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THE METHOD OF ASSESSING ROCK BURSTING HAZARD IN MINING

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Abstract:
The article discusses a concept of forecasting accident risk during longwall extraction in crump-risk conditions. In Polish mines rock burst hazard can be described as high compared to other mines around the world. It's related to increase of depth of longwall field operation, preparation works, including drilling of mine face pavements which leads to systematic deterioration of geological and mining conditions. Depletion of coal is also the reason why mines operate in high mining tremor risk conditions. Mines more and more often operate in decks, where there is large number of edges and remains of older decks. Rocks bursts still remain one of the most dangerous natural hazards and therefore are fundamental problem and have the greatest impact on safety in mining industry. The proposed method for forecasting accidents and losses in people and goods can contribute to improvement of work organization methods and mine safety management system.

Key words: *ruck burst hazard, work organization methods*

INTRODUCTION

Rock bursting in Polish coal mining occur mainly in north and central limb of Upper Silesian Coal Basin main anticline. Primarily they are related to operation of decks of anticline group (500), lying between thick and strong rock layers [1]. In the last 10 years there was a significant decrease in number of rock bursts in mines counted among endangered by rock burst hazard that isn't the result of giving up the operation in high risk conditions. It is the result of proper risk assessment, therefore, it's also a way of risk reduction. As the technology develops, the number of rock bursts in coal mines decreased from 506 in 1949 to 2 between 1996 and 2000. On the other hand, according to statistical analysis, between 1949 and 2010 there were on average 64 rock bursts per annum. Since 2000 in accordance to records defining place and conditions of rock bursts that occurred between 2000 and 2010 it can be said, that these events were accompanied by rock mass tremors that had energy of 105-108 J. Generated seismic activity is undoubtedly related to operation of deck remains, in particular with concentration of mine working in areas of operation edge influence [2]. It's evidenced by the fact that with fixed decline tendency of mining operation output fallen from 102 mln tons in 2001 to 82 mln tons in 2010 and approximate in that time, number of rock bursts, 1-5 every year, there was significant seismic activity generated by rock mass. Because of that, analysis of rock burst hazard conditions is still a difficult task and requires an individual approach. It's a result of increased pavement vulnerability to dynamic effects of seismic activity that has its source in pavement surrounding and is potentially affecting its workers even further [3].

DESIGNATION OF SAFETY ZONE

Designation of safety zone between longwall mining front and earlier operation edge with taking into account older pavement working applies to specific mining cases often occurring during mine working. These are the events where active longwall front is getting closer to parallel (or almost parallel) pavement working, that is not affected by older workings, as well as the workings or edges in the above or underlying deck [4, 5, 6, 7, 8]. Example of such situation is presented in Fig. 1, longwall operation can be started in Miechowice mine on 113 wall in 510 deck which is one of class III rock burst hazard decks. Operation has been performed eastward, by contrast in 418 deck with no rock burst hazard, operation has been started on the longwall 37 towards west [10].

Simultaneous operation in decks lying upon each other is permissible and possible only when vertical distance between decks is greater than 200 m, which has been fulfilled in case of longwall 113. Vertical distance between discussed decks was about 250 m while Marcel's quoted article "General situation of mining before start of the longwall 113" became an auxiliary material used for determination of operation conditions of mines that are similar mining situation as e.g. Rydułtowy-Anna [10, 12].

Operation performed like that leads to concentration of stress. As the result of that, when the coal strength I exceeded, rocks can move into working site in form of either rock burst or cave in. The effects of exceeding coal strength can be seen on stope as well as longwall (e.g. Rock burst in KWK Rydułtowy-Anna march 2010 [12]). This article is an example of possible countermeasures that can be taken to protect mining crews from the effects of undermining decks on one hand and on the other hand from the hazard of rock bursting. A method has been developed to increase miner's safety that is based on designation of so called critical zone width while longwall face is closing in to pavement and older workings. This is a method that helps prediction of hazardous events.

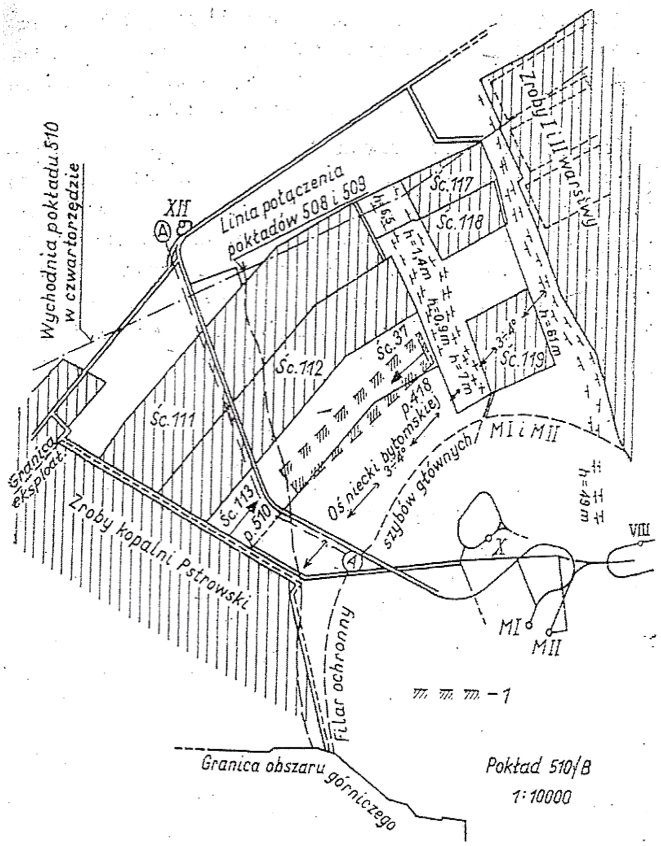

Fig. 1 General situation of mining before start of the longwall 113
Source: [10].

To solve this problem rock mass has been treated as linear-elastic, homogeneous and isotropic medium in which at certain H depth there was an operating deck that was 2a wide. The part of the rock mass lying above the pavement has been used while solving this problem, taking the midpoint of pavement width as the starting point of orthogonal coordinate system. It was also taken into account that a significant distribution of stress in the area between operating front and pavement working and in the area between pavement and older workings, is caused by: stress coming from operating longwall front, stress caused by older workings and pavement as well as natural rock stress – γH [4, 5].

CRITICAL ZONE DESIGNATION ALGORITHM [6]

Algorithm used for designation of critical zone was created by dr hab. Stanisław Krzemień in 1990. Calculative scheme is composed of subsequent stages:

Stage 1. Designation of fracture zone width near older workings (l_o) and fracture zone width on both side of the pavement. Fracture zones have been designated from the formula:

$$\left|\sum \Delta|x|\right| = \frac{\Pi k}{2} \qquad (1)$$

where:
$|\sum\Delta|x||$ – fracture zone,
l_o – fracture zone near older workings width,
x – horizontal coordinate measured from operation starting point,
k – resistance coefficient,
Equation:

$$\frac{\delta\phi(\alpha z)}{\delta z} = \left[B(1-|\alpha|z)-|\alpha|A\right]e^{-|\alpha|z}$$

$$\frac{\delta^2\phi(\alpha_1 z)}{\delta z^2} = \left[-2B|\alpha| + |A+Bz|\alpha^2\right]e^{-|\alpha|z}$$

$$\frac{\delta^2\phi(\alpha_1 z)}{\delta z^2} = \left[3\alpha^2 B - A|\alpha 2 - zB|\alpha^2\right]e^{-|\alpha|z} \qquad (2)$$

$$\frac{\delta^4\phi(\alpha_1 z)}{\delta z^4} = \left[-4B\left|\alpha^3\right| + |A+Bz|\alpha^4\right]e^{-|\alpha|z}$$

where:
z – Vertical dislocation
A, B – model parameters
α – deck inclination angle
δφ – normal vertical stress,

Has been calculated numerically using successive approximation method because of fracture zone width, which according to accepted spatial model of mine workings relay on coordinate of current x.

In equation (2) normal stress in vertical and horizontal direction have been designated as $\delta_z(x, z)$ and $\delta_x(x, z)$. Formula has been based on assumption that state of stress in linear-elastic, isotropic, two dimensional medium is described by differential equation:

$$\Delta^4\varphi(x,z)=0 \Leftrightarrow \frac{\delta^4\phi(x,z)}{\delta x^4} + 2\frac{\delta^4\phi(x,z)}{\delta x^2\delta z^2} + \frac{\delta^4\phi(x,z)}{\delta z^4} \qquad (3)$$

As well as from the dependency between stress and deformation.

$$\delta_z(x,z)=\frac{\delta\phi(x,z)}{\delta x^2};2G\frac{\delta w(x,z)}{\delta z}=(1-u)\frac{\delta^2\phi(x,z)}{\delta x^2}-u\frac{\delta^2\phi(x,z)}{\delta z^2}$$

$$\delta_x(x,z)=\frac{\delta\phi(x,z)}{\delta z^2};2G\frac{\delta u(x,z)}{\delta x}=(1-u)\frac{\delta^2\phi(x,z)}{\delta z^2}-u\frac{\delta^2\phi(x,z)}{\delta x^2} \qquad (4)$$

$$\tau(x,z)=-\frac{\delta\phi(x,z)}{\delta x\delta z};G\left(\frac{\delta w(x,z)}{\delta x}+\frac{\delta u(x,z)}{\delta z}\right)=\frac{\delta^2\phi(x,z)}{\delta x\delta z}$$

In these formulas:

$G=\frac{E}{2(1+u)}$ Kirchoff's shear modulus,

n – Poisson's coefficient (0 < n < 0,5),
u – horizontal dislocations (towards x),
w – vertical dislocations (towards z),
$\tau_{(x,z)}$ – shear stress,
Φ(x, z) – stress in linear-elastic, isotropic, two dimensional medium.

It was accepted that:
- fracture zone near old workings $l_o = 1 - x$,
- fracture zone near pavement from the old workings side $l_o^1 = x - a$,
- fracture zone near pavement from the operating mining front side $l_o^2 = -x - a = x - a$.

Stage 2. Designation of critical distance between operating mining front and pavement (1_2^{kr}) with consideration of calculated average stress in that remainder $\delta_z^{śr\,L}$

$$\delta_{ch}^{śrL}=\frac{GWo}{\Pi l_2}\left[\ln\frac{2\sqrt{\left(l^2-a^2\right)\left[\left(l^2+a^2\right)^2-a^2\right]+l^2+\left(l_2+a\right)^2-2a^2}}{l^2-a^2}\ln\frac{1+a}{1-a}+\right.$$

$$+\ln\frac{1+a}{1-a}-\ln\left|\frac{l\left(l_2+a\right)+a^2-\sqrt{\left(l^2-a^2\right)\left[\left(l_2-a^2\right)-a^2\right]}}{\left(l_2+a\right)-a^2+\sqrt{\left(l^2-a^2\right)\left[\left(l_2-a^2\right)-a^2\right]}}\right|+$$

$$\left[-\frac{1}{\sqrt{l^2-a^2}}\ln\left|\frac{l_2+a\sqrt{\left(l_2+a\right)^2-a^2}}{l_2-a\sqrt{\left(l_2+a\right)^2-a^2}}\right|\right]+p\left(1-\sqrt{1+\frac{2a}{l_2}}\right) \quad (5)$$

where:
l – distance between pavement edge and old workings edge,
a – pavement width,
$GWo/\Pi l_2$ - old workings inducted stress,
w_o – vertical dislocations towards z axis
l_2 – distance between operating mining front edge and pavement edge,
p – Initial pressure occurring at given depth.

In situation when fracture zone l0 is equal to the remainder width between pavement and workings, computer creates model of stress distribution in the remainder (without taking into account influence of operating mining front) and rest of calculations are skipped until stage 4. If fracture zone l0 includes only part of the zone between pavement and workings then stage 3 is performed.

Stage 3. In this stage average stress in the remainder between pavement and older workings is calculated $\delta_z^{śrP}$:

$$\delta_{2Ch}^{śrP}=\frac{2Gw_o}{\Pi(r-a)}\left[\ln\frac{\sqrt{l^2-a^2}+\sqrt{r^2-a^2}}{l+r}+\ln\frac{l+a}{l+r}+\right.$$

$$\frac{1}{2}\ln\left|\frac{\sqrt{\left(l^2-a^2\right)\left(r^2-a^2\right)}+lr-a^2}{\sqrt{\left(l^2-a^2\right)\left(r^2-a^2\right)}-lr-a^2}\right|+ \quad (6)$$

$$\left.+\frac{1}{2}\ln\frac{r+\sqrt{r^2-a^2}}{r-\sqrt{r^2-a^2}}*\frac{1}{\sqrt{l^2-a^2}}\right]+p\left(1-\sqrt{\frac{r+a}{r-a}}\right)$$

where:
a – pavement width,
r – distance between pavement axis and older workings, reduced by width of fracture zone near older workings
$(r = l - l_o)$

Without consideration of operating mining front, as well as there is calculated strength of the remainder $\delta_z^{śrP}$. In situation when average stress $\delta_z^{śrP}$ exceeds value of critical stress $\delta_z^{śrP}$ model of stress distribution in the remainder is made like in stage 2. In equation (6) „r" distance between pavement axis and older workings, reduced by width of fracture zone near older workings $(r = l - l_o)$

Stage 4. When average stress in the remainder between pavements and older workings $\delta_z^{śrP}$. has value lower than the strength value of that remainder δ^{wp}, then the average stress in the same remainder is calculated for the most extreme position of operating mining front (in the line of pavement, $l_2 = 0$). This stress is marked by $\delta_z^{śrP2}$. In situation when stress $\delta_z^{śrP2}$ exceeds value of critical stress δ_z^{krP} critical distance between working front and pavement l_1^{kr} is calculated in accordance to stress in the remainder between pavement and older workings, while in opposite situation, as width of hazardous zone value 1_2^{kr} is used that has been designated in stage 1. If 1_1^{kr} has been calculated, then as hazardous distance between operating front and pavement is taken as $1_2 = 1_2^{kr}$ is greater than 1_1^{kr}, or $1_2 = 1_1^{kr}$, when 1_1^{kr} is greater than 1_2^{kr}. In both cases, calculated stress distribution in both remainders with distance 1_2 as shown above. Distance 1_2 is the distance between operating mining front when in one or the other zone stress attains critical value. If 1_2 is equal 1_2^{kr}, average stress and strength of the remainder between pavement and operating mining front dependency is tabulated from the distance between operating mining front and pavement. If 1_2 is equal 1_1^{kr} average stress and strength of the remainder between pavement and older workings dependency is tabulated from the distance of operating pavement front.

Initial data for this method must include values presented in order shown below:

1. Deck depth in meters [m],
2. Average specific weight of the rock mass [KN/m^3],
3. Inclination angle of the deck [^{o}],
4. Inverse of elastic delay time of the rock mass [1/year],
5. Average value of shear modulus of the rock mass [MPa],
6. Coal elastic constant [MPa].
7. Average value of Poisson's coefficient of the rock mass,
8. Distance between pavement and older workings [m],
9. Pavement width [m],
10. Thickness of older workings operation [m],
11. Value of operational coefficient dependent on the way of filling in space in older workings,
12. Average thickness of operation ahead of active front [m],
13. Value of operation coefficient dependent on the way of conducting the roof in operating deck
14. Average annual progress of the operation front [m/year],
15. Control parameter of value equal to [-1].

DESCRIPTION OF KROLL SOFTWARE

Methodology used for designation of safety zone between longwall front and the edge of older operation with consideration of influence of pavement mine working has been implemented in Visual Basic v. 6.3. environment, where practical tool has been created – KROLL software, that can be used by Polish mines. User Panel is embedded in standard Excel spreadsheet that relates to Visual Basic application in the background. After launching the software, the main panel can be seen (Fig. 2) that shows the setup of workings in deck with consideration of accepted coordinate system.

On the main panel, "Wprowadź dane" (Insert data) button is placed, that opens data spreadsheet (Fig. 3), "Schemat blokowy" (Flow chart), shows calculation algorithm and "O programie" (About software) button provides information about software origins. The next step is insertion of data in the form provided specifically for that task. Data should be inserted in provided field with simultaneous checking of its correct.

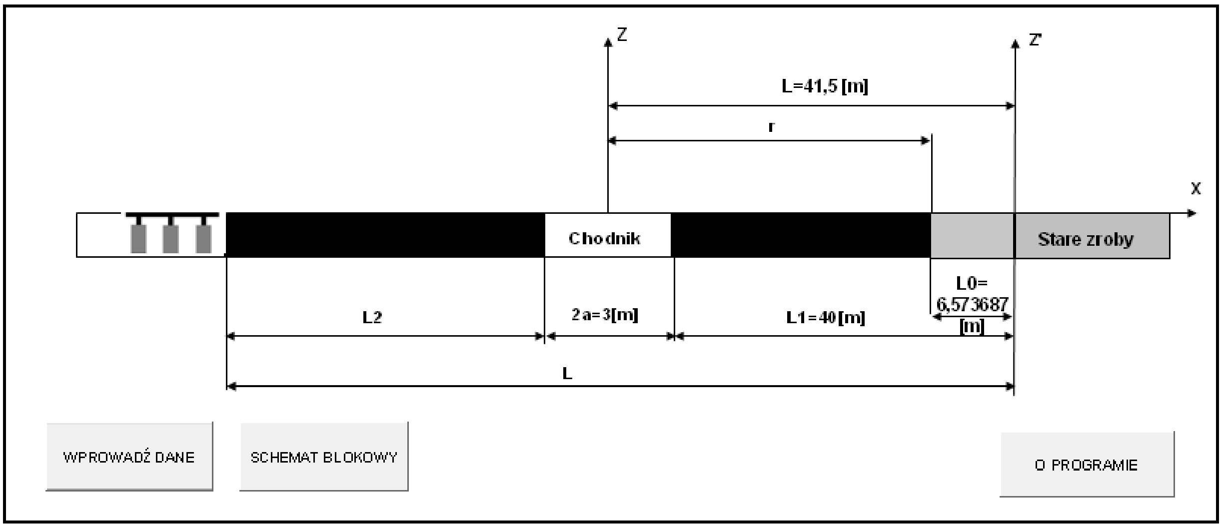

Fig. 2 Main panel of "KROLL" software

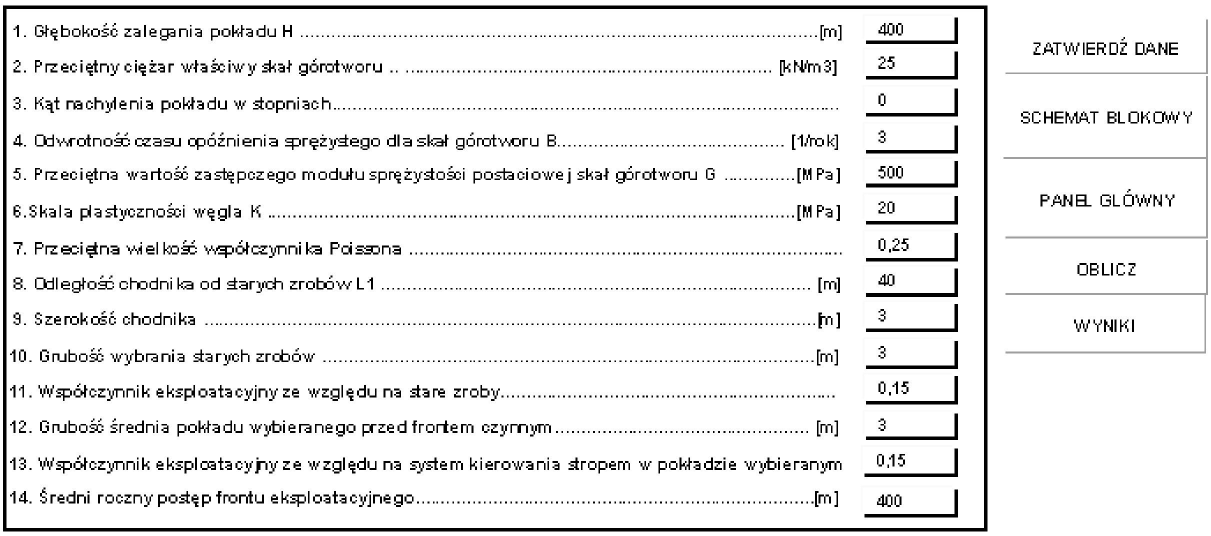

Fig. 3 Data entry form for „KROLL"software

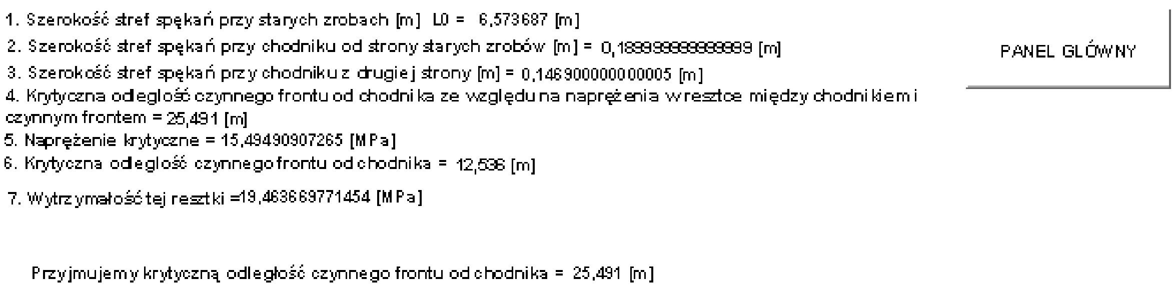

Fig. 4 Result spreadsheet of "KROLL" software

After that it is advised to enable calculation process using "Oblicz" (Calculate) button. User can follow different stages of the calculation process on the flow chart, where different blocks will be highlighted in green colour if the requirements emerging from character of problem at hand are met. The results will be generated on the main screen, illustrated in Fig. 4.

Afterwards, on the new sheet, there will be generated with graph of stress distribution in the remainder between pavement and old workings without consideration of the influence of the active front or creation of stress distribution model in both remainders with distance l2 between active front and pavement.

EXEMPLARY CALCULATION

Specific situation has been investigated that included longwall front moving towards pavement located parallel and in the area influenced by old workings. The aim is designation of safe distance l2bezp, that moving longwall front can move into, towards the pavement, with following parameters that describing operation conditions and material constants of the rock mass [4]:

1. Deck depth H = 400 m
2. Average specific weight of the rock mass 25,0 KN/m^3
3. Deck inclination angle $\alpha = 0^0$
4. Inverse of elastic delay time of the rock mass β = 3,0 1/year

5. Average value of replacement shear modulus of the rock mass G = 500 MPa
6. Coal elastic constant K = 20 MPa
7. Average value of Poisson's coefficient n = 0,25
8. Distance between pavement and older workings l_1 = 40 m
9. Pavement width 2a = 3 m
10. Thickness of older workings operation g = 3 m
11. Value of operational coefficient dependent on older workings η= 0,15
12. Thickness of older workings operation g = 3 m
13. Value of operational coefficient dependent on older workings η_2 = 0,15
14. Average annual progress of the operation front 400 m/year

Size of safety zone will be dependent on stress in the area between longwall front and pavement working and on the stress between pavement and older workings. As the longwall front will get closed to the pavement, the stress will grow and can attain critical value in both first and second zone. Because of that in the software there are both stress distribution models provided. Comparing them with permissible stress values, calculated for every part of the deck separately allows designation of critical distances l_1^{kr} and l_2^{kr} with taking these stress values into account. As safe distance, higher critical distance value should be used. Increase of this distance, by using safety coefficient is not necessary, because 1^{kr} contains safety margin that comes from average values used for calculation of material constant values. This issue can be evaluated unmistakeably after performing specific research and observations in the mine.

For specific conditions provided in this example; after software performed its calculations the results are:

- critical distance between the active front and pavement considering stress in the remainder between pavement and active front l_2^{kr} = 25,6 m,
- critical distance between active front and pavement considering stress in the remainder between pavement and older workings l_1^{kr} = 13,1 m.

Critical distance equals l_2^{kr} = 26 m. Critical distance can also be designated graphically by drawing the course of average stress in the remainder between active front and pavement, and then compare it with the graphs of this remainder strength.

Calculations, considering actual mining conditions shows that the safe distance that active front can move close to the pavement influenced by older workings is dependent on value of vertical stress in zone between this front and the pavement as well as the value of vertical stress in zone between pavement and older workings. In the situation when in one or the other zone exceeds vertical stress permissible value, there is a hazard of cave in or rock burst. Using calculation software hazardous zone can be designated, distance between active front and pavement $1^{kryt.}$, considering stress in zone between front and pavement l_2^{kryt}, considering stress in zone between pavement and old workings l_1^{kryt}. Amongst calculated values l_1^{kryt} and l_2^{kryt}, higher value should always be chosen and it should be taken into account that safe distance between active front and pavement meets the requirement:

$$1^{bezp} > 1^{kryt} = \max\left[l_1^{kryt}, l_2^{kryt}\right] \qquad (7)$$

In mines working conditions it should lead to adequately early creation of closing wall and taking technical measures leading to relaxation of danger zones (rock blasting, pumping in water etc.) Provided example show that for the most unfavourable mining conditions (with operation depth values up to 1000 m) hazardous zone does not exceed 80 [m]. It's not greater than the length of average longwall. Width of critical zone can be designated considering vertical stress between active front and pavement with skipping of calculations between pavement and old workings, assuming that:

1. Pavement is located in significant distance from older workings. This distance is one of actual, for given mining conditions, mechanical rock mass parameters and technical-organizational operation parameters. From analysed examples, where the most unfavourable conditions were considered, results show that the distance between pavement and older workings, that is decisive for designation of critical zone is stress area between front and pavement 80 [m],
2. When distance between pavement and older workings is entirely fracture zone then created earlier in a result of stress induced by stopped mining operation (older workings).

SUMMARY

Designed methodology of assessing rock bursting hazard is very important factor preventing occurrence of hazardous events that can have catastrophic consequences. This applies to specific mining situations often occurring in normal mine working conditions. These are situations when active longwall front is closing in to parallel (or almost parallel) pavement working, that is not influenced by older workings, as well as workings themselves or edges in above or underlying decks. Methodology shown in this article, used to designate safety zone, during longwall working, in rock burst hazard conditions, takes into account legal requirement set before mines management and specialized services that is active assessment of hazardous events risk that can occur in workplaces [9]. Research and scientific issues of rock bursting even is essential [12]. Forecasting rock mass tendency to burst allows for appropriate choosing of preventative measures and at the same time leads to increase of safety of mine working. Crew that is warned in time, before incoming rock burst is evacuated from endangered zones. In favourable situations there is also an actual possibility of taking active preventative measures and stopping rock burst from happening. Therefore developed KROLL software should find wide practical application for determination of mine working parameters.

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