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ASSESSING THE QUALITY OF DRILLING-AND-BLASTING OPERATIONS AT THE OPEN PIT LIMITING CONTOUR

Purpose. To develop a methodology for assessing the quality of drilling-and-blasting operations when setting the side to the final position. In this regard, it is necessary to study the nature of deformations in the near-side masses of the design open-pit contours and to assess the seismic impact of blast waves in accordance with damage in the near and far zones from the open-pit boundary, as well as the level of generated seismic vibrations.

Methodology. A methodology for assessing the quality of drilling-and-blasting operations at the limiting contour of open pits is developed using the analysis of the mining-and-geological conditions of the rocks constituting the field, in-situ surveying of the state of the open-pit sides, analysis of the physical-mechanical properties of the host rocks, analytical studies and instrumental measurements of the blasting effect.

Findings. Based on the analytical methods, the calculation and analysis of the seismicity coefficient of the rocks at the field have been performed. By means of instrumental measurement of the blasting effect in open pit, data have been obtained on the seismic impact of blasting operations on the near-side mass. Based on the results of these works, a methodology for assessing drilling-and-blasting operations at the limiting contour of the open pit has been developed.

Originality. In this work, to assess the blasting effect, the seismicity coefficient of the rock mass is used, which characterizes the degree of elastic response to external dynamic influence and is a parameter that determines the elastic seismic wave intensity with distance from the site of blasting operations. Based on the calculation, a map of the seismicity coefficient distribution in the open-pit area has been compiled. Using the method of instrumental measurements, which serves to determine the seismic impact of blasting on a rock mass, the degree of blasting effect on a near-side mass has been revealed. This made it possible to develop a method for assessing the blasting quality, based on determining the percentage of permissible deviations in the face drilling quality.

Practical value. The results of the work will be used to calculate the safe parameters of conducting the blasting operations when setting the side to the final position. This method for assessing the quality of drilling-and-blasting operations can be applied at any mining enterprise conducting open-cut mining of minerals.

Keywords: *contour blasting, open-pit side stability, seismic impact, drilling-and-blasting operations, blasting quality*

Introduction. The modern stage of development of mining deposits is characterized by the complication of mining-and-geological conditions [1, 2] with a simultaneous increase in requirements to reduce the negative impact on the environment [3]. The issues of reducing landslide phenomena in mining areas are especially acute [4]. The intensive development of open pit mining is accompanied by an increase in the volumes of overburden and the depth of mining. Along with an increase in the depth of mining, the risks associated with the loss of the rock mass stability increase [5].

A significant role when solving the problems of the rational use of mineral resources is assigned to the management of the rock mass state [6] and, in particular, to the issues of determining the stability of the open-pit sides [7]. The purpose of this management is to ensure safe mining and reduce the volumes of overburden while maintaining the stability of the slopes in the benches. Managing the state of natural and technogenic masses during open-cut mining of mineral deposits is in a set of measures to maintain and bring the benches, sides and dumps of the open pit into a stable state, close to the limiting one, by changing the geometric parameters of the slopes during the mining process, which provides economic and safe mining operations [8].

When conducting the mining operations in open pits, ensuring the stability of the working sides depends on many factors, including the mining-and-geological conditions and the tectonics of the field, as well as the impact of drilling-and-blasting operations on the near-side mass [9]. This is especially important when mining is approaching the design limiting contour of the open pit, where the requirements for technological blasting change [10].

One of the main requirements for the technology of breaking at the limiting contour of the open pit is to ensure the maximum degree of preservation of the formed rock benches – the slope and the berm [11]. This is conditioned by the need to maintain a safe state of the benches for sufficiently long-time natural resources mining [12] and sustainable development of deposits [13]. The main way to fulfill this requirement is obvious: it is necessary to reduce the intensity of technogenic impact on the surrounding rock mass to the minimum acceptable level, which would ensure, on the one hand, a sufficient degree of preservation of the marginal mass and, on the other hand, sufficient produce-ability of drilling-and-blasting operations [14]. To ensure the open-pit side stability, technologies of the contour blasting have been developed which make it possible to suppress the blasting effect on rocks [15], as well as a number of mining technologies that make it possible to reduce the impact of technological equipment on the open-pit permanent side [16].

In open pits, the setting of the sides to the final position on rocky benches is performed by the method of contour blasting. The slot is created by the instantaneous blasting of a number of blast-holes 244.5–250.8 mm in diameter drilled at an angle of 55–75°. The contour blast-holes are drilled by SBSh-190/250-60 rolling-cutter drilling rigs in accordance with the developed passports.

The distance between the blast-holes is taken as 1.5–3.0 m, depending on the rock hardness. The charge in the blast-hole is formed at the rate of 3.6–5.8 kg per 1 long meter of the blast-hole, to the full depth [17]. The charge is placed in a hose with a diameter of 50–120 mm. The blasting charge design is shown in Fig. 1. Charging and blasting of contour blast-holes are allowed with a sequential alternation of charged and empty blast-holes through one in case of ensuring the implementation of design solutions.

When mining is approaching the limiting contour of the open pit, a border zone is left, which is blasted after formation of preliminary presplitting. The maximum width of the boundary zone should be no more than 6 rows of blast-holes and the minimum is not less than three rows of blast-holes. When charging the slot, one end blast-hole from the side of the pillar is not charged. The charge in the blast-holes of the last row in the contour zone is reduced by 25–35 %. The contour row of blast-holes at the edges of the blasted block must be ahead of the last row of blast-holes near the contour by at least 10–13 meters.

The hose charge is produced at the Base warehouse of explosives at a stationary station of hose charge preparation. The hose charges are produced using a device for mechanized charging UMZ-1 by simultaneous production of a hose from a tape polymer film, filling it with granular brittle explosives (Granulotol) and placing the formed charge on the drum.

Due to the fact that the mining enterprises of the Republic of Kazakhstan annually take measures to reduce the use of prefabricated explosives in production, with each contract concluded for the supply of Granulotol, its cost increases, which directly affects the production cost. In addition, the growth in the cost of Granulotole is influenced by the conditional fixed costs of the manufacturer, an increase in the cost of road and rail transportation, an increase in the cost of raw materials used, and others [18].

The industrial emulsion explosive NPGM or the explosive Petrogen D70 is proposed to use instead of Granulotole.

The use of new explosives leads to the possibility of the formation of an unstable permanent open-pit side. Therefore, it is necessary to develop a methodology for assessing the quality of blasting operations when setting the side to the final position.

Methods. Theoretical studies on the nature of the wave field distribution from the blasted explosive charge are based on a model of a medium close to a real anisotropic medium of the mass. The initial model is an inhomogeneous infinite medium with a system of parallel fractures. The physical-mechanical properties of the fracture filler differ from the properties of the medium itself. Detonation of the charge along its length occurs instantly, and the seismic wave is taken into account at a considerable distance from the site of blasting operations. Since all types of waves, excitated by blasted industrial explosives, are characterized by small amplitudes; the theory of sound wave propagation is most often used when solving the problems of the blasting effect.

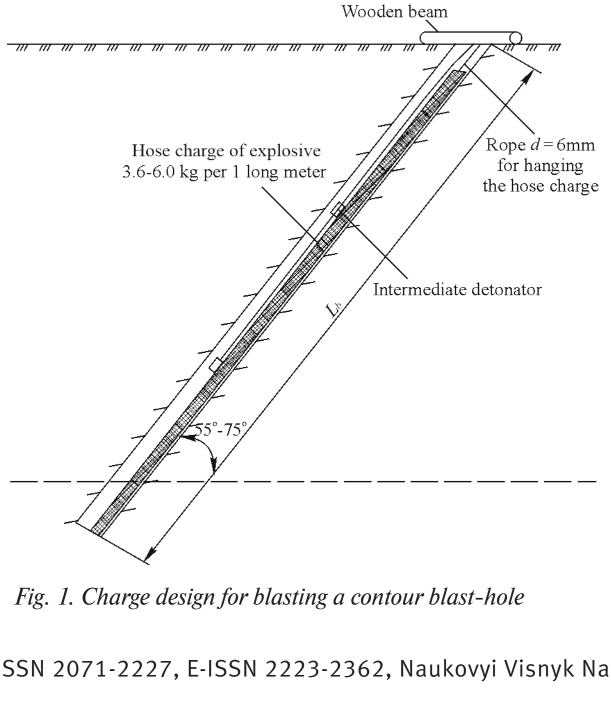

Fig. 1. Charge design for blasting a contour blast-hole

Further, the vibration process is analyzed by its amplitude-frequency spectrum, which makes it possible to determine the band of frequencies that carry the main energy of seismic vibrations.

Using the relationship between the wave propagation velocity and the vibration frequency *f,* the frequency range that takes up the maximum load is determined by the direction along the fractures ($\varphi = 0°$) at an angle ($\varphi = 45°$) and perpendicular to the fractures ($\varphi = 90°$).

Calculations for various open pits show that within the same type of rocks that constitute the mass, the values of the seismic wave propagation velocity and the vibration frequency change depending on the diffraction angle.

In granites, the values of the propagation velocities of seismic waves in the directions along the fractures and perpendicular to them differ by 2.0–3.8 times, and for limestones – by 1.1–1.3 times. An increase in the propagation velocity of seismic waves in the direction along the fractures and its significant decrease perpendicular to the fractures once again convincingly confirm the differences in the basic properties of the medium.

The shielding effect of the fracture relative to the seismic wave leads to the fact that the wave propagation velocity is significantly reduced. This is the reason why the values of the vibration velocity in the indicated direction are minimum, and, therefore, the axis of the isoseismic ellipse coincides with the main direction of the fracture anisotropy.

Since the elastic wave parameters change with increasing distance from the site of blasting due to the unequal absorbing properties of the medium in different directions of the anisotropic mass, the shape of the isoseismic contour is conditioned by the seismic anisotropy coefficient ($k_{sa} > 1$), which depends on the ratio of the wave length λ to the width of a single fracture d in a system of the fractured mass.

To assess the blasting effect on a rock mass, it is best to use the seismicity coefficient of a rock mass, which characterizes the degree of elastic response to external dynamic influences and is a parameter that determines the intensity of an elastic seismic wave with distance from the site of blasting. In this case, the value of the seismicity coefficient k_s of the mass is determined as follows [19]

$$k_c = 0.13 \cdot f^{0.395}[(1 - \eta) \cdot U_s]^{0.25},$$

where f is the rock hardness coefficient according to the Protodyakonov scale; U_s is specific energy of explosive, kgm/kg, is determined by the formula; η is fraction of the initial energy remained in the detonation products at the moment of complete expansion of the chambered cavity, units.

To determine the patterns for the elastic wave propagation over a mass, two most typical cases are considered – a concentrated charge and a linear charge. In this case, the value of the seismicity coefficient k_s of the mass (for concentrated charges) is determined by the formula

$$k_c = K_d \cdot \frac{\sigma_c \cdot g}{\gamma_d} \cdot \left(\frac{c_p}{\sigma_t}\right)^{0.5} \cdot \left(\frac{3}{4\pi} \cdot \sqrt{\frac{2}{g}}\right)^{0.5} \cdot \left[\left(1 - \eta\right) \cdot U_s\right]^{0.25} \times$$
$$\times \left(\frac{d_0}{D_z}\right)^{\frac{k-1}{2}} \cdot \left(\frac{5}{K_t}\right)^{0.5}, \qquad (1)$$

where d_0 is the concentrated charge diameter, m; K_d is the dynamic hardening coefficient, relative to the problem with point symmetry, being $K_d \approx 2.0$; $D_{c.}$ is the charging cavity diameter, m; γ_d is mine rock density, kgs/m^3; c_p is P-wave velocity in the rock, m/s; K_t is blasted rock category; k is adiabatic exponent of the equilibrium part expansion of detonation products in the framework of the ideal gas model ($k = 1/4$), units.

In order to determine the degree of blasting effect in accordance with the adopted passports of drilling-and-blasting operations, experimental studies are organized. To determine the seismic impact of blasting on the rock mass, the ELLISS-3 seismic-acoustic system is used. It consists of a seismic station, seismic-acoustic receivers (geophones) and a data transmission wire (streamer).

Instrumental recordings of seismic-acoustic waves in industrial seismic surveying are conducted during blasting of both single and mass charge systems. The selected equipment for studying the rock mass seismic properties should provide not only measurements of the vibration velocity, but also a program for the spectral analysis of the vibration process of the "blasting source – rock mass – object" system in relation to its seismic resistance, technical condition, and the like.

The ELLISS-3 seismic survey system is designed to perform seismic surveys at shallow depths with various sources of action of the main and secondary seismic waves. The main area of the ELLISS-3 system application is the implementation of engineering surveys for studying the earth's surface structure to a depth of 1500 m.

The main purpose of seismic measurements is to reveal the patterns of interaction of seismic-acoustic waves in the system, taking into account the frequency characteristics of vibrations. Based on the results of these measurements, the mass vibration velocities are determined in various frequency ranges. Seismic observations make it possible to quantify the level of vibrations, and then develop recommendations for the safe operation of objects that are protected in conditions of blasting operations. The value of the seismic safety criterion should not exceed the permissible values according to the standards.

The seismic impact of a decked charge is characterized by a greater intensity of soil vibrations compared to blasting a concentrated charge of an equal total explosive mass. This is explained by the fact that the larger the surface area of the charge contact with the rock mass is, the more energy from blasting the explosive charge is transferred into the environment.

Based on the results of seismic surveys of mass explosions in order to create conditions for seismic safety of blasting operations, it is possible to assess the stability of objects depending on the type of used explosive, the charge mass, the location of the blast-holes and the blasting scheme.

The blasts are assessed and seismic impact intensity is regulated based on the value of the maximum velocity of wave oscillations. The velocity must be less than the permissible value adopted by the existing norms.

To organize the recording of seismic waves arising in the mass as a result of blasting, observation stations are set at 12 points along the contour of the open-pit side. The observation station is a mass section, marked on the slope surface of the bench. The layout of the observation stations is shown in Fig. 2.

After each blasting, a survey of fractures is performed at organized observation stations. This makes it possible to assess the dynamics and the degree of gradual development of technogenic fracturing and a decrease in the rock mass stability [20].

It should be taken into account that the development of fracturing can occur gradually, not only due to a sharp rupture of the rock continuity, but also during the opening and growth of tiny fractures, which can also be the result of the weathering process.

Then, to determine the main parameters of the dynamic impact of blasting on the rock mass, a seismic profile is placed on the upper bench of the open pit side, consisting of eight three-component geophones, located in accordance with the scheme shown in Fig. 3.

Fig. 2. Observation station example

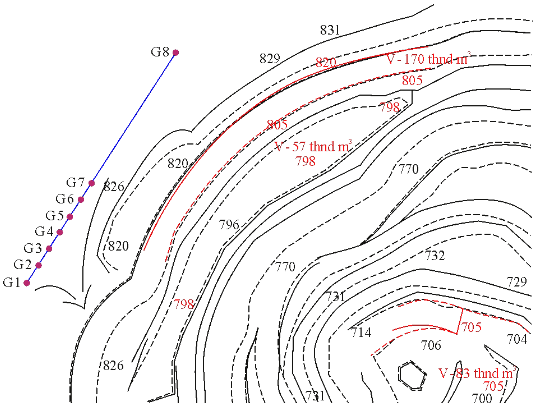

Fig. 3. Seismic profile layout

In this case, the distance between the geophones is 2.5 m. Geophone G8 is set 20 m away from geophone G7 to increase the baseline length in order to more accurately determine the propagation velocity of seismic waves.

Results. As a result of the research, 8192 values have been recorded for 24 channels with a discretization interval of 1ms, which makes it possible to register the dynamic state of the mass before blasting, the seismic vibrations themselves and their extinction.

The intensity of the blast wave is large enough to cause destruction and large irreversible changes in the rock mass on which it affects.

Under such influence, disturbances of various nature arise in the studied mass. They propagate with finite velocities. The value of the disturbances depends on the rock mass properties and the nature of deformations in the form of disturbance waves, called stress waves. Disturbances, propagating in rocks, form areas that expand over time and are limited by a part of the mass surface and the surface of the stress wave front.

Each area of disturbances is determined by its own stress-strain state, characterized by a stress tensor and a deformation tensor. Disturbance areas can be divided into primary and secondary. The area of disturbances of loading wave is the primary area. The areas of disturbances of unloading waves and reflected waves are secondary areas. They are always located inside the area of disturbances of the loading wave and are areas with initial stresses and deformations.

Stress waves of various nature, propagating in the rock mass, interact with each other, which leads to the formation of new areas of disturbances, redistribution of stresses and deformations.

The stress state of the wave-loaded section of the rock mass can change so quickly that the resulting deformations and destructions do not have time to propagate, as the stress distribution changes.

Fig. 4 shows the nature of a change in the seismicity coefficient k_s depending on the ratio σ_c/σ_t (the calculations are made based on the physical-mechanical properties of rocks from the Kusmuryn field and for explosive Petrogen D70).

It can be seen from Fig. 4 that the correlation coefficient ($R^2 \approx 0.60$) is above average. This indicates a sufficient relationship between the seismicity coefficient k_s and the σ_c/σ_t ratio, which determines the relationship between the main strength properties of the blasted rocks. The given equality (6) characterizes the seismicity coefficient, when blasting a charge placed in a rock mass at a considerable distance from the free surface.

With regard to a linear charge of infinite length, the value of the mass seismicity coefficient k_s is determined by the (1). Fig. 5 shows the nature of the change in the seismicity coefficient k_s depending on the ratio σ_c/σ_t.

From the obtained graph (Fig. 5), it is also seen that the correlation coefficient ($R^2 \approx 0.6$) is above the average. This indicates a sufficient relationship between the seismicity coefficient k_s and the σ_c/σ_t ratio, which determines the relationship of the main strength properties of the blasted rocks.

Based on the calculation, a map of the seismicity coefficient *ks* distribution in the open pit area of the Kusmuryn field has been compiled (Fig. 6), from which it follows that the seismicity coefficient varies unevenly from the center to the periphery.

The time-base diagram of the elastic waves' propagation is a seismogram. In this case, the seismogram (Fig. 7) shows seismic records (traces) for 24 channels.

For the subsequent work with seismic records, preliminary data processing is made, consisting in the received signal normalization in the dynamic range of amplitudes, which makes it possible to identify low-observable impulses and take them into account.

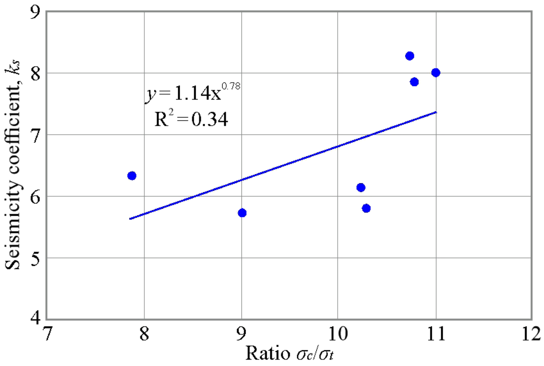

Fig. 4. The nature of a change in the seismicity coefficient k_s depending on the ratio σ_c/σ_t for Petrogen D70 and concentrated charge

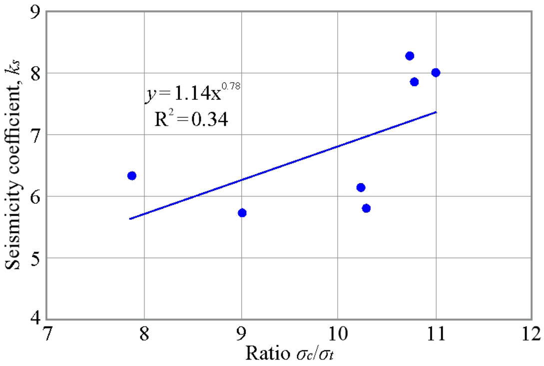

Fig. 5. The nature of a change in the seismicity coefficient k_s depending on the ratio σ_c/σ_t for Petrogen D70 and linear charge

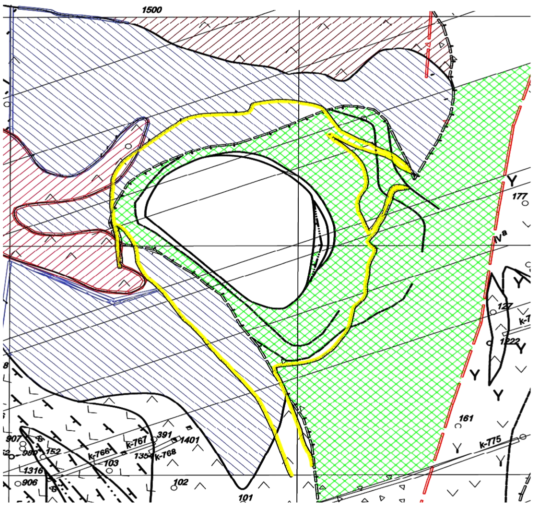

Fig. 6. The seismicity coefficient ks distribution in the open-pit area

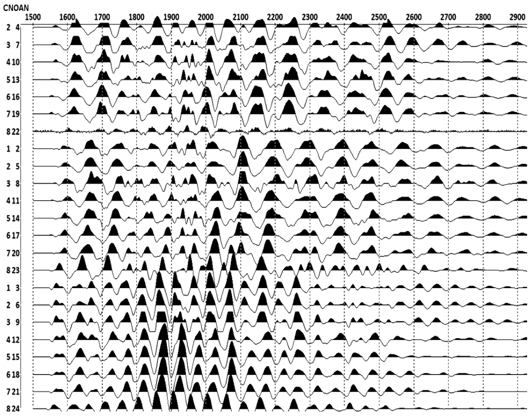

Fig. 7. Mass explosion seismogram

In the process of normalization, the amplitude of each trace is multiplied by the function $g(t)$

$$g(t)\begin{cases} 1, & t_0 < 0 \\ 1, & t_0 = 0 \\ e^{k(t-t_0)}, & t_0 < 0 \end{cases},$$

where t_0 is the normalization parameter; k is the exponential correction factor.

The normalization factor is calculated for each position of the time window of a given length, sliding along the trace with a step of one sample. The resulting value is applied to the selected sample within the window.

The obtained seismogram is exposed to energy and spectral analysis. The energy analysis performed for a time window of 1500–1700 ms has revealed the maximum wave front intensity in the 1625–1650 ms interval. In this case, the maximum energy is in the band spectrum below 50 Hz.

For a more accurate identification of the central frequency of the studied wave packets, it is necessary to perform a spectral analysis of the obtained wave field.

Spectral analysis of a digital seismic signal requires its discretization not only in the time domain, but also in the frequency domain. This means that the continuous spectrum $S_d(\omega)$ must be represented by a set of its values $S_d(n\Delta\omega)$ at discrete frequencies.

A similar spectrum is obtained from the $S_d(\omega)$ by periodically repeating the sequence $x(k;\ \Delta t)$ with the period $T_c = N \cdot \Delta t$. The interval between adjacent spectral lines is $\Delta\omega = 2\pi/T_c = 2\pi/N \cdot \Delta t$, that is, a periodically repeating signal corresponds to the discrete spectrum.

An integral Fourier transformation is then performed. In the general case, for complex functions, the square of the norm (signal energy) corresponds to the expression

$$\|s(t)\|\langle s(t),s(t)\rangle=\int_0^T s(t)\cdot s^* dt.$$

If the norm of a function has a finite value (integral convergence), then the function belongs to the space of functions that are integrable with square (the Hilbert space) and has finite energy. In the Hilbert space, based on a set of orthogonal functions with zero scalar product

$$\|v(t)\|\langle w(t)\rangle=\int_0^T v(t)\cdot w^*(t)dt.$$

After that, a system of orthonormal "axes" is created (the basis of space), and any signal belonging to this space is represented as a weight sum of the signal projections onto these "axes" – basis vectors. The values of the projections are determined by the scalar products of the signal with the corresponding functions of the basis "axes". The integration of samples in the frequency domain forms the linear spectrum of the studied signal.

In the studied area of the wave field, sections with horizontal X, Y and vertical Z components of the seismic wave have been identified and combined linear spectra have been plotted (Fig. 8).

According to the data of the wave field linear spectra, it can be seen that each of the three components has its own frequency maximum. In this case, the central frequencies of the X, Y and Z components are equal to 12, 14 and 20 Hz, respectively.

In addition, the following peculiarities should be taken into account:

- different types of waves are characterized by different frequency composition. This makes it possible to identify useful waves and suppress noise waves;
- rock properties such as porosity and saturation can influence the frequency composition;
- layers with different thicknesses cause anomalies in different frequency ranges;
- waves with a high vibration frequency have a greater effect; however, they also attenuate earlier, being absorbed by the medium.

Thus, for further analysis and modeling, a wave packet with a central frequency of 20 Hz is taken.

To simulate the seismic wave propagation, an omnidirectional source type with previously specified seismic pulse parameters is selected.

The seismic parameters of the elastic vibration propagation medium are set based on the results of field measurements and the physical properties of rocks. In this case, the wave velocity in the pores filled with water is taken equal to 1500 m/s.

According to the numerical modeling results of the seismic blast wave propagation in the studied mass area, no critical values of the vibration velocities have been revealed. However, as a result of re-reflections and mutual interference of stress waves, local areas of dynamic load can form, which, in combination with acting static stresses, can adversely affect the rock mass state. This is a decrease in the strength characteristics of individual mass sections due to the opening of old and the formation of new fractures.

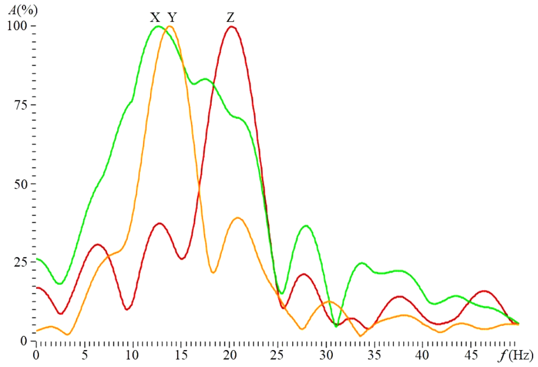

Fig. 8. Linear spectra of the wave field by components

The areas adjacent to the contacts of various lithological varieties and geological faults are more susceptible to the indicated influence. Thus, as a result of the seismic data analysis and comparison of fracture surveys, it has been determined that the degree of influence of blasting the explosive charges on the mass is moderate. The revealed deformations are confined to the zones of geological faults.

The results of each blasting should be monitored and analyzed to further correct the design with account of changing slope conditions. The results should be assessed on the basis of damage in adjacent and distant zones, as well as the level of induced seismic vibration.

When reaching the final open-pit boundary, the design bottom and the edge of the bench should be obtained, and damage caused by blasting operations should be visible on the slope. When the extraction work is completed, the open-pit side should be inspected and analyzed for excessive rock overbreak. Damage should be classified into the following categories for subsequent correction of the project for drilling-and-blasting operations (Figs. 9, *a–c*).

There is no visible damage: the fractures are dense; there are traces of teeth on the slope, but no cutter breaks; the bottom and upper edge of the bench are clearly visible, as well as traces of blast-holes/preserved parts of blast-holes from preliminary formation of slits (Fig. 9, *a*).

Insignificant damage: fractures have opened; the edge loss is less than 1 meter; traces of blast-holes are visible, as well as parts of blast-holes from preliminary formation of slits; extraction work can be performed 1 meter beyond the design position of the slope (Fig. 9, *b*).

Moderate damage: displaced blocks; loss of the upper edge by 1–3 meters; extraction work can be performed 1–3 meters beyond the design boundary of the bench (Fig. 9, *c*).

Severe damage: the slope is crushed; the blocks are displaced and turned; extraction work can be performed 2 meters or more beyond the design boundary of the bench (Fig. 9, *d*).

The seismic stability of the rock mass is determined by the absence of residual deformations during the passage of seismic blast waves. The criterion for the mine rock seismic resistance is the relative elastic deformation (E_0), which is calculated by the formula

$$E_0=U/V_p,$$

where U is vibration velocity of soil particles of a seismic wave, m/s; V_p is seismic wave propagation velocity, m/s.

It has been determined that the greatest danger is caused by the type of waves that, in terms of the frequency spectrum at the maximum values of vibration amplitudes, is the closest to the spectrum of natural vibrations of the open-pit contour. Given that during blasting, the stresses and relative deformations of objects are directly proportional to the vibration velocity, seismic hazard will be created by those types of waves in which these parameters are maximal.

Analysis of the experimental data indicates that one of the main reasons for the change in fracture formation is the unequal frequency composition of vibrations in different directions, as well as different propagation velocity of seismic waves. Thus, based on the above research, the relationship of seismic anisotropy with the anisotropy of the rock mass has been determined which makes it possible to deepen knowledge in the study on the physical and technical foundations of the distribution pattern of seismic waves.

A practical assessment of the quality of performed operations on face drilling is calculated as follows

$$\Delta i=\frac{K-m}{K}\cdot 100\,\%,$$

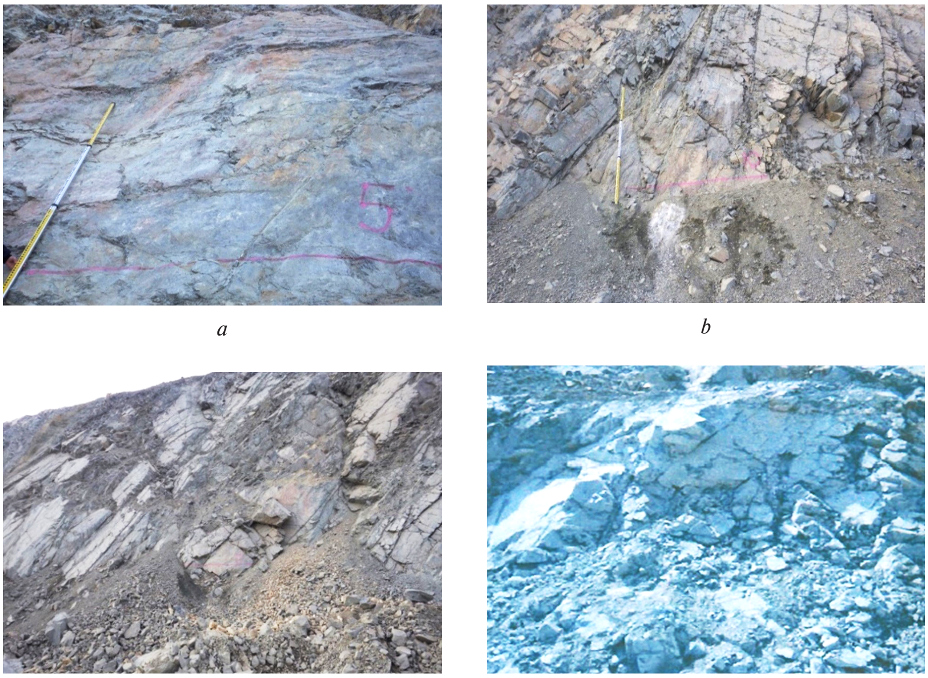
a *b* *c* *d*

Fig. 9. Damage after blasting operations:
a – absent; b – insignificant; c – moderate; d – severe

where K is the number of sample measurements; m is distances between blast-holes.

The percentage of measurements that are within the permissible deviations is calculated from the expression.

$$\Delta j = \frac{N - i}{N} \cdot 100\,\%,$$

where N is the number of blast-holes drilled; j is the number of overdrills.

The percentage value of permissible deviations in the quality of drilling a rock mass is determined by the formula, %

$$b_k = \frac{\Delta i + \Delta j}{3}.$$

If b_k is within 95–100 %, then the drilling quality is "excellent", with b_k = (90–95) % the quality is "good", with b_k = = (80–90) % – "satisfactory" quality and with $b_k < 80$ % drilling is considered defective.

To calculate the seismic stability of a multilayer open-pit side in conditions of a mass explosion, it is necessary to correctly determine the path of seismic wave propagation and the degree of its absorption by rocks. In these conditions, all objects adjacent to the open pit are exposed to the seismic wave influence, regardless of the horizon of their location.

In this research, an anomalous nature in the displacement velocity change is observed during the propagation of seismic waves, respectively, up and down the benches of the open pit. At a certain distance along the height of the open pit, the minimum displacement velocities are observed, after which they begin to increase. This can be explained by the passage of a wave through rocks with low seismicity coefficient k_s.

The minimum displacement velocities are observed at a distance of 80–100 m from the site of blasting, regardless of the horizon of the blast unit location. This nature of the change in the displacement velocity with depth indicates its uneven distribution along the open-pit side. At a certain distance, it tends to increase.

The use of the ELLISS-3 measuring equipment allows calculating the vibration velocity in the rock mass with a sufficient degree of accuracy, but it is problematic to determine their permissible value in this way. This is conditioned by the fact that the seismic factor in terms of the strength of its impact may be insignificant, but it is decisive in the general list of reasons for the occurrence of residual deformations (new fractures).

Systematic surveys of the state of the open-pit limiting contour are conducted in order to identify its changes after blasting operations. The assessment of the seismic resistance of the open-pit contour should be made with a permissible vibration velocity, since this indicator most reliably correlates with the energy that disrupts the continuity of the open-pit sides as a result of seismic impact.

Conclusions. As a result of the research performed, the rock mass seismicity coefficients, as well as the lowest displacement velocity for the rocks of the Kusmuryn field have been determined. Seismic surveys were performed for determining the propagation velocity of elastic waves arising in a rock mass as a result of blasting operations.

When determining the nature of a change in the seismicity coefficient depending on the ratio of the actual values of σ_c/σ_t of mine rocks within the deposit, the correlation coefficient ($R^2 \approx 0.60$) value is above the average. This evidences a sufficient relationship between the seismicity coefficient k_s and the σ_c/σ_t ratio, which determines the relationship between the main strength properties of the blasted rocks.

Seismic surveys were performed for determining the propagation velocity of elastic waves arising in a rock mass as a result of blasting operations. Based on the results of numerical modeling of the seismic wave propagation after blasting operations in the studied mass area, the critical values of the vibration velocities have not been revealed.

The research performed made it possible to develop a new technology for conducting drilling-and-blasting operations at the open-pit limiting contour and to create a methodology for assessing the quality of the blast performed during contour blasting.

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Оцінка якості ведення буропідривних робіт у приконтурній зоні кар’єру

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Мета. Розробити оцінки якості буропідривних робіт при формуванні кар’єру в кінцеве положення, при цьому розглянувши характер деформування прибортових масивів у приконтурних зонах кар’єру та оцінку сейсмічного впливу вибухових хвиль відповідно до пошкоджень у ближній і дальній зонах від межі кар’єру з урахуванням рівня сейсмічних коливань.

Методика. Розробка методики оцінки якості буропідривних робіт у приконтурній зоні кар’єру виконувалась за допомогою аналізу гірничо-геологічних умов залягання гірських порід, натурних обстежень стану бортів кар’єру, аналізу фізико-механічних властивостей уміщуючих порід, аналітичних досліджень та інструментальних вимірів дії вибуху.

Результати. На основі аналітичних методів виконано розрахунок і аналіз коефіцієнта сейсмічності гірських порід родовища. Шляхом інструментального виміру дії вибуху в кар’єрі отримані дані щодо сейсмічного впливу підривних робіт на прибортовому масиві. За результатами цих робіт розроблена методика оцінки буропідривних робіт у приконтурній зоні кар’єру.

Наукова новизна. У роботі для оцінки дії вибуху використано коефіцієнт сейсмічності породного масиву, який характеризує ступінь пружної реакції на зовнішні динамічні впливи, та є параметром, що визначає інтенсивність пружної сейсмічної хвилі по мірі віддалення від місця вибуху. На основі розрахунку побудована мапа розподілу коефіцієнта сейсмічності в кар’єрному просторі. За допомогою методу інструментальних вимірів, що служить для визначення сейсмічного впливу вибуху на масив гірських порід, виявлена ступінь впливу вибуху на прибортовий масив. Це дозволило розробити метод оцінки якості проведеного підривання, що ґрунтується на визначенні відсотка допустимих відхилень за якістю оббурювання вибою.

Практична значимість. Результати роботи будуть використані для розрахунку безпечних параметрів ведення підривних робіт під час формуванні кар’єру в кінцеве положення. Даний спосіб оцінки якості ведення буропідривних робіт може бути застосований на будь-якому гірничому підприємстві, що веде відкриту розробку корисних копалин.

Ключові слова: *контурне підривання, стійкість бортів кар’єру, сейсмічна дія, буропідривні роботи, якість вибуху*

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