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A MODEL OF ROCK MASS FRACTURING AHEAD OF THE LONGWALL FACE AS A CONSEQUENCE OF INTENSITY OF EXPLOITATION

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ABSTRACT
In Czech and Polish underground hard coal mines of the Upper Silesian Coal Basin high-energy seismic phenomena are periodically recorded, the sources of which are located ahead of the longwall. Generally, these types of tremors are rooted in very strong, thick layers of sandstone, which are subject to the deformation border. The consequences are discontinuities and cracks with a range depending on the mechanical properties of destroyed rocks: the mechanical parameters of layers. Forecasting methods, developed in the Central Mining Institute, for stress concentration, seismic energy, fault zone and range, together with methods of rock fracturing using liquid or explosives, ,allow precise identification of suitable locations for controlled fracturing of rock mass with a pre-established direction.

The size and range of discontinuities have an impact on mining parameters, dependent on basic exploitation intensity and expressed by the average daily progress of the longwall face. The rockmass is locally weakened because of exploitation or technical measures of discontinuities in the roof-rock on the longwall face. To prevent rockburst, measures are needed to reduce the amount of energy accumulating in the rockmass in the area of the longwall face.

Knowledge of where stress is concentrated is extremely important for the development and implementation of effective preventative methods. For many years several research centres have been working on defining the range of these areas.

In this paper, basic information is presented on methods developed by Central Mining Institute and used in Polish hard coal mines for forecasting energy concentration and assessing how it can be reduced.

1. INTRODUCTION

The Carboniferous rock mass in the Upper Silesian Coal Basin (USCB) is inhomogeneous. It is the result of complex geological processes connected with the formation of hard coal deposits and long-term and intensive mining exploitation in this area (Jaroszewski, 1980). Localization of discontinuities and their density determine the inhomogeneity of the rock mass. The primary divisibility (textural) and secondary divisibility (mechanical) have a strong influence on the value of elastic energy which is accumulated in the rock mass, and consequently on the possibility of the occurrence of dynamic phenomena which can destroy the working environment of underground hard coal mines.

It is difficult to quantify reliably all factors determining the work safety in coal mines. For a given area of the mine, it is possible to predict the level of seismic hazard arising from the specific situation of coal seam exploitation. Unfortunately, experience shows that, despite the seemingly good knowledge of the rock mass and the use of a number of preventive treatments, there are nonetheless events that disturb the production process or prevent its continuation. Existing natural discontinuities in the rock mass favour the generation of dynamic phenomena accompanying mining operations. Proper assessment of the destruction of rock in the vicinity of the excavation process helps to characterize this environment and the impact of mining on its destruction. Faults are areas of non-uniform stress distribution, regardless of the size of the throw, in which the accumulated energy can be released in stress concentration zones in the form of a seismic tremor, which creates a real danger of rock burst. Adequate recognition of geological deposits enables implementation of the most effective exploitation technology for the given conditions.

Measurements of displacements of the roof rock layers revealed them to be horizontal, relative displacements continuing at large distances from the longwall face (Drzewiecki, 2000). This indicates a high capacity to preserve transverse continuity of the rock mass layers, despite their strong deformation in the area of the dynamic edge, which is the longwall face.

In real conditions, the longwall face is moved at variable speeds, because of current technical and geological conditions, and natural hazards. In the rock mass, where the rock layers are able to accumulate energy, the longwall advancement determines which rock layer and which part is involved in the process of energy accumulation. Proper identification of rock layers allows prediction of the amount of the changes in accumulated energy, depending on the intensity of exploitation.

For many years, research has been conducted in the Central Mining Institute in order to develop a model of roof rocks over an exploited coal seam destruction, with the aim of explaining the mechanism of seismic tremor occurrence in the roof of the longwall face. The physical models of rock destruction have been developed mainly for earthquakes (Brune's model, Madariaga's model, and others). There are limited possibilities to apply them to seismic events induced by mining, where the energy level is lower.

Therefore, knowledge of the initiation and propagation of real destruction processes in the rock mass, infringed on due to mining, is essential if a reliable model of a tremor is to be developed. From the work-safety point of view, it is important to explain the genesis of tremors, the sources of which are located on the face of the longwall. Knowledge of the destruction of rocks in this area is essential for developing effective rockburst prevention or to reduce high energy seismic events.

2. DEFORMATION AND DESTRUCTION PROCESSES DETERMINING THE HIGH SEISMIC TREMORS

Loss of stability in a large volume of rock mass is usually the cause of tremors. Movement of rocks occurs in the direct vicinity of mining operations under the influence of gravity and inertial forces. The range of movement is a function of the size of the goaf. The extent of the area in which the movement of the layers occurs depends on the intensity of exploitation (Drzewiecki, 2004).

The construction of the Carboniferous rock mass and physico-mechanical properties of each layer, exploitation technology and intensity all determine the extent of the area in which the oriented rock motion is observed. It is accompanied by dynamic divisibility of the rock mass in strictly defined areas.

Researches and measurements realized in the Central Mining Institute resulted in a series of analytical solutions which allowed a set of values to be calculated characterizing the rock mass disturbed by longwall operations. Programmes based on the analytical methods of calculation are particularly suitable for the definition of deformation and destruction processes resulting from mining:

- the level of pressures on the horizon, and exploited seams and tremor-prone rock layers, including faults (Kabiesz et al., 1994; Drzewiecki, 2011),
- the size and range of deformation of selected tremor-prone layers in the roof of the operated seam (Szpetkowski, 1988, 1995; Drzewiecki, 2004),
- principal stresses in the rock mass (Makówka and Drzewiecki, 2011),
- mechanism of sources of mining tremors (Stec and Drzewiecki, 2012).

Use of the above programmes to determine the causes, mechanisms and prognosis of strong dynamic phenomena allows us to perform analysis of this type of phenomena in the context of destructive processes induced by mining activities. Particularly important is that the analyses are based on methods and programmes using results of tests and measurements *in situ* (both geophysical and geodetic) of displacements and deformations of the rock mass.

As the results of excavations in the rock mass, the deformation and its partial displacement is in the direction of the selected area, and discontinuities or cracks occur. These phenomena are accompanied by an emission of wave energy. Its value is a function of, inter alia, the energy accumulated in the rock mass, mechanical properties and the way in which the deformed layers are restrained. High-energy seismic wave phenomena larger than $1\text{x}10^5$ J are important in their impact on crew safety. These types of seismic phenomena are generated by cracking of a layer, or a group of layers, and stratification of the rock mass (Fig. 1). Another element to consider in terms of safety is the location of seismic tremors. Mining experience indicates that the most dangerous tremors are dynamic phenomena located in close proximity to the mine workings and are phenomena with a regional range. The latter, with energies above $1 \cdot 10^7$ J, are caused by mining operations acting on a very large volume of unstable rock or by violation of the energy balance of large fault zones (Fig. 1).

Tremors localized in front of the longwall face are the most crucial for ongoing mining operations because of the movement of the crew, haulage and transport of material. In practice, those areas with geological disturbances or faults are the sources of dynamic phenomena. This follows from the fact that they are surrounded by large or very large stress anomalies. The imbalance causes the propagation of stress in existing discontinuities or creation of new ones. This is equivalent to local concentration or deconcentration of elastic energy. Technical methods for initiating this type of dynamic phenomena involve fracturing in precisely defined volumes of rock mass using hydraulic methods or explosives. These types of fractures could have a predefined orientation and their dynamic propagation is accompanied by seismic events. They may be a direct source of high seismic tremors or the initiator of one of the other source mechanisms.

3. IDENTIFICATION OF AREAS OF POTENTIAL DISCONTINUITIES CAUSED BY LONGWALL MINING

Mining operations disturb the natural state of stresses in the rock mass. Anomalies in the stress values in relation to the natural state characteristic for a given depth are the consequences of mining operations. Negative anomalies in the stress zones are generally associated with areas of exploitation or use of active rock burst prevention measures. Positive

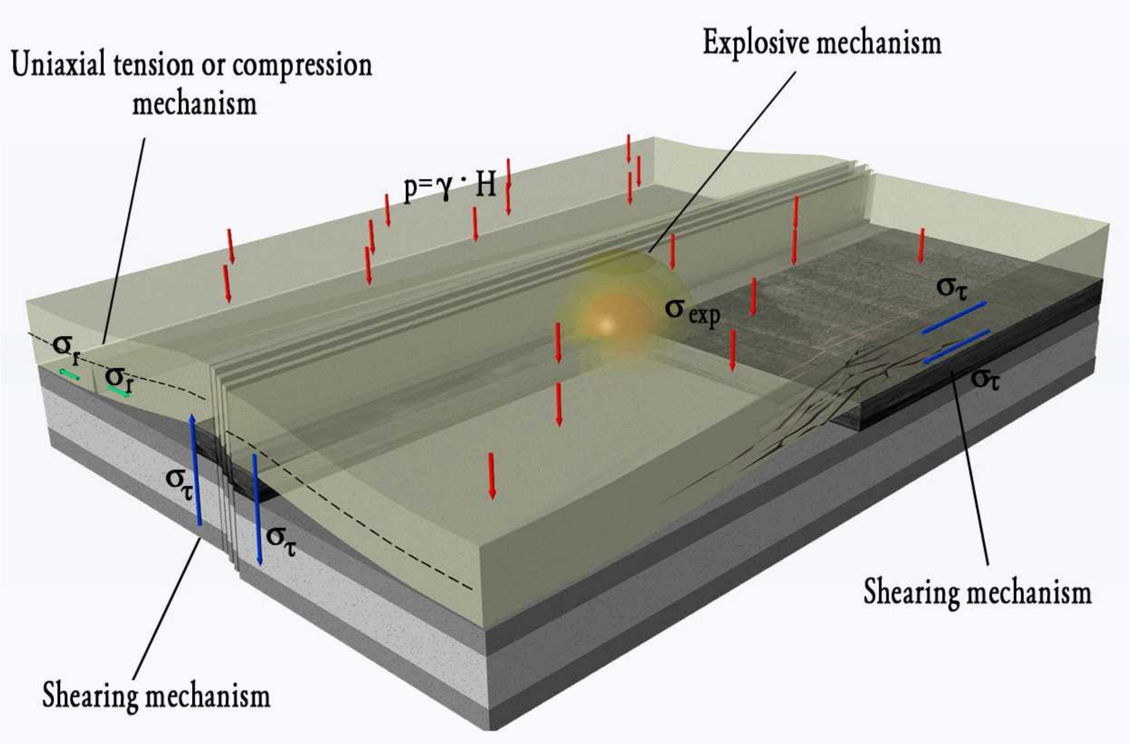


Fig. 1 Areas of potential seismic hazard and possible focal mechanism.

stress anomalies occur in the zones surrounding gob areas, pillars, and the static and dynamic edges of excavation. It is possible to determine the range and intensity of the impact of the zones using the empirical relationship between seismic wave velocity anomalies and stress (Dubiński, 1989). This relationship is developed for USCB mines at the depth of 500–900 m in the general form:

$$v/v_0 = A(p/p_z)^b \tag{1}$$

where: v – velocity of the compressional wave,
v$_o$ – average velocity of the compressional wave in the area of investigation,
v/v$_o$ – seismic anomaly, %
p – calculated isotropic part of stress tensor ,
p$_z$ – isotropic part of stress tensor caused by gravitational force,
p/p$_z$ – likely decrease / increase of vertical stress, %
A and b – specific parameters for a given depth of the edge.

This formula was the basis for the development of an analytical–empirical method for forecasting stress fields in the rock mass (Kabiesz et al., 1994). When parameters are added to estimate the influence of faults on the range of its impact (Drzewiecki, 2011), it is possible to calculate stresses in the seam and in the adjacent horizons, which are presented in Figures 2 and 3.

The geometrical method was used to determine the final vertical displacements and deformation of the undermined sandstone layer (Szpetkowski, 1988, 1995). The final displacements at some point in the rock mass comes from below the exploited region represented by a rectangular area of the seam with the dimensions *s* and *l* and described by the formula:

$$w(x,y,H) = \\ = w_{\max}\frac{1}{\sqrt{2\pi}}\int_{\frac{a-x}{\sqrt{2BH}}}^{\frac{b-x}{\sqrt{2BH}}} e^{-\frac{u^2}{2}}\,du\cdot\frac{1}{\sqrt{2\pi}}\int_{\frac{c-y}{\sqrt{2BH}}}^{\frac{d-y}{\sqrt{2BH}}} e^{-\frac{v^2}{2}}\,dv \tag{2}$$

or by a simplified equation:

$$w(x,H) = w_{\max}\left[0.5+\Theta\left(\frac{1}{\sqrt{2b}}\cdot\frac{x}{\sqrt{H}}\right)\right] \tag{3}$$

where:
w – subsidence, mm
Θ – primitive function of the expression $e^{-\frac{u^2}{2}}$
H – depth of exploitation, m
B – constant characteristic for a rock mass acquired through in situ measurements at vertical distance = 25m
a, b, c, d, x, y, p – as in Figure 4.

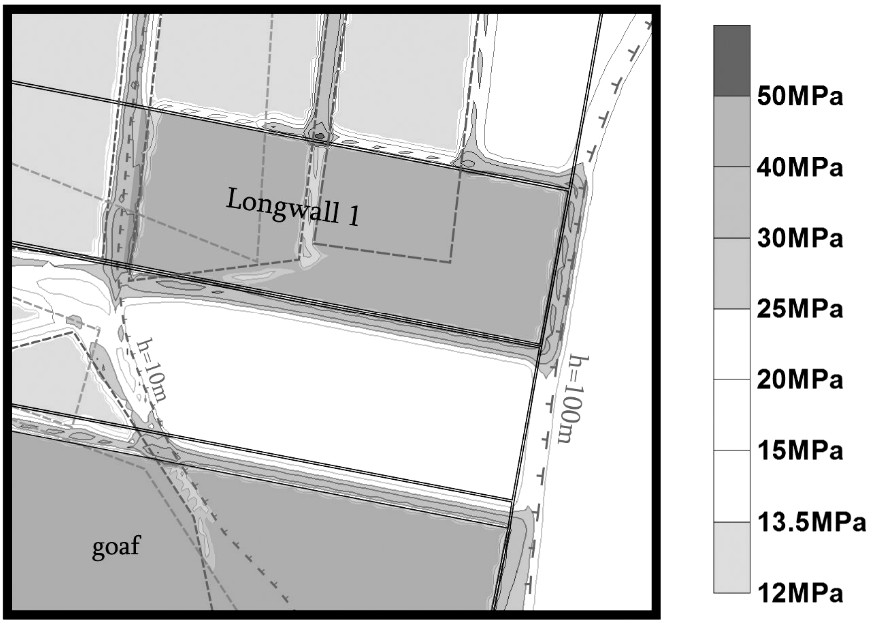


Fig. 2 Example of the vertical stress distribution on the seam at a depth of 600 m with fault impact zones (fault displacement amplitudes h = 10 m and h = 100m), the edges of the adjacent seams in overburden indicate by dashed line.

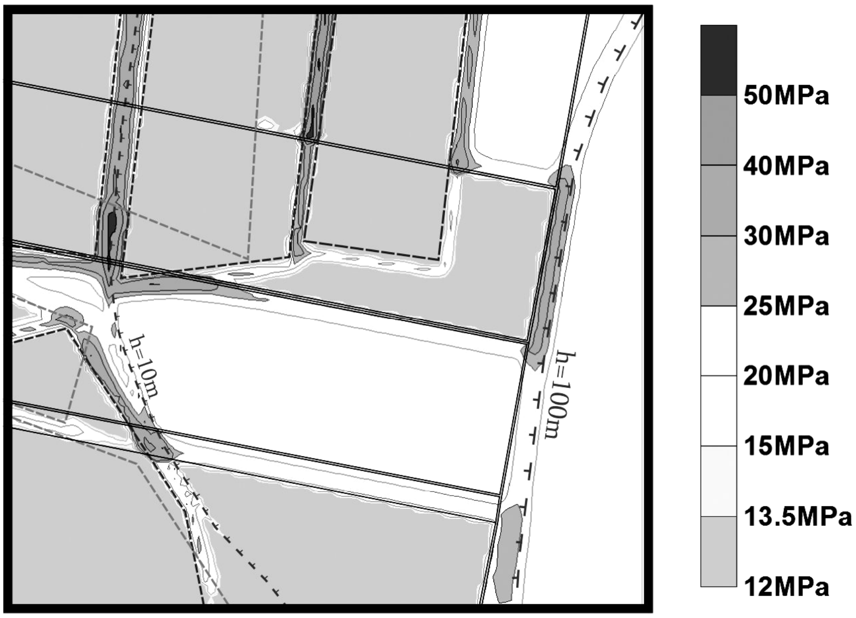


Fig. 3 Example of the vertical stress distribution at the horizon 15 m above the seam, exploited at a depth of 600 m.

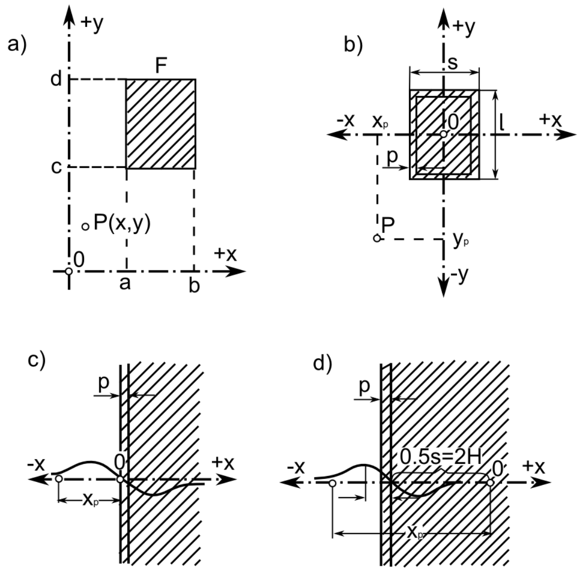


Fig. 4 Possibilities of the location of the computational point P and centre of x, y axes of the coordinate system, related to the mining panel, in which the point 0 is situated:
a) at any point within the panel,
b) above the panel,
c) above the edge of the half-plane of the panel,
d) above the mining panel at a distance of 0.5s≅2H.

The subsidence of any point of the surface (as shown in Fig. 5) is expressed by the formula (4):

$$w(a,g,H,\rho,x,y,p) = w_{\max} \cdot A_x \cdot A_y \tag{4}$$

where:

$$\begin{aligned} A_x &= \Theta(v_1) + \Theta(v_2) \\ A_y &= \Theta(u_1) + \Theta(u_2) \end{aligned} \tag{5}$$

and the dimensionless factors *v* and *u* are equal to:

$$\begin{aligned} v_1 &= \frac{-x + 0.5s - p}{\rho}; \qquad & v_2 &= \frac{x + 0.5s - p}{\rho} \\ u_1 &= \frac{-y + 0.5l - p}{\rho}; \qquad & u_2 &= \frac{y + 0.5l - p}{\rho} \end{aligned} \tag{6}$$

$\rho = 400k^{-1} \cdot H^{0.5}$ – dimension unit (in metres).

The results of calculations and their graphical representation suggest potential locations of occurrence for dynamic phenomena in the seam and the overlaying strong elastic layers. They are the basis for predicting the energy of the dynamic phenomena that would be expected during mining operations in areas of the largest impact of stress anomalies.

In situ researches conducted by the Central Mining Institute have demonstrated directed movement of separate parts of the rock mass in front

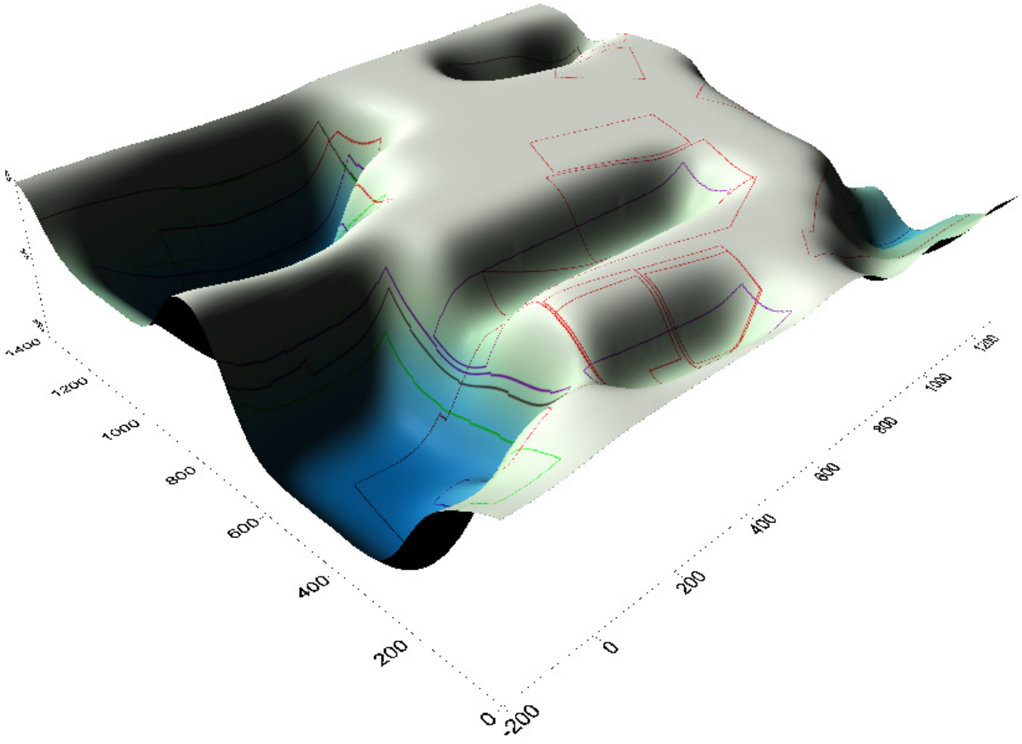


Fig. 5 Example of distribution of subsidence on the horizon of rock layer.

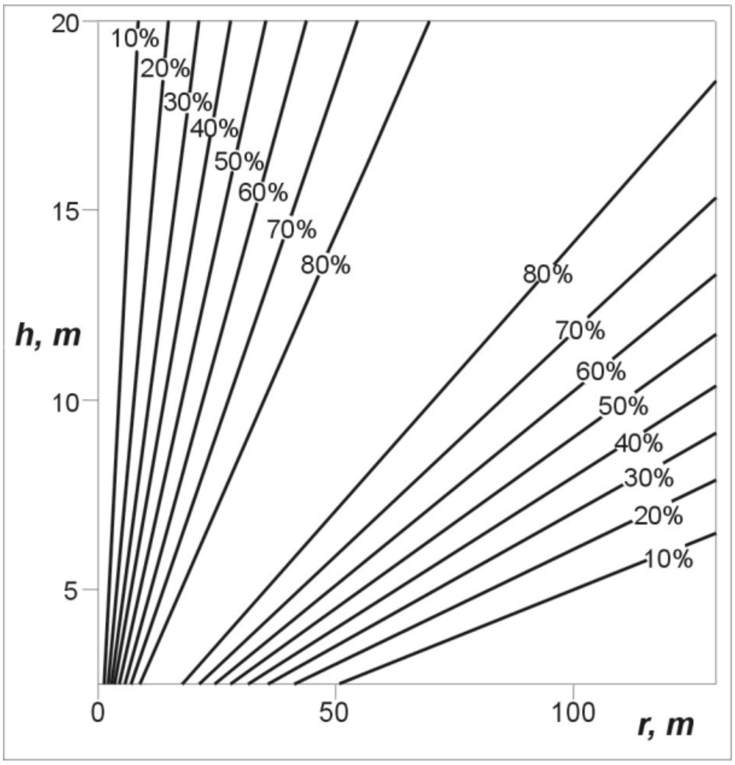


Fig. 6 The share of energy Φ_r emitted by the cracking layer within the total energy E_c, r – range of delaminating towards the longwall face, h – thickness of the elastic layer (Drzewiecki, 2004).

of the longwall face, accompanying the exploitation. The geometric forms of the rock mass where such rock mass movement and its size were observed result from the location of the planes of the operating division (Drzewiecki, 2000). The energy E_c of separated layers is the energy of distortion, being the product of the elasticity modulus E and strain ε_r (in terms of strain calculated from the curvatures of their deformation), or the gravitational energy increased by the energy resulting from the impact of past mining operations or geological disturbances.

The calculation requires consideration of a number of parameters, such as coal seam depth, longwall face speed, dimensions of the splitting rock mass in front of the exploitation (including the dimensions of the separated layers), their mechanical parameters and, finally, the level of stresses resulting from natural geological disturbances and mining.

Due to the mechanical property values of the separated layers, the process of layer division or cracking could be dynamic, and the process could be accompanied by seismic phenomena. Their energies Φ remain in proportion (equation 7) to the total accumulated energy E_c (Fig. 6)

$$\Phi = 37 \cdot S^{1.37} \cdot e^{-0.27 \cdot S} \tag{7}$$

where: Φ – lost energy, %
S – slenderness of layer.

The slenderness S of the separated layer is calculated for a given speed of exploitation υ (Fig. 6).

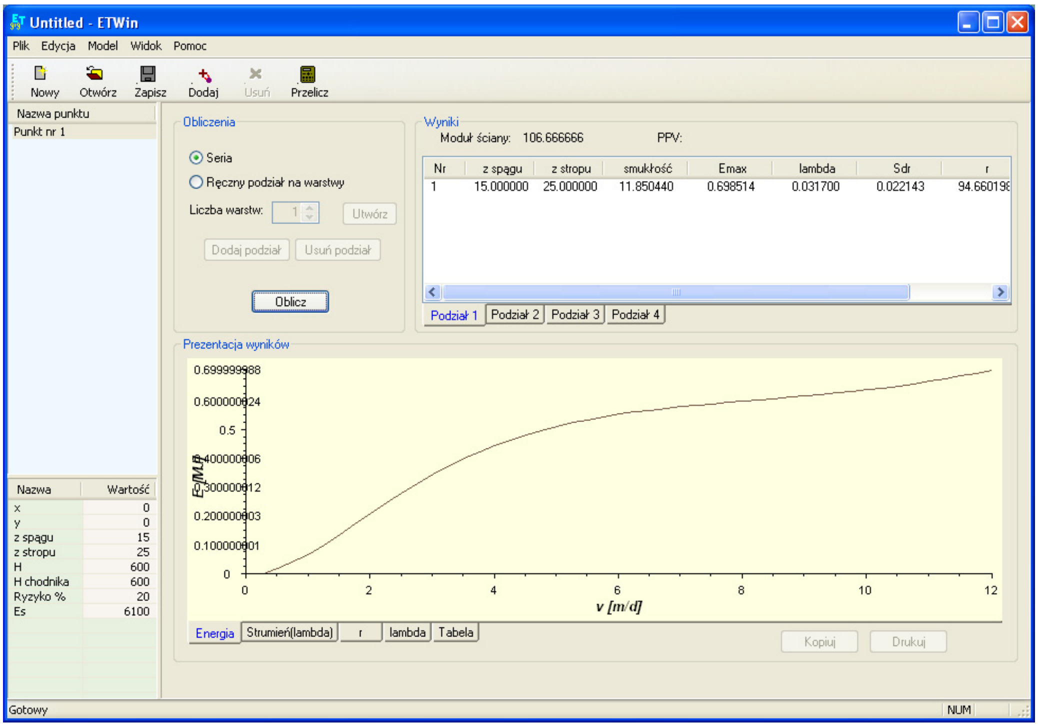
$$S = \frac{h}{r_{śr}} \tag{8}$$

where: h – thickness of separate layer, m
$r_{śr}$ – the average horizontal distance of cracks delaminating the rock mass in the direction of the longwall face, for a given face advance:

$$r_{śr} = 0.5(r_{roof} + r_{floor}) \tag{9}$$

The programme developed in the Central Mining Institute enables estimation of the amount of seismic energy that may be emitted by the released or cracking layer as a result of longwall mining. In addition, this programme allows estimation of the range of the destructive impact of the tremors, with a given probability of destruction of mine workings. The figures below presented show the interface of the programme with graphs of the seismic energy that may be released from a thick layer of sandstone (Fig. 7) and of sub-layers from which it has been divided (Fig. 8) for exploitation, with the face advancing by up to 12 m/day.

The location of layers and their geometrical dimensions determine the energy that may be accumulated for different values of face advance. For this reason, efforts should be made to divide them into several thinner parts in front of the longwall face. To optimize this process, it is necessary to determine



Nazwa punktu
Punkt nr 1

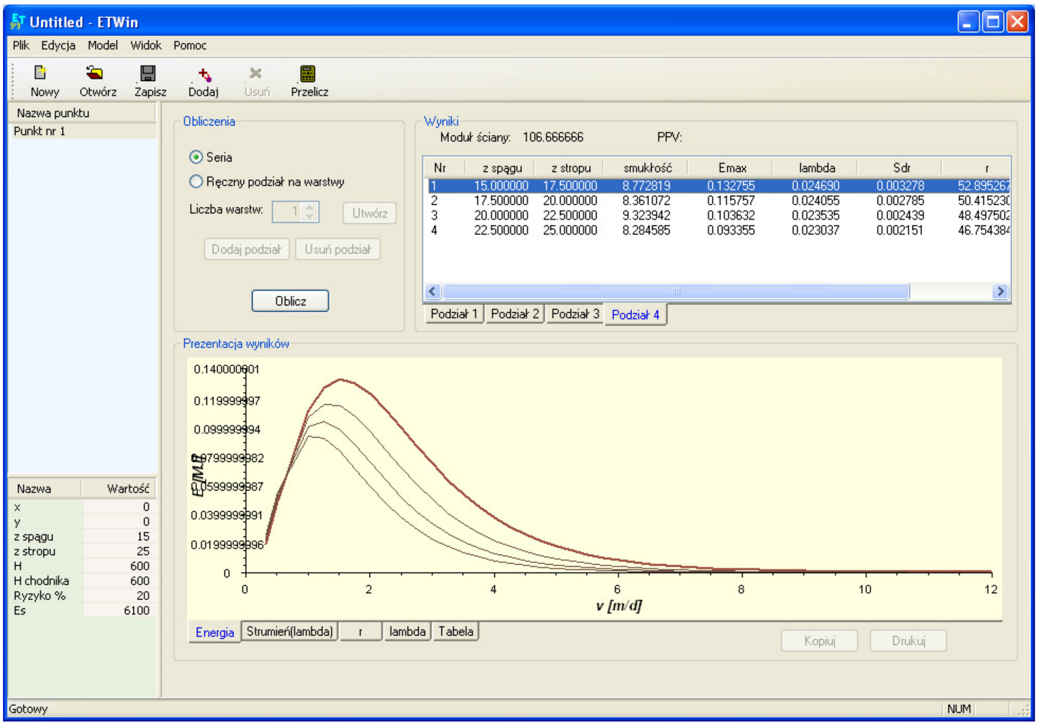
● Seria
○ Ręczny podział na warstwy
Liczba warstw: 1

Moduł ściany: 106.666666 PPV:

Nr	z spągu	z stropu	smukłość	Emax	lambda	Sdr	r
1	15.000000	25.000000	11.850440	0.698514	0.031700	0.022143	94.66019

Nazwa	Wartość
x	0
y	0
z spągu	15
z stropu	25
H	600
H chodnika	600
Ryzyko %	20
Es	6100

Fig. 7 Graph of seismic energy that can be released from a layer of sandstone as monolith for a face advance of up to 12 m/day.



Nazwa punktu
Punkt nr 1

● Seria
○ Ręczny podział na warstwy
Liczba warstw: 1

Moduł ściany: 106.666666 PPV:

Nr	z spągu	z stropu	smukłość	Emax	lambda	Sdr	r
1	15.000000	17.500000	8.772819	0.132755	0.024690	0.003278	52.89526
2	17.500000	20.000000	8.361072	0.115757	0.024055	0.002785	50.41523
3	20.000000	22.500000	9.323942	0.103632	0.023535	0.002439	48.49750
4	22.500000	25.000000	8.284585	0.093355	0.023037	0.002151	46.75438

Nazwa	Wartość
x	0
y	0
z spągu	15
z stropu	25
H	600
H chodnika	600
Ryzyko %	20
Es	6100

Fig. 8 Graph of seismic energy that can be released from a layer of sandstone split into four layers for a face advance of up to 12 m/day.

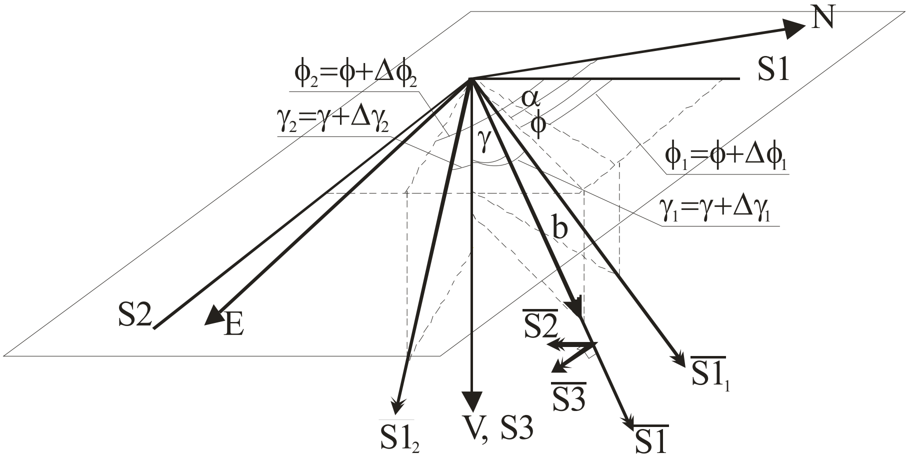


Fig. 9 Diagram of geometry and coordinate system for determining the parameters of boreholes (Makówka, 2006).

appropriately the principal stress directions for the large dimensions of the medium (Makówka and Drzewiecki, 2011).

The method for calculating the values of principal stresses in a fragment of the rock mass, with dimensions comparable to the range of deformation around an excavation (Makówka, 2006), is based on the solution of Ljunggren and Nordlund (1990). Determination of the main components of the state of stress is based on measuring pressure and flow rate during hydraulic fracturing in several boreholes of different spatial orientations. On the basis of the pressure and flow recorded, the opening and closing pressure of the initial fracture is determined during re-pumping of liquid. Re-closure pressure of the initial fracture corresponds to the ‘perpendicular-to-initial’ fracture plane component of the stress. A series of measurements made in a number of boreholes allows the values and orientations of the main components of stress to be calculated.

Figure 9 shows a three-axis coordinate system, S1, $S1_1$ and $S1_2$, for independent boreholes. During the fracturing of the rock mass, the following measurements were recorded: changes of pressure and flow at the moment of production fractures P_c, closure P_s, re-opening P_r and re-closing P'_s.

The values of the principal stress components S_H, S_h and S_V, and the angle between the horizontal projection of the borehole and the axis S1 along which the stress S_H acts, are calculated from equations for independent measurements in four boreholes. The system of equations to calculate the parameters is:

$$\begin{cases} P_s=\left(S_H\cos^2\phi+S_h\sin^2\phi\right)\sin^2\gamma+S_V\cos^2\gamma \\ P_{s1}=\left(S_H\cos^2(\phi+\Delta\phi_1)+S_h\sin^2(\phi+\Delta\phi_1)\right)\sin^2(\gamma+\Delta\gamma_1)+S_V\cos^2(\gamma+\Delta\gamma_1) \\ P_{s2}=\left(S_H\cos^2(\phi+\Delta\phi_2)+S_h\sin^2(\phi+\Delta\phi_2)\right)\sin^2(\gamma+\Delta\gamma_2)+S_V\cos^2(\gamma+\Delta\gamma_2) \\ P_{s3}=\left(S_H\cos^2(\phi+\Delta\phi_3)+S_h\sin^2(\phi+\Delta\phi_3)\right)\sin^2(\gamma+\Delta\gamma_3)+S_V\cos^2(\gamma+\Delta\gamma_3) \end{cases} \tag{10}$$

where: $\Delta\phi_1$, $\Delta\phi_2$, $\Delta\phi_3$ $\Delta\phi_1$, $\Delta\phi_2$, $\Delta\phi_3$ – horizontal angular deviation of boreholes 2, 3 and 4 in relation to the first borehole; $\Delta\gamma_1$, $\Delta\gamma_2$, $\Delta\gamma_3$ $\Delta\gamma_1$, $\Delta\gamma_2$, $\Delta\gamma_3$ – vertical angular deviation of boreholes 2, 3 and 4 in relation to the first borehole.

The assumption that the smallest horizontal stress acts along a direction perpendicular to the excavation simplifies and reduces the number of variables and necessary boreholes.

Execution of the presented analyses and measurements is necessary to optimize both passive and active rockburst prevention, for both planned and current mining operations. Discontinuities or cracks formed in the rock mass weaken it and reduce its ability to accumulate energy. The amount of energy accumulated depends on the thickness of the layers. For the safety of future mining operations, it is preferable to divide the thick layer thinner.

The possibility of applying a number of methods of calculation, measurements or computer programmes to predict future changes in the deformation and stress in a rock mass during mining operations, allows us to plan rock burst prevention more precisely.

4. SUMMARY

Rock burst and high-energy seismic events are random and therefore hard to predict in terms of space and time. They are usually the result of human activity that causes uncontrolled phenomena, destroying rock mass in the vicinity of the activity.

Recognition and estimation of parameters determining the level of rock burst hazard is crucial for safety of mining crews. Implementation of research aimed at understanding the causes of this threat, by direct measurement of principal stresses, changes in deformations of the rock mass and its potential displacement, are important in defining and describing the processes of mining in the specific deposit conditions.

In coal mines, where there are recorded the high seismic activity induced by mining operations, proper design of the technical parameters of the mining exploitation, taking into account the measurement results and analysis, can help to improve safety conditions. Taking the proposed methods into consideration, it should be considered possible to plan for a real mining situation using a set of preventative measures consisting of weakening the rock mass by a number of discontinuities. This can be achieved, for example, by the methods of active rock burst prevention such as directed hydro-fracturing (Drzewiecki and Kabiesz, 2008).

Subsequently, taking into account the role of the speed of exploitation in energy generation, the analytical methods presented in this paper indicate what a safe rate for mining operations should be from the point of view of seismic activity. Reasonable control of the face advance, which is one of the parameters determining the energy of seismic events, may contribute to the improvement of mining operations.

Controlling the velocity of the advance of the longwall face and tremor-prone layers by delamination methods allows the area in front of the longwall to be controlled, where otherwise dynamic phenomena may have a negative impact on excavations. This is particularly important in exploitation conditions in the vicinity of geological disturbances, or areas of impact at the edges of exploitation.

The proposed set of measurement and analysis methods contributes to the development of effective seismic and rock burst prevention, both passive and active: passive, by determining parts of the rock mass that are particularly exposed to the influence of strong seismic events; and active, consisting not only of the active execution of a series of discontinuities that weaken the rock mass, but also the development of individual metrics for a longwall face advance to minimize tremor energy.

It should be emphasized that the creation of discontinuities in rock mass of pre-selected volumes allows the locations of tremor sources to be "controlled", which is crucial for their relocation away from the active excavations.

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