Assessment of elastic seismoacoustic vibration propagation through coal and rock mass within the extraction column during directional hydraulic fracturing (DHF) implementation

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Abstract. The article reveals information about implementation of roof rock directional hydraulic fracturing technology when face was advancing under tough roof. The authors justify application of directional hydraulic fracturing. They developed the scheme for roof softening considering mining and geological conditions of “Esaulskaya” mine. The authors describe technological process taking place during implementation of directional hydraulic fracturing and give the list of the applied general and specialized equipment. Considering the results of the performed operations the authors made a conclusion in relation to the effectiveness of the conducted work. They assessed the qualitative characteristics of the performed activities aimed at roof softening. The authors determined physical and mechanical characteristics of the active roof on the basis of seismic survey data analysis.

1. Introduction
At present moment long pile mining which implies providing high-performance powered mining complex in working faces is the most wide spread coal field underground development system. The sphere of its application has grown during recent years due to mining of seams with tough roofs which makes longwall work significantly more complicated. Dynamic roof caving threatens mining safety, destroys equipment, machinery and workings. Besides, poor roof caving leads to concentration of rock pressure on unworked coal in the working face area and in places where the working face crosses the workings. That results in destruction of mine workings and, accordingly, disrupts standard operating conditions in the development mining sections and destabilizes face ventilation modes.

It is common knowledge that poor caving of longwall face roof rock where it is linked with airway and conveyor roadway promotes formation of vast cavities under the hanging roof where methane accumulates. Besides, a part of fresh air current that should ventilate the working face goes to gob. As a result, working face is not supplied with the estimated amount of air, which in its turn leads to emergency shut down due to exceeding threshold limit value of methane, and as a consequence, that brings about lower productivity. Increase of horizontal stress due to poor main roof caving after extraction of the previous panel leads to destruction of coal pillars and their fall in the workings [1, 2] (figure 1).
2. Main Part

Industrial experimental works aimed at adaptation of directional hydraulic fracturing to different process charts have been taking place in Kuzbass.

Longwall face 26-32 of “Esaulskaya” mine has been mined under tough roof conditions. Mining-and-geological and mining-engineering characteristics of the seam are given in table 1.

Table 1. Mining-and-geological and mining-engineering parameters of the working area.

| No. | Indicator name                      | Indicator characteristics | Value    |
|-----|------------------------------------|---------------------------|----------|
| 1   | Working area                       |                           | 26-32    |
| 2   | Seam                               |                           | 26а      |
| 3   | Coal grade                         | Zh (fat coal)             |          |
| 4   | Operating ash content              | %                         | 30.7     |
| 5   | Mining depth                       | m                         | 430-450  |
| 6   | Extracted seam thickness           | m                         | 2.15     |
| 7   | Angle of seam inclination, from - to: | degree                   |          |
|     | along longwall face                |                           | 0-2      |
|     | along the pillar                   |                           | 1-9      |
| 8   | Length of the working area         | m                         | 876      |
| 9   | Length of the mining face          | m                         | 210      |
| 10  | Weight of loose coal in the 1st block | ton                     | 566      |
| 11  | Weight of loose coal at one meter face advance | ton | 708      |

According to mining-and-geological forecast, the immediate roof of seam 26а with average thickness from 8 to 19 m is composed of fine and coarse siltstones. In some parts lower part of the immediate roof which is 0.10-0.32 meter thick acts as a false roof as it falls after coal extraction. Considering stability, immediate roof acts as semi-stable one. However, the main roof is composed of
coarse siltstones and sand rock along the whole extraction area and is characterized as a tough roof. Impending of tough roof in vast areas in places where it is linked with development workings leads to higher pressure in the verges of coal and rock mass. To reduce negative effect of high rock pressure on the stability of mine workings with tough roof, the authors decided to use directional hydraulic fracturing for roof softening [7].

According to “Instruction on the choice of method and parameters of roof softening at the excavation sites” the staff members of the Institute of Coal of the Federal Research Center for Coal and Coal Chemistry (Siberian Branch of the Russian Academy of Sciences) in collaboration with “Esaulskaya” mine technical department members worked out a directional hydraulic fracturing implementation process flow to guarantee timely and stable roof caving after working face advance (figure 2) [3].

Figure 2. Directional hydraulic fracturing implementation process flow: a) location of wells for hydraulic fracturing; b) well drilling direction.
Directional hydraulic fracturing was implemented using standard and special mining equipment. Well drilling and initiating crack cutting was performed using pneumatic drilling roof bolting machine. For well drilling rock crowns with 46 mm diameter were used. Initiating cracks were cut using powered crack initiation devices (figure 3), which were set on the steel stems of the drilling machine instead of the crown [6].

Figure 3. Crack initiation device SHCHM – 45/1: a) – motion direction; b) sample prototype.

Sealing of the initiation crack area was made using hydraulic sealer (“Taurus” type) (figure 4). Sealer was directed to the bottom of the well by means of special set of high-pressure pipes. Compression unit was connected with the end of the pipe projecting from the borehole through special adapter (collector) by means of high-pressure flexible hoses. Liquid pumping in the initiating crack area was made using high-pressure unit of the power-operated complex. Effectiveness of drilling and the process of directional hydraulic fracturing implementation were controlled using video endoscope. That helped ensure that the boreholes are drilled up to the designed depth, and the initiating crack was cut in the bottom of each well (figure 5).

First of all, hydraulic fracturing was made in the vertical wells where the artificial cracks expanded parallel to the strata. After that it was performed in the slant boreholes, and the crack expanded at an angle to the strata. In this case artificial crack extended up to the junction of the immediate and main roofs and spread further along the contact area (figure 4). When liquid was supplied into the borehole, the process of roof hydraulic fracturing started in 5-10 seconds after the emulsion had been pumped into the system. In addition to that, there was sudden decrease of pressure on a manometer in the area of the initiating crack [8, 9].

Figure 4. Sealer “Taurus”: a) external view; b) placement in the mine opening.
Figure 5. Borehole with initiating crack before hydraulic fracturing: a) video endoscope; b) borehole mouth; c) borehole bottom.

For assessment of the qualitative characteristics of the performed hydraulic fracturing the changes in coal and rock mass structure were monitored by means of a seismic survey [10-11], which in contrast to, for example, registration of the immediate changes in gas release from coal seams at hydraulic fracturing implementation [12-14], makes it possible to determine the spatial boundaries of hydrodynamic impact on the enclosing rocks.

To assess effectiveness of the taken measures aimed at roof softening the area near the extraction column was studied in the interval more than 150 m using seismic inspection method by means of transmitted waves. Moreover, more than 100 shots were made. They were performed in two stages of seismic vibrations impulse registration. First, registration of seismic data was made on the examined part of the extraction column which remained intact after hydraulic fracturing. Then seismic data was recorded on the same area when physical and mechanical state of the roof had changed as a result of hydraulic fracturing. The process of seismic shooting of the extraction column area included taking measurements in mine (coordinate reference system adjustment; placement of seismic recording equipment; signal initiation and registering) and office work (basic data preparation; data processing; data analysis and interpretation).

During taking measurements in mine, the authors used a system of seismic sensors. Seismic receivers (geophons) were placed at certain intervals along the sides of the working. They were connected with an autonomous seismic recording system. To perform geophysical study, the authors placed geophysical pickets for receiving and excitation of seismic vibrations along the sides of the parallel mine wordings at 10 meter intervals. Adjustment of coordinate reference system to the real conditions of the extraction column area was made based on the map of mine workings and taking the real placement of mine workings and other mine facilities into account. In compliance with safety requirements for initiation of acoustic waves in mines, the authors used mechanical impact vibration sources which had a time break system. Recording units and time break system were synchronized with each other just before taking measurements. Mistiming of the synchronized devices in this case was not more than 1 msec per day. The data with 1 msec discretization interval were continuously registered using autonomous seismic recording stations with filtration on the cut-off frequency equal to 500 Hz and recorded in the files containing up to 3 600 000 readings.

Velocity parameters of seismic signal were taken as the main source of data for assessment of physical and chemical characteristics of the active seam roof. Lines of correlation were defined on the seismic records. They characterized the compressional wave going through the active roof area. According to the results of picketing, the authors determined signal velocity parameters on different measurement points, which were later converted into the time of seismic wave travel and introduced into the software for tomography data processing. The surface area of the extraction column was
analyzed using a range of tools for tomographic survey of the simulated environment that is located between two mine workings [16]. The authors determined instantaneous velocity values in different parts of the extraction column. The obtained results were saved in the system as an environment velocity model. After that velocity models were further used to design a two-dimensional representation of the examined part of the extraction column that indicated physical and mechanical properties of roof before and after hydraulic fracturing (figure 6). The authors detected a higher velocity background which is typical for sufficiently tough rock which is in a stress condition taking into account the results of the analysis considering the initial velocities of seismic waves travelling through roof which was not affected by hydraulic fracturing. The highest velocity values were compared with the maximum stresses registered in the area noted using symbol “+” in Fig. 6 within observation points (OP) OP 90-130 (Working No 1) and OP 40-90 (Working No 2). In mine Working No 1 within OP 20-60 there was an area with minimum seismic wave velocities (indicated as “-”) which probably has more fractures and is possibly damp.

General speed background on the tomographic profile of the examined part of the roof, that was altered because of hydraulic fracturing, is lower. Maximum velocity values for the given state of the roof were observed in the area “+” (OP 90-120) in Working No 1. Minimum values – in areas “-”: 1 – OP 20-80 within Working No 2; 2 – OP 10-60 within Working No 1. Thus, apart from the lower general velocity background, the analysis of velocities of seismic waves travelling through the roof before and after hydraulic fracturing showed the following results:

- Shrinking of the distribution area and redistribution of high stress of area “+”;
- Increase of the area affected by the section with lower velocities “-”, located within Working No 1;
- Formation of an area with high concentration of fractures, which is detected due to the minimum seismic wave velocities.

Moreover, to determine the effect the hydraulic fracturing had on coal and rock mass, the authors assessed amplitude characteristics in relation to lines of correlation of the recorded propagation of waves (figure 7) [15]. Signal amplitudes were calculated within different intervals of the digital representation of the extraction column, and on the basis of the analysis of their spatial distribution complex tomographic profiles were modelled which showed the changes in the following characteristics:

\[ \beta_V = \frac{V_1}{V_2}, \]

- ratio of seismic wave propagation velocities through intact roof of the examined part of the extraction column to the velocities of wave propagation through the roof of the examined section which had been altered due to hydraulic fracturing (figure 6, c).

\[ \beta_A = \frac{A_1}{A_2} \]

- dependence of seismic waves relative amplitude values in intact roof of the examined part of the extraction column in the longwall face on the relative values of the wave amplitudes in the roof of the examined section which had been altered due to hydraulic fracturing (Fig. 8-a).

\[ \beta_{V,A} = \beta_V + \beta_A \]

- relative energy characteristics factoring fluctuation of velocities and amplitudes of seismic waves (figure 8-b).

Based on the analysis of tomographic profile \( \beta_V \), the authors assessed coal mass relief degree considering records of changes in seismic wave propagation velocities through the examined part of roof which were induced by hydraulic fracturing. Tomographic profile was modelled using average values of the recorded characteristics. That made it possible to detect areas of their sharp changes excluding objects irrelevant for tomographic profile. Area “P” most relieved after hydraulic fracturing was detected within the interval OP 0-100 where coal and rock mass shifted from Working No 1 towards Working No 2.

After that the authors analyzed the tomographic profile \( \beta_A \). Taking into consideration different nature of the compared values, the behavior and direction of the area most relieved as a result of hydraulic fracturing resemble the area registered for \( \beta_V \). The highest values of the examined characteristics were in two areas – “P”: OP 20-110 in Working No 2 and 10-60 in Working No 1.
Figure 6. Visual representation of changes in coal and rock mass as a result of stress relief (based on measurements of seismic wave propagation velocities): a) distribution of velocity properties before hydraulic fracturing; b) distribution of velocity properties after hydraulic fracturing; c) ratio of velocities before hydraulic fracturing to velocities of wave propagation after hydraulic fracturing - $\beta_{V}$.

To determine the location of the area most relieved after DHF more precisely, the authors analyzed tomographic profile $\beta_{V,A}$. That complex characteristic was used because earlier the authors identified that directions of the represented area for $\beta_{V}$ and $\beta_{A}$ are similar. Assessment of inversions of the relative energy value which relies on changes in different signal parameters (velocities and seismic wave amplitudes) made it possible to exclude possible alterations of each value which could be caused by their physical properties. The area most relieved as a result of hydraulic fracturing considering characteristic $\beta_{V,A}$ was determined within Working No 2 - OP 40-80.

On the basis of analysis and interpretation of the obtained data the following was established:
- Decrease of general velocity background after hydraulic fracturing implementation;
- Decrease of distribution area and redistribution of high stress in area “+”;
- Increase of the affected area of the lower velocity section “-”, located within Working No 1;
- Emergence of an area with high number of fractures characterized by minimum seismic wave velocities;
- Presence of an area in the roof most relieved as a result of DHF for $\beta_{V}$ – “P” within the interval OP 0-100 with change of its position within the bulk of the face directed from Working No 1 to Working No 2;
- Presence of an area in the roof most relieved as a result of DHF for $\beta_{A}$ with the highest values of the assessed characteristics on two sites – “P”: OP 20-110 in Working No 2 and 10-60 in Working No 1;
- Presence of an area in the roof most relieved as a result of DHF for $\beta_{V,A}$ within working 2 OP 40-80.

To assess roof softening as a result of DHF the authors chose the criterion of high crack concentration in the examined rock mass. It implies the ratio of crack volume and cavities in the examined rock mass to the volume of rock mass. In the process of calculation the authors considered dependence of compressional wave velocity on the porosity factor, which implies ratio of pore volume to the volume of rock mass. [17, 18]:

$$\frac{1}{V_p} = \frac{k}{V_\phi} + \frac{1-k}{V_n},$$

(1)
where $k$ – porosity factor, which considers presence of cracks, pores and cavities in the examined rock; $V_p$ – compressional wave velocity in the examined mass; $V_\phi$ – compressional wave velocity in fluid; $V_\pi$ – compressional wave velocity in the rock mass.

**Figure 7.** Dependence of average seismic wave amplitude level on the location of the observation point in Working No 2 in case when coal and rock mass was intact and affected by DHF.

**Figure 8.** a) Visual representation of changes of seismic wave relative amplitude values in the examined area affected by DHF $\cdot \beta_A$; b) Visual representation of change in the value of the complex characteristic $\beta_{V,A}$ in the examined area affected by DHF.

The authors assumed that in the given individual case of compressional wave reception and initiation the whole volume of cracks having different directions formed as a result of roof softening had an impact on the signal parameters due to the difference in the level of parallel workings and alteration of vibration excitation points.

To assess changes in roof condition induced by DHF, the authors used fracture density $k'$ instead of $k$. As $V_\phi$, the authors considered compressional wave velocity in methane-air medium; $V_\pi$ – wave velocity in the mass before DHF $V_p$, $V_p$ - wave velocity in the mass after DHF. In this case transformed formula is the following (1):
Besides, initial fracture density of the coal and rock mass which was not affected by DHF was determined taking geological survey data into account. In case there were no such data, the value was calculated as a ratio of cracks and cavities volume in the examined coal and rock mass to the volume of rock mass. from formula (1) where \( V_p \) was replaced with \( V_1 \):

\[
\frac{1}{V_2} = \frac{k}{V_p} + \frac{1-k}{V_2}.
\]  

Using formulae (2) and (3) the authors calculated \( k' \) and \( k \) respectively taking determined velocity values. Thus, they calculated fracture density characteristic after implementation of DHF \( k^* \):

\[
k^* = k \cdot k'.
\]  

On the basis of the assessment the authors determined that according to formula (2) the coefficient that characterizes fracture density in the examined coal and rock mass varies from 0 to 0.1. The distribution of its values within extraction column corresponds to distribution \( \beta_{V} \) of the ratio of velocities before DHF to wave propagation velocities after DHF.

3. Conclusions

As a result of industrial experiment works the authors performed roof softening using DHF. They determined that application of DHF secures timely roof caving after working face advance. It excludes the possibility of roof hanging in places adjacent to development workings and promotes stable ventilation in the extraction area. To assess the effectiveness of roof softening the authors took roof seismic measurements. As a result, no abnormal structural notions were detected in the examined area of coal and rock mass. DHF did not have any negative effect that could make mining more complex and difficult. Besides, the authors determined decrease of stress in the examined part of the extraction column, which appeared as decrease in energy characteristics of seismic signal. They determined the area of maximum relief which located within OP 40-80 of Working No 2. Calculated variations of the coefficient that characterizes roof fracture density lie within the range from 0 to 0.1.

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