REDUCING THE IMPACT OF MASS EXPLOSIONS ON THE CONTOUR ARRAY OF THE QUARRY

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Abstract

The increase in the depth of the quarries revealed an important problem of maintaining the stability of the sides of the quarries due to changes in the structure of the rock mass under the influence of industrial mass explosions both directly in the fracture zone, revealing closed cracks, and by wave influence in the pre-collapse zone at a considerable distance, where new cracks and prerequisites for the creation of crack nuclei are generated. Blasting operations near slope structures without taking into account these changes in the massif often causes a violation of their stability, the occurrence of landslides, up to catastrophic. It is proved that with explosive masses on underground blocks up to tens of tons, the effect of their explosions on the array can be traced to at least 50 m, with intensive decompression up to 20 m. Consequently, in quarries with explosive masses on blocks of hundreds and even thousands of tons of explosives, even greater “long-range” distances should be expected. In most cases, the protection of the sides of quarries from the effects of mass explosions is carried out by mowing down the sides of the quarry, preceding a mass explosion in the instrument area. The paper proposes a new technology for conducting mass explosions with downhole detonation along the work front and the start of the explosion from the side of the quarry to the slope of the ledge, due to the constant deep clamping of exploding charges by an array of rocks of the untouched part of the block. Its main advantage is a threefold reduction in the effects of stress waves in the direction of the side of the quarry. Ten years of experience in using such technology has made it possible to form a stable side of the quarry on the limit contour without the use of additional measures to mow the side.

Keywords: side of the quarry; slope of the ledge; downhole blasting; skewing of the side of the quarry; creation of shielding surfaces and contour slits.

Problem statement

Currently, as the depth of development in open-pit mining increases, the most important scientific and technical problem is to maintain the stability of the sides of quarries both in the working position and, most importantly, when placing them in the limit position. Numerous studies [1-14] have established that, along with natural factors affecting the stability of ledges in the extreme position, such as the structural and tectonic structure of the massif and the properties of the rocks composing it, the technological features of blasting have the greatest influence on the degree of disturbance of the massif. This is a completely human-controlled technological factor, which can be controlled to achieve both positive and negative results.

Considering the structural array of each industrial block, it is possible to identify certain zones that are "harmful" from the point of view of the stability of the slope of the overlying ledge. First of all, this is the zone of the future first row of borehole charges of the next industrial block. It is exposed to the greatest impact of stress waves, therefore, the greatest disturbance of the rock mass occurs, which, if the side is placed in the limit position, will be the focus of subsequent weathering of rocks and a violation of the stability of the slope of the ledge. Studies [1] have established that "the explosion of charges on the underlying ledge forms nuclei of maximum chipping stresses in the overlying ledge with a magnitude of 3 to 12 MPa, which, as blasting operations approach, gradually shift from the sole to the roof of the overlying ledge, preparing it for subsequent collapse following the dislocation of such nuclei." Therefore, insufficiently careful blasting operations near the slopes of the sides of the quarry can cause a violation of their stability and lead to landslides with large volumes of rock collapse, up to catastrophic. A striking example of this phenomenon is the giant landslide at the Bingham Canyon quarry (Fig. 1) [2].

Fig. 1. The collapse of the side in the Bingham Canyon quarry (USA)

"In this regard, the creation of a shielding barrier between the sole of the overlying ledge and the front of blasting operations on the underlying ledge should be carried out at a time when the distance from the explosion to the lower edge will be at least three ledge heights (for 15-meter ledges it is about 45 m). Otherwise, creating such screens is inefficient." At the same time, neither the essence of the shielding barrier nor the methods of its formation are considered in [1]. In [3], it was proposed to leave a single-ended rear sight as such a shielding barrier, which will then be worked out using a gentle technology with downhole blasting and a cut-off slot. At the same time, the sequence of blasting from the exposed surface of the ledge to the design contour of the side of the quarry is recommended. In [4], the width of the structural whole is already considered from the point of view of the regularities of rock destruction by explosion: about 32 m for a charge with a diameter of 215 mm and 38 m for a charge of 250 mm). According to [5], the structural whole must be developed with a reduced number of rows of wells and the mass of explosive charges in them, which leads to an increase in the number of visits, a decrease in the quality of the rock mass in the collapse and, as a result, a decrease in the productivity of excavation machines.

To assess the effect of the degree of impact of mass explosions on the size of the zone of residual deformations in large-block hard-to-explode rocks of the Kachkanarsky GOK quarries, residual deformations of the massif were measured along profile lines from scoring benchmarks oriented normally to the extension of the ledge to the rear of the massif [6]. The measurements were carried out with 3 – 5 row detonation according to diagonal schemes of MSV (the mass of the charge in the deceleration stage is 1650 – 2750 kg, respectively). The distance between the borehole charges in the deceleration stage and the deceleration intervals between the stages were changed by the appropriate installation of a precinct explosive network from the convergence coefficient m = 1.2 to 8-14. The largest values of deformations in the array are noted: with a single–row CV on a retaining wall made of exploded rock mass, with MSV according to diagonal schemes with m = 1.2 and along gentle diagonal ones with m = 8.0. The width of the zone of residual deformations with these methods of blasting reaches 45 ~ 50 m, and the values of deformations are 600-850 mm. A significant decrease in the values of deformations in the array occurs when exploding with a single-row CV on a selected face, MSV according to schemes with m = 8.0 and steep mounting of diagonals, as well as with m = 8.0-14.0. The value of the horizontal component of the residual deformations is reduced to 80-200 mm, and the width of the deformation zone is up to 35~40 m. The use of a flat diagonal scheme with m = 8.0 with a deceleration between charges in a row of 20 ms increases the effect of the explosion on the array of the total mass of the charge of the entire exploding volume of explosives as a single charge. Exploding according to steep diagonal schemes of MSV with m = 8,0–14,0 leads to a decrease in the magnitude of the residual deformations transmitted to the array.

After analyzing the results, the company switched to working out the end–mounted rear end with tapes, the width of which allows you to place at least four rows of wells with rock stripping according to the schemes of MSV with m = 8,0-14,0. In this case, the deceleration interval between the charges of the terminal row at a = 5.5 m should be at least 35-40 ms, and between adjacent charges of two terminal rows – at least 50-60 ms. Charges detonated with the same deceleration interval should be located at a distance of no closer than 2.8 a to exclude mutual influence.

Measurements of deformations and amplitudes of rock displacement velocities were carried out at the Korshunovsky quarry in limestones, mudstones and sandstones with f = 3-12 to determine the dependence of the size of the zone of residual deformations and their values on the direction of explosive breakage of the ledge [7]. Parameters of mass explosions: the mass of explosive blocks is up to 283 tons, the mass of explosives at the deceleration stage is up to 8 tons, the specific consumption of explosives is 0.45–0.65 kg/m^3. A grid of wells with a diameter of 243 mm and a depth of 16-25 m, measuring 8x9 m.

According to experimental data, a clear dependence of the values of the maximum horizontal relative deformations ε on the angle φ between the direction of a number of borehole charges of the deceleration stage and the extension of the edge of the ledge was obtained. The maximum value of ε is observed in the frontal direction (φ = 0), the minimum value is observed on the flank (φ = 90). At the same time, the ε on the frontal profile is 12 times higher than this value on the flank. Such a significant difference is due to the fact that in the frontal direction the wave is close to a flat one, and in the flank direction it is cylindrical, the attenuation of which is due to a geometric discrepancy. The dependence of ε on the strength of rocks in the range f = 3-12 has not been revealed. It has been established that in the near explosion zone at τ = 35 ms, an independent velocity field is formed from each stage of detonation of a group of charges as from a separately exploded charge (weighing up to 8 tons in this case), i.e. the effect of triggering a quasi-single charge of high power occurs. Therefore, the dynamic impact of such large mass explosions creates in the rock mass a zone of residual deformations up to 100 m wide along the surface of the ledge. This is despite the fact that the structural array is no longer affected by the energy of the entire mass of the explosive block (283 tons), but only by the sequential effect of quasi-single charges of stages with a mass of 8 tons, less than 35 times. The thesis of the long-range effects of mass explosions in quarries is also confirmed by the effect of voltage waves up to 50 m during the development of a mass explosion visually recorded on the surface of the ledge during accelerated video shooting with a frequency of 240 fps (Fig. 2), as well as the manifestation of a voltage wave from the explosion of the first borehole charge on the surface of the ledge to the boundaries of the block with a length of 110 m [8].

Fig. 2. Visualization of the propagation of stress waves
of a mass explosion

In [9], experimental measurements established that with explosive masses in underground chambers of hundreds of kg, "the area of influence of explosions from the chamber extends to a distance of at least 50 m, and the area of intense decompression of the surrounding massif extends to a distance of about 20 m. A remarkable feature of the analyzed technological explosions is their "*long-range effect*": the noted deformations of the arrays extend around the formed cavities much further than can be expected from classical concepts of the zone of explosive destruction of a continuous medium by about an order of magnitude." Consequently, in quarries with masses of charges on blocks of hundreds of tons of explosives, even greater “long-range” distances should be expected not only on the surface of the ledge, but also in the depth of the array. At the same time, the maximum seismic explosive effect is observed in the direction of a sequential short circuit of individual explosive charges or their groups [10-18]. Consequently, the currently generally accepted direction of the blasting scheme from the exposed surface of the ledge to the design contour of the quarry obviously multiplies the impact of a mass explosion on the instrument array.

Methods of protecting the instrument array from the effects of mass explosions

With the advent of non-electric detonation systems (NES) with waveguides and electronic detonators, the possibility of downhole detonation appeared, which significantly reduces the mass of a really exploding single borehole charge and its effect on the contour array of the technological block. Thus, in [19] it was found that the calculated deceleration intervals of 100 ms between borehole charges in a row and 67 ms between rows make it possible to completely form theoretically possible crushing zones for each of the exploding charges, reducing the output of the oversized by 1.5 times and the camber width by 5-10 m. It is confirmed that the quality of crushing rock mass is improved and the seismic effect of the explosion on the block's contour array is reduced with an increase in the deceleration intervals between successively exploding charges due to the redistribution of explosion energy in favor of crushing action.

In [20], a comparison was made of the variants of seismic effects on the structural array of the exploding block during the sequential detonation of individual borehole charges along diagonal and series-counter surface blasting schemes. The possibility of reducing the seismic impact to acceptable parameters on a protected object located 80 m from the contour of the exploding block was revealed only with a series-counter explosion with a deceleration interval of 200 ms between explosions of individual charges by increasing the specific deceleration between rows of wells by an order of magnitude – from 37 to 450 ms/m. At the same time, a shielding surface is formed around each exploding charge, which makes it possible to reflect and refract the energy of the stress wave and, thereby, use the bulk of the energy of the stress wave for crushing, minimizing the seismic impact on the structural array.

Thus, serious experience has been accumulated in changing the technology of conducting mass explosions in the instrument area according to the schemes of detonation of both groups of charges connected by a DSH and downhole detonation. However, this creates an additional technological process for the formation of a contour gap with inclined drilling of wells located closely in the same plane, often of considerable depth. With a large depth of inclined contour wells, there is a serious problem of preserving their lower part in the plane of the formed cutting gap. Difficulties also arise when manually charging with garlands of explosive cartridges or hose charges [21-35]. The allocation of the zone of the instrument cluster with its subsequent development by gentle methods further complicates the conduct of drilling and blasting and excavation and loading operations.

The question arises: is it really necessary to work on the preliminary creation of screening barriers to protect the overlying ledge from the effects of mass explosions associated with the problems of drilling inclined wells, their subsequent manual charging with garlands of patronized explosives and blasting with a certain advance? And if these shielding barriers are created during the development of a mass explosion of each block, excluding additional technological processes? This technology of explosive loosening of rocks in deep clamping by rocks of the exploding block was created and has been used for several years in the gold mining pits of the Far East [36-38].

Technology of explosive loosening of rocks in a deep clamp

The essence of this technology lies in the fact that the starting impulse for a massive explosion of an industrial block is fed to a block row of borehole charges located second or third from the rear edge of the block from the side of the overlying ledge. Therefore, the development of a mass explosion towards the open slope of the exploding ledge occurs with the clamping of triggered charges by an undisturbed rock mass. The deceleration interval between successively exploding charges in the block row is not less than 100 ms, and in the perpendicular direction along the rows of boreholes is twice as high. It is known that under the action of a cyclic alternating load, an energy flow occurs to the tip of the crack [39], while the tensile and compressive stresses of the same absolute magnitude create equal energy flows, but their effect on crack growth is directly opposite. The energy of compressive stresses has a strengthening effect and crack growth cannot occur at the stage of action of the compressive load; only the energy of tensile stresses is directed at breaking the bonds at the tip of the crack, and not all the energy of tensile stresses is spent on crack growth, but only its excess over the energy of deformations of the medium. Therefore, it is necessary to create time for the voltage drop in the array from the explosion of the previous downhole charge by increasing the interval between the deceleration stages by an amount that ensures both the germination of fracture cracks from the exploding charge to a theoretically possible depth and the interaction of voltage waves in the pre-collapse zone.

The technology of explosive loosening in a deep clamp with extended deceleration intervals has been developed, tested and applied at several enterprises in the Far East for more than 12 years with good results [40-42]. The Albyn quarry in the Amur region has been working on the technology of explosive loosening of rocks according to the 150x200 ms blasting scheme with non-electric detonation systems with waveguides (NESI) for 8 years, from the beginning of work in 2012 to the end in 2020. The quarry side, rebuilt in its final position, as of June 2024. it looks very good and is almost the same both on the upper ledges (standing for 12 years) and on the lower ones (standing for 4 years). And this is despite the fact that no special work has been carried out on contour blasting and the creation of shielding surfaces (Fig. 3).

Fig. 3. The board of the Albyn quarry is in its final position as of June 2024.

Consequently, the technology of explosive loosening with large decelerations and the start of blasting from the depth of the block from the side of the quarry to the slope of the ledge with an intact massif clamp not only improves the quality of crushing rock mass [42], but also significantly reduces the seismic impact on the on-board rock mass, and precisely due to the redistribution of explosion energy to crushing.

To prove the thesis about the redistribution of explosion energy to various types of impact on the rock mass, we will model the impact of blasting in a 50-meter contour zone for existing technologies starting from the slope of the ledge to the side of the quarry and blasting technology starting from the side of the quarry to the slope of the ledge [40]. Graphical modeling is performed according to the methodology described in [41], using the actual parameters of the experimental mass explosion of block No. 518-190-4 91-B, conducted at quarry No. 5 (Vostok), mountain. + 200 m [40] (Fig. 4).

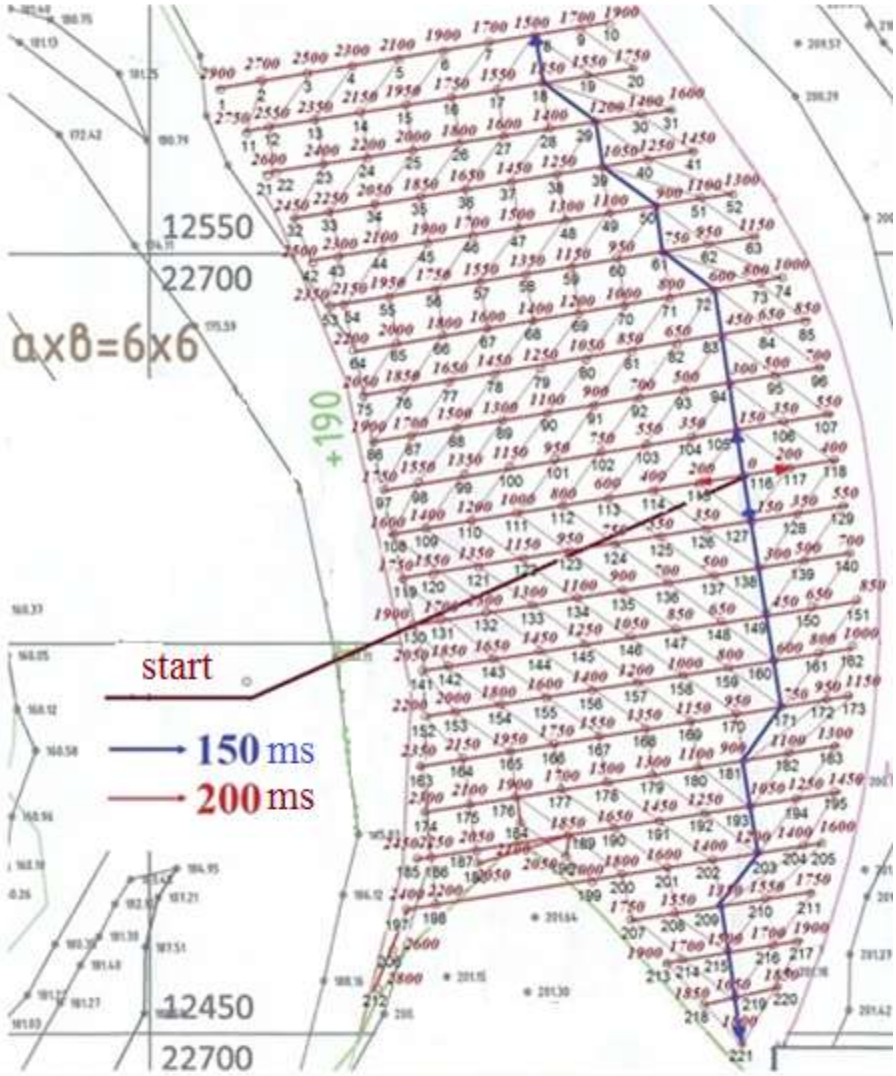

Fig. 4. Copying the block blasting scheme from the project for a massive explosion

The results of the experimental explosion from the point of view of rock loosening are described in detail in [40]. Here we focus on the influence of wave processes of a mass explosion on the block array in a 50-meter zone behind the contour of the exploding technological block with various explosion schemes.

For graphical modeling, a conditional block of 81 borehole charges (9 rows of 9 wells) was adopted. To calculate the number of effects of voltage waves from successive explosions of individual borehole charges of the block on the array towards the side of the quarry, the grid of wells of the conditional block is virtually continued and highlighted in green. Figure 5 shows a graphical model of the development of a mass explosion for four explosion schemes at the third stage of deceleration with a start from the depth of the array to the slope of the ledge. For the readability of the graphics, only the last 4 vertical rows of the conditional block and all 9 rows of the virtual grid are shown.

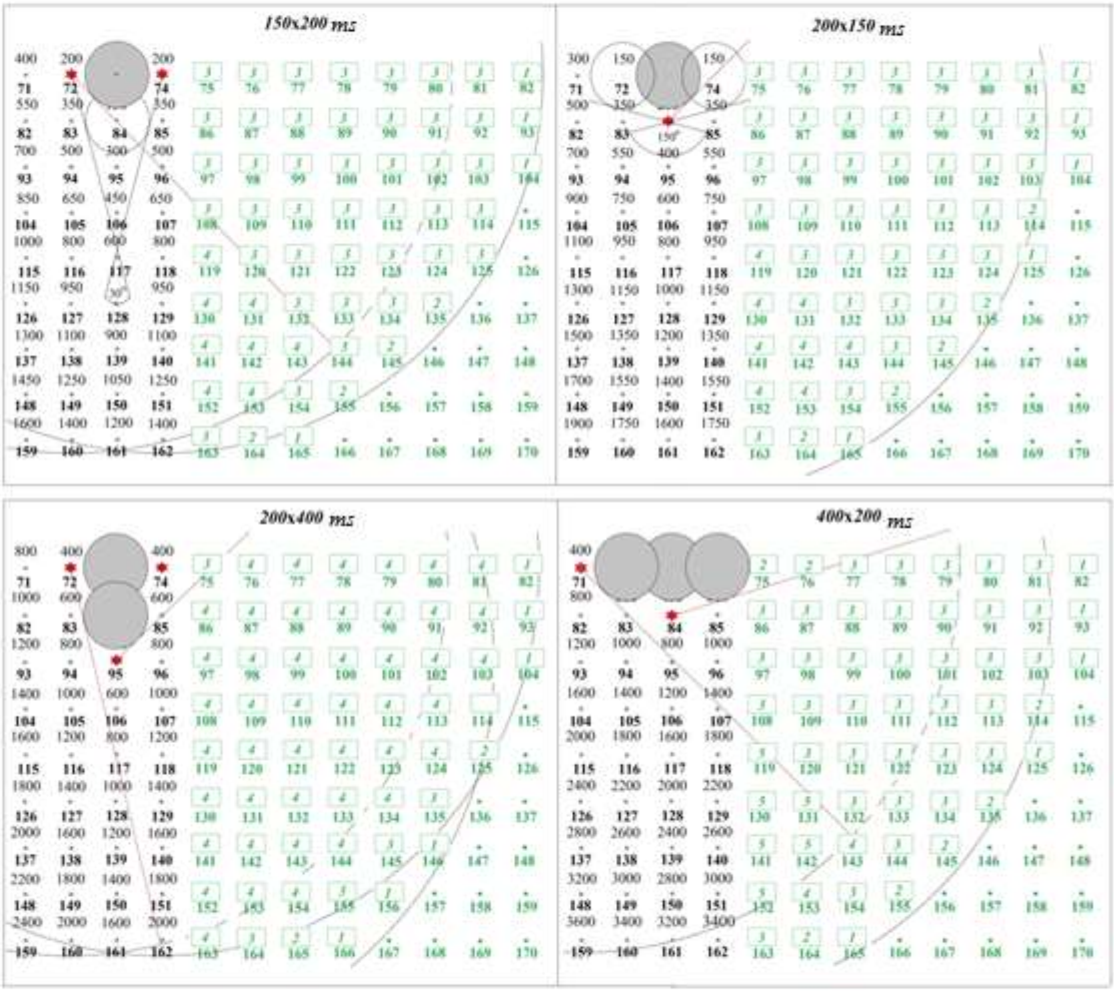

Fig. 5. A graphical model of the development of a mass explosion at the third stage of deceleration with a start from the side of the quarry to the slope of the ledge

The borehole charge is represented by a circle, below it is indicated its serial number in the project for a mass explosion, above it is the value of the deceleration interval from the initial charge. In modeling, the zone of rock destruction by a borehole charge is assumed to be 40 charge radii [43] (for a borehole charge with a radius of 107 mm – 4.3 m), and the fracture zone – according to actual measurements of induced fracturing at various enterprises – 20-25 m [44, 45]. The virtual grid shows the number of voltage waves that have passed through the well location zones in its nodes.

The voltage wave from the exploding charge does not pass through the zone of rocks destroyed by the borehole charge, formed earlier than 75 ms, while the boundaries of the zone reflect up to 30% of the energy of the voltage wave into the volume destroyed by this charge, and the remaining 70% of the energy is refracted into the zone of destroyed rocks, producing additional destructive effects on them [10]. The 150x200 ms explosion circuit at the 200 ms deceleration stage has a destruction zone from the charge 84 triggered at the 150 ms deceleration stage, i.e. in 50 ms (<75 ms), it is still "transparent" to voltage waves from simultaneously triggered charges 72, 74 and is indicated by a circle. The remaining zones of destruction of triggered borehole charges, in which the voltage wave is partially reflected into the zone of the exploding charge, and partially refracted into the exploded rock mass, have a fill. Therefore, the area of action of the voltage wave is limited to a sector of a circle with a radius of 50 m between the rays coming out of the center of the exploding charge relative to the zones of destruction with filling.

The analysis of Fig. 5 allows us to draw the following conclusions. The start of blasting schemes from the side of the quarry to the slope of the ledge with a cut in the second row from the edge of the block with the direction of development of a mass explosion along the stretch of the ledge (front of work) can significantly reduce the wave effect of successive explosions of borehole charges. When decelerating in a log cabin row smaller than in the rows of wells, a wedge–shaped log cabin is formed with an angle at the top of the order of 30, and when decelerating more than in the rows of wells, the angle changes to 150, which affects the formation of a wave effect on a structured rock mass.

The blasting schemes 150x200 ms and 200x150 ms carry out sequential blasting of individual borehole charges with a deceleration interval between them after 50 ms (the spread of retarders from the nominal value is not taken into account). The duration of the destruction process on the conditional block increases from 1400 ms for the 150x200 ms explosion circuit to 1750 ms for the 200x150 ms circuit. In addition, the 200x150 ms scheme has the effect of wave processes on the contour array not only of the 4th vertical row (single for the 150x200 ms scheme), but also of the 5th, and in a sufficiently large amount in total (Fig. 6).

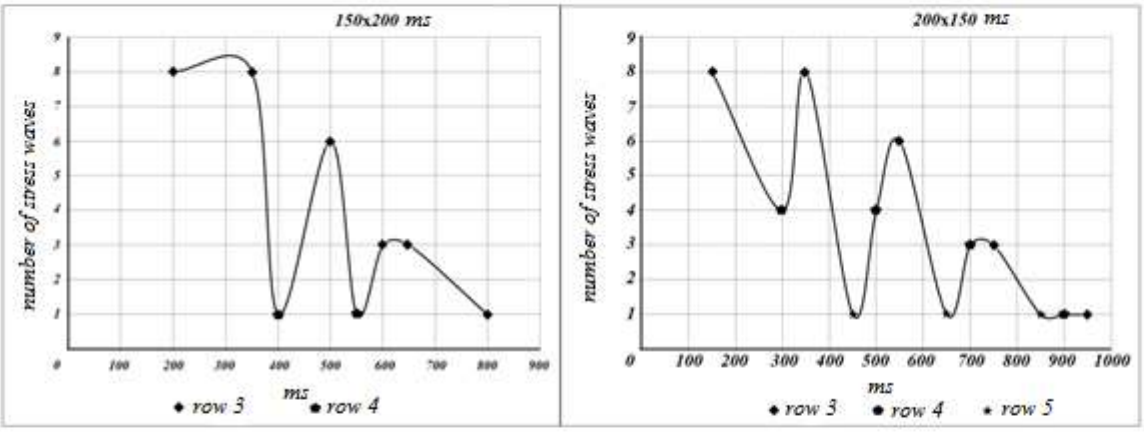

Fig. 6. The effect of voltage waves from borehole charges of vertical rows behind the log cabin on the near-circuit zone

To compare the quantitative effect of voltage waves on the contour array outside the technological block within a radius of 50 m, Fig. 7 shows a graphical model of the development of a mass explosion of a 150x200 ms explosion circuit at a deceleration stage of 1000 ms with a start from the slope of the ledge to the side of the quarry (Fig. 7, *a*) and from the depth of the array to the slope of the ledge (Fig. 7, *b*).

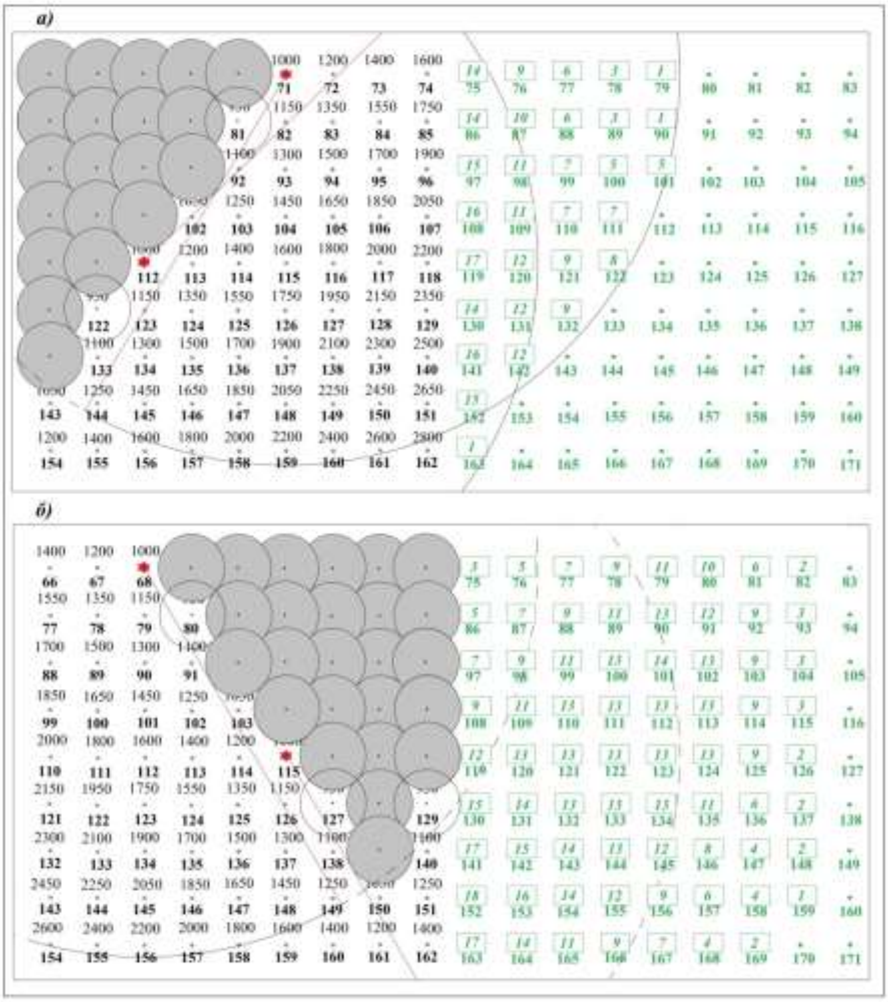

Fig. 7. Graphical model of the development of a mass explosion at a deceleration stage of 1000 ms when exploding from the slope of the ledge to the side of the quarry (*a*) and from the side of the quarry to the slope of the ledge (*b*)

The graphical model presented in Fig. 7 shows a significant change in the pattern of seismic impact of borehole charges on the instrument area of the quarry under different start schemes. At the start of a mass explosion, 8 sequentially exploding borehole charges in a horizontal row are triggered from the slope of the ledge to the side of the quarry, therefore, it is necessary to take into account the multiple amplification of the seismic effect in this direction. In [15], it is emphasized that the amplification factor of the explosion in the direction of sequentially exploding charges reaches a value of 6.02. In the opposite direction – 2.19, in the lateral direction – from 1.47 to 2.99. At the start of a mass explosion from the side of the quarry to the slope of the ledge with the development of an explosion along the front of the work, the seismic effect in the direction of the side of the quarry occurs laterally and only from the borehole charges of the log row and adjacent to it from the side of the quarry with an explosion amplification factor towards the side of 1.47–1.82, and along the side in the direction of the log – 6.02.

Discussion of the results

With a 400x200 ms blasting scheme for borehole charges arranged in a square grid measuring 6×6 m, the additional energy from voltage waves refracted into the shielding medium is a multiple (2.35 times) higher than the energy required for complete destruction of rocks in the maximum possible charge area. This excess energy is spent not on scattering the rock, but on crushing it due to the constant clamping of the destruction zone by the surrounding rock mass [42].

The results of graphical modeling of the total effect of voltage waves from borehole charges on the contour zone in the form of the number of voltage waves passing through the nodes of the virtual grid of wells are shown in Fig. 8. Fig. 8 shows that according to the first vertical row (a distance of 6 m from the boundary of the exploding conditional block), the impact of stress waves at launch from the side of the quarry is significantly less than from the slope of the ledge to the side of the quarry. So, for the explosion circuit: 200x400 ms is 4.7 times less, 150x200 ms is 3.9 times, 200x150 ms is 3.4 times, 400x200 ms is 2.6 times. At a distance of 24 m: for schemes 150x200 and 200x400 ms – 2.3 times, 200x150 – 2.2 times and 400x200 ms – 1.9 times, and only in the final section the effect is almost the same.

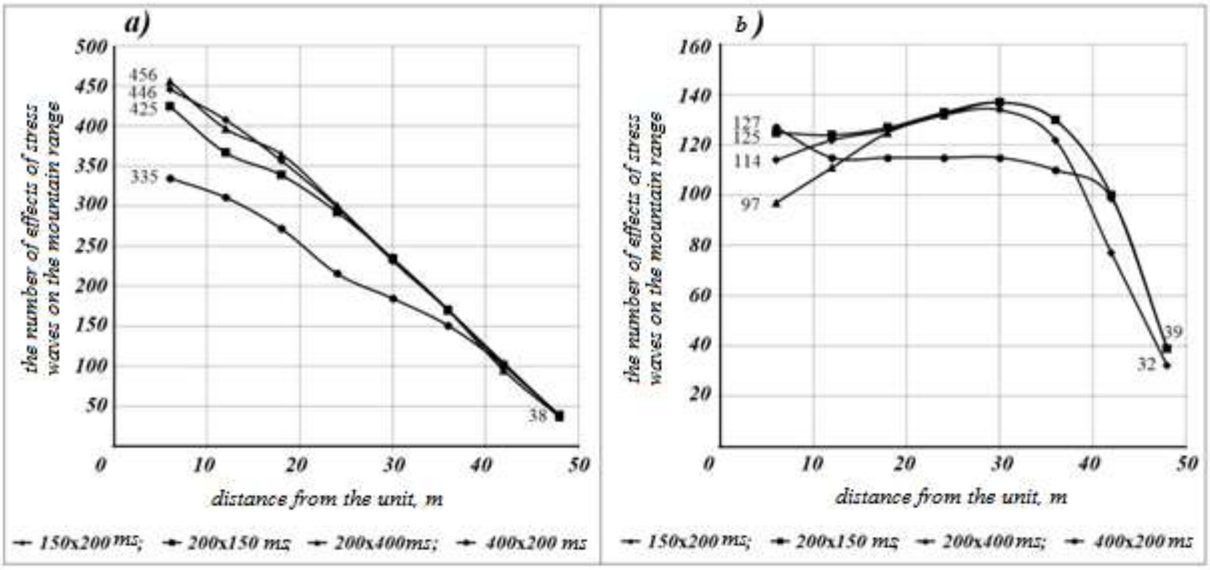

Fig. 8. Comparison of the total effects of voltage waves on the port area
in vertical rows at the start:
a) – from the slope of the ledge to the side of the quarry;
b) – from the side of the quarry to the slope of the ledge

According to graphical modeling data, blasting schemes of 400x200 ms and 150x200 ms with a start from the side of the quarry to the slope of the ledge can be considered preferable for use in terms of reducing the seismic impact on the instrument area. The total number of voltage waves affecting the nodes of the virtual grid of wells is 837 for the 400x200 ms circuit and 864 for the 150x200 ms circuit versus 882 for the 200x400 ms circuit and 915 for the 200x150 circuit. The 150x200 ms scheme has proven its effectiveness in practice using the example of the Albyn quarry, and the 400x200 ms scheme is easily implemented in practice even in the absence of industrial production of 400 ms retarders by serial connection of two 200 ms retarders. Fig. 9 shows comparative indicators of the effects of a mass explosion on the instrument area with a 400x200 ms explosion scheme, where it can be seen that when a mass explosion starts from the side of the quarry to the second or fifth nodes in the depth of the virtual grid of wells, these indicators are stable.

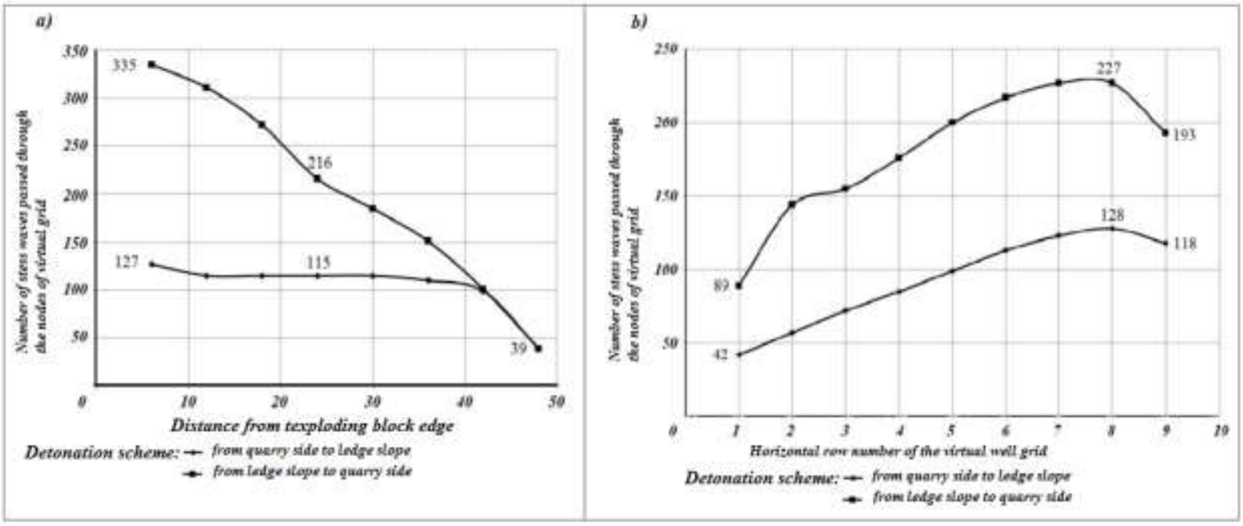

Fig. 9. Comparison of the total effects of a mass explosion on the portside zone according to the 400x200 mm explosion scheme along vertical (*a*) and horizontal (*b*) rows

Conclusion

The lowering of the level of mining operations at quarries continues at an accelerated pace, and the depth of the quarry at 600-800 m is already becoming a familiar phenomenon. Problems of stability of the sides of deep quarries have also become almost a familiar phenomenon – landslide phenomena no longer capture only the upper horizons. Therefore, the number of publications devoted to the issues of the preservation of rock formations in quarries is increasing.

The analysis of the performed studies showed that the main direction of technical solutions to increase the stability of the instrument area of quarries is reduced to changing the technology of conducting mass explosions at a certain distance from this zone – an additional process of protective measures appears to reduce the influence of wave processes of mass explosion on the instrument array of rocks. A separate technological process for the formation of protective shields in an array of rocks that prevent the passage of voltage waves from borehole charges into the instrument array is considered necessary and most effective. Here, the abandonment of security targets with their subsequent development by gentle methods, and a decrease in the parameters of the well grid and the magnitude of charges, up to the transition to the approaches, and an obligatory element is advanced crevice formation.

There is a clear trend of conducting industrial mass explosions in the instrument area with an increase in deceleration intervals of up to 100 ms between wells in a row and 67 ms between adjacent wells in rows and the sequence of explosions – from the exposed surface of the ledge to the design contour. If an increase in the deceleration intervals allows for the complete completion of the cracking process in the charge operation zone and the use of explosion energy specifically for crushing, reducing the seismic effect, then the sequential explosion of charges on the protected zone increases the seismicity coefficient to 6.02 units, despite the fact that laterally it is half as much: 2.41 and 2.99.

At the same time, the technology of conducting mass explosions with a sequence of detonation of individual charges along the work front with a start from the depth of the massif to the slope of the ledge and deceleration intervals between rows 150-400 ms and 200-400 ms has been used in the gold mines of the Far East for more than 10 years. It provides high-quality crushing of the rock mass while preserving it in the contours of the industrial block, allowing to triple the number of voltage waves passing through the instrument area and increase the stability of the ledges both at the current and at the final contour of the quarry. The use of such technology since the beginning of the development of one of the deposits has made it possible to achieve a stable side on the limit contour of a 340 m high quarry.

The direction of further research should be considered an instrumental practical assessment of changes in the indicators of disturbance of the array in terms of the depth of the ledge in the contiguous zone of industrial blocks at various parameters of mass explosions.

In the Khabarovsk Territory, Amur Minerals LLC has started the development of the largest polymetallic deposit in the Far East – Malmyzhsky. At the moment, the development of the Dolina quarry has begun, the limit contour of which is adjacent to the overpass of the conveyor line for feeding rock mass from the quarry to the concentrator. The authors express their gratitude to Amur Minerals LLC for the opportunity to carry out instrumental measurements to assess the impact of mass explosions on the instrument area of the Dolina quarry at various parameters of exploding industrial units.

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