Acta Geodyn. Geomater.Vol.1, No.1(133), 19-26, 2004

DETERMINATION OF POTENTIAL LEVEL OF ROCKBURST HAZARD BASED ON THE RESULTS OF ANALYTICAL PREDICTIONS OF STRESS DISTRIBUTIONS AND THE LEVEL OF INDUCED SEISMICITY

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(*Received* September 2003*, accepted* November 2003)

ABSTRACT
The presently applied method of mining reconnaissance used for the designing of mining works in areas subject to seismic hazards is often providing erroneous read-outs involving the states of potential rockburst hazards. It results from the fact that a number of factors characterizing the influence of mining works on the stress-energy state of rockmass are not taken into consideration. In the paper it is suggested developing the currently binding method of mining reconnaissance which consists in allowing for the results of analytical stress predictions pertaining to mining conditions and the level of induced seismicity, in the classification of potential rockburst hazards. Making use of a real example of mining project the article presented how to apply the results of prediction calculations to determine the state of potential rockburst hazard.

KEYWORDS: rockburst hazard, vertical stress, vertical strain, analytical predictions

1. INTRODUCTION

As specified by the currently binding 'Complex method involving the estimation of rockburst hazard in mining plants extracting hard coal' (1996), the planning of mining works in these conditions should be preceded by the analysis of hazard state depending on mining-geological conditions.

Appropriate planning of mining works in rockburst hazard conditions can decide whether the works can be carried out, or can help to avoid the application of time consuming and expensive means of rockburst prevention.

The estimation of potential rockburst hazard states is performed using the method of mining prospecting. This method is applied at the planning stage of mining works, for the selection of long-term methods for elimination or reduction of hazard state. The potential rockburst hazard state defined in such a way is also taken into consideration when estimating the real state of hazard.

In the method of mining prospecting we allow for the influence of various mining-geological factors on the formation of the level of the potential rockburst hazard with respect to planned mining works. They are among others as follows:

- depth of carried out works,
- earlier crump incidents in a given seam,
- strength of coal,
- inclination of coal to crumps,
- occurrence of thick, hard rock layers in the roof of the extracted seam,
- presence of edges and residues in heading gangways of the planned works,
- thickness of seam, height of the planned winning workings,
- shape the abandoned workings of the past mining in the seam subject to extraction,
- localization of the planned works with respect to other headings or geological dislocation,
- destressing of the seam,
- method of roof control.

The influence of the above factors on the state of potential crump hazard is by no means questionable. What can however be controversial is their significance in the oveall estimation of hazard state.

The application of the analytical prediction method of stress distribution allows us to provide more precise estimation involving the influence of some factors (change of depth, distance of extracted parts of beds, residues, etc.) on the state of stresses and potential crump hazard than in the case of mining prospecting. This method has been successfully applied for many years for the estimation of stress conditions in heading gangways of the planned mining works (Białek et al., 1998; Drzęźla et al., 1988).

In spite of strong idealization of the mechanical properties of rockmass (homogeneous, isotropic, elastic medium) and a simple dislocation boundary condition, with which the vertical settlement has a constant value $w_{(x,y,0)} = w_0 = a*g$ (where a – subsidence coefficient, g – height of the coalface) over the elementary extraction of the sides 2a x 2b, and over the unmined coal its value is zero, the equations (Gil, 1991) are successfully applied for the prediction of characteristic stress zones in heading gangways. Already with relatively small vertical and horizontal distances from the mining edge, the phenomenon involving non-continuity of boundary condition is declining, and the distribution of stresses and dislocations are close to the ones described with equations derived with continuous boundary condition, and due to the accepted assumptions for the discussed solution, we can apply the principle of influence superposition.

Strong idealization of rock medium accepted in the applied algorithms necessitates the application of a typical comparative approach. It means that the prediction made in advance for the discussed scope of planned mining should be preceded by testing calculations (comparative prediction) covering a specific scope of mining works already carried out in a given area or in the neighbourhood with known evidence involving rockmass pressure and rockburst hazards. The carried out testing calculations let us estimate the values of material constants occurring in algorithms - so called substitute values. These are such values for which the results of comparative predictions performed for the already completed mining works correspond, in spite of the accepted simplifying assumptions, with the measurement (observation) results.

The experience accumulated over years involving the application of the analytical method indicates that with an appropriate estimation of the parameters of the method, the prediction results of stress distribution are generally in fairly good agreement with the real evidence of rockmass pressure and rockburst hazards observed in the vicinity of the driven headings. It results from the fact that, in spite of the simplicity of the applied model (based on the solution of dislocation boundary problem of the three dimensional elasticity theory – Gil, 1991; Dymek, 1968) the algorithms allow for the influence of many parameters which decide in some cases of strong diversification of stress conditions in heading gangways of the driven or planned headings (influence of time-space system of past mining, extraction parameters).

During prediction calculations, it is controlled if the strength of rocks has not been exceeded due to additional deformation and stresses generated in effect of mining works. For this reason, the effort index W is calculated, understood as the ratio of the occurred substitute stress to the rock strength. For $W \geq 1$ the strength of rock has been exceeded. The values of substitute strength and stress are dependent on the accepted strength hypothesis. For the accepted rockmass model the value of the index is calculated according to hypotheses of Coulomb-Mohr and Burzyński (Sałustowicz, 1955).

The calculation results make it possible to distinguish the following zones in heading gangways of the planned headings, characteristic in terms of the predicted values of vertical component of the three dimensional state of stresses and the value of effort index:

- zones of damaged rocks - in congruence with the results of the applied strength hypothesis, the strength of rocks has already been exceeded, outside the damaged zones, the range of the following zones is defined:
- destressed - the predicted stress is lower than initial (absolute values of stresses),
- raised stresses - the predicted stresses are higher than initial, but lower than the so called critical ones, posing hazard to the stability of coal side walls,
- concentration of stresses – predicted stresses exceed critical values.

Based on the results of analytical predictions involving the distribution of stresses in the seam subjected to mining, it is possible to estimate first of all the potential rockburst hazard state of the seam (stress) character. At present, there are more and more rockbursts effected by cracking of a thick, strong rock layer deposited in the roof (roof crumps) or in the floor (floor crumps) of the bed being extracted. A number of rockbursts are taking place in the situation when an impulse coming from the cracking rock layers deposited above or below the extracted seam comes to the very stressed part of coal seam. With respect to the above, it seams reasonable, at the prediction stage of potential rockburst hazard state, to allow for not only the distribution of stresses in the parts of seam subjected to mining, but also the deformation state of strong rock layers, whose damage can have the influence on the rockburst hazard level involving the planned mining works.

In the case when the level of rockburst hazards depends on the processes taking place in strong rock layers (floor or roof ones), significant information can be obtained by analyzing the deformation state of these layers. As it has been found out in earlier investigation studies (Bańka, 2000), the level of seismicity induced by mining works can be associated (using correlation relations) with the deformation state of tremor-prone rock layers.

In the situation when the number of seismic events recorded during the hitherto extraction is too low to define the correlation relations which bind the deformation state of rock layers with the level of induced seismicity, the quantitative prediction of the number (summary energy) tremors is not possible. We can only in this case provide qualitative estimation of the seismicity level.

From among the determined deformation indexes of rock layers, there are vertical deformations which are particularly relevant, being the counterpart of vertical stresses predicted in coal seams. For the estimation of deformation influences of the mining process, we make use of the space-time development of the theory of Budryk – Knothe (Knothe, 1984). The choice of this theory was dictated by the following reasons:

- it is commonly used in Polish mining industry for the prediction of mining influences,
- small number of parameters in the theory, which, together with its widespread application, means that their values can be easily defined,
- sufficiently accurate description of rockmass subsidence over the bed being mined,
- simplicity of equations, which translates into high numerical effectiveness of programs calculating deformation indexes of rockmass.

The article presents an example for the application of the results of analytical predictions involving the determination of rockburst hazard states in the heading gangway of the planned longwall heading in the area subjected to high-risk rockburst occurrence. The proposed method develops the methodology presented in earlier works – Dubiński et al., 1998; Jaworski et al., 2000; Bańka and Jaworski, 2002.

2. APPLICATION OF RESULTS OF ANALYTICAL PREDICTIONS FOR THE ESTIMATION OF POTENTIAL ROCKBURST HAZARD STATES

The method involving the estimation of rockburst hazard states of headings based on the results of analytical predictions for the distribution of stresses has been presented in the project 'User's guide on how to make use of the results of analytical method in the complex estimation method of rockburst hazard states' (1998).

The state of rockburst hazard in the heading is defined as presented by the Table 1.

Taking into consideration the deformation state of tremor-prone rock layers (roof or floor ones), we suggest the acceptance of the following criterion values of vertical deformations.

The above criterion values result from a number of carried out analyses involving the deformation state

Table 1 Estimation of rockburst hazard states based on the results of predictions for the distribution of stresses.

Hazard state	Value in points	Basic parameters of estimation	
		Value of vertical component of stress σ_z	Damage of the coal seam
a Lack	2	$\sigma_z > -\gamma H$ vertical stresses are higher than initial stress $-\gamma H$ resulting from the mining depth H	Does not matter
b Weak	4	$\sigma_z <= -\gamma H$ vertical stresses are close to (slightly lower) than the initial stress $-\gamma H$ resulting from the mining depth H	$W \geq 1$ The coal seam is damaged
c Medium	8	$\sigma_z < -\gamma H$ raised vertical stresses; they exceed by at least several MPa the value of initial stress $-\gamma H$ resulting from mining depth H	$W < 1$ Structure of coal bed left intact
d High	16	$\sigma_z << -\gamma H$ concentration of vertical stresses, occurrence of critical stresses frequently of the value above –30 MPa	$W < 1$ Structure of coal bed left intact

Table 2 Criterion values of vertical deformations ε_z [mm/m].

Hazard state	Values in points	Value of vertical strain ε_z [mm/m]
a Lack	2	$\varepsilon_z >= -0.5$
b Weak	4	$-0.5 > \varepsilon_z >= -1.0$
c Medium	8	$-1.0 > \varepsilon_z >= -2.0$
d High	16	$\varepsilon_z < -2.0$

of tremor-prone rock layers, but they require further investigation studies.

We suggest carrying out the overall estimation of the potential rockburst hazard state by selecting each time the higher denotation from the two methods discussed above.

3. EXEMPLARY ESTIMATION OF POTENTIAL ROCKBURST HAZARD STATE

Below we present the example of how to apply the results of analytical predictions for the estimation of potential rockburst hazard state involving specific mining works planned with the occurrence of complex, generally unfavorable geological-mining conditions. The estimation involves preparatory works planned in the close-to-roof layer of seam 510 in the fields of longwall 623g planned for extraction.

In the analyzed area, but outside the field of planned longwall, the layer of the seam 510 was extracted using the floor mining with hydraulic filling. At present the roof layer is being extracted using fall of roof method (longwall 621/622g), and the further extraction of the bed in this area is being planned to carry out with longwall 623g.

There are the following conditions which decide about the level of potential rockburst hazards of headings in the analyzed part of seam 510:

- big thickness (about 9m) of the bed and considerable depth of its deposition (700-720m),
- location of a considerable part of longwall fields in non-destressed plot of the bed referred to as the area 3rd degree crump hazard,
- numerous past mining conditions in longwalls 507, 504, 418 and 419 as well as a sediment field in the seam 507 located over the end section of heading gangway of the longwall,
- a considerable non-uniformity of bed extraction and faults of the throws 2.5 m occurring in the longwall field.

It should be emphasized that in the direct and basic roofs of the seams 510-507 there are deposited alternated layers of mudstones and sandy shales of relatively low strength parameters. The nearest sandstone layer of the thickness of about 10m is deposited at the distance of about 50m above the seam 510 – which is advantageous in view of tremor and rockburst hazards. During the past mining works within the period from 08.1997 to 05.2003 there were no high-energy tremors of rockmass. Table 3 presents the values of recorded seismicity with respect to particular energy classes and as summary energy.

The number of seismic events recorded during the hitherto extraction is too low to define the correlation relations which bind the deformation state of rock layers with the level of induced seismicity. We can only in this case provide qualitative estimation of the seismicity level – in accordance with Table 2.

Figure 1 presents the printout of mining contours in seams 510 and 507 with marked foci of recorded tremors.

Below we present the analytical prediction of the distribution of the vertical component of the three dimensional stress state in the heading gangways of the planned mining works in seam 510wg. In the prediction calculations we allowed for the influence of all extractions carried out in the analyzed area.

The following is of influence on the distribution and scope of compressive stresses in the analyzed lot of the seam 510wg:

- deposition depth – about 700m, initial stresses 17-18MPa,
- neighbouring edge of abandoned workings of the already completed filling mining (with longwall 621-622d) in the floor layer of seam 510,
- edges and abandoned workings of the filling mining completed to different extent in layers I and II of the seam 507 deposited from 2 to 6 meters under the seam 510,
- sediments in the seam 507 and edges of the seam 504 – in the further planned heading gangway of the longwall 623g.

The carried out calculations of stress distribution made it possible to single out, in heading gangways of the planned mining works, the characteristic zones in view of stress intensity, as presented below:

Table 3 Recorded number and cumulative energy of tremors in the area of longwalls 619-622 within the period from 08.1997 to 05.2003.

Energy [J]	Number of tremors	Cumulative energy [J]
10^2	17	8.1e3
10^3	67	2.6e5
10^4	25	8.9e5
10^5	2	3.1e5
TOTAL	111	1.5e6

Fig. 1 The area of planned mining in seam 510wg with contours of past mining in seams 510wd and 507 with marked foci of recorded tremors.

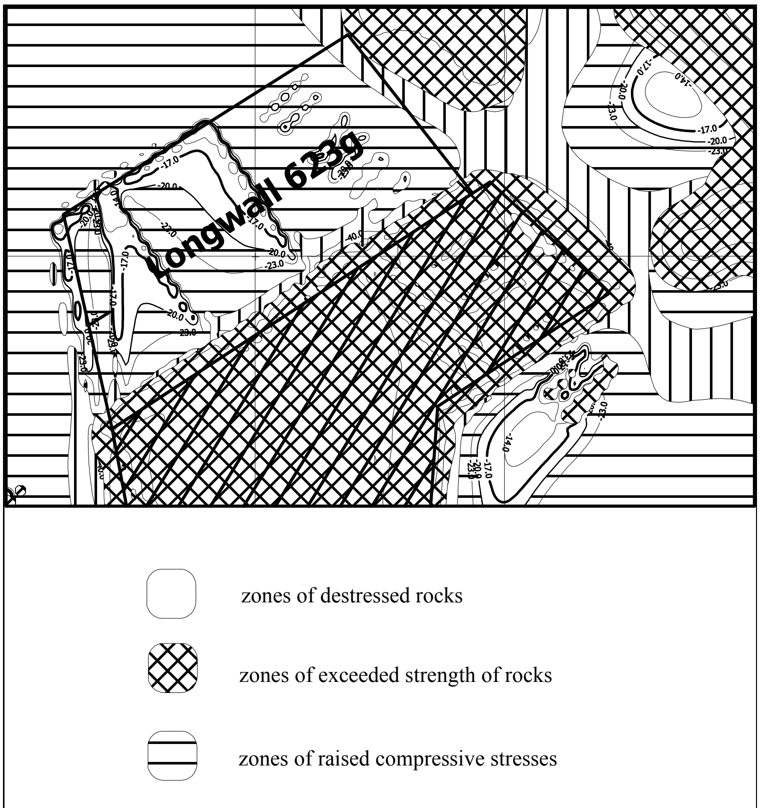

Fig. 2 Distribution of the vertical component of three dimensional state of stress in the analysed area.

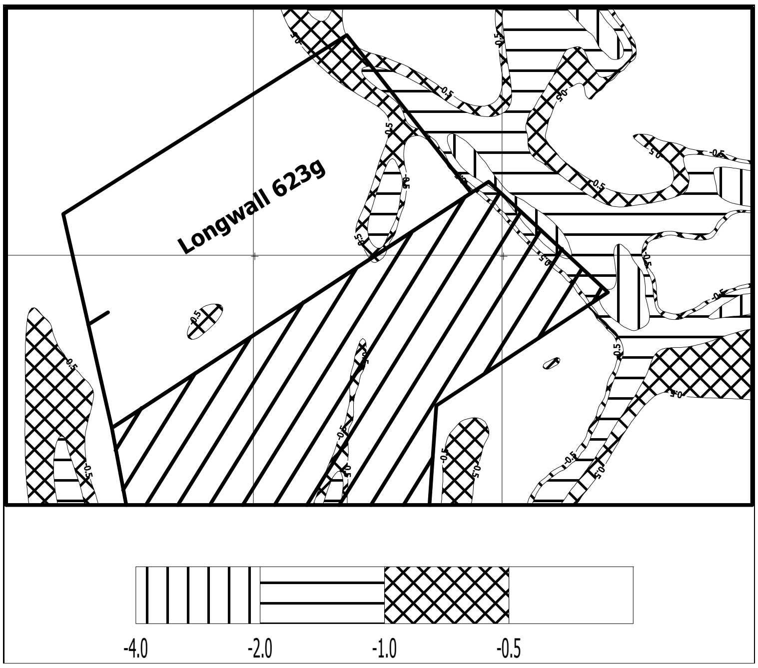

Fig. 3 Distribution of vertical compressive deformations ε_z [mm/m] in a sandstone layer under the seam 510 in the investigated area.

- zones partially destressed (excluded from the damage process) – in which, due to the reaction of abandoned mining of the completed mining, the vertical stresses are, according to prediction, lower or close to the primary stresses resulting from the deposition depth. The headings in these zones can be treated as having potentially lower risk of rockbursts. The above zones in Fig.2 were not additionally marked.
- damaged zones – in which due to the reaction of mining effected by exceeding the compression strength of rocks and in effect of tensile stress, it may have resulted in such weakening of unmined coal seam and dissipation of accumulated elastic strain energy that it should not be a dangerous concentrator of stresses or energy. The heading in such zones can be treated as posing potentially weaker hazard to rockbursts. However, in such zones there might be some problems with driving and maintaining of headings, especially gang-way/gallery headings. The above zones were marked in Fig.2 with crossing lines.
- zones of raised compression stresses (not subjected to the damage process or destress process) – in which the predicted compression stresses exceed the value of vertical stress (17-18 MPa) resulting from deposition depth. The heading in these zones should be treated as having potentially higher risk of rockbursts. These zones were marked with horizontal lines.
- zones of compression stress concentration – in which the predicted compression stresses can reach critical values (above 30MPa) due to the stability of coal side walls. In these zones a considerable amount of elastic strain energy can be accumulated. The heading in these zones should be treated as potentially subjected to strong rockburst risk. Rockbursts in these zones, and in particular in gateroads before the longwall front, may even bring about medium-energy tremors, with the foci sufficiently close to the side walls of the heading. These zones were marked with vertical lines.

Figure 3 presents the distribution of vertical deformations in a sandstone layer under the seam 510.

As it follows from the carried out prediction calculations, in the area of planned mining, a relatively good deformation state of rock layers will be maintained. Relatively small fragments of the planned works are located in the areas where raised ($|\varepsilon_z|$ above 0,5 mm/m) vertical compressive deformations are predicted.

Figure 4 presents the estimation of potential crump hazard states elaborated on the basis of the combined interpretation of calculation results involving the distribution of stresses in the seam 510 and deformation of rock layers deposited under the seam.

In view of the results of calculations carried out with the analytical method, the incline Va, located near abandoned workings of the wall 621/622g should

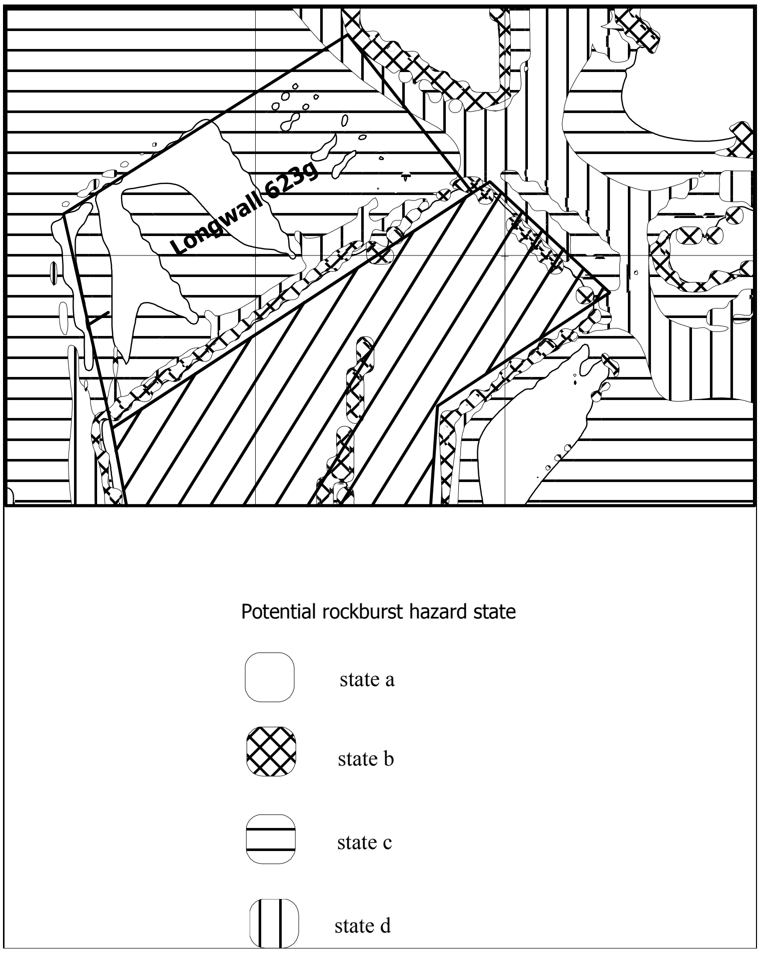

Fig. 4 Potential rockburst hazard in the area of the planned works.

be treated as posing low crump hazard – state a or b. Hazard state c was ascribed to very small section of the incline Va.

The incline VIa, which is contouring the field of longwall 623g from the north will be made and maintained at the state of high (parts of the initial section of the planned length of the incline and the final section of over 30m) potential rockburst hazard (state d). The potential rockburst hazard of the remaining section of the incline run was defined as medium – state c.

The cross-cut of longwall 623 during the driving is classified along its predominant length as potentially posing low and medium rockburst hazard (states a and c). Hazard states b and d were ascribed to small sections of the planned run of this heading.

4. SUMMARY

Analytical methods have been for many years applied for the estimation of stress situation in heading gangways of the carried out mining works. They can be also used to predict (based on the determined regression equation) the level of induced seismicity. The predictions can be applied long time period before the planned project wherby it affords time for their optimization in terms of minimizing the level of potential rockburst hazard. We should emphasize that they can be used in areas in which, due to the lack of headings, it is not possible to apply other geophysical methods for the estimation of stress state (for examle seismic or microgravimetric).

The application of the results of prediction calculations at the stage of estimation of potential rockburst hazard state, may help to make the estimations more accurate as compared to the estimations obtained as a result of obligatory methods of mining prospecting used in the areas subject to strong rockburst hazards.

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