Safety of longwall mining with caving in the light of data from monitoring systems

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Abstract. Shield supports are usually perceived as devices consisting mainly of mechanical and hydraulic parts, while other apparatus, mainly related to electronics, is often treated as a necessary supplement to the system which ensures its control. However, the development of features closely related to the latest electronic equipment in the mining complexes, mainly connected with measuring and registration possibilities, also allows for more and more frequent use of various types of monitoring. It enables observation of the operation of the mining complex in real time or with a slight time delay. What is more, it also enables signalling the operating states of the shield constituting specific threats or irregularities. The most advanced systems found abroad are equipped with functions analysing changes in specific monitored parameters to develop warnings about possible future threats to allow the operator to react with sufficient time in advance. Developing such a forecast system requires gathering and then analysing a sufficiently large and complete database of measurements and observations. These are primarily associated with various difficulties in operating a shield support, and especially with strictly emergency states, such as rock slides, shield clamping conditions, etc. The developed warning identifiers also depend on the mining and geological situation of the specific mining panel. The monitoring currently used, concerning a part of the mining complex related to the shield support, mainly concerns the pressures in the hydraulic props of the shield and the measure of the shifter advance. It allows determining the position of the section on the longwall panel length. The current instantaneous shield geometry and dimensions of the excavation itself, such as height, setting and inclination, are determined in situ much less often. The information obtained is often also sent to the surface of the mine. The data from monitoring of shield support operation, through proper development of dependencies and analysis results, can optimize the safety of crew, reduce difficulties in maintaining the roof of longwall excavations and thus have a positive impact on the obtained economic results.

1. Introduction

The purpose of shield support, in brief, is its cooperation with the roof as a result of developing adequate bearing capacity and impact on maintaining proper excavation stability. These factors are also dependent on the specific geological and mining conditions characterizing the given mining panel. The selection of a particular type of shield support is usually made earlier by means of analytical calculations. In Poland, for example, the most often used for this purpose is the calculation method based on the theory of deflection of floor layers, developed by A. Biliński [1], which is still being further developed at GIG (determination of roof bearing capacity index ‘g’).
Each analytical calculation of the shield support selection always aims to calculate a specific value of the support bearing capacity resulting from its design parameters and the adoption of the excavation dimensions, which has a significant impact on the value of rock mass loading. Until the appearance of effective monitoring systems for shield support operating parameters, it was not possible to verify these assumptions with the conditions of actual operation. Only selected random control measurements were carried out, which were performed sporadically, usually of a modest range during occasional measuring actions. Only when electronic measurements of process parameters could be carried out over a period of time in the range of seconds and concern all or most of the shields, one can speak of effective observation of the operation of the shield support.

Pressure measurements under the piston of hydraulic props of shield support against the time axis are the basic source of information determining the support bearing capacity. In order to determine accurately the bearing capacity of the shield, it is necessary to determine its current geometry. However, due to the high complexity and costs of such measurements during mining, they are very rarely implemented. In order to understand how the shield support works it is necessary to present the operation cycle of the shield.

Most often, measurements of pressure in the sub-piston parts of props and their courses refer to the reference pressure pattern shown in the Figure 1.

![Figure 1. The course of pressure changes in the props during the shield support cycle [2].](image)

Section 0-s corresponds to the period of support setting, followed by the increase of the bearing capacity in the section s-a, caused by the increase in load due to the yielding of the neighbouring shield. Then, a fairly stable and long period of increase in the rock mass pressure in the section a-b begins. The section b-c shows the influence of the increasing load, as a result of coal cutting to the height of the shield, thereby increasing the extent of the excavation. However, the fast-growing section c-d shows the increase in pressure associated with yielding of the neighbouring shield. Section d-e shows a sharp drop in the pressure during yielding.

In mining practice, the speed of changes, pressure values, times of particular sections can be subject to large fluctuations, depending on many factors of a geological, mining and technical nature. According to our previous measurement experience, the values for the extreme points of the s-a section are difficult to be clearly identified/obtained, due to the very variable shape of the pressure courses during the setting of shield in our mines – generally, due to too low setting pressure (low initial bearing capacity), most common in cases of manual setting of shields in shearer longwalls. On the other hand, in the case of plough longwalls, the shield support is usually run automatically, and the used shield advance algorithms do not always require sequential, subsequent section advance, therefore specific sections may be subject to changes in relation to the presented, model cycle of shield support in the shearer longwalls.

The presented model course can also be changed and supplemented with phenomena such as periods of operation of working valves initiated with pressure drops from the maximum level (subsequent sections of changes similar to the ‘saw teeth shape”) or with rapid pressure increases due to loads (dynamic phenomena) from the rock mass, initiated by sudden increases in pressure. In cases of individual phenomena, e.g. breaking of rock layers, changes in the corresponding shapes of pressure changes will also be of a one-off, non-periodic nature.

The basic function of the advanced monitoring system is therefore the possibility of using an algorithm for effective identification of all shield operation cycles (based on pressure changes - or e.g.
hypothesized apparatus signalling of the beginning and end of the cycle) in accordance with the presented diagram of shield support cycle, and possible described changes and modifications that complement it. On the basis of cycle parameters (time and values) determined on its basis, it is only possible to build algorithms for automatic recognition of emergency states and hazards (assuming appropriate limit values for permissible changes). Another issue, after statistical analysis of sets (possibly numerous) of such events, and linking them to various types of obstacles occurring during exploitation, constructing threat prediction system.

Earlier systems, which have less frequent pressure measurements, are less useful for identifying hazards; however, some interesting information can be obtained from them.

2. Example of threat monitoring using systems with smaller frequency of measurements

Longwall A was run at a depth from about 440 m to 530 m, where the seam had a gross thickness of 3.3 to 5.3 m, and its inclination ranged from 15° to 25°. In the roof of the seam there was a layer of slate with coal up to 0.3 m thick, followed by a thin layer of coal as well as claystone and sandy claystone. Above there was a group of strata consisting of mudstone-sandstone layers (7 ÷ 17) m thick.

The floor of the seam was a layer of slate with coal with an underlying claystone. Nevertheless, due to the large variability of the thickness of the seam on the longwall panel length, it was run along coal bottom.

The uniaxial compressive strength (UCS) of both, coal in the seam and the rocks surrounding the seam was characterized by considerable variability.

The compressive strength UCS of the coal seam and surrounding rocks were within the ranges of:

- coal of the seam (7.1 ÷ 10.0) MPa,
- roof of the seam
  - laboratory testing (37.1 ÷ 56.8) MPa,
  - in-situ testing (0.0 ÷ 65.4) MPa,
- floor of the seam (22.8 ÷ 31.4) MPa.

In the analysed longwall panel, disturbances were expected in the seam and surrounding rocks of both sedimentation and tectonic character, causing changes in the thickness of the seam and changes in the stability of the roof rocks. Difficulties in maintaining the roof also occurred locally, which was associated with a deposition of a thin layer of rocks in the direct roof prone to falling after its exposure. It was also found that above the seam numerous mining exploitations were carried out, which also had a significant impact on the roof conditions.

Longall A was run with the longitudinal system with a caving of roof rocks, on the longwall panel length of around 670 m. The width of the longwall was up to 250 m.

In longwall A, the mine used shields with a working height of up to 4.4 m. This shield support was a support and shield structure based on an articulated quadrangle with a lemniscate canopy stabilization system.

The measurement system enabled the pressure measurements to be made with an accuracy of 1 MPa with a frequency of 1 minute in each of the props of all the shields. During the yielding of the shield, measurements were not carried out. Parameters of the system allowed conducting measurements of pressure under the piston of the props in essentially only static conditions. Pressure measurements covered a quantitative range of 160 shields during 208 measurement days.

The measured pressure values under the pistons of the props were referred to the area of the longwall panel as shown in Figure 2. On the chart, a single colourful point with its size corresponds to the widths of the shield over the 1m length of the run. In order to determine the location of the shield, data from the average monthly advance on the mine maps was used.

In places of maximum pressure, maximum loads could be expected from the rock mass during mining operations (which powered support was subjected to), provided that the same working height of the shield and the size of the excavation was maintained. Pressure variation in longwall panel is illustrated in Figures 2 and 3.
Figure 2. Maximum values of pressures in the area of longwall A with designated fragments of longwall run.

Figure 3. Average maximum values of pressures over the width of longwall A on the marked sections of longwall run.

For three fragments of the longwall A run, where significant variability of pressures at the length of the longwall was observed, marked and limited by lines in brown, green and purple in Figure 2, the average pressure for each shield was calculated and shown in Figure 3 in the form of coloured points. The curves in the same colours were plotted with moving averages computed for four neighbouring shields. However, shorter sections determined from linear regression calculations are additionally marked with fragments of the longwall length characteristic for the pressure levels.
For the ‘brown’ section of the run, the average variation of the measured pressure levels between section groups 35 ÷ 85 and 102 ÷ 132 reaches about 81 bar (336 bar and 255 bar respectively), while for the ‘green’ fragment of the run, the average variability of measured pressure levels between groups section 55 ÷ 85 and 125 ÷ 150 reaches about 101 bar (223 bar and 324 bar, respectively). On the purple part of the run, in the section group 25 ÷ 140, the average pressure increases practically uniformly from about 313 bar to 359 bar.

Such an analysis during monitoring may enable determination of areas of variable rock mass loads caused by different floor conditions.

It can further be noted that generally at the longwall ends there are lower pressure values relative to the central part of the longwall. The phenomenon of occurrence of higher loads in the central part of the longwall is represented in many theories and confirmed by means of measurements.

3. Examples of monitoring threats using the identification of measuring cycles in shearer longwalls

Longwall B was run with a roof caving in the seam with a maximum depth of 845 m, with layers inclination from about 16° to 30°. Mainly claystone was located above the seam, locally there were mudstone or sandstone rocks directly in the roof. The floor was a claystone.

According to the obtained data (the longwall was run along coal bottom), the strength of UCS of coal seam and surrounding rocks was:
- coal of the seam 14.9 MPa,
- natural roof of the seam (21.8 ÷ 33.8) MPa,
- floor (coal bottom) 14.9 MPa.

In the exploitation panel of longwall B, in the distance up to 160 m above the seam and below, up to a depth of 60 m, operation has not been carried out so far.

Longwall B was run with a roof caving, with a maximum height (2.8 ÷ 3.0) m, in one-sided vicinity of the goaf. The run of longwall 2 reached about 470 m, and its width was about (190 ÷ 210) m.

Shield support with a working height of up to 4.5 m was used in longwall B.

The measurement system enabled the pressure measurements to be carried out with an accuracy of up to 1 MPa with a frequency of up to 5 seconds in each of the props of all powered support shields. Pressure measurements covered the volume range of 135 shields. The parameters of the measurement system already allow tracking the cycles of the support with a higher frequency (every 5s); however, events that are shorter than 5 seconds may still not be identified.

During the start-up and at the beginning of the longwall run, the courses indicating a decrease in pressure after setting the support, as in Figure 4, there was also the fall of floor layers.

![Figure 4](source FAMUR)
A staff congress was organized for the longwall B excavation to assess the situation and further analyses related to pressure courses were conducted. The reasons for the difficulties were complications related to the unfinished longwall start-up and the carelessness of shield setting. On further fragments of the longwall run, and with careful running the interlayer and setting the support, the support cycles obtained the correct form, as in Figure 5.

![Figure 5. The exemplary course of correct pressure values on longwall B after start-up.](image)

During pressure observations in the hydraulic props, it was possible to notice locally operating periods of working valves resulting from floor conditions, as shown in Figure 6, in the form of ‘saw-shape’ pressure courses before yielding. Another identified phenomenon was the shield groups with increasing or decreasing pressure. The most likely cause of sequential pressure changes were differences in the load of breaking sandstone strata in the direct roof, as in Figure 7.

![Figure 6. Example pressure waveforms during operation of valves in longwall B.](image)
Figure 7. The exemplary course of pressure values presenting the sequence of pressure lowering in longwall B.

4. Examples of threat monitoring using the identification of measuring cycles in plough longwalls

Difficulties associated with the roof maintenance, manifesting themselves in numerous falls of its layers, were noted in the plough longwall C. Due to the similarity of strength characteristics to the longwall D, where the situation was correct and the longwall advance was extremely high, it was decided to compare data from both shield support monitoring systems regarding a single selected measurement day from each mine.

The obstacles in longwall C are illustrated in Figure 8, which indicates the shield numbers at which the roof fall was observed.

Figure 8. Location of obstacles in longwall C.

Then, the pressure courses for these groups of shields are presented, for one day, in spatial form in Figure 9, where the pressures on the vertical axis are expressed in bars.
Figure 9. Spatial graph of pressure in longwall C.

Significant differences in the developed pressure can be easily observed between the neighbouring shields. Roof fall was located in areas of reduced pressure. For comparison, spatial charts from longwall D, where the situation was very favourable, are presented in Figure 10.

Figure 10. Spatial graph of pressure in longwall D.

Not only a much more even pressure distribution between adjacent sections can be noticed, but also a significantly higher pressure level in general. Pressure differences can be explained to a small extent by slightly different strength conditions and parameters of the types of shield supports used. However, it was difficult to accurately estimate them due to the lack of clearly documented data related to, among others the temporary height of operation in both longwalls. It seems, however, that the main reason for the difficulties in longwall C was the very large diversity of maintained pressures (and thus bearing capacity) between adjacent sections, with their quite low average level calculated along the width of the longwall.
5. Conclusions
Based on the examples and analyses presented, the following comments can be made:
1. The scope of signalling of possible difficulties is closely related to the technical capabilities and the monitoring software used.
2. Nevertheless, any properly used monitoring system can provide valuable information on the mining process being conducted.
3. Simple observations of measured pressure levels can easily eliminate basic difficulties related to, e.g. insufficient shield setting at the interlayer or lack of tightness of props.
4. Signalling of operating states with a higher level of complexity requires the determination of a set of limit values for the measured parameters needed to initiate specific warnings. Responsible designation requires the collection of an appropriate measurement and observation database as well as an appropriate analysis to identify them.
5. One can observe a natural desire not to share knowledge about the difficulties occurring during longwall mining. However, in this way we clearly limit the scope of analysis of such states. The question remains whether it possible to achieve a different way of thinking and acting so that knowledge about the possible threats would become the dominant value?
6. Monitoring of shield support and proper data analysis can provide a lot of useful information improving work safety and efficiency of the mining process.

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