Journal of Sustainable Mining 17 (2018) 167–174

Contents lists available at ScienceDirect

Journal of Sustainable Mining

journal homepage: www.elsevier.com/locate/jsm

Research paper

# Mining-induced seismicity of a seam located in rock mass made of thick sandstone layers with very low strength and deformation parameters

Jan Drzewiecki*, Jacek Myszkowski

*Department of Rockburst and Rock Mechanics, Central Mining Institute, Katowice, Poland*

ARTICLE INFO

*Keywords:*
Coal seam exploitation
Thick-layered rock mass structure
Mining-induced separation of roof layers
Large-size blocks
Seismic activity

ABSTRACT

The paper presents the results of calculations and analyses aimed at explaining the cause and mechanism of strong seismic events $E \geq 10^5$ J (local magnitude, $M_l \geq 1.7$). Their source are thick and at the same time weak layers of sandstone, theoretically unable to accumulate elastic energy during the exploitation of the seam 209 in hard coal mine Ziemowit in the edge area of seams 206/1, 206/1–2 and 207.

In the developed method of forecasting the pressure/stresses in the areas of the rock mass, which are affected by mining exploitation, the formulas linking the results of geophysical measurements of the longitudinal wave anomaly to the pressure values in its impact zone are used. This method was used to locate areas where elevated pressure occurred compared to gravitational pressure, which had a decisive impact on confinement of layers affected by mining exploitation. In such areas the level of confinement/stiffening of the layers is very high, that is why their deformation in the direction of the gobs is limited. In the case of a formation of a large area of gobs, large-size rock blocks are formed in the rock mass, whose mining-induced separation causes their the impact on the ground. Seismic energy accompanying this event is a function of the impact energy reduced by damping resulting from the physiomechanical properties of the cracked substrate.

## 1. Introduction

Mining of hard coal seams with the longwall system in Poland is accompanied by seismic activity of varying degree. Periodically, high-energy seismic tremors exceeding $10^5$ J (local magnitude, $M_l > 1.7$) are registered, which poses a real threat to the crew and mine workings. The analysis of mining-induced seismic events, their causes, which has been conducted since the late 1950s, indicate that their source is both strong, elastic sandstone layers capable of accumulating energy, and very thin layers that are periodically cracked transversely to bedding (Drzewiecki, 2004). Particularly, the development of geophysical methods has made it possible to clarify the concept of the seismic tremor mechanism (Gibowicz, 1989; Stec, 2015), the direction of wave propagation (Lurka, 2008; Mutke, Lurka, Dubiński, & 2009) or the location of stress concentration zones in the rock mass resulting from the past or present coal seam exploitation (McGarr, Spottiswoode, Gay, & Ortlepp, 1979; Dubiński, 1989). It should be emphasized that the main source of dynamic effects are strong, elastic layers of sandstones. However, in the mines exploiting laziskie beds (seams 200), orzeskie beds (seams 300), Carboniferous layers build weak rocks of considerable thickness, which can be accompanied by seismic energy emissions exceeding considerably $10^5$ J when collapsed. In this case, the sources of the strongest seismic events are located in the areas where the stress caused by gravitational pressures is increased by the stresses resulting from the former exploitation or the impact of remnants or pillars.

In deep hard coal mines, the rock mass is formed by sedimentary rocks, which are characterized by clearly defined boundaries of petrographic changes that determine their distinctiveness in the process of the rock mass disturbance by exploitation. Particularly important for this process are the physical properties of the Saddle Beds (Gustkiewicz et al., 1999), because they are the subject of exploitation, and destruction processes occur in them as a result of the exploitation of coal seams (Goszcz, 1999).

The range of the mining-induced rock mass disturbance towards the surface is greatest when the seam is extracted by means of a longwall system with caving. In the case of multi-seam exploitation, the level of rock mass disturbance will be a result of rock mass disturbance by each exploitation.

The physicomechanical properties of the Carboniferous rocks are strongly differentiated (Dembowski, 1972). Significant for the generation of mining-induced dynamic effects are rocks characterized by high physicomechanical parameters combined with primary cohesion forces. Differences in their deformability determine the formation of discontinuity in the roof and ahead of exploitation front (Drzewiecki,

* Corresponding author.
*E-mail address:* j.drzewiecki@gig.eu (J. Drzewiecki).

https://doi.org/10.1016/j.jsm.2018.08.002
Received 29 November 2017; Received in revised form 3 August 2018; Accepted 8 August 2018
Available online 09 August 2018
2300-3960/ 

2004). The extent of the impact of the rock mass is due to the depth of exploitation, the system and the advance and the degree of rock mass disturbance caused by mining exploitation. Actual dimensions of the disturbed rock mass range include with its range a number of mine workings, including active ones. Particularly the latter, due to the processes of rock medium destruction in their environment cause it to weaken, which is decisive on its periodic instability. This process is finite for the closed range of exploitation.

Particularly important for safety are strong seismic events in the area of the longwall run. Discontinuities, determined by exploitation, parallel and perpendicular to stratification are the source of tremors. The size and range of discontinuities in the longwall run area depends on the location/distance of the tremor-prone layers from the seam and the intensity of its exploitation, i.e. the velocity of the longwall front advance (Drzewiecki, 2004). It is to be emphasized that the extent of the area in which the dynamic separation of stratification occurs is changing with the advance. For two different advances in exploitation, its impact range in the direction of the surface may or may not include thick layers which, in the event of transverse continuity disruption, will dynamically/forcefully impact the layers deposited in their floor in this coal seam. This is equivalent to the situation when, for instance, a thick layer of weak sandstone may or may not be a source of dynamic effects. This is determined by the interaction between the intensity of the exploitation, the thickness and distance of the layer from the exploited seam and its mechanical properties.

Analysis of the structure of the rock mass requires in the first place defining what roof layers and at what distances from the seam can maintain continuity in the area of their operational deformation. Such layers form a kind of skeleton that preserves continuity until the deformation limit values of the layers that form it are exceeded in any part of it.

In the case when the roofs of the exploited seams are made of weak layers that are not capable of elastic deformation and accumulation of energy, the seismic events associated with this exploitation have a nature of a gravitational impact. These events are due to the fracture/cracking of thick but weak layers into blocks. The size of the blocks will be due to the range area of the yielded/cracked substrate, which includes the area of the gobs and strongly cracked floor of worked-out seams. The energy of these events is determined by the size of the blocks and their degree of freedom in the direction corresponding to the force of gravity. For multi-seam exploitation, the multiplicity of the layers extraction is determinant of the size of the blocks and the extent to which they are divided into blocks. In the case of multi-seam exploitation, the cracking of the weak layers will occur on the continually higher horizons of their deposition as a function of the multiplicity of their extraction.

The model of rock mass destruction developed in Central Mining Institute, depending on the intensity of seam exploitation which disturbs its equilibrium, can be used to estimate the extent of exploitation impact towards the floor and longwall advance (Drzewiecki & Iwaszenko, 2008). This is necessary for evaluation:

- which layers,
- of what thickness,
- how far from the exploited seam,

will be deformed due to the direct impact of the front of the conducted exploitation. It should be emphasized that in the case of multi-seam exploitation the range of deformation/separation of the roof will be due to the disturbance multiplicity of the layers forming it and will be increased towards the surface. This type of exploitation will also cause the separation into smaller blocks from already isolated parts of the roof layer due to the conducted exploitation. (Drzewiecki, 2009). In addition, the existing edges and remnants in the seams will be factors confining the underlying layers or their fragments. This will affect both the dynamics of their fracturing as a result of their undercutting, as well as the location of the discontinuities that determine the size of the blocks. In order to analyse such phenomena in the calculation process, the method of forecasting pressures on the given horizon resulting from the conducted exploitation was applied.

This method uses the results of geophysical measurements of the wave velocity anomaly in the area of edges impact taking into account the time of its formation (Dubiński, 1989). The method does not refer to modeling, uses well-known, verified and used in Poland analytical methods for calculating stresses in the vicinity of edges of exploitation. These methods have been developed on the basis of long-term in situ measurements of the seismic wave velocity anomalies in the region of current mining activity and their development. This is used in analytical methods of seismic energy prediction, destruction of the excavation under the influence of seismic wave energy and estimation of rock mass elasticity (Drzewiecki, 2009).

## 2. Data and methods

### 2.1. Geological and mining characteristics in block E, seam 209

The analysed area is mainly located in the block "E" of "Ziemowit" deposit and the "Imielin-Południe" and "Piast" deposits. It is limited:

- from the north-east by Imieliński I fault and thrust of 80 m,
- from west by Wschodni fault with thrust in the range of about 100–150 m,
- from the south and south-west by the R-1 remnant in seam 207 of the KWK "Piast" and the transport roadway 081 and side road 082.

The roof of seam 209 is made of Quaternary, Tertiary, Triassic and Carboniferous formations. Essential for the analyses included in this paper are Carboniferous formations, especially Carboniferous sandstones and the surrounding clay slate and coal beds. Uniaxial compression strength of coal seam 209, roof and floor rocks was estimated based on 45 penetrometric measurements. Uniaxial compression strength of coal seam 209 is 21.0 MPa, roof rocks is 27.4 MPa and floor rocks is 24.3 MPa.

The exploitation conducted so far has resulted in a number of gob areas in seams 209, 206/1, 206/1–2 and 207. Particularly significant from the point of view of seismicity accompanying the exploitation of seam 209 has the location of edges in seams 206/1, 206/1–2 and 207 relative to the exploited panels in seam 209. The exploitation in seams 206/1 and 206/1–2 was conducted from 1994 to 2006 to a thickness of 2.0–3.5 m. The distance between these seams and seam 209 is approximately from 174 m to 180 m. Subsequent exploitation of seam 207 was conducted between 2006 and 2012 to a thickness from 2.95 to 3.25 m. The seam 207 is located at a distance from 95 to 115 m above seam 209. The distance between seams, against the location of thick layers of weak sandstone in the rock masses determines the possibility of their exploitation-induced deformation/destruction. The size of mining works completed in the analysed area and currently carried out in seam 209 indicates that energy analyses should cover the whole rock mass in which the effects of exploitation occur. It should be emphasized that the results of the calculations, in addition to the mutual distances between the seams, are affected by a time relationship of the performed, carried out or planned exploitation and the mechanical properties of the rocks. Considering the mechanical properties of rocks for energy analyses, the basic parameter is the thickness and elasticity of the layers. A general description of these layers (card of borehole Ziemowit 257) indicates that they can reach a total thickness between seam 209 and 207 of 115 m, between 207 and 206/1–2 of 70 m; however, above the seam 206/1–2 to the layers of mudstone and seam 205/5 the thickness is equal to 46 m.

Attention should be paid to a very general description of these layers. In fact, in each of the distinguished separations, there are a number of very thin and weak layers that are decisive whether sandstones are separated into the thinner layers as a result of their mining-induced disturbance. At the same time, knowing their low strength, comparable to that of coal, i.e. not exceeding the compressive strength of 30 MPa, it can be assumed that they will be cracking at relatively low disturbance/deformation/deflection. Summing up the data on basic mining and geological information it should be stated that:

- in block E over the area of conducted and currently carried out and exploitation in seam 209, the rock mass has been affected by the exploitation of seam 207, 206/1 and 206/1–2. The exploitation in these seams produced a number of edges, with directions close to perpendicular and parallel to the front lines in seam 209. In addition, as a result of these operations, remnant fragments of the seams were created that affect the sandstone layers deposited above the seams 207 and 209.
- the time compliance of the current exploitation in block E in seams 206/1 and 206/1–2 and 207 results in that the greatest impact on the level of stress concentration on the sandstones horizons above the seams 209 and 207 have the remnants and edges in seam 207 and to a lesser extent the former exploitation in seams 206/1 and 206/1–2.

### 2.2. Registered seismic activity

Exploitation area of seam 209 in block E of hard coal mine Piast-Ziemowit Ruch Ziemowit is monitored by SOS seismic network. The seismic energy calculation is based on digital seismograms recorded by SOS seismic network at the Ziemowit colliery. The seismic network was composed of 32 vertical low frequency seismic geophones located underground at the level of coal seams. The recording stations were horizontally and vertically distributed in the analysed area at distances ranging from 300 to 6000 m and from 200 to 800 m, respectively. For analysis were taken only the nearest stations in which were the first P-wave displacement pulses explicit. Monitoring of seismic events was carried out with seismic stations located outside of analysed area and therefore is not shown in figures.

Seismic events, located with the use of MULTILOK software (Mutke, Lurka, & Dubiński, 2009) exhibit uncertainties in the epicentral coordinates of the order of ± 50 m, which are much smaller than the uncertainties in depth determination of the order of 100 m. This is because of the location of seismic stations at the level of coal seam. In the MULTILOK software seismic event location is carried out with one of the following minimization algorithms: Simplex, modified Powell algorithm, and the Davidson-Fletcher-Powell algorithm. This software used for the location of mining tremors and for seismic energy calculation in mines in Upper Silesia.

Over 1800 seismic tremors have been recorded over the exploitation of seam 209 with longwalls 100, 101 and 102. In this group there were 199 tremors with energy exceeding $10^5$ J (local magnitude, $M_l \geq 1.7$). In Table 1, the number of high-energy tremors that were recorded during the course of mining the longwalls 100, 101 and 102 in the block E seam 209 was shown in Table 1, while in Fig. 2, the location of their sources against the background of the workings and the edges of already conducted exploitation in the seams 206/1 and 207.

**Table 1**
Number of recorded high energy tremors during the exploitation of seam 209 with longwalls 100, 101 and 102.

| Longwall no. | Number of tremors of energy | | | |
|---|---|---|---|---|
| | > $10^5$ J | > $10^6$ J | > $10^7$ J | > $10^8$ J |
| 100 | 24 | 14 | 2 | – |
| 101 | 40 | 28 | 3 | 1 |
| 102 | 56 | 28 | 3 | – |

It should be emphasized that in the analysed area of seam 209, the layout of the exploitation edges in the overlying seams caused the formation of pillars with apparent non-regular contours forming the edges in the overlying seams, Fig. 2. Such pillars include rock mass sections in which there is elevated level of stress in comparison to gravitational stress. Mutual position of the edges in the seam and the seams overlying the seam 209 results in a superposition of the stresses at the level of seam 209. As shown in Fig. 2, three areas in which this phenomenon may cause elevated level of stress can be determined in the analysed area of the seam 209. Two of them are marked in circles and one in the form of an ellipse. In them or in their surroundings, the focus of the strongest seismic tremors during the exploitation of seam 209 with longwalls 100 to 102 were recorded.

The basis for determining the causes of high energy tremors in distinguished areas is the forecast of the stresses to be expected in the run of longwalls 100 to 102, prior to commencement of the exploitation of the seam 209.

### 2.3. Forecast of the areas with increased stress level in block E

By analysing the seismicity accompanying the exploitation of the seam 209 with longwalls 100, 101 and 102, attention should be paid the actual level of stresses that occur at the deposition levels of layers that are potential sources of seismic energy. It was estimated by means of an analytical method using programs developed in the Central Mining Institute, using in-situ measurements of the wave velocity anomaly in the impact area of exploitation edge, considering the time of its formation (Drzewiecki, 2002; Dubiński, 1989). In each longwall panel, a priori, i.e, before commencing its exploitation, the sections on its run should be identified, where the effect of the faults, edges, and remnants in the overlying seams is marked. This allows the image formation of the stresses anomaly which result from the analytical calculations developed on the map of seam 209 prior to its exploitation, Fig. 3. In the above Figure, the ellipses indicate the locations of the greatest impact of the former exploitation in seams 206/1, 206/1–2 and 207. It should be emphasized that in these areas, the "loading" of seam 209 and overlying layers, including the roof layers of seams 206/1, 206/1–2, will determine their stiffening in the rock mass. As a consequence, such parts of floor horizons and seam 209 will be more confined in the rock mass relative to their surroundings.

The degree of confinement of the layers or their fragments resulting from their exploitation-induced separation will be particularly visible in the superposition zones of the existing stresses with operating pressures. Figs. 4–6 show the calculation results of the stress anomaly prediction on the map of seam 209 for the selected mining situation of seam 209 exploitation stage. Three situations of exploitation development, characteristic for the assessment of stress anomalies are presented below:

1. The prediction of stress anomalies, shown on the map of seam 209 for the situation of the longwall 100 front location at the impact level of the remnant in seam 207 and the edge of seam 206/1–2, Fig. 4. Analysing the forecast image, attention should be paid to the two moments of longwall run. The first, marked with a circle on the ventilation roadway 91, exploratory, when the front of longwall 100 was approaching the edge zone of the seams 206/1 and 207. Due to the inclined position of the edge and front line, the impact zone of edges comprised a substantial section of its run. This is equivalent to the asymmetry of the confinement of the overlying layers, which is reflected in the seismic activity accompanying exploitation. The second, indicated in Fig. 4 with an oval, at the level of the edge effect of the remnants in seam 207 and the edge of seam 206/1–2 in the area of all three longwalls, a wide belt of elevated stresses relative to gravity is indicated. Taking into account the parallel position of the edges and the front line, the zone of former exploitation impact and exploitation pressures and stress level maintained in it

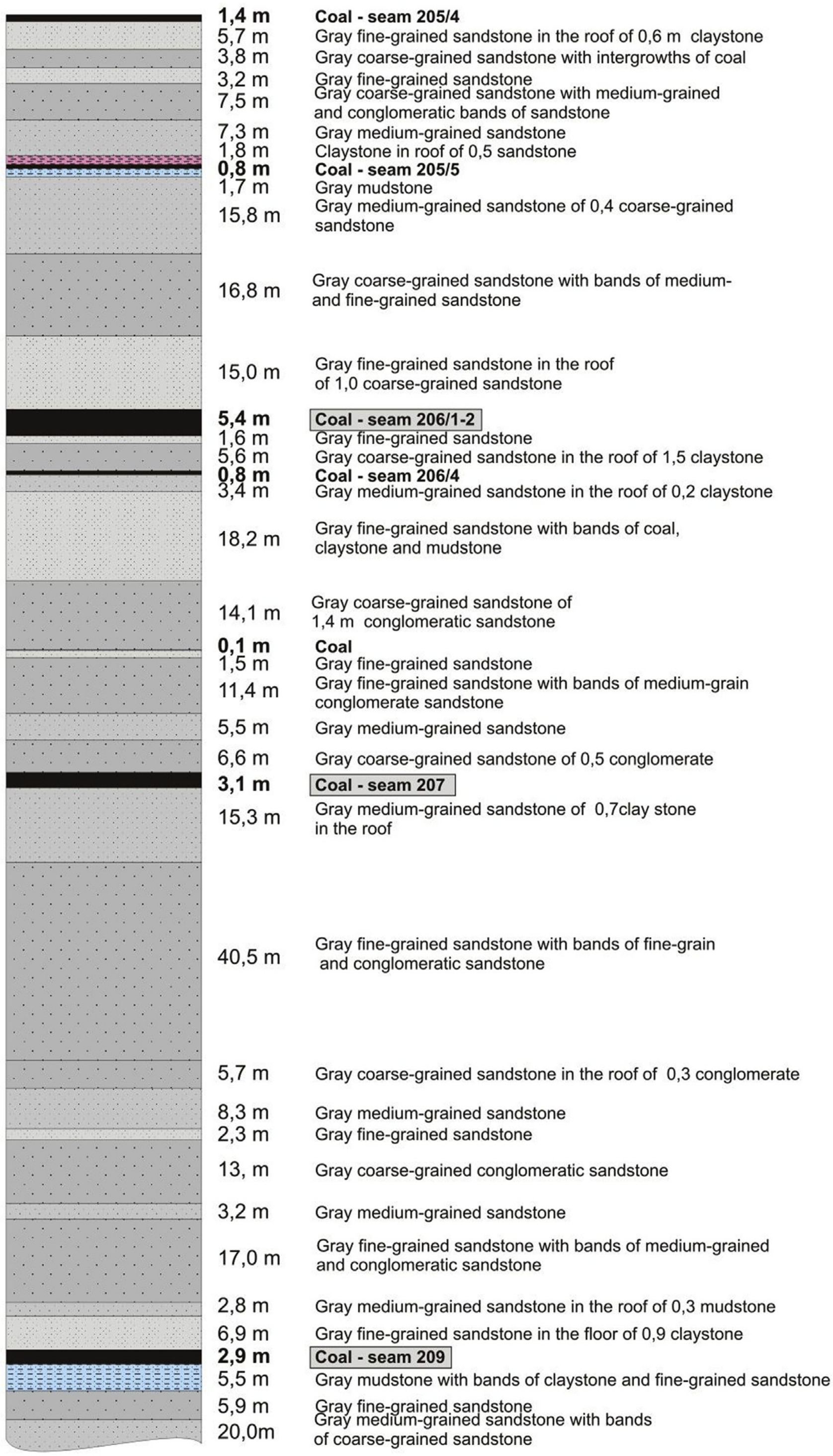


**Fig. 1.** Drilling hole fragment according to the borehole Ziemowit 257.

caused the local strong confinement of the overlying layers resulting in a limited degree of freedom for deformation. The consequence of the above was the increased dynamics of the block pieces impact of high roof resulting in the high energy of the recorded gravitational seismic events. This situation also occurred in the longwalls 101 and 102, when their fronts approached the above mentioned edges and remnants. It should be emphasized that these longwalls in the analysed area of the run were mined in one-sided environment of the gobs, which substantially enhanced the possibility of roof dynamic phenomena, impact of rock from the roof and accelerated their occurrence.

2. Forecast of stress anomalies presented on the map of seam 209 for the situation of the front of the longwall 101 at the impact level of the edges in the seams 207 and 206/1, Fig. 5. Analysing the obtained results, it should be stated that the front of longwall 101 was run in one-sided surroundings of longwall 100 gobs and approached the edge zone of the seams 206/1 and 207, and the asymmetric loading limited their movement to the gobs. As a result of this, also on this section of the longwall run there was a dynamic collapse of the separated floor layers on their substrate. Similarly, as in the case

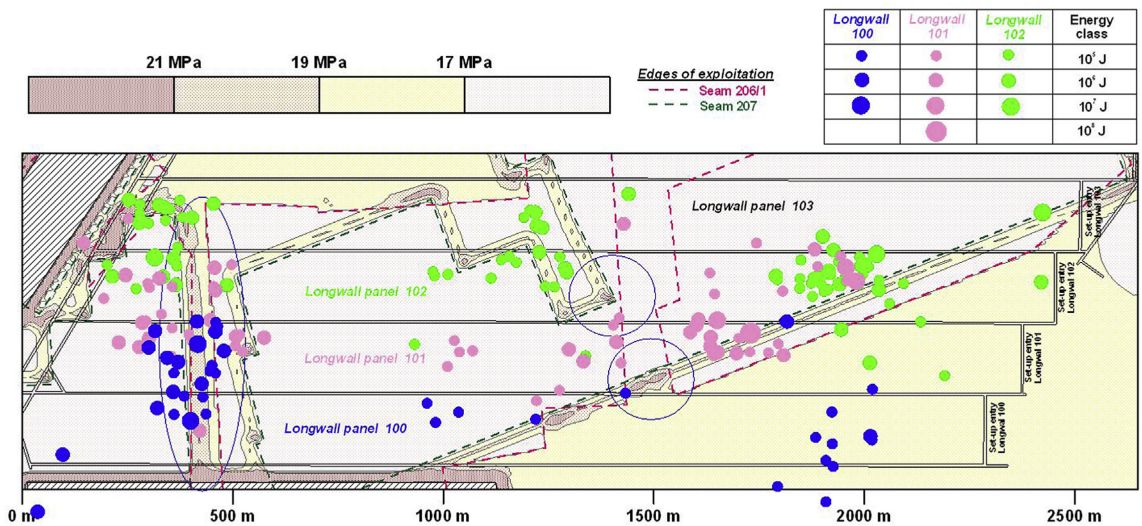


**Fig. 2.** Locations of sources of tremors with energy E ≥ $10^5$ while driving longwalls 100, 101 and 102 in block E.

of the longwall 100, there was an increase in the impact dynamics of the high-roof blocks, which was tantamount to the high energy of the seismic gravitational phenomena recorded.

3. Forecast of stress anomalies shown on the map of seam 209 for the situation of the longwall 102 front at the impact level of the edges in the seam 207 and 206/1–2, Fig. 6. Analysing the graphical results, it should be noted that the face of longwall 102 was run in one-sided vicinity of longwall 101 gobs and in the considerable part within the impact zone of R-1 remnants, located aslope to the exploitation front, and the edge in seam 206/1–2. Such a loading of the floor layers impact has limited the freedom of its movement on the distinguished section of its run, which was reflected in the intensity of the seismic tremors and their high energy. Also, in this case, the tremor mechanism was of an impact/gravity nature of the high roof block fragments on the substrate.

In summary, based on the graphical presentation of the calculations, it is possible to indicate where and to what extent the already conducted and currently conducted exploitation has affected the limitation of the freedom of deformation of the layers or the large-size sections separated from them. It allows us to estimate what stress values should be taken into account during the longwall run at seam roof level and near the deposited layers. In other words, it is possible to approximate the apparent depth at which the seam 209 was exploited and the apparent deposition depth of the roof layers that were subject to block separations.

## 3. Results and discussion

The exploitation of seam 209 in block E was accompanied by seismicity, whereas the intensity of recorded tremors and their seismic energy were the result of the size of the deformation area of the roof, the mechanical properties of the layers that form it, their distance from the exploited seam and the intensity of exploitation in the individual longwall panels. Taking into account the depth of exploitation of the seam 209, about 700 m and the size of the seams 206/1, 206/1–2 and 207 exploitation, it can be assumed that the roof layers over these areas have been destroyed. Such an image of destruction indicates that further exploitation of seam 209 will cause a systematic cracking of its roof layers, and this process will deepen the level of cracks in the roof layers of seams 206/1, 206/1–2 and 207. In other words, the seismic phenomena accompanying the exploitation of seam 209 will be localized both in the roof of this seam and in the roofs of seams 206/1, 206/1–2 and 207. The mechanical properties of the roof and floor rocks of the exploited seams in block E and seam 209 are similar. The estimated strength of their uniaxial compression varies from 21.0 MPa to 27.4 MPa. Such strength values indicate that it is difficult to distinguish in the depth range from seam 205 to seam 209, a group of strong resilient elastic layers capable of accumulating elastic energy. Bearing in mind the mutual distances of the seam 209 and the thick sandy shoals

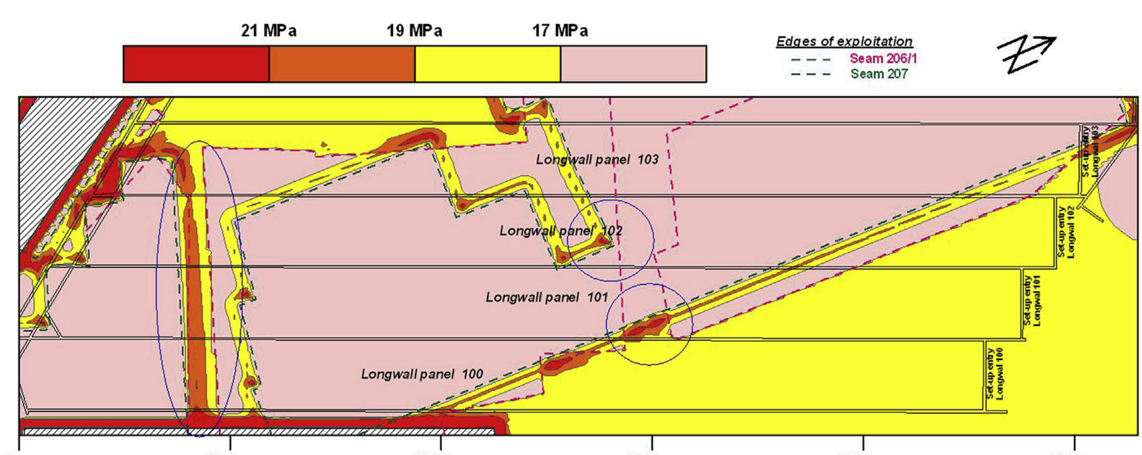


**Fig. 3.** Forecast of stress anomalies shown on a map of seam 209 prior to its exploitation with longwall 100.

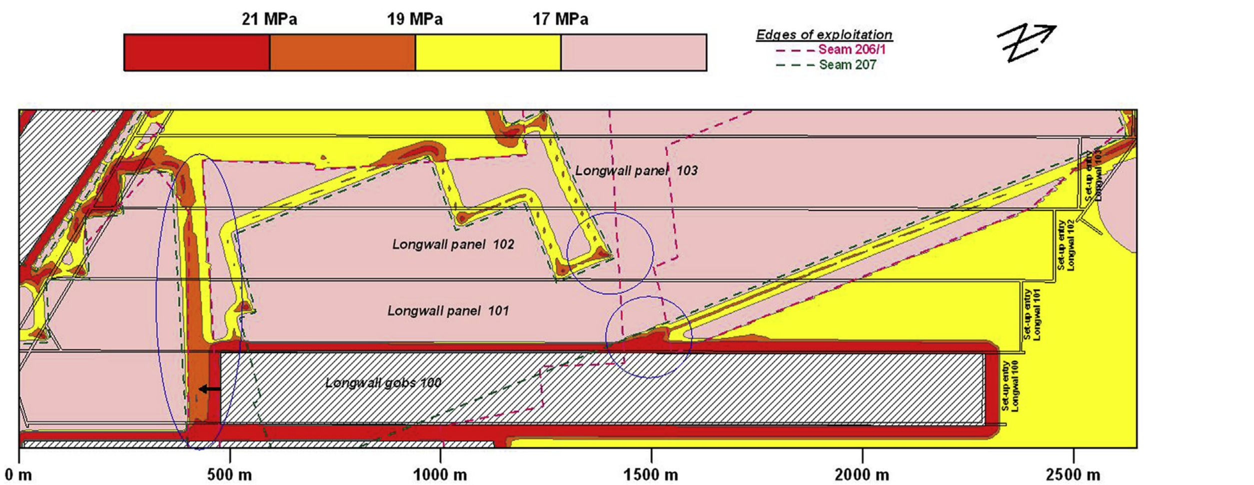


**Fig. 4.** Forecast of stress anomalies shown on the map of seam 209 for the situation of the longwall 100 front position at the impact level of the remnants in seam 207 and the seam edge 206/1–2.

of weak sandstone over the gob area of seams 206/1, 206/1–2 and 207 and formed gobs in seam 209, it should be assumed that the mechanism of discontinuity formation in the seam has and will continue to have a gravitational nature, i.e. the periodic separation of thick layers undercut in large areas and their collapse over the areas of formed gobs. The velocity of gobs formation and their impact range towards the surface is due to the intensity of the exploitation. In seam 209, the average daily advance of longwalls 100 to 102 was maintained at the level from 8 m to 10 m. Such advances indicate that the range towards the surface of the so-called active volume of the rock mass is from 60 m to 80 m, Fig. 7(Drzewiecki, 2004). This means that considering this distance above the seam 209 one should take into account the separation of the roof into the blocks which exceeds the longwall front.

The Ziemowit 257 borehole card (Fig. 1) indicates that coarse- and medium-grained sandstones with thickness is up to 40 m are found above the seams 209, 206/1, 206/1–2 and 209. In the profile of this borehole above the gobs of above mentioned seams a number of layers of weak sandstone, which form in the immediate vicinity of the floor chaotic caving, can be distinguished. Its range is a multiplicity of the thickness of the exploited seam above which the thick sandstone layers are broken into large blocks. Every exploitation under these areas deepens the separation of such blocks or increases their degree of freedom in the rock mass. As a result, new blocks may be created or the existing ones released as a result of destruction of the jointers keeping the neighbouring blocks in balance. The question arises, how does this process affects the exploitation advance?

The model of range of rock mass division initiation before longwall front developed in Central Mining Institute, as shown in Fig. 7 and the profile of Ziemowit 257 borehole, which shows the main layers of its stratification (low strength layers), indicates that every exploitation of the coal seam in such a rock mass will result in a strong cracking of the direct roof layers and easiness of overlying layers separation. The scope in the direction of the roof of dense network of cracking will be comparable to any speed of exploitation. This is due to the mechanical properties of the layers that form it, i.e., the lack of formation of the supporting structure that is made of the elastic layers. It can therefore be presumed, based on Fig. 7, that the range of a dense network of cracks in the floor layers, which is synonymous to their fragmentation, will increase with decreasing progress.

At the same time, this process will result in the yielding of the substrate for the blocks formed in the rock mass above the seam 209 and the blocks over the gobs of the exploited longwall, i.e. seam 206/1, 206/1–2 and 207. In other words, due to the lack of elastic layers in the analysed rock mass, it is not capable of accumulating elastic energy as a result of deformation of its formation layers, irrespective of the intensity of their undercutting/daily advance of the longwall fronts. The dynamics of the separation of the undercut thick weak sandstone layers or the impact of already isolated sandstone blocks is affected by the

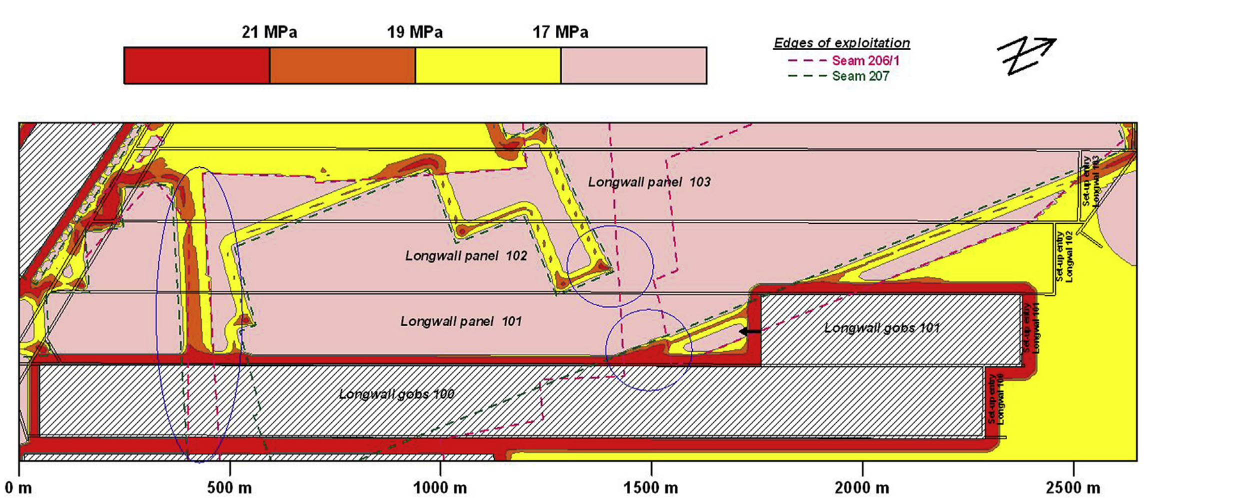


**Fig. 5.** Forecast of stress anomalies shown on the map of seam 209 for the situation of the front of longwall 101 at the impact level of the edges in the seams 207 and 206/1.

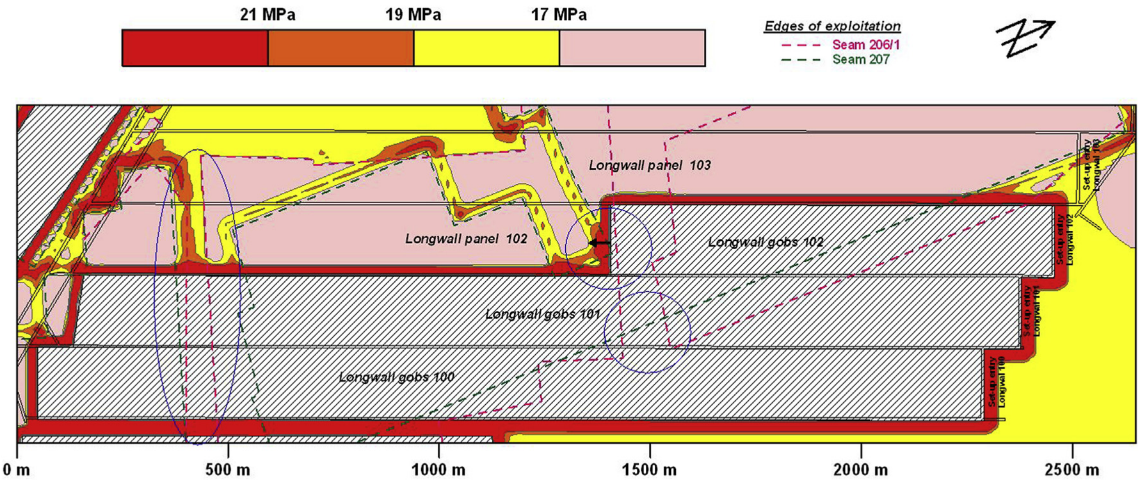


**Fig. 6.** Forecast of stress anomalies shown on the map of seam 209 for the situation of the front of longwall 102 at the impact level of the edges in seam 207 and seam 206/1–2.

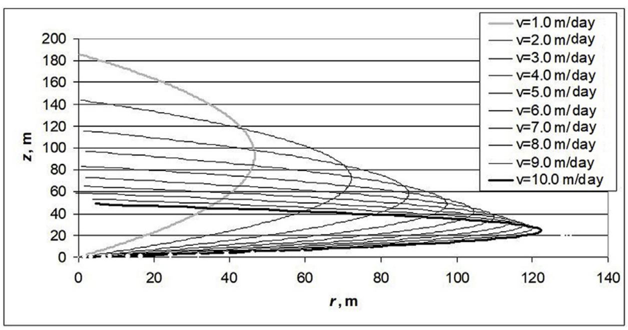


**Fig. 7.** The curves of the area of the rock mass ahead of the longwall front in which it is divided regarding average daily advance from 1.0 m/day to 10.0 m/day; *r* - horizontal distance, *z* - vertical distance from the seam floor of the rock discontinuity initiation layer.

level of their confinement in the rock. It is the result of confining forces, both layers before their separation as well as large-size blocks formed of them. In the case of such blocks, in a relatively short distance above the seam (several dozen meters), they can be destroyed, for example by shooting, irrigation, de-stressing drillings, etc. (Dubiński & Konopko, 2000; Konopko et al., 1997; Myszkowski, 1996; Pawłowicz, 1996). However, in multi-seam operation, rock-stiffening forces increase in the area of exploitation interactions of individual seams, i.e. their origin, edges and remnants and geological disturbances at a considerable distance above. On such stretches of their interactions the exploitation is carried out under conditions of increased stresses, which occur at higher depths - the apparent depth of exploitation. In such areas of the rock mass, both the dynamics of the distribution of the number of weak sandstones and their large blocks will be significantly higher than those where only gravity pressure occurs. It should be emphasized that such dynamic processes have occurred and will be recorded both, in the high roof of seam 209 during its operation and periodically in the high roof of seams 206/1, 206/1–2 and 207, irrespective of the daily advance of the longwalls in seam 209. The effects of high-energy seismic tremors of the above-mentioned genesis will be felt to a greater extent on the surface than in mine workings. This is due to the mechanism of wave energy dissipation in the area of strongly cracked roof of seam 209.

## 4. Conclusions

The paper presents results of calculations and analyses aimed at explaining the cause/mechanism of very strong seismic events with seismic energy significantly exceeding the level of $10^5$ J, which are caused by thick, very weak layers of sandstone, unable to accumulate elastic energy. This type of sandstone layer is found in the roof of 100 Libiąskie Beds, 200 Łaziskie Beds and 300 Orzeskie Beds (Dembowski, 1972).

The exploitation of these seams, especially multi-seam exploitation in a small area, causes them to collapse over the areas of gobs accompanied by the emission of seismic energy. In such areas, the level of confinement/stiffness of the overlying layers is very high, so that their deformation towards the gobs is limited. In the case of a large gobs area, a thick layer of sandstone under the overburden load bursts into large blocks of rock with one dimension comparable to the length of the longwall. The weight of such blocks is very large, so their potential/gravitational energy is large. Periodically, with the advance of the exploitation, the release of such a part of the layer causes its impact on the substrate, which, due to the large weight of the isolated rock mass/block, is equivalent to the emission of seismic energy. The seismic energy associated with this event is a function of the impact energy reduced by attenuation resulting from the physicomechanical properties of the substrate. The strongest seismic events are located in areas where gravitational pressures are amplified by stresses arising from the effects of exploitation or the effects of remnants or pillars. The proposed solution assumes that the source of the tremor energy are layers of weak sandstone, which is not capable of elastic deformation, thus accumulating the elastic energy. They are confined in the rock mass due to the effects of natural disturbances, former exploitation and currently conducted mining exploitation. High-energy seismic events are the result of the cracking of thick layers of weak sandstone, which are subdivided into large blocks. The size of the isolated blocks is due to the range of the zone of the yielded/cracked substrate of exploited seams. The mutual distance of the fractures in the cracking layer, i.e. the mass of blocks separated by these fractures, decreases with the distance to the exploited seam. In conclusion, it can be stated that:

1. A model of rock mass separation ahead of the longwall front, which is shown in Fig. 7 and the profile of the borehole Ziemowit 257 (Fig. 1), on which the main horizons of its separation into layers (low strength layers) are marked, indicate that each exploitation of coal seam in such rock mass will result in a strong cracking of the direct roof layers of exploited seams and the easy separation of layers overlying the large blocks.
2. In the case of a large-size blocks impact on cracked substrate, a high-energy phenomenon of gravitational nature is recorded. The sources of such events are located at a considerable distance from the seam.
3. The range of the dense network of cracks will be comparable to any rate of exploitation. This is due to the mechanical properties of the

layers that build it, i.e., the lack of the supporting structure formation, which is built of the resilient layers. Based on Fig. 7, it can be assumed that the dense network of cracks in the roof layers, which is tantamount to their fragmentation, will increase with decreasing advance. At the same time, this process will result in the yielding of the substrate for the existing sandstone blocks above the seam 209 and blocks over the gobs of already exploited seams, i.e. seam 206/1, 206/1–2 and 207.

4. For multi-seam exploitation, as it is in the analysed area, in the successively exploited seams there are weak sandstone layers. The cracking process will occur not only in the roof of the seam being exploited but also in the roofs of overlaying seams, where the separation of thick sandstones as a function of their undercutting multiplicity will occur. Rock mass structure in the vicinity of seams 206/1, 206/1–2, 207 and 209 indicates that such events have accompanied and will accompany their exploitation.
5. The dynamics of the separation of thick weak sandstone layers or the impact of already isolated sandstone blocks is affected by the level of their confinement in the rock mass resulting from forces stiffening the rock mass. They increase in the area of exploitation impact, i.e., former exploitation, edges, remnants and geological disturbances, which means that the exploitation of the seam on such sections is carried out under pressure conditions occurring at a greater depth. As a result of this, the dynamics of the separation of thick weak sandstones as well as the impact of the separated large-scale blocks will be larger compared to such processes occurring in the areas of gravitational pressures only.
6 Lack of ability to accumulate elastic energy in the roof layers of seams 206/1, 206/1–2, 207 and 209, due to their low strength/elasticity, separation into large blocks of thick layers of weak sandstone deposited in the roofs of the above seams, gravitational nature of dynamic events indicates that the analysed rock mass is not capable of accumulating the elastic energy in the layers which form it, irrespective of the intensity of their undercutting, i.e. the velocity of the longwall fronts dislocation.
7. Dynamic processes induced by exploitation-related works in block E of hard coal mine Piast-Ziemowit, Ziemowit Ruch took place and will be recorded both in high roof of seam 209 during its exploitation and periodically in the high roofs of seams 206/1, 206/1–2 and 207, irrespective of the daily advance of longwalls in seam 209.
8. The effects of high-energy seismic tremors of the above-mentioned genesis will be felt to a much greater extent on the surface than in the mine workings of seam 209. This is due to the spread of wave energy in the area of strongly cracked roof of seam 209.

## Conflict of interest

None declared.

## Ethical statement

Authors state that the research was conducted according to ethical standards.

## Funding body

Polska Grupa Górnicza sp. z. o.o. KWK Piast-Ziemowit – Ruch Ziemowit.

## Acknowledgements

The article was developed based on work titled "Analysis of the dependence of seismic activity induced by exploitation of seam 209 in block E from the speed of movement of front longwalls for KWK Piast-Ziemowit" and developed in the Central Mining Institute in Katowice (Poland) at the request of Polska Grupa Górnicza Sp. z.o.o. KWK Piast-Ziemowit – Ruch Ziemowit (Work No. 58318587-141, unpublished).

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