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ORIGINAL PAPER

DETERMINATION OF THE VALUE OF THE ELASTIC MODULUS OF THE ROCK MASS E_{srm} DISTURBED BY A LONGWALL OPERATION

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ABSTRACT

This paper presents a method of determining the value of the elastic modulus of large-size piece of rock in the Bobrek mine. The basis of the analyses were relations between the mechanical and geometrical parameters of the rock mass in the environment coal seam 503, the intensity of its exploitation and its associated seismicity. The correct estimation of physico-mechanical and geometrical parameters of the rock mass is crucial for safety. As a result of changes in rock mass, due to the exploitation, some rock mass parameters change their value. The result of the analysis is a method of calculating the value of the elastic modulus E_s for large fragments of rock disturbance by panel 1 operation. The results of the analyses are presented in graphical form. The results of the analysis indicate that for the correct seismicity forecasts, induced by coal seam operation, it is necessary to calculate the elastic modulus layers for the in situ conditions, i.e. for areas in which there are registered strong seismic phenomena. The developed formulas can be used both for ad-hoc analysis and long-term forecasts of seismic events energy.

1. INTRODUCTION

In the Upper Silesia Coal Basin (USCB) conditions a total thickness of claystones, siltstones and sandstones, disturbed by longwall mining, can reach several tens of meters. Due to safety reasons their localization in connection to the mining operations (Stec and Drzewiecki, 2000; Dubiński and Mutke, 1996), the intensity of their disturbance (Drzewiecki, 1996; 2004) and the geometrical (Biliński, 1985) and mechanical parameters (Bukowska, 2005) which determine their ability to accumulate and release energy (Cabala et al., 2004) and seismic activity according to exploitation (Marcak and Mutke, 2013) are important. In this group of parameters, elasticity is of fundamental importance for proper prediction of the energy that layer accumulates as a result of deformation during mining exploitation, and their reduction by blasting methods (Koniček et al., 2013).

Taking into account the material and strength anisotropy of the rock mass, the mechanical parameters obtained from the small-sized samples, does not reflect the real mechanical properties of stratified rock mass.

The effect of size on unconfined compressive strength clearly indicates that the strength of the rock mass is affected by size and density of fissures and cracks (Bieniawski and Heerden, 1975). Considering the area disturbed by mining operations and the influence of density and size of fissures and cracks to assess its mechanical properties, the Geological Strength Index GSI must be taken into account (Hoek and Brown 1997). This parameter is presented in the graph in Goodman (1989), after Bieniawski's and Van Heerden's (1975), and it allows estimate the strength of the rock mass *in situ*. Each of these methods, unfortunately, does not include the real instantaneous strength of the rocks that they have under confining pressure.

Mining operations result in deformation of coal seam and host rocks. This process is time-varying due to both the intensity of mining and rheology. The mined-out and nearby volumes of rock are characterized by strong gradient of stress and time-dependant elastic properties. These points to the need to estimate the mechanical parameters of stratified rock mass, which take into account the changes in the amount of the confining pressure.

Such information can be obtained from the analysis of the propagation velocity of seismic waves in the rock of variable stress gradient - in situ measurements. Areas of heterogeneous stress are indicated gradients *P*-wave velocity (Mutke et al., 2009), for these areas the instantaneous dynamic elasticity parameter which combine a change of medium density as a function of velocity *P*/*S*, can be estimated (Barton, 2007). The instantaneous dynamic elasticity of the rock mass parameter can also be determined basing on the registration of seismic events induced by mining activities, without in situ measurements. The basis of this method is developed in the Central Mining Institute which predicts seismic energy that can emit bursting in elastic bed violated by exploitation, expressed in meter per day (Drzewiecki, 2004).

Table 1 Rock mass parameters around the seam 503.

Material	Density volume	Internal friction angle	Cohesion	Young modulus	Poisson ratio	Tensile strength	Compressive strength
	ρ	φ	c	E	ν	R_r	R_c
	kg/m^3	^{0}	MPa	Gpa	-	MPa	MPa
Sandy shale	2690	25.0	7.2	11.2	0.24	2.1	22.5
Clay shale	2600	24.0	6.0	10.0	0.25	1.9	19.2
Sandstone	2510	25.3	11.3	18.0	0.27	3.3	35.7
Coal 503	1290	24.0	3.3	3.6	0.24	0.5	15.8

Having a set of seismic events recorded from the area of mining activity - their location and energy, for that area the value of the modulus of elasticity E_s can be estimated. It is realized by searching the value of the modulus of elasticity for which the condition of the comparable energy values predicted by seismic methods GIG with the energies of shock registered is fulfilled. It should be emphasized that the new registered seismic shock changes an instantaneous value of the module. The method uses the actual seismic energies, to estimate the elasticity of the rock fragment disturbances by mining operations, which makes it closer to geophysical methods for determining the dynamic modulus by *in situ* measurements.

2. THE BASIC INFORMATION

Coal seams in the area under consideration are located at a depth of 600 m to 850 m. Disturbance of the overlying layers of the exploited seam 503 in the area covering three longwall panels should be considered taking into account the former extraction in adjacent seams. In the area of the panels 1 to 3, the total thickness of extraction exceeds 25 meters. Such intensive exploitation repeatedly disturbed the initial structure of rock mass, i.e. the continuity of layers over abandoned mining areas both, alongside and transverse to the planes of sedimentation.

The lithological system of this region is characterized by the predominance of rocks with high strength: sandstone and mudstone capable of storing are elastic energy. Figure 1 and Table 1 below present the basic geometric and physico-mechanical parameters of beds in the vicinity of the seam 503 and Table 2 presents geometric parameters of coal seams located above and under close to extraction coal seam 503 which gobs influence the stress distribution in the sandstones located above 503 coal seams.

During the coal seam 503 exploitation registered high-energy seismic events exceeding 10^5 J.

The daily face advance rate for panels 1, 2 and 3 and the total energy of high seismic events are shown in Table 3 and the time of their registration in Figure 2.

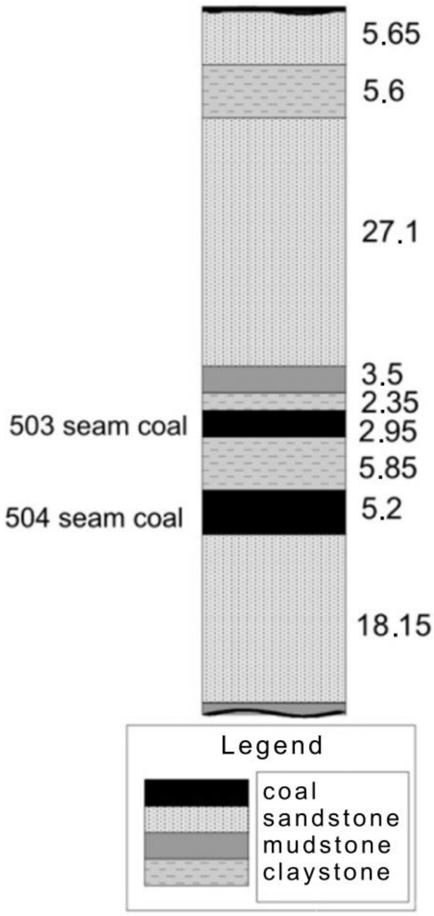


Fig. 1 Slice of geological borehole.

Table 2 Coal seams extracted close to the coal seam 503.

Coal seam	Thickness of exploitation [m]	Depth [m]	Exploitation period [year]
419	1.8-2.1	710	1975-1977
501	3.0	720	1969, 1978
503	**3.0-3.45**	**720**	**2006-2011**
504	2.0	740	2010 – 2011

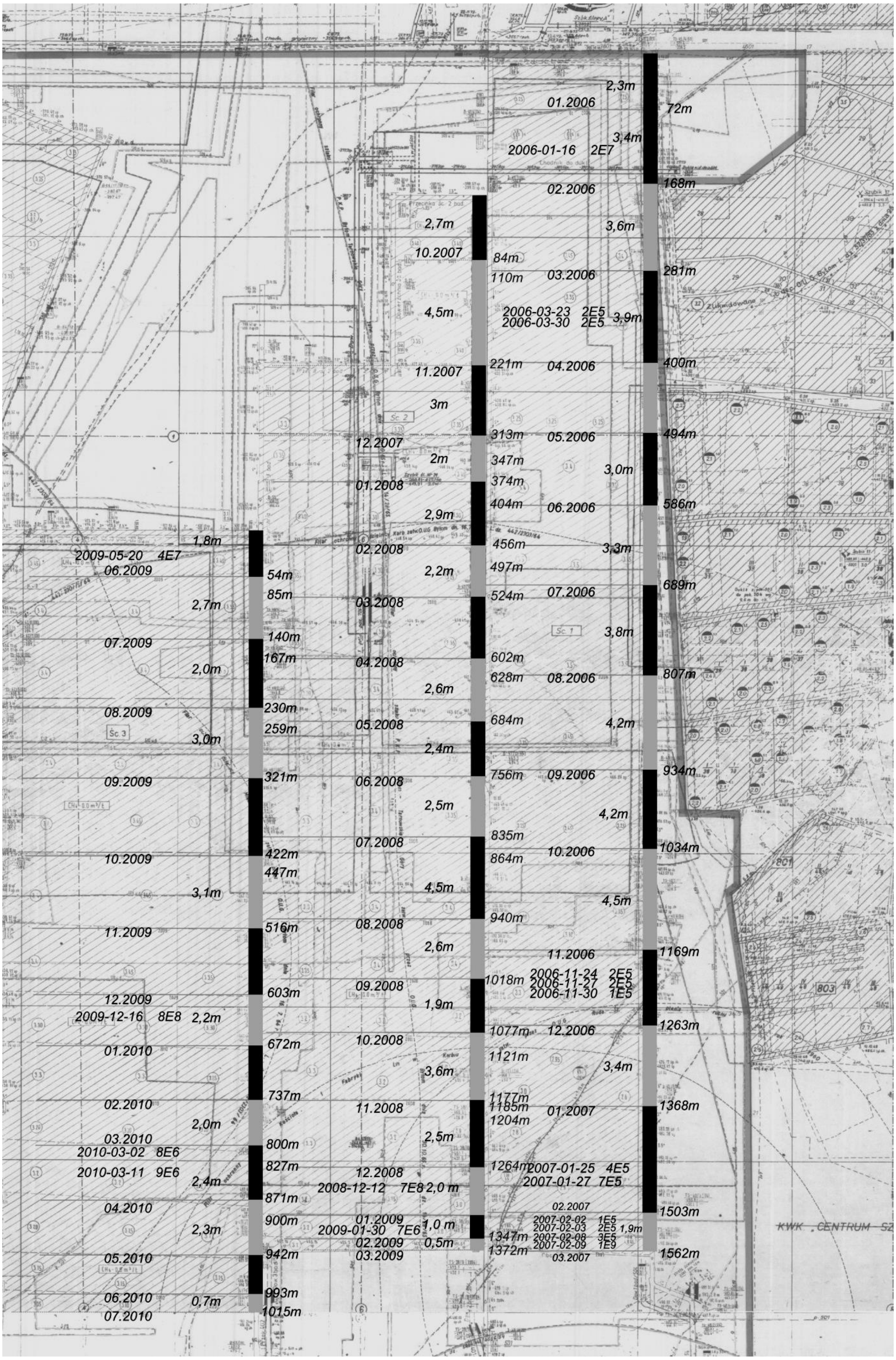


Fig. 2 The fragment of map section of the coal seam 503 with marked average daily face advance of 1, 2 and 3 panel and marked date of high energy seismic events.

Table 3 The daily face advance rate panels 1, 2 and 3 and the high-energy seismic events exceeding 10^5 J.

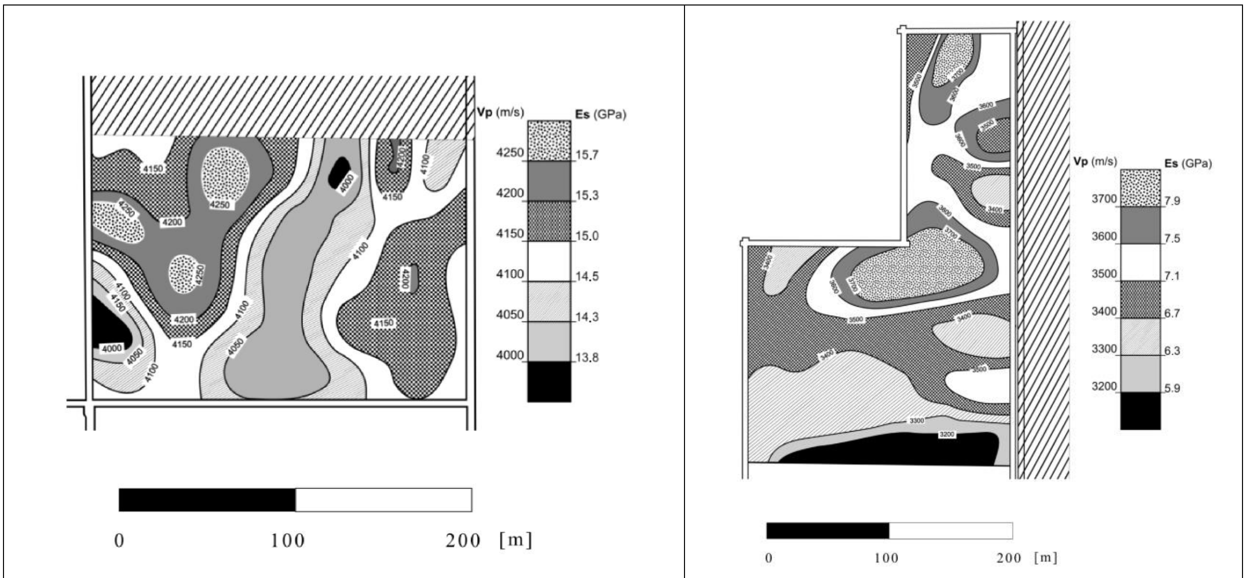
Date of seismic events	average daily face advance / seismic events energy
	m/J
16.01.2006 start-up panel	3.4 /2x10^7
23.03.2006	3.9 /2x10^5
30.03.2006	3.9 //2x10^5
24.11.2006	3 /2x10^5
27.11.2006	3 /2x10^5
30.11.2006	3 /1x10^5
25.11.2007	4.8 /4x10^5
27.01.2007	4.8 /7x10^5
2.02.2007	1.9 /1x10^5
3.02.2007	1.9 /2x10^5
8.02.2007	1.9 /3x10^5
9.02.2007 regional seismic event	1.9 /1x10^9
12.12.2008 regional seismic event	2 /7x10^8
30.01.2009	1 /7x10^6
20.05.2009 start-up panel	1.8 /4x10^7
15.12.2009 regional seismic event	2.2 /8x10^8
2.03.2010	2.4 /8x10^6
11.03.2010	3 /9x10^6

3. DETERMINATION OF THE VALUE OF THE ELASTIC MODULUS E_{DYN} OF THE ROCK MASS DISTURBED BY LONGWALL OPERATION ON THE BASIS OF *IN SITU* MEASUREMENTS

The seismic profiling technique was used to locate the areas of the increased stress ahead of the longwall face. The measurement is based on the principles of the algebraic tomographic reconstruction of the velocity field (Dubiński, 1986). The calculation techniques based on iterative calculations to solve the system of equations to minimize differences between the measured and the theoretical values of the input parameters, such as the time course or amplitude decrease from inducing point-to-point delivery.

Energy stress concentration zone in the roof is determined by the two-dimensional velocity distributions of the seismic waves distribution, which are generated between the mining excavations and tomographic reconstruction of the velocity field. The measured relative quantitative change in velocity of seismic *P* wave propagating in the coal seam and the appropriate increments, p_z^o vertical stress component has been developed which allows to calculate specific seismic anomalies $A_n = v/v_p^o$, registered at the depth *H*, (where $p_z = p_z^o + p$).

The results of algebraic reconstruction of the velocity field of seismic wave propagation and attenuation of the fragment of the coal seam 503 is the form of the maps of the baseline velocity distribution (m / s) of the longitudinal seismic wave in the rock mass fragment, for a given situation of the panel 1 and 2 extraction.



Panel 1	Panel 2

Fig. 3 Distribution of P-wave velocity image (m/s) and the dynamic modulus of elasticity E_{dyn} estimated by geophysical measurements.

Assuming that ρ = 2600kg / m^3 and $V_s = \frac{V_p}{\sqrt{3}}$ and using the equation (Barton, 2007)

$$E_{dyn} = \rho \cdot V_s^2 \frac{3 \cdot \left(\frac{V_p}{V_s}\right)^2 - 4}{\left(\frac{V_p}{V_s}\right)^2 - 1} \quad (1)$$

the dynamic Young's modules E_{dyn} was calculated for fragments of the longwall panel 1 and 2 of the coal seam 503. The graphic image of the results of the measurements and calculations are shown in Figure 3.

The dependence of the dynamic elastic modulus as a function of the P-wave velocity is similar to the exponential function, the graph and detailed form of which is shown in Figure 4.

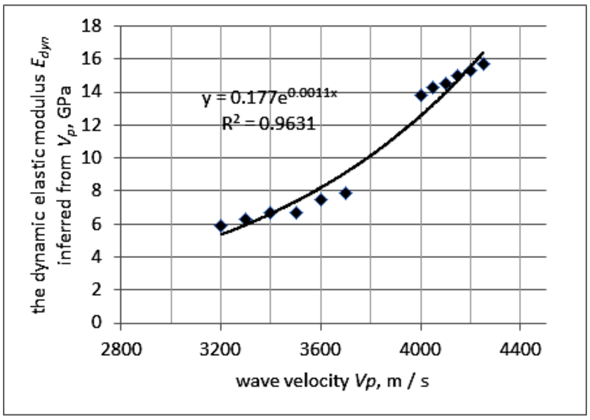


Fig. 4 Graph function of the value of the elastic modulus of the rock mass E_{dyn}, GPa and P-wave tomographic velocity (m/s).

4. DETERMINATION OF THE VALUE OF THE ELASTIC MODULUS OF THE LARGE-SIZE FRAGMENT OF ROCK MASS E_{SWG} DISTURBED BY A LONGWALL OPERATION ON THE BASIS OF SEISMIC ENERGY EVENTS, GIG METHOD

THE STRESS DISTRIBUTION ON THE SANDSTONE LEVEL CLOSE 503 COAL SEAM

For the calculation of the value of the stress parameter SIGMAZ computer program, developed in the Central Mining Institute, was used to calculate and assess the impact of excavations edges for forecasting stress fields distributions in the rock mass (Kabiesz and Makówka, 2009). The program uses a quantitative measure of pressure growth, defined on the basis of the results of *in situ* studies of seismic profiling and scanning, (Table 4). This research was carried out for space-time distributions of anomalies of the velocity of longitudinal seismic wave in the seam connected with the existence of the exploitation edge with caving on backfilling exploitation (Dubiński, 1989).

For the seam 503 depth *H* of about 700 m, empirical equations of dependences on the relative growth of propagation of longitudinal seismic waves velocity in the coal seam with the relative pressure increases describe the empirical equations (2) and the diagram in Figure 5,

$$\Delta V = 43.36 \Delta p^{0.725} \quad (2)$$

$$\frac{\Delta v}{v_p^o} = 0.738 \left(\frac{\Delta p}{p_z^o}\right)^{0.692} \quad (3)$$

where:

ΔV - longitudinal seismic waves propagation in the coal seam in stress area, m/s

$v_p{}^o$ - longitudinal seismic waves propagation in the coal seam, m/s

Δp - pressure growth in stress area, MPa

$p_z{}^o$ - pressure growth, MPa.

The quantitative measure of pressure growth for depth interval *H* from 700 ÷ 900 m, forming the basis for their calculations and their graphical form are presented (Dubiński, 1989) in Table 4. It should be emphasized that the program of forecasting stress distributions in the rock mass developed in the Central Mining Institute makes it possible to use the results of direct seismic measurements, while the total calculated value of the stress is the sum of the gravitational stress and its local pressure growth.

The calculation results of stress distribution at the layer of sandstone with a thickness of 27 m and the distance of 6m from the roof of the seam 503 in the area of the designed panels 1, 2, 3 are shown in Figure 6.

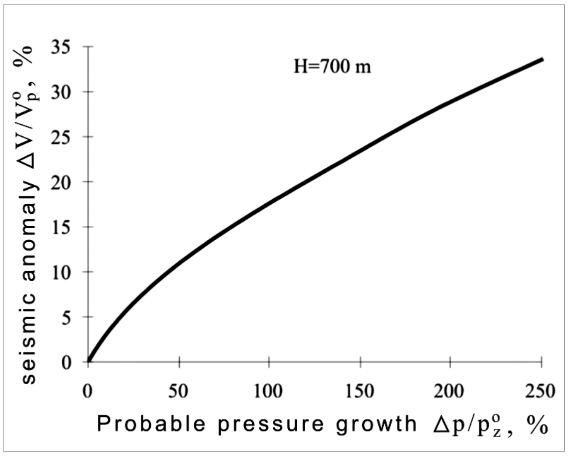


Fig. 5 The dependence of the relative growth in velocity of longitudinal seismic wave propagation in coal seams at a depth of 700 m, with the relative pressure increases, (Dubiński, 1989).

Table 4 Seismic scale of the pressure increase assessment in the conditions of the USCB (H=700÷900 m).

Level of stress increase	Characteristics of pressure growth	Seismic anomaly v/v_{p}^{o}; [%]	Probable pressure growth p/p_{z}^{o}; [%]
0	none	below 5	below 20
1	weak	5 ÷ 10	20 ÷ 60
2	average	15 ÷ 25	60 ÷ 140
3	large	above 25	above 140

Fig. 6 Forecast of stress distribution at the level of sandstone with the thickness of 27m deposited 6m above the seam 503 in the area of the designed panels 1, 2, 3. (including the gobs in coal seam 419, 501, 504).

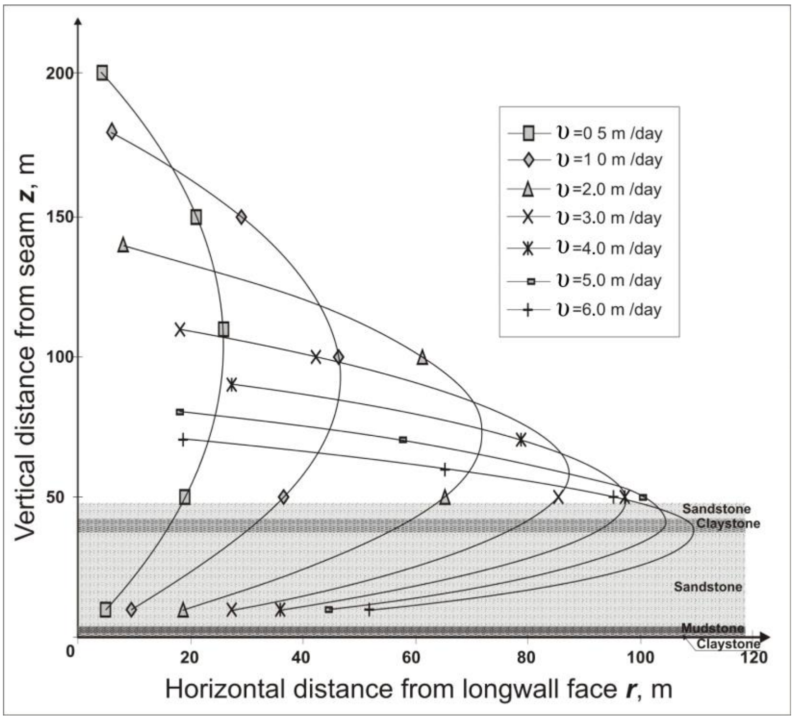


Fig. 7 Plot of the parabolas outlining the rock mass regions in which bed separation for various face advance rate takes place (Drzewiecki, 1997).

For the calculation of the portion of total energy *E* % radiated, GIG method was used. The results of *in situ* tests of rock deformation as well as geophysical and laboratory tests allowed to develop an algorithm for calculating the energy that accompanies the process of deformation and destruction of the elastic layers disturbed by mining activities it also allowed to determine the relationship which link the energy accumulated in the elastic bed with:

- curvature of the layer being deformed,
- the size of the area in which the energy is stored,
- dimensions of beds separated in the process of exploitation-induced rock mass division,
- the scope of the area ahead of the longwall front, where energy is collected,
- test results of mechanical properties of tremor-prone layers.

The part of the rock mass extended towards the line of the front exploitation, in which the storage of the energy induced by the carried out exploitation takes place, is dependent on the longwall advance and it is determined by the formulas developed on the basis of in situ measurements (Drzewiecki, 1997):

$$r = \upsilon \cdot z + c(\upsilon) \cdot z^2 \tag{4}$$

where:

r – horizontal distance of the place of delamination initiation from the longwall front, m,

z – vertical distance of formed discontinuity from the roof of the seam, m,

υ - average daily front advance calculated in the period of 10 calendar days, m/day,

$c(v)$ – parameter dependent on the longwall front advance expressed by the function:

$$c = -0.0017(\upsilon^2 + 2 \cdot \upsilon + 0.1588) \tag{5}$$

whose diagrams in a form of a series of parabolas for a variable υ >0 are presented in Figure 7.

Presented in Figure 7, parabolas indicate the initiation scope of the rock mass division ahead of the longwall front for different average daily advances of the longwall front - v. This area alters with the change in intensity of mining activity. Due to the physical and mechanical properties of the rock mass the changes within the extent of this area will have a dynamic character (steplike), and this process will be accompanied by seismic effects, with an energy Φ_s equal from 0.1 % to 2 % the energy Φ lost by fractures the beds - shear failure mechanism. The energy Φ is determined by the relationship in 6 relative to the total energy E accumulated by the beds within the active volume of the rock mass (relationship developed on the basis of numerical modeling (Drzewiecki, 2004)) (Fig.8). Energy E of the beds is the energy of their deformation estimated as gravitational energy increased by the energy arising from the impact of former mining or geological disturbances. For calculation of this energy GIG

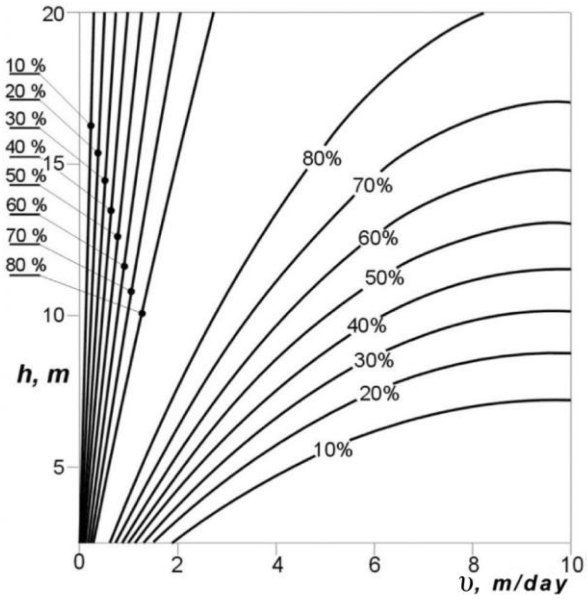


Fig. 8 Share of energy emitted through fracturing layer above the seam in the total energy *E*; *υ* – average daily front advance, m/day; *h* – layer thickness, m.

Table 5 Summary of the calculated values of the modulus of elasticity for each registered tremor and its average value for the whole panel.

Date of seismic events	average daily front advance υ / seismic events energy Φ_s	calculated $\mathbf{E_{swg}}$
	m/J	***MPa***
23.03.2006	3.9 /2x10^5	**5700**
30.03.2006	3.9 /2x10^5	**5700**
24.11.2006	3 /2x10^5	**6000**
27.11.2006	3 /2x10^5	**6000**
30.11.2006	3 /1x10^5	**5600**
25.11.2007	4.8 /4x10^5	**6000**
27.01.2007	4.8 /7x10^5	**6400**
2.02.2007	1.9 /1x10^5	**6200**
3.02.2007	1.9 /2x10^5	**6600**
8.02.2007	1.9 /3x10^5	**6800**
30.01.2009	1 /7x10^6	**12000**
2.03.2010	2.4 /8x10^6	**8500**
11.03.2010	3 /9x10^6	**8700**
		Mean: 6900

where: $\upsilon\ /\Phi_s$ - average daily advance of the panel, m/registered seismic energy, J.

program use the stress distribution at the level of sandstone (Fig. 6).

$$\Phi = 37 \cdot S^{1,37} \cdot e^{-0,27 \cdot S} \qquad (6)$$

where:

Φ - lost energy, %

S – slenderness of the layer,

Slenderness S of a layer is calculated for the adopted exploitation speed .

$$S = \frac{h}{r_m} \qquad (7)$$

where:

h – thickness of the layer, m,

r_m – the average horizontal dimensions of beds separated in the process of exploitation-induced rock mass division, for the adopted exploitation speed v, m.

$$r_m = 0.5(r_{roof} + r_{floor})$$

On the basis of preliminary calculations relating to the region of panels 1, 2 and 3, using the registered seismic tremors of energy greater than 10^5J during the longwall panels run (Table 3).

From this set of seismic data the seismic events of focal mechanism in which shear processes dominated – normal slip focal type were selected for the further analysis, the source of which were the sandstones located above the operated coal seam 503 (Table 5). These seismic events identified by the mine's staff using MULTILOK software exhibit uncertainties in the epicentral coordinates of the order of ±50 m, 24 vertical Wilmore seismometers were located at the level of coal seam.

Elasticity modulus is generally determined on the basis of laboratory tests, in situ measurements or through analysis of the seismic velocity of the medium (dynamic modulus). This parameter can be also determined by seismic data using the program for assessment of seismic energy value developed in GIG.

In this program, one of the main parameters that determine the predicted seismic energy value is the modulus of elasticity Es of the layer which is the source of seismic events. The proposed method of estimating this parameter is multiple introduction of its value into the calculation program, until the calculated energy of the seismic events is equal to the energy of recorded seismic events. In this sense the modulus, as it is the case with the analysis of seismic wave velocity, is a dynamic modulus and, therefore, will determine the instantaneous local mechanical property of a large fragment of the rock mass. The energy which is accumulated in this rock mass fragment is variable and depends on the changing mining condition.

The destruction of parts of the layers due to mine operation, is accompanied by seismic activity. When the seismic event occurs the accumulated energy of the layer in this area decreases, while in other parts of the layer increases. In this case, the decomposition of the instantaneous parameter of elasticity in the area of

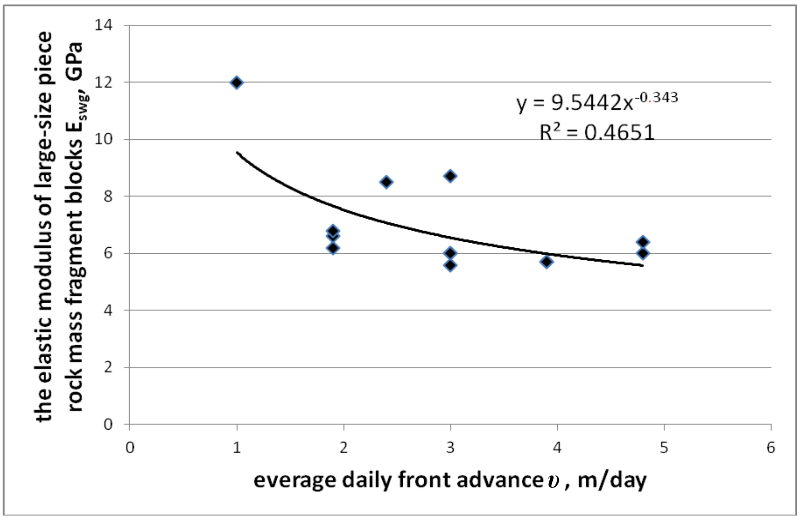


Fig. 9 The graph function of large-size rock blocks the elastic modulus E_{swg} and average daily front advance ***υ*** based on seismic energy events.

the infringed mining is uneven. Thus, even for the same operating speed of the coal face the events with different levels of seismic energy are recorded and, therefore, the instantaneous value of the parameter of elasticity will also be different.

The proposed method of estimating the elastic modulus was to find its value using the calculation program where the condition of equality between energy of recorded seismic event and theoretically calculated energy of this tremor is assumed. Estimating E_{swg} value of Young's modulus of the large-size elastic layer located in the rock mass disturbed by mining operation is conducted each time from the recorded seismic energy of the events during mining operation. The assumed geomechanical model shows that the efficiency of seismic source is 2 % of the energy lost by fracturing of the beds, thus calculated E_{swg} parameter is the value related to this geomechanical model.

As a result of calculation, the E_{swg} value of Young's modulus of the elastic large-size layer located in the rock mass disturbed by mining operation was estimated at 6900MPa. It is a macroscopic form characterizing the elasticity of the large-size layer for in situ conditions.

The graph function of the value of the elastic modulus bed located in the rock mass E_{swg}, GPa and average daily front advance *υ* based on seismic energy events is presented in Figure 9.

DISCUSSION AND CONCLUSION

The correct estimation of physical and mechanical parameters of the rocks mass is of decisive importance for the protection of the staff and machinery exposed to the effects of the dynamic phenomena occurring in the rock mass. Therefore it is important that this type of value parameters correspond to the present state of stress, because its changes with time as a result of the current mining operations. This analysis indicates the possibility of minimizing the error of estimating the elastic layers of the rock mass building. As a result of the analysis the methodology to calculate the elastic modulus of rock mass E_{swg} for large-size rock mass fragments disturbed by mining operation was developed. The formula can be applied for both ad-hoc analysis and long-term prognostic value of seismic energy forecasts of the generated rock burst operation.

The use of the proposed method for calculating the value of Young's modulus E_{swg} for large-size rock mass fragments disturbed by longwall operation, according to the authors, improves the quality of predictive analysis, and consequently improves the safety of the staff in terms of mining and reduces the rock burst hazard.

- In the carboniferous rock mass geological conditions are bad. For the safety, localization of the mining operations intensity and the geometrical and mechanical parameters of elastic layers and their ability to accumulate and release energy are important. In this parameter groups, elasticity is of fundamental importance for proper prediction of the energy.
- Considering anisotropy of strength and structure of the rock mass, using the mechanical parameters calculated from small-sized samples, the real mechanical properties of stratified rock mass are not reflected. Each of the methods determines the mechanical properties, geological strength index GSI, but unfortunately does not include the real temporary strength of the rocks that they have under confining pressure.
- The elasticity of rock will correspond to the instantaneous situation of mining. The parameter of the rock mass which corresponds to this

situation is "instantaneous dynamic elasticity" E_{swg} i.e it characterizes large-size rock mass fragments disturbed by mining extraction for *in situ* conditions.

- The "instantaneous dynamic elasticity" of the large-size rock mass parameter can also be determined basing on the registration of seismic events induced by mining activities without in situ measurements. This rock mass parameter can be used for the prediction of seismic energy events induced by mining activities for new adjacent panels.
- The basis of this method, developed in the Central Mining Institute, is prediction of seismic energy that can influence bursting resilient layer violated by exploitation, expressed in meter per day. Average daily front advance affects the amount of energy accumulated in rock mass, thus changing the intensity of exploitation can decide on the amount of seismic energy.

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