Features of seismic wave travel along a coal pit wall

VF Yushkin
Chinakal Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
E-mail: L14@ngs.ru

Abstract. Triple gain of the maximum amplitudes or massif vibrations in a final phase of the consecutive blasting of groups of borehole charges during the propagation of a seismic blast wave outside the mined block in the Quaternary deposits of a coal mine slope has been experimentally established. The effect of “rocking” the massif occurs stepwise, and it is synchronized according to the selected delay intervals at detonation.

1. Introduction
The effect of large-scale blasts inducing structural and deformational changes in the coal mine slopes in the coalfield areas composed of Quaternary deposits is primarily associated with their destructive effect on the mined blocks, however the specificity of blast wave propagation in the rock mass outside the mined blocks has remained largely underexplored. In the normative documents for conducting blasting operations on the day surface, there is some conservatism in risk evaluation with respect to the induced impacts of large-scale blasts on the mountain range [1]. Their first manifestations in coal sections were noted by seismologists back in the 60s of the 20th century [2]. Owing mainly to researchers from the VNIMI Intersectoral scientific center (with the Scientific-research Institute of mining geomechanics and mine surveying), this problem has been dealt with observance of the rules developed for the safe open-pit mining operations involving blasting technologies in the conditions of increasing depth of burial, which has reduced the risk of rockfall in the coal mine slopes, however, efficient utilization of blasting energy in the mined blocks is still problematic.

As shown in [2], natural and induced (mining induced) seismicity in coalfields within the Quaternary interval has reached the stages when, in addition to natural earthquakes and small-foci induced seismic events, a new type of seismic activity—swarm seismic events alternating with relatively large-magnitude earthquakes—has been increasingly often observed in the areas of open-pit operations. According to [2], the epicenters of the latter are confined to deeply penetrating faults which are equated with effects of tectonics and orogeny (e.g. tectonic earthquake). The accumulated tectonic energy is believed to be the main trigger of such earthquakes, assuming however that the time and place of its discharge are controlled to a considerable extent by induced events.

The accumulated actual data on the processes of deformation, transformation, destruction and degradation and retreat rate of coal mine slopes (in the context of both surface and deep underground mining) show that such changes are mainly a result of geological and hydrological, engineering and technological, natural and climatic factors or their combinations. Therefore systematic quantitative observations using appropriate 3-5D measuring and monitoring systems must be carried out for the purpose of the coal mine slopes control and finding correlation between their degradation and seismic events.
2. Analysis of seismic oscillation records

The geodesy and mine surveying are the most accessible and proven methods that enable remote monitoring of mining induced structural and deformational changes, including degradation observed on the surface of rock formations [3]. These are often supplemented with the seismic methods [3, 4] based on the study of elastic wave propagation in the subsurface. The seismic methods are widely used for solving problems of structural geology, whereas they appear largely underestimated in the quantitative control of the deformation - wave processes evolution in rock masses at the scale of the open-cast section of the mine site. The applied therewith schemes of instrumental seismic measurements can be adapted to specific mining and geological conditions [3, 4].

Coalfields located within sedimentary deposits exhibit relatively low yield and compressive strengths of soils and rocks in comparison with stronger igneous or metamorphic rocks, which favors the seismic energy discharge. Characteristic indicators of yield strength of the surrounding rocks in coal deposits from several coalfields are shown in Table 1.

Table 1. Strength of Quaternary deposits reported from a number of coalfields [5]

| Coalfield                  | Rock    | Density, t/m³ | Compressive strength, MPa |
|---------------------------|---------|---------------|----------------------------|
| Different coal deposits   | Mudstones  | 2.50 – 2.90   | 20 – 70                    |
|                           | Siltstones |               |                            |
| Kuznetsk coal basin       | Hard coal | ~ 1.3         | 30 – 50                    |
|                           | Hard coal |               |                            |

The objective of this work is to study by the seismic method the wave propagation outside the blasted block in Quaternary deposits of the coal mine slopes for small depths and distances (within 50 m) along the elevation profile. To register the blasting induced elastic wave propagation, we chose a bench face of the observation deck.

Seismic surveys were conducted along the bench face slope in the form of seismic profiling using a system of reversed time-distance curves; geophones (seismic receivers) with the sensitive axes orientated horizontally and vertically were used as a source of elastic vibrations of the blast wave in the Y–Y and Z–Z arrangements, respectively.

Figure 1. A view of the observation slope showing the scheme of seismic receiver pairs, marked by ×, with their numbers listed next to them (receivers with vertical (1–7) and horizontal (8–13) orientation of the sensitive axes towards the rock mass). Distances are given in meters.
The seismic methods applications for shallow subsurface study of rock massifs are characterized by wave pattern characteristics dependent on the downhole excitation and ground receiving mode of the vibrations (seismic oscillations). Evaluation of the blast wave propagation in the open-pit mine slopes involved the analysis of its dynamic and kinematic growth in the massif in the context of observation deck of the bench face slope at absolute elevations (between mountains) of +245.7 and +265.7 m (Figure 1).

The horizon corresponding to observation deck is represented by weakly stable soils: clays admixed with loams associated with interlayers of flattened rotted rock up to 1 m in thickness, underlain by “compacted” slightly cemented fine-grained sandstone, reaching tens of meters in thickness, which when exposed to wetting and mechanical effects can be broken with concomitant substantial decrease in the cohesion forces, and become fairly loose. The parameters of rocks composing the bench face are: clay (yield strength coefficient \( f = 0.7 – 0.8 \), density \( \rho = 1.6 – 1.8 \ \text{t/m}^3 \)); rotted rock ( \( f = 0.8 – 1.2, \ \rho = 1.27 – 1.33 \ \text{t/m}^3 \)); sandstone ( \( f = 2 – 4, \ \rho = 2.56 – 2.6 \ \text{t/m}^3 \)).

Figure 1 shows location of the seismic receivers array for recording the blasting-induced seismic wave propagation within the sandstone bench face and the observation deck slope. The diagram is oriented in the direction of the blasted block and is located at an angle of \( \sim 45^\circ \) to the horizon along the bench face slope, which is chosen to be without visible cracks within the measurement interval. In the photo, one can see riverbed depressions to a depth of 0.3-0.5 m formed by the rainwater runoff.

Seismic oscillations were recorded taking into account the methodological recommendations set out in [3, 6–8] and using the Laccolit 24-M seismic station [9] and GS20-DX seismic receivers—a total of 13 pieces installed within the observation deck slope. Seismic receivers 1 – 7 are placed with the orientation of axis of maximum sensitivity vertically to ground, seismic receivers 8–13—with horizontal orientation of axis of maximum sensitivity in the direction of the observation deck slope. The length of the seismic trace was 49.5 m (except the 5 m branch on the horizontal surface of the sandstone bench face (Figure 1).

The adopted orientation of the seismic receivers allowed recording vertical and horizontal components of elastic wavefield in the open-pit mine slope. The selected profile provided record of a seismic wave caused by massive blasting of the mined block at a distance of \( \sim 750 \) m from the observation deck. The blasted block was located on the lower horizon, deep in the open-pit mine. During the experiment, a full-scale seismogram of the massive blasting-induced elastic wavelet propagation in the massif was obtained. Due to the time limit \( t \) (duration of the signal record by the seismic station < 1.5 s), the initial and final phases of the blast wave were recorded on the seismogram.

![Figure 2](image-url)
Figure 2 shows a fragment of seismogram of the wave generated by blasting groups of borehole charges in the mined block. For correlation with the measurement scheme (Figure 1) the record on the left shows a scale with indication of the channel numbers corresponding to the seismic receivers. The record reflects changes in the oscillation rate for each measurement channel and shows the actual attenuation ratios of the wave propagation along the trace.

The seismograms analysis revealed a tendency for the amplitude of vertical component of the seismic wave propagating along the bench face to decrease by about 1.3–1.4 times in the area between the seismic receivers 1–7, and by 1.2–2.6 times between the seismic receivers 2–3. Note that the deposits upon which the seismic receivers 3–5 are spread are confidently connected to the sandstone massif through the rotted rock layers. Given that the sandstone bench face is strongly jointed in the area between the seismic receivers 1–2, the amplitude of the seismic signal shows almost a 4-fold reduction there. When expanding into the sandstone, the amplitude changes not more than by 1.7 times. The formation of a crack in the sandstone (Figure 1) at the bottom left, is associated with natural and climatic factors.

In [3], the example of a limestone quarry shows the decoding of a seismic record of the blast wave with the amplitudes maxima tied up with the detonation time of the groups of borehole charges, taking into account the deceleration intervals during the blasting. As such, the interpretation enables determination of a shift in frequencies of the oscillation velocity spectral peaks for the blasting-induced seismic wave, which are discriminated by the deceleration intervals when blasting the ordered groups of borehole charges. Each of the groups of blasted boreholes in the mined block excites its own oscillations with a frequency dictated by the specific conditions in the rock massif.

First arrivals of elastic wave can be distinguished for each of the groups of borehole charges while blasting, from the deceleration intervals accordingly on the seismogram [3]. The seismogram shows that at the moment corresponding to arrivals of elastic oscillations excited by the blasting of a group of borehole charges in the subsequent deceleration interval, the rate of rocks vibration from the previous blasting does not have time to become zero, although it experiences a significant attenuation. When the charges are detonated with the accepted deceleration, the mined block of rocks therefore fails to have enough time for the “abatement” and the seismic wave from the previous blasting impact overlaps the subsequent one. Thus, the existence of “self-rocking” potential in the massif is observed, while the amplification of the resulting seismic wave amplitude occurs stepwise, in accordance with the deceleration intervals.

![Figure 3](image)

**Figure 3.** Variations in the velocity of seismic oscillations on the bench face surface reflected by the seismic record in the initial (a) and final (b) phase of the blasting for the vertical and horizontal components of the seismic wave. The gap observed in the horizontal component of the graphs is associated with the seismic receiver failure in channel 10.

Figure 3 shows variations in the maximum values of the amplitudes of vertical and horizontal components of the oscillation velocity in a rock massif on the stacked trace for the initial and final phase...
of the blasting wave propagating along the observation deck slope. The observed almost 3-fold amplification of the maximum amplitude of seismic oscillations in a rock massif during the final phase of successive blasting of groups of borehole charges indicates potential for the rock mass “rocking”. This fact accounts for the blasting capability of producing a triggering effect enhancing thereby seismic activity near the coalfield, when minor energy events can trigger more powerful ones.

Figure 4 shows the changes in the spectra of vertical and horizontal components of seismic oscillations for each channel measuring the blast wave propagation. The graphs exhibit a shift in the oscillation amplitudes maxima to the low frequency region, which is characteristic of “pendulum” type of waves. The average velocities of the vertical (1013 m/s) and horizontal (685 m/s) components of the elastic blast wave propagation in the Quaternary deposits of the studied bench face of the open-pit mine were calculated from the hodograph of first arrivals.

Figure 4. Change in the blast wave spectra according to the multi-channel data. All the graphs are normalized in decibels.

A comparison of oscillation periods of the blast wave based on the deceleration intervals with the results of visual inspection of blasted rock mass allows to evaluate the blasting operations quality, and to determine the fractional composition of the rock mass referenced with location of the mined block, which is critical for further processing of the extracted raw materials and can serve as a basis for parameters adjustment for drilling and blasting operations. In the future, appropriate structural and geomechanical studies involving application of surveying tools can be used as a basis for improving the method for evaluation of the blasting operations quality using blast seismograms.
3. Conclusions
The elastic blast wave propagation patterns in rock mass of Quaternary deposits within a coal mine slope outside the mined block are considered. The seismic oscillation records conducted at a distance of ~ 750 m from the blasted block in the lower horizon, allowed an inference that the amplitude of the ground vibrations accompanying the wave propagation along the open-pit mine slope is attenuated to be about 1.3–1.4 times lower. It has been established that the maximum amplitudes of the vertical and horizontal components of the seismic oscillation velocity in a rock massif showed almost three-fold increase as a result of its rocking in the final phase of sequential blasting of groups of borehole charges in accordance with the accepted deceleration intervals, which is indicative of the “rocking” potential of rock mass. This fact can serve as a compelling evidence of the triggering effect of a technological blasting operations enhancing seismic activity near the coal mine slopes, when a minor energy event can initiate another one of greater magnitude.

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