Geophysical and geomechanical analysis of coal mass condition during directional hydraulic fracturing (DHF)

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Abstract. The article reveals the information about the technology of roof rock directional hydraulic fracturing (DHF) performance when the longwall face was operating under tough roof conditions. The authors justify the application of the DHF method. They developed a scheme for roof softening under mining and geological conditions of mine Yubileynaya. The article presents the description of technological processes during DHF implementation and gives the list of general and special tools used during the process. Based on the results of the measures taken, the authors made a conclusion in relation to the efficiency of the performed work. The authors assessed the qualitative characteristics of the measures aimed at roof softening. They implemented the approach to active roof physical and mechanical characteristics determination based on seismic survey data analysis.

1. Introduction

At present day longwall coal mining, when the working face is equipped with a high-performance mechanized complex, is the most wide spread system of underground mining. Increase in its application area during last years is due to extraction of seams having tough roofs which makes mining more complicated. Dynamic roof falls have adverse effect on safety during mining, destroy machines, equipment and workings. Moreover, poor roof caving leads to mining pressure concentration on coal masses near the working face and the place where it joins the workings. This results in mine workings destruction and, consequently, leads to interruption in normal operation of production units, as well as to disruptions in face ventilation mode.

It is a fact that longwall face poor roof caving, where it is joined with ventilation working and belt roadway, forms vast empty areas under the hanging roof where methane accumulates. Besides, a part of fresh air current which should ventilate the working face goes to the gob. As a result, the estimated amount of air is not supplied to the working face leading to emergency shut downs due to exceed in methane maximum concentration limit and, consequently, results in the reduced productivity. Horizontal stresses increase due to main roof poor caving after the previous longwall face mining which leads to forcing coal pillars into the workings [1,2] (figure 1).
2. Main part
Industrial experimental works aimed at introduction of directional hydraulic fracturing technology during working face operation under the conditions of tough roof have been taking place in Kuzbass [1,2]. Roof softening has been performed in relation to the mining and geological conditions of longwall face 16-19 of seam 16 in a mine area of “Yubileynaya” Mine” Ltd. extraction section.

The main roof of seam 16 is tough. It consists of siltstones having the size from fine grain to coarse grain, as well as fine grain sandstone. Rock hardness of siltstone varies from 3 to 9 according to Podyakov scale, while sandstones have hardness from 6.0 to 12.0. The thickness of the immediate roof represented by fine and coarse siltstone is mainly from 2.0 to 3.0 meters. The depth of mining is 345 meters. Seam 16 is prone to sudden coal and gas outbursts, coal displacement, and dynamic destruction of bedrock starting from 268 meter deep point. It is hazardous in relation to rock bumps from the depth of 400 meters.

Thus, poor caving of tough roof on vast areas in places where there are junctions with development openings leads to increase in stress in end sections of coal and rock mass. To reduce negative impact of high ground pressure on sustainability of mine workings with tough roof, the authors decided to use DHF method for its softening [7].

In collaboration with mine Yubileynaya technical service workers the personnel of the Federal Research Center of Coal and Coal Chemistry of the Siberian Branch of the Russian Academy of Sciences according to the “Instruction on the method and parameters for roof softening in working
areas” the authors developed a DHF technological scheme to guarantee timely and stable roof caving after working face advance (figure 2-4) [4]. The effective depth of the boreholes was 7.8 meters.

**Figure 2.** Process diagram of borehole placement for DHF implementation after the mechanical complex removal from the installation chamber.

**Figure 3.** Vertical scheme of borehole placement for implementation of DHF from airway 16-19 (cross section A-A).
Implementation of directional hydraulic fracturing was performed using both standard and special mining equipment. Borehole drilling and initiation crack cutting was performed using pneumatic drill roof bolt setter. The authors used 46 mm rock drilling crowns to drill boreholes. Initiation cracks were drilled using mechanical crack initiation devices (figure 5), which were set on the rock drill bars instead of the crown [6].

Area near the initiating crack was sealed using hydraulic sealer of “Taurus” type (figure 6). The sealer was forced into the borehole face by means of a special high-pressure pipe set. The compression unit was joined with the end of the pipe protruding from the borehole using special collector (adapter) by means of high-pressure flexible hoses. Pumping of liquid into the initiation crack was performed using high-pressure station of the mechanized complex.
Control over drilling efficiency and measures taken within DHF was maintained using video endoscope which, as a result, helped the authors find out that the boreholes were drilled down to the estimated depth, and that there is an initiation crack in the face of each borehole (figure 7).

First of all, hydraulic fracturing was made in the vertical boreholes where artificial cracks spread parallel to the formation, then in the inclined ones the cracks developed at an angle to the formation where the artificial crack spread up to the border between the immediate and main roofs and with its further development along the contact line (figure 4). When the liquid has been supplied into the borehole the roof hydraulic fracturing process started 5 – 10 minutes after the emulsion has been pumped into the system. During this process there was a sharp pressure decrease on the manometer in the area of the initiation crack [8,9].

![Figure 6. Sealer “Taurus”: a) exterior view; b) its placement in the mine working.](image1)

![Figure 7. A borehole with initiation crack before the hydraulic fracturing: a) video endoscope; b) borehole mouth; c) borehole face.](image2)

To assess the efficiency of the measures taken within the scope of work aimed at roof softening, in the particular part of the extraction column near pickets 55-64 the authors analyzed the changes in its condition as a result of hydraulic fracturing in two boreholes based on seismic examination using transmitting waves [10-11]. In comparison with, for example, the registration of immediate changes in coal seam gas release at hydraulic fracturing implementation [12,14], seismic survey makes it possible
to determine spatial boundaries of hydrodynamic impact on adjacent strata. The process of seismic examination of extraction column part included taking measurements in the mine (gridding, placement of seismograph equipment, signal initiation and registration) and office work (preparation of initial data, processing, analysis and interpretation of the data). Measurements were taken in the mine on three stages: 1 – registration of the data obtained during seismic survey for the extraction column part, which was not affected by hydraulic fracturing; 2 – registration of information for the same part after hydraulic fracturing in borehole No. 1; 3 – registration of seismic information for that area after hydraulic fracturing implementation in borehole No. 2. This sequence of operating procedures made it possible to assess how the characteristics of seismic signal changed by means of direct comparison as a result of changes in roof.

The registration of seismic data was made on the bases of linear interval placement of seismic sensors (geophones) on the wall of a working, which were connected with autonomous seismic recording system “R-1” [15]. To initiate elastic seismic waves in the mine according to safety regulations, the authors used mechanical shock vibration sources complemented by the time break system. Seismic recorders and time break system were synchronized just before taking measurements. Mistiming between the synchronized devices was not more than 1 ms / 24 hours.

The interval between the pickets receiving and initiating elastic vibrations within the walls of airway and belt entry was 10 meters. Gridding of measurement systems to real conditions of the extraction column was made on the bases of mining plan and actual placement of mine workings and mine facilities. Data registration was performed with discretization interval equal 1 ms in continuous-wave mode with filtration on 500 Hz cut-off frequency in the separate files which consisted of 3 600 000 counts.

To assess measurement of physical and mechanical characteristics of the seam active roof the authors analyzed speed tomographic slices of the investigated site obtained taking into account the transmitted wave propagation time and reflecting physical and mechanical roof properties before and after hydraulic fracturing [15]. Based on the analysis of the initial velocities of seismic wave propagation in the roof which was not affected by hydraulic fracturing, the authors registered higher speed background (figure 8a). The registered speed change interval 3,15-3,4 km/sec probably corresponds to the active roof which consists of tough strained siltstone in the condition close to tough one. Within belt heading near PK 59-60 there is an area with decreased seismic wave speed – “1”. In the interval PK 59-60 within the airway there is an area where seismic waves are reduced insufficiently – “2”. Such an area is also present within the area near pickets PK 55-57 (between the mine roadways) – “3”.

On the tomographic slice of the investigated roof part which had been changed as result of hydraulic fracturing in borehole 1 general speed background compared to the initial state is reduced (figure 8b). Minimum speeds were registered in areas “1” (PK 59-60 in the belt roadway), “2” (PK 58-60 in the airway), “3” (within the area near PK 55-57) between the mine roadways). On the tomographic slice of the investigated roof part which had been changed as result of hydraulic fracturing in borehole 2 the speed background is sufficiently lower than in the roof in its initial condition (figure 8c). And the changes in wave propagation velocity in areas “1”, “2”, “3” are minimal.

Sharp changes in seismic wave propagation velocities are registered almost in all investigated area apart from areas “1”, “2”, “3”, where they are insignificant. Minimum velocities were registered in areas “4” and “5” which were located within the intervals PK 55-56 and PK 63-64 in the belt roadway and “6” within the interval of PK 55-57 in the airway. In general, according to the results of seismotomographic slices assessment the authors determined the following signs of roof stress relief caused by hydraulic fracturing: general velocity background was reduced, spread of areas with reduced seismic wave velocity within the extraction column, emerging of areas with increased fracturing which have minimum seismic wave velocities such as areas “4” – “6” [16-17].
Figure 8. Visual representation of propagating wave velocity changes in the active roof due to hydraulic fracturing: a) spread of velocity characteristics before hydraulic fracturing; b) spread of velocity characteristics after hydraulic fracturing in borehole 1; c) spread of velocity characteristics after hydraulic fracturing in borehole 2.

For additional assessment of the performed hydraulic fracturing parameters the authors prepared a complex tomographic slice which showed the change in the ratio of the seismic wave propagation velocity in the intact roof of the investigated area of the extraction column to the wave propagation velocity in the roof of the investigated area which was changed after hydraulic fracturing:

\[ \beta = \frac{V_{n-1}}{V_n} - 1, \]

where \( V_{n-1} \) - velocity of wave propagation in the previous measurement; \( V_n \) - velocity of wave propagation in the next measurement.

On the tomographic slice \( \beta_{V1-3} = \frac{V_1}{V_3} \) (figure 9) the authors determined the roof stress relief induced by the performed hydraulic fracturing in boreholes 1-2. The changes in parameter \( \beta_{V1-3} \) were recorded in the whole investigated area. Minimum values were recorded in vast area “D” which was spread along the whole interval of the measured area of the extraction column – 90.

Figure 9. Seismographic slice reflecting the roof rock relief level determined by the correlation between wave propagation velocity in the roof before and after hydraulic fracturing.
In general, according to the results of seismic survey in the investigated area of the active roof, the authors confirmed that the performed hydraulic fracturing made in boreholes 1 and 2 had different impact. Besides, they did not register any negative influence in the investigated area which could have resulted from hydrodynamic impact on the roof.

3. Conclusion
Thus, the authors determined that roof softening by means of hydraulic fracturing, when the mechanical complex was taken out of the installation chamber, made it possible to implement safe initial roof caving. Moreover, there was no enhanced gas release which takes place when there is a sudden “instantaneous” gas displacement from the gob that usually happens when there is a simultaneous main roof rock fall which had been hanging on vast areas. The authors determined that the value of the relative stress coefficient in the end sections of coal seam decreased after directional hydraulic fracturing. That demonstrates that the stresses were redistributed in the coal and rock mass. The results of the performed seismic monitoring confirm the efficiency of the hydraulic fracturing conducted in the seam roof within the scope of work aimed at roof softening to guarantee safe operation of the working area. The registered changes in the geomechanical roof state are characterized by the decrease of the general velocity background, spread of the existing areas and emerging of new zones with reduced seismic wave velocity. The authors also determined that the total stress relief for two hydraulic fracturing boreholes, expressed through changes in the energy characteristics of the seismic signal, is not limited only to section PK 55-64 (90 m) and is noticeable in bigger area of the roof extraction column.

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