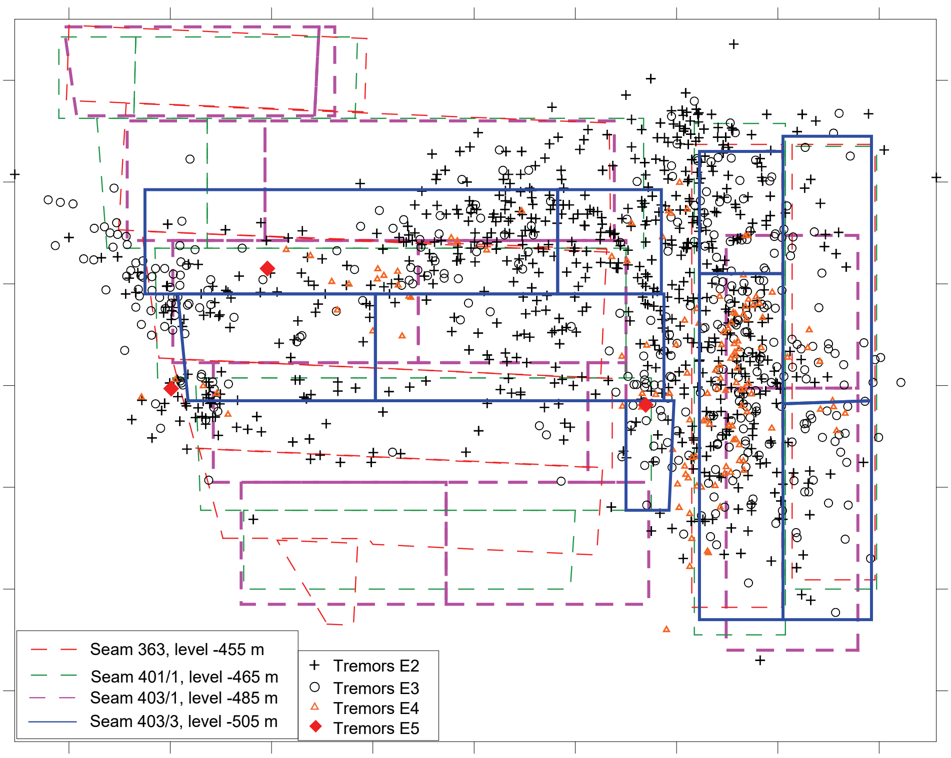

Fig. 5. Location of tremors in horizontal plane during mining seam 403/3 in zone No. II

percentage of sandstones in the geological structure of the rock mass and a pillar situated between the groups of panels with the W-E direction and the panels with the S-N direction.

Table 3. Recorded tremors during mining seam 403/3 in zone No. II

Panel No.	Number of tremors with a given energy				Tremors total	Total energy, J
	E2, J	E3, J	E4, J	E5, J		
2 (part)	20	5	2		27	1.69E+05
3	143	52	14	2	211	1.75E+06
4	305	114	21	1	441	1.99E+06
5	212	145	80		437	5.61E+06
6	8	53	10		71	4.54E+04
Total	688	369	127	3	1187	9.56E+06

In zone No. II of seam 404/1, six panels were mined out in a similar way as in the case of seam 403/3, nonetheless the panels with the E-W direction were commenced from the East (Fig. 6). The site of the tremors observably changed, since during the exploitation of seam 404/1, they were recorded mostly in the western part of the zone. In this area, the panels completed their run in the zones of overlapping edges left in the overlying coal seams. All the tremors with the energy of about 10^5 J were recorded after the completion of the panels No. 3 and No. 5. Observably, also the tremors with the energies of about 10^4 J occurred mainly in the area of mining disturbance, whereas they occurred only sporadically in the middle parts of the panels.

According to Table 4, the number of tremors during mining panels Nos. 1, 2 and 6 was exceptionally low (29÷39 tremors), which was caused by the exploitation below the zone distressed by seam 403/3 at a distance of approximately 25 meters. In addition, the total number of tremors recorded during the exploitation of seam 404/1 amounted to 697 and it was nearly two times less than for seam 403/3, whereas the total energy was exactly the same and it amounted to $9.5*10^6$ J.

Table 4. Tremors recorded during mining seam 404/1 in zone No. II

Panel No.	Number of tremors with a given energy				Tremors total	Total energy, J
	E2, J	E3, J	E4, J	E5, J		
1	13	12	3	1	29	3.95E+05
2	19	18	2		39	1.39E+05
3	71	61	26	8	166	5.20E+06
4	176	112	11		299	7.20E+05
5	59	57	10	3	129	2.96E+06
6	10	25			35	9.66E+04
Total	348	285	52	12	697	9.51E+06

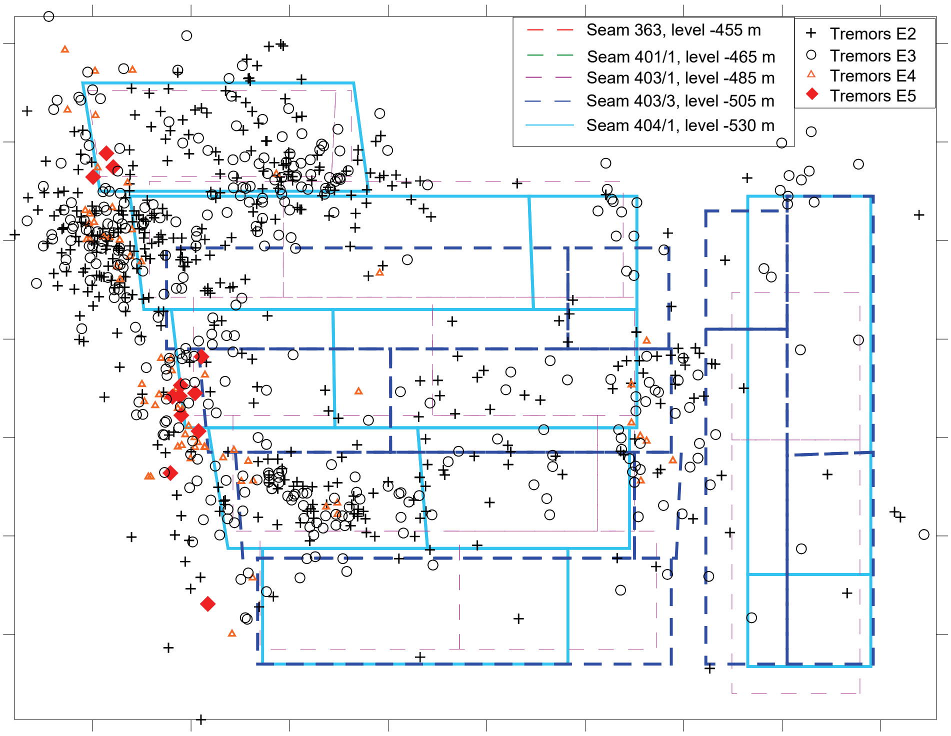

Fig. 6. Location of tremors in horizontal plane during mining seam 404/1 in zone No. II

4. STATE OF STRESS AROUND THE SEAMS PLANNED FOR EXPLOITATION

In order to calculate the distribution of mining-induced stress, a theoretical solution of Dymek (1969) was utilized, assuming the shape, dimension and position of an individual exploitation field. A 3D state of stress in the rock mass is analytically determined in the area of the rectangular exploitation field. In the next step, using the rule of superposition on the basis of a single solution, a solution for the 3D system of exploitation fields with any possible dimensions is obtained in a numerical way.

The state of displacement in a uniform isotropic and continuous rock mass, formed as a result of the exploitation of any rectangular field "*i*", allows the components of displacement vector $[u] = \{u, v, w\}^T$ to be determined.

Having determined the displacement vector components, the strain components are calculated from the geometric equations

$$[\varepsilon] = \{\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, \varepsilon_{zy}, \varepsilon_{zx}, \varepsilon_{xy}\}^T \tag{1}$$

followed by the calculation of the components of the elastic strain tensor from the generalized Hook's rule

$$[\sigma] = \{\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \sigma_{zy}, \sigma_{zx}, \sigma_{xy}\}^T. \tag{2}$$

In order to describe a rheological behavior of the rock mass, the elastic-viscous mechanical models are used. In the general case, the relaxation of stress after time t_{oi} can be determined from the following formula

$$\{\sigma(t_{oi})\} = \chi(\Delta t_{oi})\{\sigma\}_s \tag{3}$$

where

$\{\sigma(t_{oi})\}$ – stress tensor at a given point after time t_o, originating from the *i*-th exploitation field, MPa;

$\{\sigma\}_s$ – stress tensor at the moment $t = 0$, originating from the *i*-th exploitation field, MPa;

t_{oi} – period of time that passed from the moment of exploitation of the given exploitation field "*i*" to the analyzed moment of time, year;

i – number of exploitation field, –;

$\chi(\Delta t_{oi})$ – stress relaxation (weakening) coefficient, originating from the *i*-th exploitation field; it depends upon the shear modulus, the shear loss modulus and the time that passed from the completion of exploitation, the general form of formula is $\chi = 1{,}017e^{-0{,}082\ t_{oi}}$, –.

The solution presented above allows hazard zones and mutual impact of two seams mined out in the same area to be estimated with quite a good approximation, although this solutions contains many simplifying assumptions, i.e., layers are continuous, isotropic and elastic.

The calculations of vertical stress distribution and vertical stress concentration coefficient were carried out for seam 404/2, which is planned for exploitation within zones I and II and is situated approximately 20–25 m below seam 404/1 analyzed earlier. The analysis assumes that value of stress concentration coefficient indicates:

- lack of stress concentrations when coefficient's value is less than 1.00,
- low stress concentrations when coefficient's value is 1.01–2.00,
- middle stress concentrations when coefficient's value is 2.01–3.00,
- high stress concentrations when coefficient's value is more than 3.01.

In zone I, the calculations were carried out in the layer of sandstone, situated approx. 45 m above seam 404/2, which potentially may become a stratum capable of elastic energy accumulation. In other cross sections there are usually thin shale strata. The map of vertical stress distribution shows that their distribution is affected by the edges of the seams mined out above, mainly seam 404/1 (Fig. 7).

Due to the short period of time between the completed and planned exploitation, the values of vertical stress in the area of the hitherto extracted seams range between -30÷-40 MPa (compressive stress), whereas in the case of stress around seam 404/2, planned for exploitation, the highest values are obtained in the area of the beginning and finishing of the panel. In the area of the end of panels No. 1 and No. 2, the value of vertical stress amounts to –50 MPa.

It may, therefore, be stated that it is only in that region that a significant concentration of stress can occur (Fig. 8), since in other areas no serious changes of the state of stress are recorded in relation to the part of seam 404/2, which is still not subject to mining works. Within the mined out area of the panels in seam 404/2, as well as in the exploited area of the overlying seams, the distressed zone can be observed, since the value of stress concentration coefficient is less than 1.0. Hence the highest accumulation of energy in the layer of sandstone, and possibly its dynamic release in the form of tremors, may take place

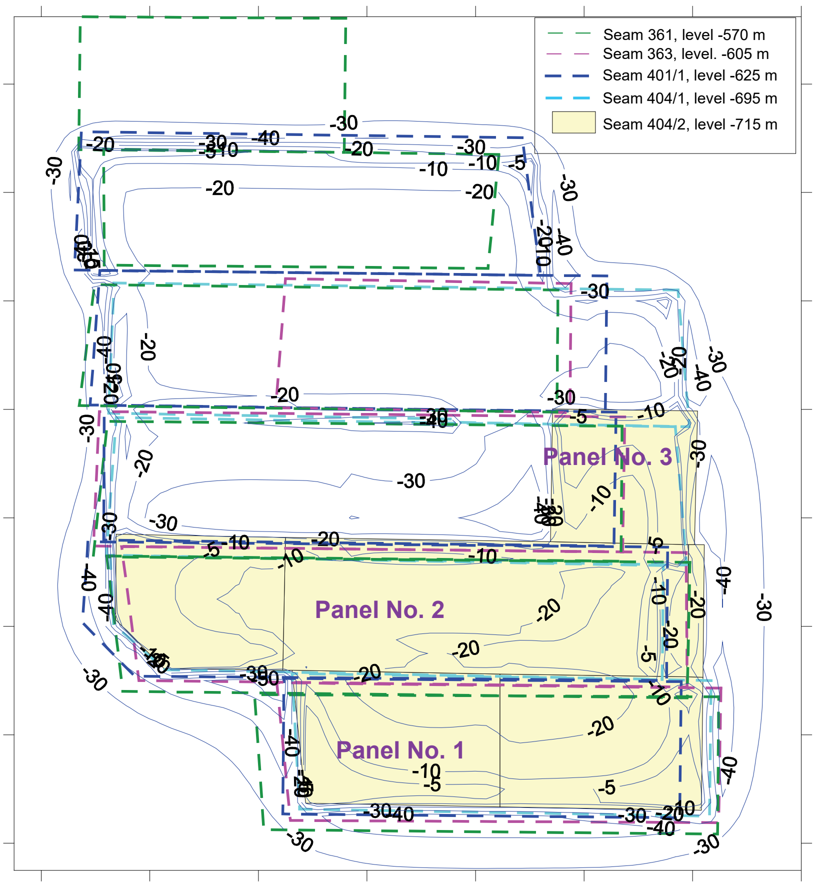

Fig. 7. Distribution of vertical stress in sandstone layer above seam 404/2 in zone No. I

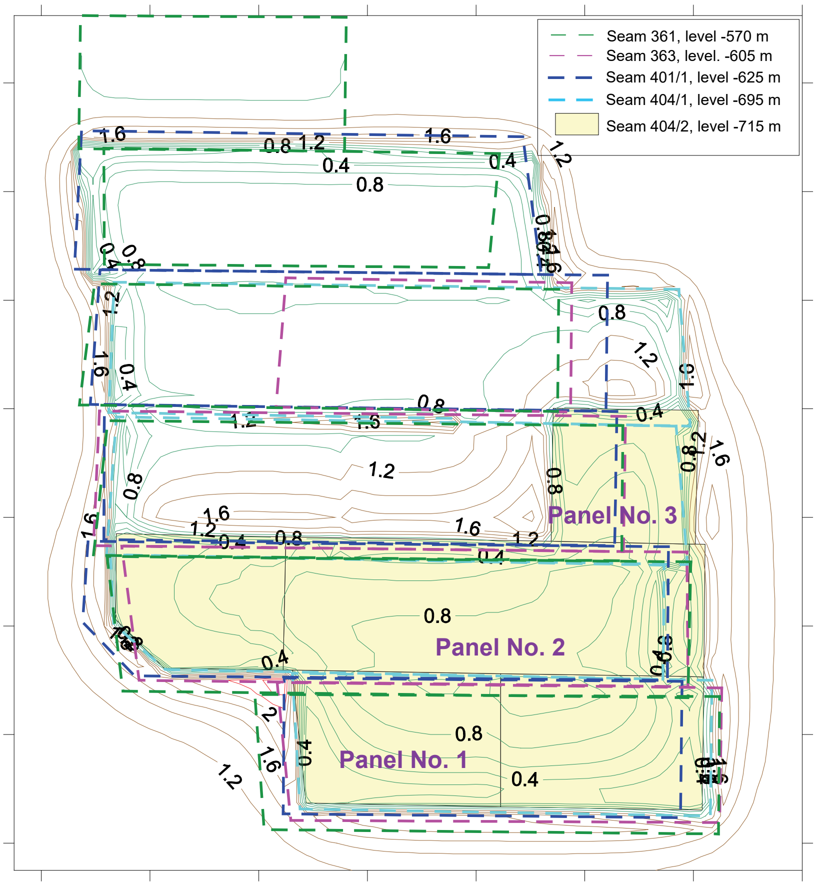

Fig. 8. Distribution of vertical stress concentration coefficient in the sandstone layer above seam 404/2 in zone No. I

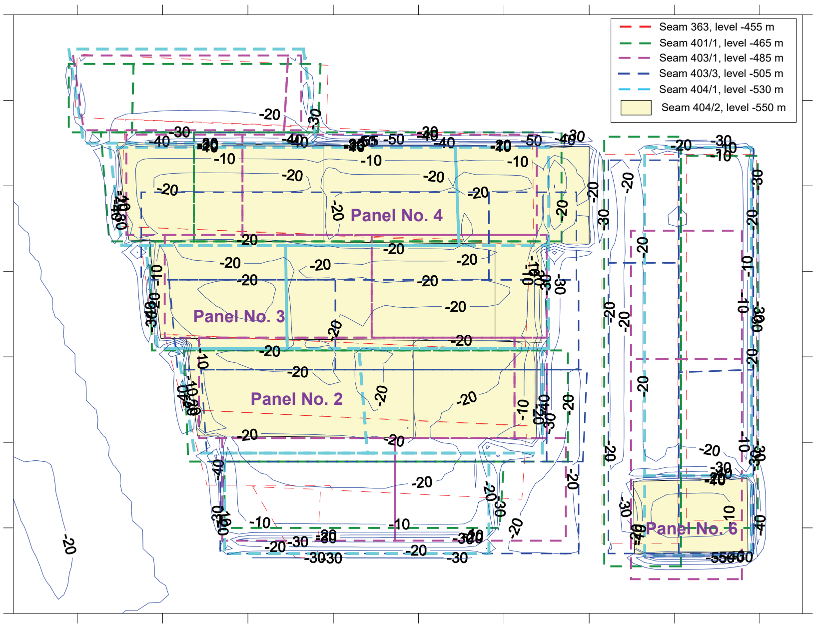

Fig. 9. Distribution of vertical stress in sandstone layer above seam 404/2 in zone No. II

in the area of outer boundaries of exploitation. In the remaining areas, the occurring tremors would be characterized by low energy, which would not produce any negative phenomena in the headings of seam 404/2.

In zone II, the calculations were carried out in the layer of sandstone situated approximately 15 m above seam 404/2, which potentially may become a stratum capable of accumulating elastic energy. The map of

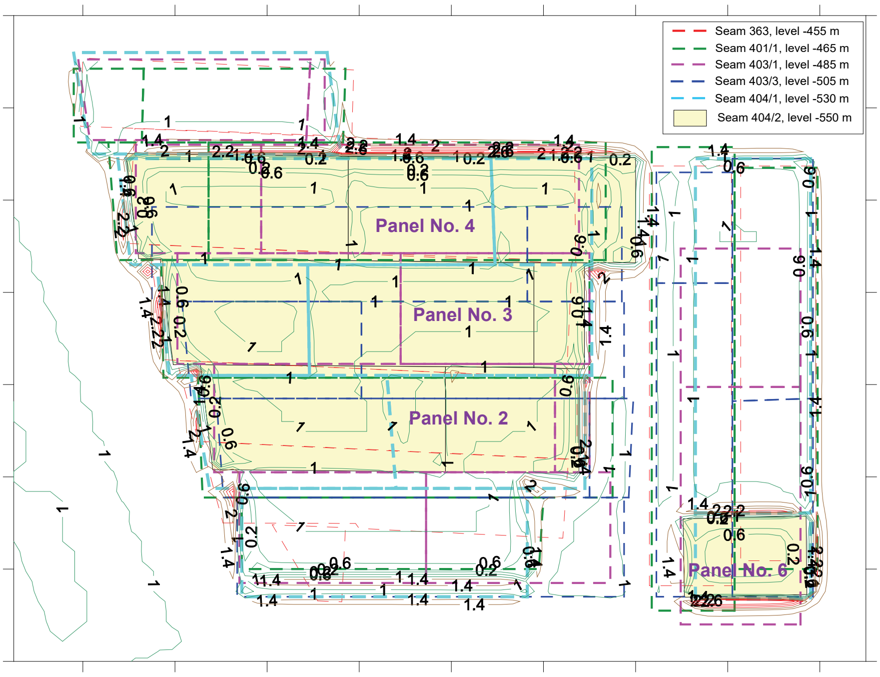

Fig. 10. Distribution of vertical stress concentration coefficient in the sandstone layer above seam 404/2 in zone No. II

vertical stress distribution shows that their distribution is mostly affected by mining out the panels in seam 404/2 (Fig. 9). The values of stress in the contours of the panels planned for extraction in the analyzed seam range between the values of –35 MPa to –50 MPa. The highest values are observed in the area of finishing the panel, i.e., from the West, but also from the northern side of panel No. 4, and at the beginning of panel No. 6. The majority of panels will be exploited in the distressed area, since the values of stress in those areas amount to approximately 20 MPa (cf. Fig. 9).

Therefore, as the above considerations show, the coefficient of vertical stress concentration within the contour of the planned panels does not exceed the value of 1. In the roof of seam 404/2 no serious concentration of stress should occur resulting in the accumulation of energy and its dynamic release. High values of vertical stress concentration coefficient, ranging between 2.0÷2.4, occur in the area of the overlapping of subsequent exploitation edges (Fig. 10).

5. CONCLUSIONS

The following conclusions may be drawn from the present study:

- in the areas of multi-seam exploitation, seismic phenomena seem likely to occur even in the situation of the lack of strata capable of accumulating elastic energy and its dynamic release;
- the analyzed seismic activity in two selected areas shows that during the exploitation of seam 404/1, the number of tremors and their total energy are larger in zone No. II, situated at a depth of approximately 800 m, than in zone No. I, situated at a depth of approximately 970 m. In both areas analyzed, tremors with the energy of about 10^2 J and 10^3 J prevailed; there were only occasional tremors recorded with the energy of about 10^5 J;
- all the tremors with the energy of about 10^5 J and the majority of tremors with the energy of about 10^4 J were situated in the area of the edges of the mined out seams or also in the area of the edges remained in the overlying seams;
- the prediction of vertical stress distribution and vertical stress concentration coefficient indicates that the highest stress concentration is expected in the area of overlapping exploitation edges of subsequent seams. In the areas where the vertical stress concentration coefficient amounts to 2 or more, accumulation of elastic energy and its dynamic release are to be expected;
- despite a relatively low recorded and predicted seismic activity, the occurrence of tremor-enhanced mining damage in the workings cannot be completely excluded. The present study clearly indicates that the areas of overlapping exploitation edges in subsequent seams are most hazardous.

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