THE PROBLEM OF BEDS STABILITY IN THE CONDITIONS OF UNDERMINING HIGHER DEPOSITED BEDS IN THE CONTEXT OF SELECTED ANALYTICAL SOLUTIONS

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Summary. Underground mining of useful mineral deposits causes changes in the virgin rock mass stress state and may affects on rock masses and mining excavations damages. The result of exploitation may be tremors and rockbursts. Most often, in the case of deposits (of coal) exploitation, the higher lying beds are mined first. Sometimes, it is necessary to mining the lower lying bed first and undermining the upper bed. The clue is not to damage the undermined bed, and the damage raiser the distance between both beds is.

Keywords: rock mass stability, undermining, submining, rock damage, rock cracking, safety distance between mined beds

1. Introduction

Exploitation of on-bed deposits is associated with a number of problems related to technological and economic requirements as well as work safety in mines. One of the factors is the sequence of individual beds are mined.

The commonly used method of mining from shallow to deepest beds is profitable from the point of view of utilization the deposits. Under some conditions the sequence is not possible to use. In the event of a rockburst hazard, it is necessary to carry out rock burst prevention, which most often requires conducting stress relief exploitation of rockburst beds.

Under market economy conditions, economic criteria drive mines to select the deposits to be mined. The produced coal must correspond to specific, usually high quality requirements while maintaining the cheapest possible mining costs. That is why information

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about the impact of an already operated bed on the higher lying beds has fundamental importance. Information allows selection and sequence of mining bed.

Of the many cases of undermining coal beds, they are most often associated with ongoing anti-rockburst prevention.

Analytical methods for determining influence of undermining based on the past experience and theoretical solutions.

Extensive research material related to the problem of undermining coal beds was collected by Staroń (1975, 1979).

For the purposes of the analysis, Staroń distinguished three groups of mining impact of the mining lower bed lying on the upper bed.

Staroń qualified to the *first group* of cases for which no clear effects of undermining were found in the uplying bed during its exploitation, and assumed that the uplying bed did not have any influence from earlier exploitation.

The *second group* included the cases in which there were clear influences in the form of folding the bed floor and its cracking, but these changes did not cause significant difficulties in the mining of the bed earlier subjected to exploitation. The intensity of impact in the undermined beds included in this group were defined as the average influence.

The *third group* included those cases in which there were significant influences in the form of folding the bed floor and/or its cracking, which caused great difficulties in the mining of the undermined bed. The intensity of impact of the undermined beds in this group was defined as strong influence.

Data from the observations analysed by Staroń included over 60 cases of undermining of beds that were upper in deposits under the roof caving operation, distinguishing the scale of the observed characteristic undermining effects.

The discussed data cited by Staroń showed that when the distance between the mined and undermined beds was less than five times the thickness of the mined bed, strong influences were observed in the undermined bed.

In the case where the distance between the mined and undermined beds was between five and seven times the thickness of the mined beds, medium or no negative influences were observed in the undermined beds. If the distance between the mined and undermined beds was greater than seven times the thickness of the mined bed, no negative influences were observed in the undermined beds.

The research material discussed above indicates that the intensity of influence in the undermined bed is significantly influenced by the type and properties of rocks lying between the mined and undermined beds, the depth deposition of the bed and the distance between the beds.

The problem of determining the range and size of influence zone when undermining coal bed has been the subject of interest for researchers and engineers for many years. Due to the complexity of nature of the rock mass deformation process in the immediate vicinity of the mining exploitation, the hypotheses were based mainly on observations carried out in hard coal mines and were related to geometric quantities, such as thickness of the mined bed and distance between the mined and undermined bed. Attempts were also made to connect them with the strength properties of rocks lying between the beds and the depth deposition of the beds. The most important formulas for determining size and range of damage influences of undermining can be divided into the following groups:

- *group* I. - containing formulas for the required distance between mined and undermined beds as a function of the thickness of the mined bed,
- *group* II. - containing formulas for the required distance between mined and undermined beds as a function of mined bed thickness and rock loosening coefficient,
- *group* III. - containing formulas for height of the zone of the damage effects of exploitation of the undermined bed as a function of thickness of the mined bed, depth deposition of the beds and rock strength,
- *group* IV - containing formulas for determining the occurrence probability for damage effects of bed undermined bed.

Group I. including formulas for the required distance between mined and undermined beds M as a function of mined bed thickness g, includes solutions of:

- Czechowicz - the required safety distance between mined and undermined bed is:

$$M = 12g$$

where

g - thickness of the mined bed.

- Davidianz - the required safety distance between mined and undermined beds is:

$$M = 20g$$

- Dziunikowski, Rzempiel et al. - the required distance between mined and undermined beds is

$$M = 8g \text{ for a regression factor of } 0.144$$

$$M = 12g \text{ for a regression factor of } 0.229$$

- Kiliashkov – the required distance between mined and undermined beds

$$M = 12g + 3{,}5g^2$$

- Krupiński, Czechowicz et al. - the required distance between mined and undermined beds

$$M = 12g \quad \text{for } g \leq 1.5\text{m}$$

$$M = 8g \quad \text{for } g > 1.5\text{m}$$

The II. group including the formulas for the required distance between the mined and undermined beds M as a function of undermined bed thickness g and loosening coefficient k_r, includes, among others, work of:

- Chudek and Olaszowski - the required distance M between mined and undermined beds

$$M = \frac{g}{k_r - 1} \cdot \frac{1}{1 - \eta_1}$$

where

$$\eta_1 = \frac{k_r - k_r^{'}}{k_r - 1}$$

k_r - rock loosening coefficient,

k'_r - loosening coefficient of the rocks after pressing the rocks in the caving zone,

g - mined bed thickness.

- Makeyev Research Institute - the required distance between mined and undermined beds

$$M = \frac{3g^2}{k_r - 1}$$

- Kuznetsov - the required distance between mined and undermined beds

$$M = \frac{(3+1{,}5g)g}{k_r - 1}$$

- Staroń - the required distance between mined and undermined beds

$$M = g\left[\eta_1 + \frac{4}{\pi(k_r - 1)}\right]$$

The III. group including the formulas for the required distance *M* between the mined and undermined beds as a function of thickness of the mined bed *g*, the deposition depth *H* and the tensile strength of rocks R_{rs} can include, among others Chudek's formula. Intensity of harmful effects of undermining is calculated from the formula:

$$M = 3{,}5g\sqrt{\frac{p_z}{R_{rs}}}$$

where

g - mined bed thickness,

p_z - vertical primeval stress,

R_{rs} - average tensile strength of rock (layers) lying between mined and undermined beds.

The IV. group including the formulas for determining the occurrence probability of undermining influences may include, among others, formulas of:

- Budryk and Bes - the probability of strong influence *p* is calculated as

$$p = 100\exp(-0{,}092\frac{M_H}{g})$$

and the probability of medium and strong influence *p*

$$p = 100\exp(-0{,}046\frac{M_H}{g})$$

where

M_H - distance between mined and undermined beds,

g - mined bed thickness;

- Staroń - the probability of loosening, the undermined bed (strong and medium influence p)

$$p = 100 \exp(-0{,}065 \frac{M_H}{g})$$

A large number of analytical solutions raises doubts, when choosing one of them to be used in a particular case. Before choosing a solution, it is important to know how they are related to observation in practice.

Comparison of cited analytical solutions with observations in mines can be made for individual groups. Comparing the results of calculations obtained on the basis of the formulas of group I, it can be stated that the largest required distances between the mined and undermined beds are obtained from the Davidianz's and Kiliashkov's formulas. These formulas show that the required distance between the mined and undermined bed is about 20 times the thickness of the mined bed; the smallest distances - Dziunikowski and Krupiński - 8 times the thickness of the mined bed.

Based on the observations in the coal mines, it can be stated that the calculations based on the formulas of the discussed first group give in an overwhelming majority of cases the results outnumbered. Studies show that if the distance between the mined and undermined beds is greater than seven times the mined bed thickness, no significant damage effects were found in the undermined beds (see Staroń, 1975).

Such a relatively small accuracy of matching the results of calculations carried out using the formulas for mine observations results, due to, among others, limiting only to geometrical factors (e.g. distance between beds, mined bed thickness) and omitting the geological structure of the rock mass, strength and deformation of rock properties.

Formulas of the second group have been expanded and in addition to only geometric factors, e.g. distance between the beds, mined bed thickness, they take into account the properties of rocks surrounding the beds by introducing so-called rock loosening coefficient.

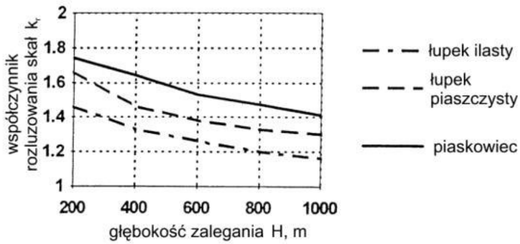


Fig. 2.1. Relationship between the rock loosening coefficient k_r (vertical axis) and the depth deposition H (horizontal axis) for different types of rocks; - -·- · - - shale, - - - - sand shale, —— - sandstone

Using the rock loosening coefficient, both the deposition depth of the beds and the type of rock surrounding the analysed beds, can be taken into account in a simplified way. On the basis of laboratory tests, the values of rock loosening coefficient has been determined for individual rock types for specific depths.

Figure 2.1 presents the variability of the rock loosening coefficient k_r depending on the depth of bed depth deposition H for three types of rocks: shale, arenaceous shale and sandstone.

The figure 2.1. indicates the highest value of the rock loosening coefficient k_r was obtained for shale, and the lowest - for sandstone. It means that if the roof layers are more difficult to cave in, then the rock volume increases strongly, and effect visibly increasing their loosening coefficient.

The second characteristic feature is the downward trend of the rock loosening coefficient k_r as the depth H increases. For depth H from 200 m to 1000 m, the rock loosening coefficient k_r takes values as follows:

- for shale 1.17-1.45,
- for arenaceous shale 1.30-1.65,
- for sandstones 1.40-1.75.

The loosening coefficient k_r of rocks significantly influences on the amount of required distance between the mined and undermined beds at which the undermined bed will not be damaged.

Figure 2.2 shows influence of the rock loosening coefficient k_r on the required distance between the mined and undermined beds.

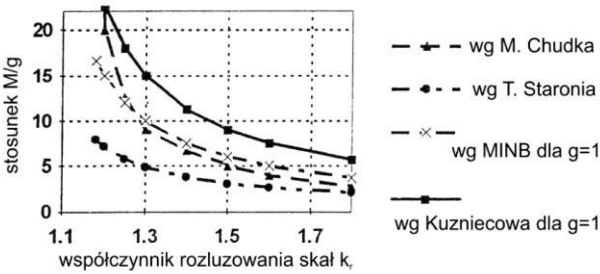


Fig. 2.2. The relationship between the rock loosening coefficient k_r (horizontal axis) and the ratio of the safe distance M between the beds and the thickness of the mined bed g (vertical axis); ▲- after Chudek, ● - after Staroń, x - after Makeyev Institute of Science and Research, ■ - after Kuznetsov

The characteristics presented in the figure, drawn on the basis of calculations carried out according to the formulas of Chudek, Staroń, Makeyev Institute of Science and Research and Kuznetsov, are of similar shape, however, the values of the required distance between the mined and undermined beds M are different, expressed as times the thickness of the mined beds M/g.

The graph shows that the smallest required distances M between the mined and undermined beds result from the formula given by Staroń, and the largest - from the Kuznetsov's formula. The results of calculations carried out according to the formulas of Chudek and Makeyev Institute of Science and Research are similar.

In order to compare the results of calculations carried out according to the formulas of the second group, Chudek's and Staroń's formulas were chosen.

Figure 2.3 shows the relationship between the thickness of the undermined bed m and the ratio of the safe distance M between the beds and the thickness of the mined bed g for different values of rock loosening coefficient k_r.

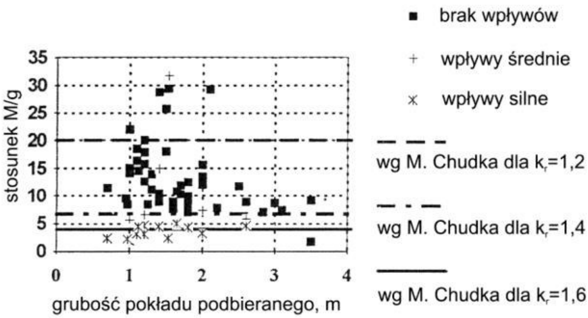


Fig. 2.3. The relationship between the thickness of the undermined bed *m* and the ratio of the safe distance between the beds *M* and the thickness of the mined bed *g* (vertical axis) for different values of rock loosening coefficient k_r (horizontal axis) according to Chudek; k_r=1.2, 1.4 and 1.6, ■ - no influence, + - medium influence, * - strong influence

It turns out that for the value of rock loosening coefficient k_r from 1.2 to 1.6 there is a large increase in the required distance between the mined and undermined bed *M*, e.g. for the loosening coefficient k_r equal 1.2, the required distance between the mined and undermined bed *M* is equal to 20 times the thickness of the mined bed, while for a coefficient k_r=1.6 the required distance is about four and a half times the thickness of the mined bed.

These results differ from those obtained on the basis of the formula given by Staroń (Fig. 2.4).

According to Staroń, for the rock loosening coefficient k_r=1.2, the required distance between the mined and undermined beds is equal to about seven times the thickness of the mined decks. For the rock loosening coefficient k_r=1.6, the required distance between the mined and undermined beds is approximately 3 times the mined bed thickness.

The presented analysis of formulas included in the second group shows that the required distance *M* between the mined and undermined beds determined on the basis of the Staroń's formula is definitely smaller than the calculated *M* values with all other formulas.

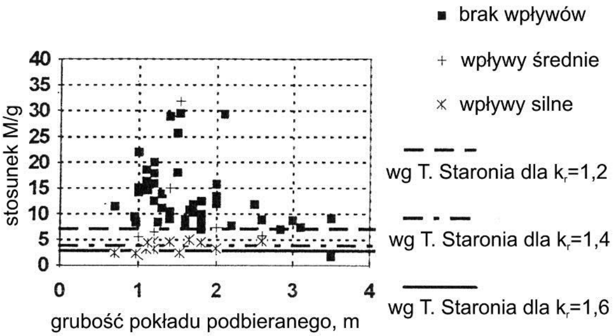


Fig. 2.4. The relationship between the thickness of the undermined bed *m* and the ratio of the safe distance *M* between the beds and the thickness of the mined bed *g* for different values of rock loosening coefficient k_r according to Staroń (k_r=1.2, 1.4 and 1.6); ■ - no influence, + - medium influence, * - strong influence

It should be assumed that for conditions of the Carboniferous rock mass with properties such as in the Upper Silesian Coal Basin, it will be most advantageous to determine the required distance *M* between the mined and undermined beds based on the formula developed by Chudek and Olaszowski.

Group III. includes the formula given by Chudek for determining the amount of damage impacts from mining during undermining.

The formula, the range of damage effects of mining on undermining depends on the thickness of the exploited bed, the depth of deposition expressed in the form of the primeval vertical stress in the virgin rock mass and on the average tensile strength of the rocks lying between the mined and undermined beds.

Figure 2.5 shows the relationship between the range of damage mining impacts *M*/*g* on undermining to the ratio of vertical primary stress in the virgin rock mass to the average tensile strength of the rocks lying between the mined and undermined beds p_z/R_{rs}.

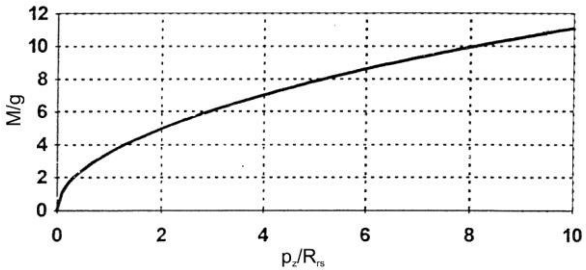


Fig. 2.5. The relationship between the ratio of the vertical component of the primary stress p_z and the tensile strength R_{rs} and the ratio of the safe distance M between the beds and the thickness of the undermined bed g

With the increase of the ratio of primeval stress p_z to the average tensile strength R_{rs}, the range of harmful effects of operation during picking up increases. It should be assumed that as the depth H increases, it is expected that the range of damage effects of undermining exploitation increases.

The IV. group includes formulas for determining the occurrences probability of undermining influences. Medium and strong influences were distinguished in the group. However, the criteria for qualifying specific consequences of undermining for strong or medium influences were not clearly defined.

Figure 2.6 compares the occurrence probability of undermining damage effects determined according to the formulas of Budryk and Staroń. The probability of strong damage influences as well as medium and strong influences is determined on the basis of Budryk and Bes's formulas. The probability of strong and medium influences is determined on the basis of Staroń's formula.

Comparing relevant characteristics, it can be stated that the probability values determined on the basis of the Budryk and Bes formula are higher than the probability values obtained on the basis of the Staroń's formula.

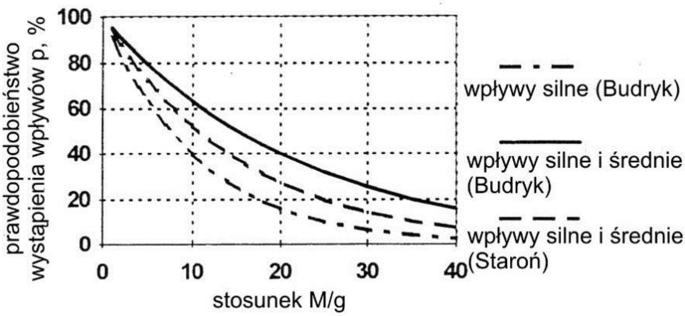


Fig. 2.6. The relationship between the ratio of the safe distance *M* between the beds and the thickness of the pick-up deck *g* and the probability of influences *p* according to Budryk and Staroń; -·-·-– strong influence (Budryk), —— - medium and strength influence, ---- medium and strength influence

3. Examples of calculations

3.1. Influence of undermining a 40I/D bed by mining the 41J bed

For the calculation of the influence of undermining the 41J bed by longwall 7-2 on the 40I/D bed, the following constant values were determined:

- bed 41I longwall 7-2,
- mining depth H=815÷850 m,
- bed thickness g_w=1.5÷2.2 m,
- height of the mining face g=2.2m,
- rock loosening coefficient k_r=1.23 (for clay and sandy shales after Fig. 2.2),
- the smallest assumed distance between the mined and undermined bed M_H=20 m.

Received results:

- required distance between mined and undermined beds:
  according to Chudek - Olaszowski (Fig. 2.1) M=15 m,
  according to Staroń (Fig. 2.2) M=13m,
  according to Staroń (Fig. 2.1) for k_r=1.23, ratio M/g=6.45, and M=14.2 m;
- probability of loosening the undermined bed:
  according to Budryk and Bes (strong influences) p=43%,

according to Budryk and Bes (medium and strong influences) p=66%,

according to Staroń (medium and strong influences) p=55%.

Analysis of results

I. The calculated values of the required minimum distance between 41J and 40I/D beds are smaller than the actual distance between both beds.

II. Comparing the obtained values with the data from observations carried out in Polish coal mines, it turns out that strong influences occurred when:

- the distance between the mined and undermined beds was less than five times the thickness of the mined bed,
- the probability of strong influences using the Budryk method was 65% higher,
- the probability of occurrence of strong and medium influences according to Budryk is equal to- or greater than 80%,
- probability of strong and medium influences according to Staroń is greater than 70%.

The distance between mined and undermined beds is much greater than 5 times the thickness of the mined bed ($5g$=11 m (12.5 m)), e.g. for B15E/1983, the distance between the 40I/D and 40I/C beds is about 36.4 m), and the obtained probability of influences p values are less than *borderline*. Therefore, strong influences should not be expected.

Average influences observed in coal mines appeared if the distance between the mined and undermined beds was in the range of 5÷7 times the thickness of the undermined bed, when:

- the probability of strong influences according to Budryk is equal to 50% to 65%,
- probability of occurrence of medium and strong influences according to Budryk from 70% to 80%,
- probability of medium and strong influences according to Staroń from 60% to 70% (Fig. 3.1).

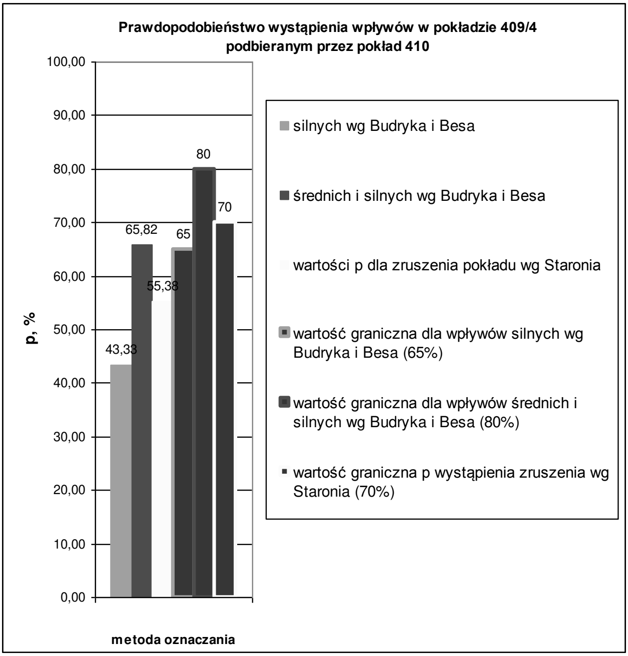


Fig. 3.1. The probability of influence *p* in the 40I/D bed undermined by 41J bed calculated by methods proposed by various authors (Budryk, Bes and Staroń); red (3 right bars) indicates the maximum "safe" p-values for the conditions in Polish coal mines and for the distance between the mined and undermined bed M_{minp} 5÷7

The obtained probability values of influences *p* are smaller than the *allowable* ones. Therefore, small, only locally medium influences are to be expected, which may cause slight folding of the bed floor and its cracking; these changes should not cause difficulties in the mining of the 40I/D bed.

3.2. Influence of undermining a 40I/C by mining the 2nd layer of 40I/D bed

For the calculation of the influence of the mining of the 41J bed with the G-B longwall on the 40I/D bed, the following fixed values were adopted:

- bed 40I/D lonwalls G-B, G-D, G-F, G-Fa,
- mining depth *H* (see Table 3.1),

- thickness of strata g_w,
- height of the longwall face g=3.0 m,
- loosening coefficient k_r=1.23 (for clay and sandy shales according to Fig. 2.2),
- smallest assumed distance between the mined and unmined beds M_H=18 m.

Tab. 3.1

Basic data on the mining of the 40I/D bed.

Bed	Longwall	Mining depth H, m		Longwall face height g, m		
		min	max	min	max	2nd layer (underfloor)
40I/D	G-B	775	835	3.80	5.00	3.00
	G-D	800	875	4.00	5.20	
	G-F	830	890	4.70	5.20	
	G-Fa	860	940	4.20	4.60	

Received results:

- required distance between mined 40I/D and undermined 40I/C beds:
- according to Chudek - Olaszowski (Fig. 2.1) M=20m,
- according to Staroń (Fig. 2.2) M=17.7m,
- according to Staroń (Fig. 2.1) for k_r=1.23, the ratio M/g=6.45, and M=19.35m;
- probability of loosening the undermined bed (Fig. 3.2):
- according to Budryk and Bes (strong influences) p=57.6%,
- according to Budryk and Bes (medium and strong influences) for the longwall probability p=75.9%,
- according to Staroń (medium and strong influences) p=67.7%.

Analysis of results

I. Based on exploratory borehole (e.g. B15E/1983), it was found that the distance between 40I/C and 41J/D beds ranges from about 18.0m to about 21.8m. Calculated values of the required minimum distance between 41J and 40I/D beds M is in the lower and middle parts of this range.

II. Comparing the obtained values with the data from observations carried out in Polish coal mines, it turns out that strong influences occurred when:

- the distance between the mined and undermined beds was less than five times the thickness of the mined bed,
- the probability of strong influences *p* using the Budryk method was 65% higher,
- the probability of occurrence of strong and medium influences *p* according to Budryk is equal to or greater than 80%,
- probability of strong and medium influences *p* according to Staroń is greater than 70%.

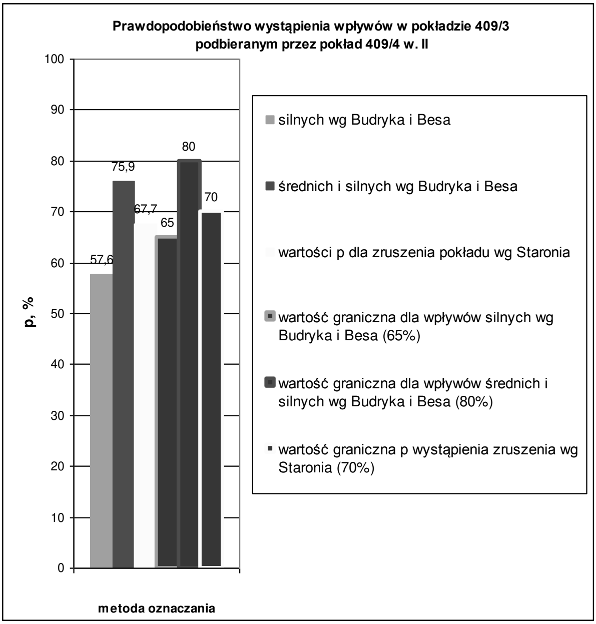


Fig. 3.2. Probability of occurrence of influences *p* in the 40I/C undermined bed by the 2nd layer of 40I/D bed calculated by methods proposed by various authors (Budryk, Bes and Staroń); red (3 bars on the right) indicates the maximum *safe* *p*-values for conditions in Polish mines and for the distance between the mined and undermined bed M_{minp} 5÷7

The distance between the mined and undermined beds is greater than 5 times the thickness of the mined bed (5*g*=15m), and the obtained probability *p* values are smaller than the *limit* values. Therefore, strong influences should not be expected.

Average influences observed in coal mines appeared if the distance between the mined and undermined beds was within the range of 5 to 7 times the thickness of the mined bed, when:

- the probability p of strong influences according to Budryk is equal to 50% to 65%,
- probability p of occurrence of medium and strong influences according to Budryk is 70% to 80%,
- probability p of medium and strong influences according to Staroń is from 60% to 70%.

The obtained probability values p belong to the central part of the *border* intervals. Therefore, at most average influences should be expected. They may cause folding of the 40I/C bed floor and its cracking, however, these changes should not cause significant difficulties in the mining the 40I/C bed.

3.3. A short numerical simulation of the influence of undermining a higher lying bed

In order to assess phenomenon of influence of undermining the bed uplying the bed below it, a simplified numerical rock mass model 1500m (W) × 300m (H_m) was built. A program FLAC v.5.0 based on the finite difference method (Itasca Consulting Groups, US) was used. The program has already been described many times. The part of rock mass was loaded by applying a vertical stress component σ_z equal to 11.0MPa to the upper edge, simulating the rock layers lying above. Two coal beds lay at a depth of -660.0m and -687.5m (floor). The thickness of both beds was 2.5m. The distance between two beds M_v was 25.0m, i.e. 10g. The rock mass was described by Coulomb-Mohr criterion. Rocks were assigned material properties characteristic of the Carboniferous sedimentary rocks of the Upper Silesian Coal Basin.

Mining with roof layers caving was simulated for mining face progress up to 600m. Figures 3.3-3.6 show selected maps of the maximum principal stresses σ_1 (which can be related to vertical stresses σ_z, Figures 3.3*a* and 3.6*a*) and damage zones in the rock mass (Figures 3.3*b*, 3.4, 3.5, 3.6*b* and *c*).

a

b

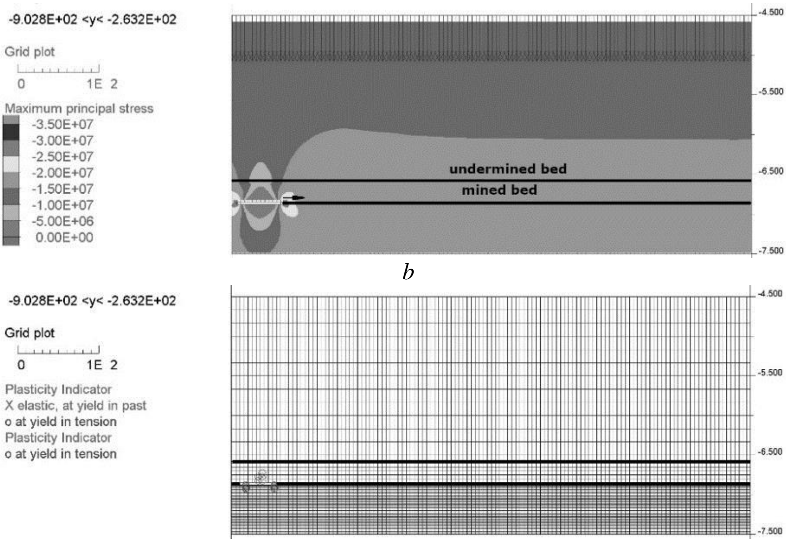


Fig. 3.3. Distribution of principal stress σ_1 (*a*) and damage zones (*b*) after face progress of the bed over a length of 50m; zones of plasticity and exceeding the tensile strength in Figure b have been marked with the signs ○ and ×

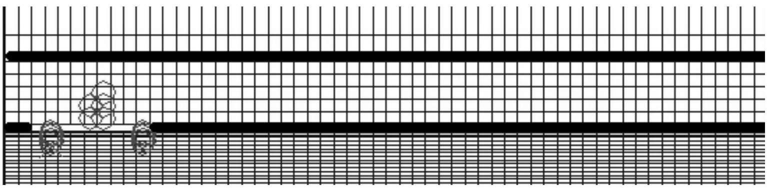


Fig. 3.4. Local view after face progress of the mined bed a length of 50m; zones of plasticity and exceeding of the tensile strength were marked with the signs ○ and ×

Limiting the comment to the range of rock mass damage zones above the mined bed, it should be stated that after exceeding the face progress length of 300 m, the damage zones covered the undermined bed. After the *finishing* of the 600 m mining, the damage zones reached 100 m above the mined bed and covered the entire undermined bed.

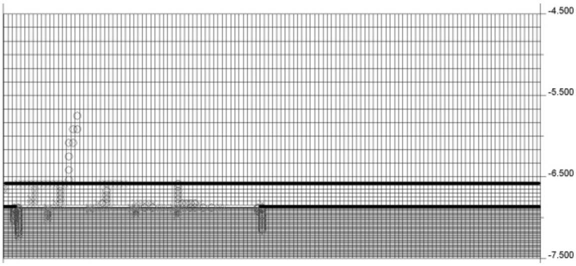
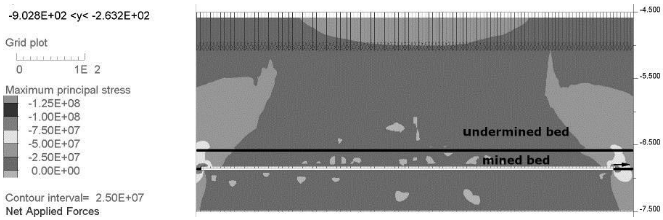


Fig. 3.5. Global view after face progress the mined bed over a length of 300m; places of plasticity and exceeding of the tensile strength were marked with the signs ○ and ×

a



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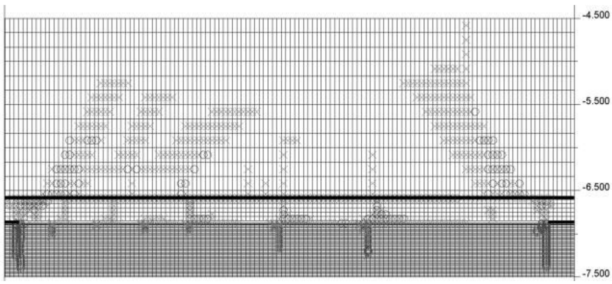

c

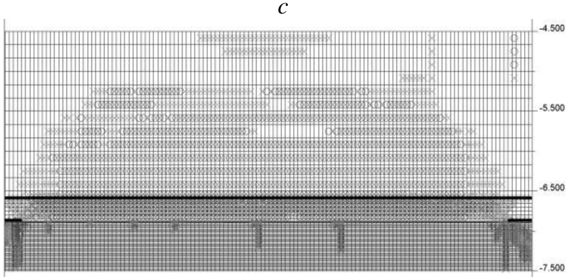

Fig. 3.6. Distribution of principal stresses σ_1 (*a*) and damage zones immediately after face progress of the mined bed over a length of 600 m (*b*) and the rock mass in equilibrium state (*c*); places of plasticity and exceeding the tensile strength in Figures *b* and c have been marked with the signs ○ and ×

The numerical model does not take into account the *support* of the filled post-mining void in caving zone- it was not *artificially* filled by adding blocks.

The obtained simulation results indicate that the extent of the damage zone above the mined bed is less directly affected by the strength and deformation properties of the rocks, and the process of filling the post-mining cavity void influenced critically.

4. Summary and final remarks

Undermining the 40I/D bed by mined the 41J bed should not result in significant influence on the 40I/D bed. The calculated values of the required minimum distance *M* between the beds (41J and 40I/D) is smaller than the actual distance between the two beds. Only small and locally medium influences may occur which may cause slight folding of the bed floor and its cracking; these changes should not cause difficulties in the mining the 40I/D bed.

Undermining the 40I/C bed by a longwall by mining the 2nd layer 40D/D bed will have some effect on the 40I/C bed. The calculated values of the required minimum distance *M* between the 40I/D and 40I/C beds is in the range of the actual distance between the two beds. The calculated values of the probability p of loosening the undermined bed indicate that there will probably be average influences. They may cause folding of the 40I/C bed floor and its cracking, however, these changes should not cause significant difficulties in the possible mining the 40I/C bed.

Due to the complexity of the problem of determining influences by the mined bed on the undermined bed, it is advisable to more completely determine the strength properties, including uniaxial tensile strength R_r and deformation properties, including Young's modulus *E* and Poisson's ratio □ for rocks lying between both beds and making mining computer simulation of both beds.

In turn, the numerical simulation results indicate that the extent of the damage zone above the mined bed is less directly affected by the strength and deformation properties of the rocks, and the process of filling the post-mining cavity void influenced critically.

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