The assessment of stress in an exploited rock mass based on the disturbance of the rigid overlying strata

Eva Jiránková[a], Vladimír Petroš[b] and Jindřich Šancer[c]

[a] Faculty of Mining and Geology, VŠB-TU, Ostrava 70833, Czech Republic

[b] Professor Emeritus, Research and Development on Natural Sciences and Engineering - Mining and Geomechanics, 739 51 Dobrá 86, Czech Republic

[c] Faculty of Mining and Geology, VŠB-TU, Ostrava 70833, Czech Republic

Abstract

Gravitational rules are used as the basis for the prognosis of vertical stress distribution in exploited rock masses. A decrease in stress in a worked-out area (decrease between the initial stress and the stress acting on the floor of the outmined seam) results in an increase in stress in the surrounding unworked area. The size of load in the floor of the worked-out area is determined by the degree of disturbance in the overlying strata rocks. An overall additional load in the surrounding rocks of the unworked area is determined based on the difference between the initial geostatic stress and the load in the floor of the worked-out area. The additional load, which is determined from the force of relieving the stress in the worked-out area divided by the periphery of the worked-out area, decreases per unit of length of the periphery of the worked-out area. Furthermore, the behaviour of stress in the direction of the worked-out area is calculated mathematically. In this way, the stress in the grid of points on the level of seams being mined can be calculated, and isolines of acting stress can be determined. As an example, we show calculations for a specific situation in a mine before rigid overlying strata failure and after the failure. After the rigid overlying strata failure, the additional stress decreased by approximately 40%.

Keywords: underground mining, longwall mining, stress distribution, surface subsidence, overlying strata disintegration

1. Introduction

Knowledge about the level of stress in a rock mass is very important for underground mining because many mining problems involve stress levels. Previous studies have focused on the complexity of stress in rock masses, but have not established any reliable solutions for underground mining. For instance, mathematical modelling [1], [2] can assess stress distribution, but only has good results if extensive rock disintegration does not occur. In areas of disintegrated rocks, mathematical modelling of the stress results in only approximate values. Physical modelling [3] often provides valuable results, but the modelling process is very time-consuming and expensive. For these reasons, physical modelling is seldom used. Stress can also be determined directly by measurement using hydraulic disintegration [4], [5], [6] or by the recalculation of deformation measurements [7]. Because there are high costs associated with hydraulic disintegration and deformation measurements, it is not possible to apply these methods in practice yet. However, they can be used for research. A number of methods for determining the stress parameters in a rock mass exist [8], but these methods often only provide qualitative results for the acting stress. Very valuable results can be

obtained from direct stress measurements using sensors placed on the floor in the worked-out area [9]. Unfortunately, conducting these measurements in an exploited rock mass is very expensive. Nevertheless, measurements from these sensors provide a good view of the reconstruction of the state of stress in the worked-out area. This knowledge can influence the problems of mining in other faces and seams.

Our proposed manner of stress distribution assessment is based on the knowledge of the disintegration of the undermined overlying strata and a fundamental law – the law of the conservation of energy. The very low value of kinetic energy from the rate of subsidence of the undermined overlying strata can be neglected. It then follows that the total force acting in the affected area at the level of the seam being mined is constant (i.e., is equal to the weight of the overlying strata above the considered affected area). Thus, stress relief in the worked-out area is compensated by the additional load in the surrounding rock mass.

In the case of longwall mining, a number of factors influence the stress distribution. When mining operations are done below the stratified overlying strata, the disruption of the overlying strata depends on the worked-out area and the strength and thickness of overlying strata rocks. To assess the stress relief in the worked-out area, the strength composition of the overlying strata must be determined. Before rigid overlying strata failure, an irregular arch is formed above the worked-out area, the weight of which represents the load in the worked-out area. The force of stress relief in the worked-out area is determined by the difference between the weight of the overlying strata above the worked-out area and the load in the worked-out area. The force of stress relief in the worked-out area is the greatest before the failure of the whole rigid overlying strata. The failure of the whole rigid overlying strata can be determined from surface height observations [10], [11]. By dividing the calculated total force of relief in the worked-out area by the periphery of the worked-out area, a force of an additional load per 1 meter of periphery of the surrounding unworked area can be calculated. The behaviour of the additional load in the direction of the worked-out area has a characteristic shape that can be mathematically defined [12]. The distance over which the additional load is distributed can be markedly influenced by faults. This depends on the direction and size of the dip of the faults. If the dip of the fault and the friction conditions on it enable the transfer of vertical force through this fault, then the length of stress distribution is not limited. If the fault in the overlying strata inclines toward the worked-out area, then the vertical force cannot be transferred through this fault, and the additional load will be concentrated before the fault. Likewise, if the fault in the overlying strata deflects from the worked-out area, but its dip is greater than that corresponding to the friction angle, then the vertical force cannot be transferred through this fault. On the basis of these facts, the stress in the grid of points of the whole affected area can be calculated.

The theoretical analyses in this study are supplemented by a specific example of the assessment of stress distribution in the hard coal mine, ČSM Mine, which is part of the Ostrava-Karviná Coalfield (henceforth referred to as OKR) in the Czech Republic. Solving this problem is done in two ways – before the failure of the whole rigid overlying strata and after the failure of the whole rigid overlying strata.

After the failure of the whole rigid overlying strata, the stress relief in the worked-out area will be substantially reduced, as will the additional load surrounding the worked-out area. However, above the margins of the worked-out area, overhangs will remain that will continue to increase the stress in the surroundings of the worked-out area for a long time.

2. Theoretical analysis of the stress distribution during longwall mining

During underground mining, the overall stress relief is equal to the overall additional load in the surroundings of the face [12]:

$$\left(\sigma_p - \sigma_{si} \right) P_{si} = \left(\sigma_{zi} - \sigma_p \right) P_{zi} \tag{1}$$

where σ_p is the initial vertical stress, σ_{si} is the decreased stresses in worked-out areas,
P_{si} refers to the areas where decreased stresses (σ_{si}) act,
σ_{zi} is the increased stresses around the worked-out area,
and P_{zi} refers to the areas where increased stresses ($\sigma_{zi.}$) act.

The stress relief in the worked-out area can be measured directly behind the advancing face in abandoned mine workings. Unfortunately, these measurements are expensive, and, until now, such measurements have only been carried out on one face in the OKR [9]. For the specific assessment of load in a worked-out area, the state of the overall disturbance of rigid rocks above the worked-out area must be known. Knowing whether the rigid beds in the undermined overlying strata have failed or whether the disturbance of the overlying strata has been stopped at a certain height are important in determining the stress-release in worked-out areas. We can determine these features from the observation of surface subsidence [10], [11]. If the whole thickness of the rigid overlying strata is not disturbed, then surface subsidence is small and does not correspond at the given time to the worked-out area and thickness.

When mining under the rigid stratified overlying strata, overhangs of undisturbed overlying strata beds occur in the vicinity of the margins of the worked-out area. The disturbed part of the overlying strata can be approximated by an arch. This situation is diagrammatically shown in Fig. 1.
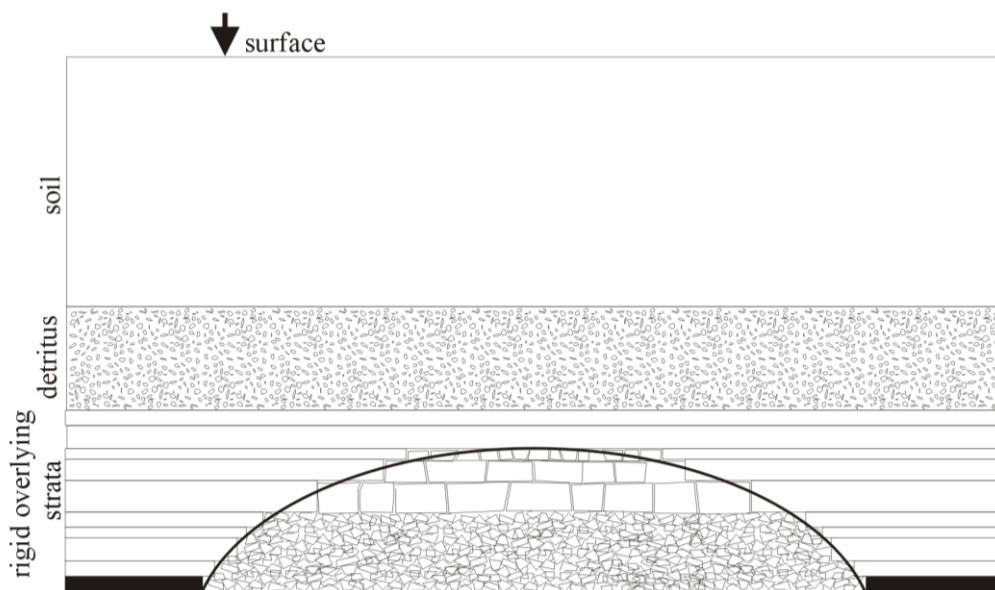

Fig. 1. State of the rigid overlying strata before complete failure.

If the width of the worked-out area in which the failure of rigid overlying strata occurs is known, the height of the arch can be estimated for certain worked-out widths. From the height of the arch and the dimensions of the worked-out area, the total weight of the rocks in the arch (F_k) can be calculated.

The overall stress relief in the worked-out area (F_s) can be calculated using the following equation:

$$F_s = P_m \sigma_p - F_k \qquad (2)$$

where P_m refers to the worked-out area.

Because the overall stress relief in the worked-out area equals the overall additional load in the areas surrounding of the face, the force of the additional load per 1 m of periphery of the worked-out area (F_{1m}) can be calculated as:

$$F_{1m} = F_s/O \qquad (3)$$

where O is the length of periphery of the worked-out area.

If the failure has already occurred in the whole rigid overlying strata, the stress in the worked-out area will change with time. The margins of the worked-out area will remain, but the stress will be relieved permanently because overhangs of rigid beds exist in the overlying strata. This situation is shown diagrammatically in Fig. 2.
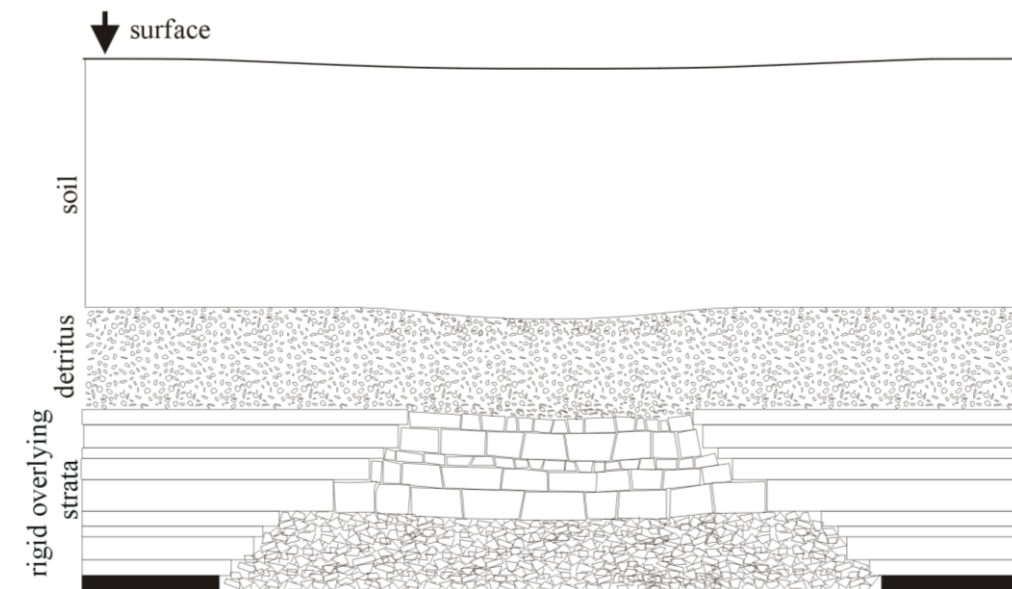

Fig. 2. State after the failure of rigid overlying strata.

The overhangs above the margins of the worked-out area do not occur if the overlying strata is disturbed artificially (e.g., by blasting).

The assessment of the time increase in stress in relation to the worked-out area is based on the knowledge that in the OKR the duration of rather marked stress relief is five years. For this

reason, the time over which the given assessment will be related must be defined when assessing the state of stress in the exploited rock mass.

The prevailing behaviour of stress in the surroundings of the worked-out area is given in Fig. 3.
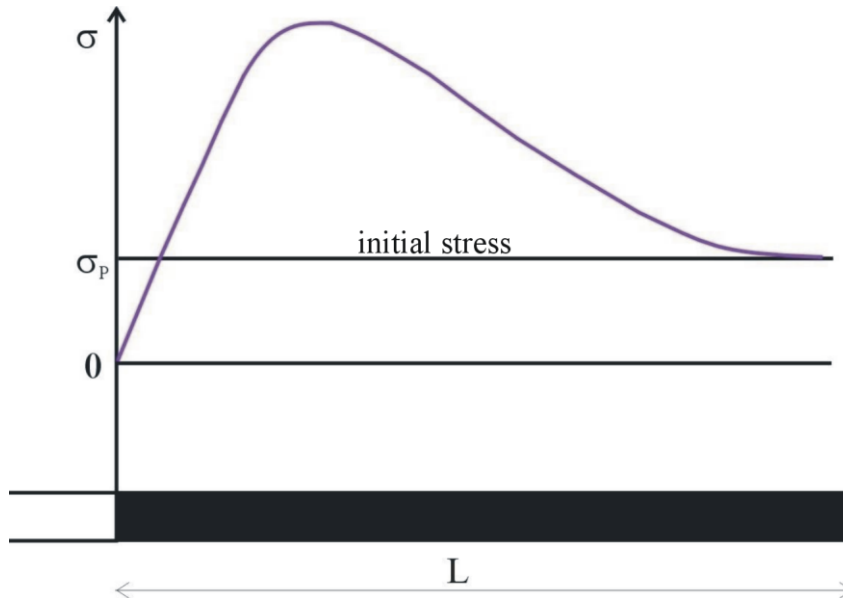

Fig. 3. Behaviour of stress in the surroundings of the worked-out area.

In the sides of mine working areas, the stress has a minimum value that depends on whether the rock (coal) is compact or disintegrated by the acting stress in the area. If the rock is disintegrated, the stress in the area is zero. If the rock is compact, a specific level of stress will act here; however, it is substantially lower than the initial acting stress. Whether the curve of stress in the surroundings of the worked-out area starts at zero or at a certain minimum stress does not matter. What is of importance is its behaviour after the initial point. For simplification, there is considered to be no stress in the sides of mine working areas. From the side of the mine working areas, the stress in the surroundings of the worked-out area increases to a maximum value and then declines again to the initial acting stress. In areas without previous mining activity, the initial acting stress is the geostatic stress, which is given by the depth of occurrence and the average volume and weight of the overlying strata rocks.

Various functions were tested to determine the most appropriate mathematical expression of the stress curve in the surroundings of a worked-out area. The behaviour of stress in the surroundings of the worked-out area is best defined by the following equation:

$$\sigma = \sigma_p \left[\frac{c_o.l}{c_1 + l} - \frac{(c_o - 1)l}{c_2 + l} \right] \qquad (4)$$

where l is the distance from the side of the mine working areas, and c_o, c_1, and c_2 are constants that must be determined experimentally.

This function was verified by values measured in equivalent material modelling [12]. The determination index (R^2) for the function specified by the computer and by the model of measured values was determined to be 0.996.

On the basis of equivalent material modelling, with a length of a face of 180 m, the additional stress is distributed in the sides over the distance of approximately 60 m from the worked-out area (i.e., a distance 1/3 of the worked-out width). The load over the 1 m of periphery of the worked-out area (F_{1m}) must correspond to the area of the curve above the level of initial stress (Equation 4). This can be determined by integrating Equation 4 and deducting the force corresponding to the initial stress as:

$$F_{1m} = \int_0^L \sigma . dl - L\sigma_p \qquad (5)$$

where L is the distance over which the additional stress is distributed.

If other workings have been driven in the seam of the pressure-affected area around the worked-out area, the stress distribution will be affected. It is generally understood that a pillar must be formed at a distance no greater than 5 m between the worked-out area and another working that has disintegrated, so that additional stress does not substantially concentrate in the area. At a distance greater than 5 m, the stress distribution is illustrated in Fig. 4.
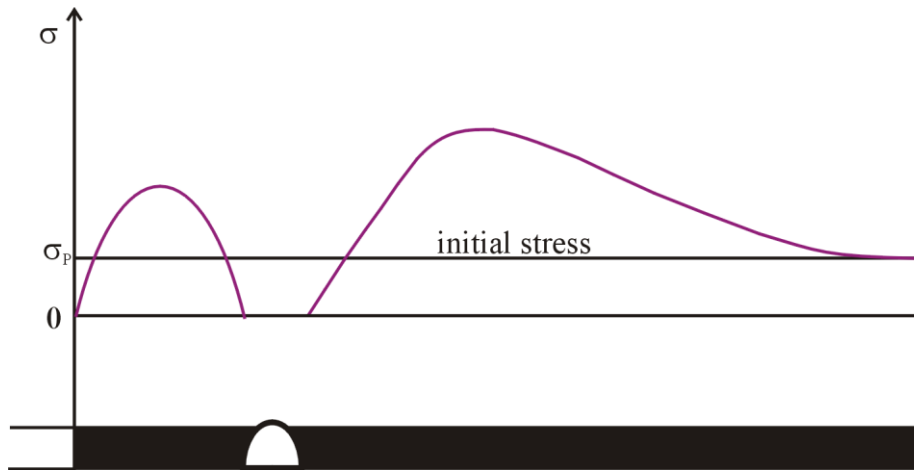

Fig. 4. Behaviour of stress in the area with a below-limit pillar.

With a known distance (L) and load (F_{1m}), it is possible to solve Equation 4 for individual parts of the affected area.

Stress both in the surroundings of the worked-out area and in the worked-out area can thereby be determined in a regular grid of points, and results can be graphically plotted in various ways (e.g., means of isolines, three-dimensional graphs, and various sections).

Calculated values of stress in the entire affected area can be checked using an average value. The average value, which is calculated from the values in the entire grid of points, must correspond to the average stress acting before mining.

3. A specific example of dealing with stress distribution

An example of dealing with stress distribution is based on the mining of Seams 29 and 30 in the southern part of Block 4 in the ČSM Mine. Geological characteristics of the rock mass in the area of concern are presented in Fig. 5.
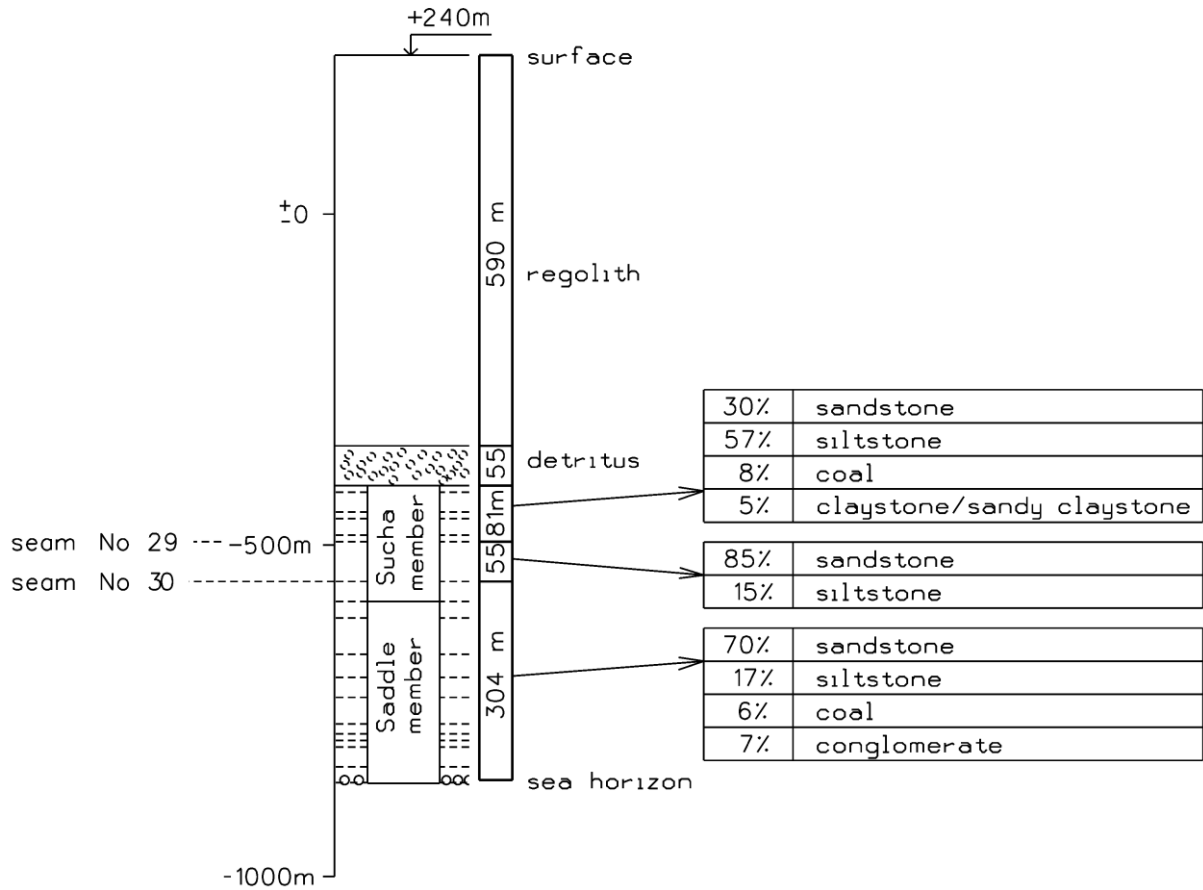
Fig. 5. Character of the rock environment in the area under evaluation.

In the area of concern, Seams 29 and 30 were mined. Seam 29 occurs at a depth ranging from 700 to 830 m, and Seam 30 occurs at a depth ranging from 740 to 860 m.

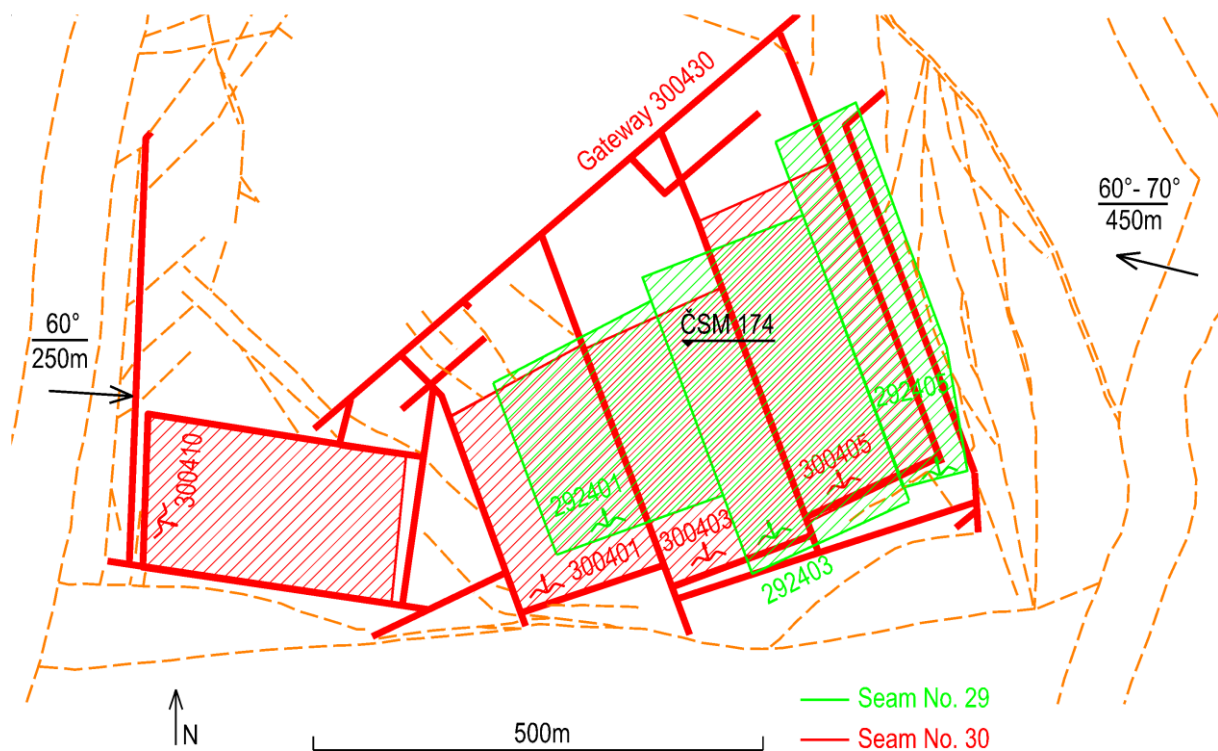Figure 6 shows all faces in the southern part of Block 4 in the ČSM Mine.

Fig. 6. The situation of all faces in the study area.

 Stress distribution was calculated in two phases. The first phase dealt with the state immediately prior to the failure of the whole rigid overlying strata above the worked-out area. From surface subsidence assessments during the mining of all faces in Seam 29, it was clear that any complete failure of the approximately 81 m thick rigid overlying strata beds had not occurred.

The failure of the whole rigid overlying strata was inferred from the observation of surface subsidence at half-yearly intervals [10]. Before the failure, subsidence was minimal. After the failure, subsidence increased rapidly. The failure took place in the time period between measurements in October 1999 and April 2000 in the course of mining Seam 30. A more exact date of the failure was determined based of the observation of seismic activity in the given area. No other marked seismic activity had occurred during the whole period of mining in the study, with the exception of the period before the end of March 2000, when three rigid seismic events were recorded. At this time, the failure of the rigid overlying strata occurred. The state of mining at that date is shown in Fig. 7.

Fig. 7. The situation of mine workings and mining before the failure of the whole rigid overlying strata.

The first phase of stress determination concerns the situation that is shown in Fig. 7. The other phase of stress determination concerns the state after the termination of mining in the southern part of Block 4 (i.e., after the working out of all faces as shown in Fig. 6).

3.1. State of stress before the failure of the whole rigid overlying strata

Considering that the phase when any failure of the whole rigid overlying strata after mining the faces in Seam 29 had not yet occurred, we assumed that above the worked-out area of approximately 320 x 540 m, the overlying strata was disturbed and formed an irregular arch at a height of approximately 70 m above the level of this seam.

The complete failure of rigid beds occurred as late as the mining of Seam 30, and this is why the assessment of stress at the level of this seam is important. It is possible to assume that above the faces in Seam 30, the overlying strata was disturbed and formed an irregular arch to the height of about 130 m as a maximum.

To calculate the load in the worked-out area, a regular grid of points spaced 20 m apart was constructed. The acting stress of individual points was calculated based on the distance from the margin of the worked-out area. In this way, the total force acting in the worked-out area was calculated and compared with the initial load from the depth of occurrence of 740 - 860 m. Thus, the stress relief in the worked-out area was determined to be approximately 2765 GN. This corresponds to the given situation of the load (F_{1m} =1680 MN) per metre of periphery of the worked-out area.

At the time of complete failure of the rigid overlying strata, a width of 320 m was calculated. This means that the additional stress was distributed over a distance of approximately 110 m.

Based on the known distance (L) and the load (F_{1m}), Equation 4 was used to calculate the stress in individual parts of the area affected.

The stress in the surrounding area around the worked-out area was determined using a regular grid similar to that of the worked-out area, with spacing of 20 m.

The stress determined for the entire study area is represented three-dimensionally in Fig. 8.
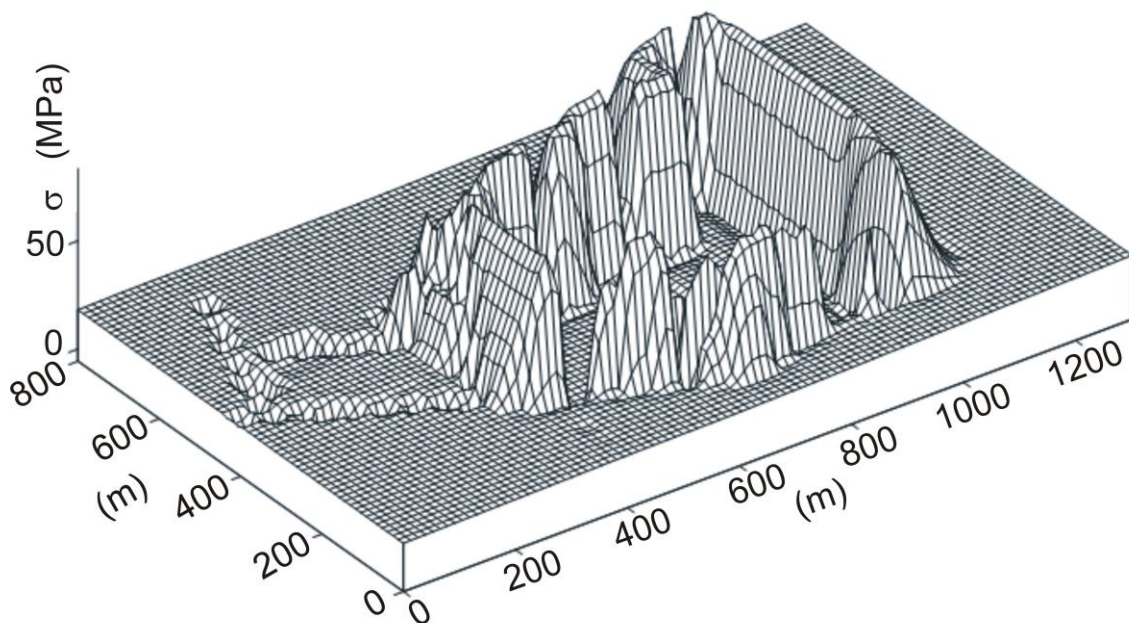

Fig. 8. The state of stress before the failure of whole rigid overlying strata.

The state of stress in the study area is influenced by several factors. First, there is a zone of faults in the southern part through which the increased stress cannot be transferred. The eastern part of the worked area is also limited by marked faults, but the dip of these faults enables the transfer of increased stress from the western part to the eastern part of the area.

Low-stress "troughs" were caused by passages in Seam 30, and the stress is almost zero in these troughs.

3.2. The state of stress after the termination of mining operations in the study area

In general, a gradual increase the stress in the worked-out area occurs after the termination of mining operations. These changes in stress have long-term character. Long-term observations in the OKR have shown that the duration of substantial stress relief in the worked-out area is five years. This fact has been incorporated in mining legislation for the OKR. From the mining point of view, the state of the stress in the rock mass at the time of commencement of mining operations in the adjacent areas is also of interest. After determining the stress in the

southern part of Block 4 (Fig. 6), mining operations were immediately transferred to the northern part of Block 4. Then, we were able to determine the stress in the rock mass immediately after terminating the mining of the southern part of the study area.

We divided the worked-out study area into two parts to examine the degree of disturbance of the rock mass due to mining. The first part consisted of Face 300410 in the western part of Block 4, and the second part consisted of the other faces.

By observations of the surface subsidence above Face 300410, it has been determined that the failure of the whole rigid overlying strata above this face has not yet occurred. Above the worked-out face, an arch that has long-term character and prevents the recovery of stress in the worked-out area was formed. Therefore, the state of stress in the worked-out area of this face, and its surroundings barely changed. From the characteristics of overlying strata beds (Fig. 5), it is possible to assume that the overlying strata above this face was disturbed and formed an irregular arch with the height of approximately 40 m.

Thus, the worked-out area behind Face 300410, with depths in the range of $700 - 733$ m, has, in comparison with the initial state, stress relieved by approximately 960 GN. The average additional load F_{1m} of approximately 1060 GN/m corresponds to this stress relief. This additional load is distributed over the distance corresponding to one third of the worked-out width (i.e., approximately 60 m). The southern margin of this face is limited by a tectonic zone, through which the increased stress cannot be transferred. A marked fault also exists on the western side of the face. However, its position enables the transfer of stress from the eastern side toward the western side.

The situation in the second part of the worked-out area is different; here, the failure of the whole rigid overlying strata has already occurred, and the state of stress changes over time. We considered, among other factors, the results of previous studies [9] in the course of determining the stress in the worked-out area. These measurements were also taken in the area with disturbance of the whole rigid overlying strata.

The mining of Seam 30 in this area was conducted from October 1999 to April 2002. Because we calculated the stress at the of end of the mining, the average time passing from the working out of the seam in this part is approximately one year and three months. Rather marked stress relief is obtained after five years; therefore, we can assume that there was a decrease by approximately 45% in the initial stress at time-affected points. The stress acting in the worked-out area is markedly affected by the distance from the margin of the worked-out area. In the centre of the worked-out area, the initial stress was reduced by 16%. The abandoned workings from the extent of the worked-out area and depths of $740 - 815$ m were stress relieved by approximately 1840 GN in comparison with the initial stress. The average additional load (F_{1m}) of approximately 1010 GN/m corresponds to this level of stress relief. The next steps in the determination of the acting stress were similar to those in stress assessment in Section 3.1. Similarly, the distance that the additional stress will be distributed was determined to be 110 m.

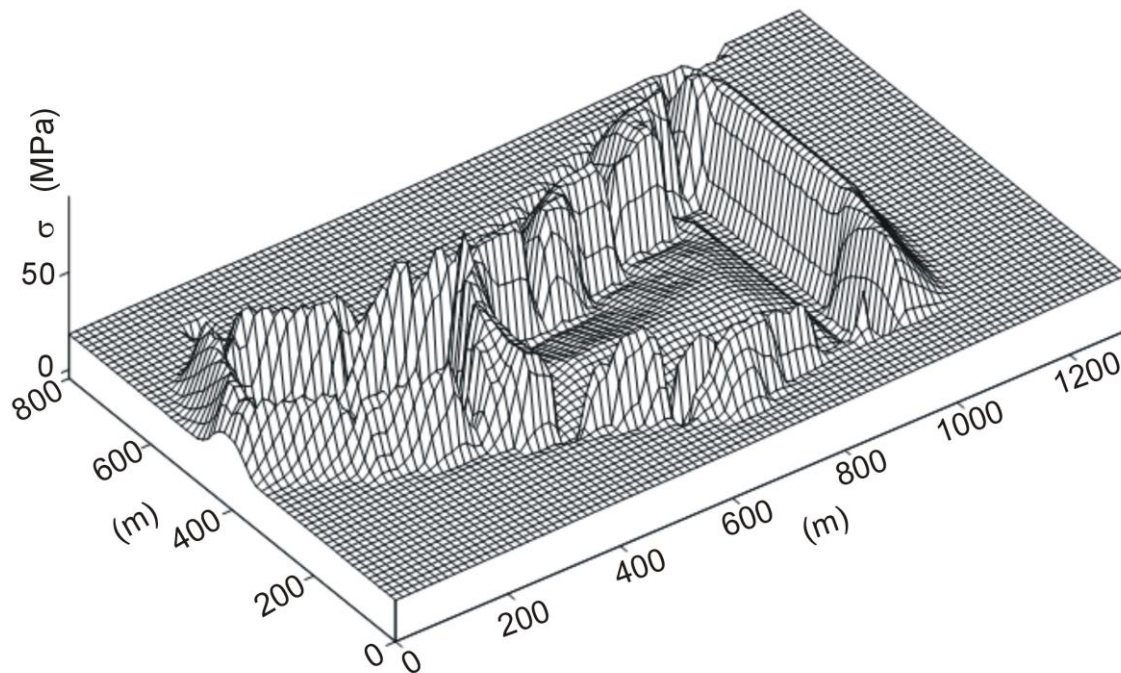The determined stress for the entire area observed is represented in three-dimension in Fig 9.

Fig. 9. The state of stress after the termination of mining in the southern part of Block 4.

From the behaviour of stress, it can be seen that the stress maximum is at the pillar between Face 300410 and the other faces.

3. Discussion

The described manner of the assessment of distribution of stress acting in the exploited rock mass provides usable specific values. The accuracy of the calculated values depends mainly on the knowledge of the load in the worked-out area. This load especially affects the disintegration of overlying strata beds. The simplest manner in which the failure of rigid overlying strata beds can be found is the assessment of surface subsidence and the specification of seismic activity. The knowledge of acting stress is of utmost importance to areas threatened by geomechanical events, such as rockbursts and gas and rock outbursts.

4. Conclusions

From the analysis of the state of stress, we were able to deduce the influence of the disturbance of the whole rigid overlying strata on the amount of additional stress in the surroundings of the worked-out area. Before the disturbance of the rigid overlying strata, the average additional load (F_{1m}) was approximately 1680 GN/m. After the disturbance and working out of other faces, the average additional load (F_{1m}) was approximately 1010 GN/m. Thus, the additional stress decreased by approximately 40%.

The surroundings of Face 300410 are additionally loaded permanently by the force (F_{1m}) of approximately 1060 GN/m, since the disturbance of the rigid overlying strata has not occurred yet.

The knowledge of acting stress is of special importance in those areas where mining operations will continue. This will be the case for the area north of Gateway 300430. The additional stress due to the described worked-out areas does not reach the area in the north of Gateway 300430. Therefore, further mining operations will not be affected by the existing faces. Significant consequences may occur if additional stresses due to further exploitation reach the area that is loaded by the described faces. In this case, the additional stresses will be additive, and a very hazardous geomechanical situation may occur.

Acknowledgements

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Corresponding author. Eva Jiránková, Tel./fax: +420 597323326

E-mail: eva.jirankova@vsb.cz