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Research paper

Regularities of the Energy of Formation Field in the Explosion of a Conical Charge

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Abstract: The process of formation of the energy field by the explosion of a conical charge has been mathematically simulated. The features of the development of the energy field, depending on the point of initiation of the truncated cone explosive charge, were determined. The complex nature of the use of a charge at the bottom of a borehole with an intermediate conically-shaped detonator is discussed. Possible technological directions for using a charge with a complex shape are proposed.

Keywords: shock wave, conical charge, density isolines, energy flow, field vector, nitromethane, potassium perchlorate, ammonium nitrate, trinitrotoluene

1 Introduction

Concentrated explosive charges in mining operations are used mainly either as intermediate detonators in the main deep-hole charge or as separate charges for secondary blasting operations. At the same time, their geometrical parameters, detonation characteristics, and the nature of the spatial distribution of the energy emitted by such a charge are only superficially taken into account or ignored. A generally known example of a concentrated charge of cumulative action (*viz.* a typical modern shaped charge, with a metal liner in the charge cavity, which can penetrate armour steel to a depth of seven or more times the diameter of the charge) demonstrates the possibility of an explosion creating a complex and controllable situation in the formation of an energy field during its explosive decomposition. Studies [1] have shown that a cumulative recess in the lower part of the charge as its structural element allows its action to be enhanced in the axial direction, namely in the direction of subdrilling, creating opportunities to reduce its length or to completely abandon this structural element in the deep-hole charge.

In most theoretical developments of the controlled mechanical effect of a concentrated charge, it is believed that initiation occurs instantly from its center, which greatly simplifies the solution. Similarly, in explosion theory, it is assumed that the detonation of an elongated charge occurs from its axis simultaneously along the length of the charge. In this case, theoretically, the symmetry of the stress and deformation field in the environment, provided it is isotropic, should develop concentrically, mirroring the symmetry of the charge, especially in the near zone of the explosion, on contact with the environment.

Under the real detonation conditions of a charge of any structure, the character of the development of the mentioned fields is more complicated through successive movement in time of the detonation front, from the initiator to the opposite end of the charge, followed by the detonation wave and, accordingly, the explosion products to the charge boundary with the medium.

The study of the effectiveness, the mechanism for the formation and redistribution of the total impulse of an explosion of a conical charge on contact with the medium is based primarily on the scientific ideas about the contact action of an elongated cylindrical charge of limited length. The contact or brisant action of a cylindrical charge explosion, which is initiated from one end, is estimated by the value of the total impulse when a detonation wave encounters an obstacle [2], Equation 1:

$$I = \frac{8}{27} s \rho l D = \frac{8}{27} Q D \quad (1)$$

where s is the cross-sectional area of the charge, ρ is the density of the explosive, l is the length of the charge, D is the explosive detonation rate, and $Q = s l \rho$ is the total charge mass.

If a cylindrical charge is initiated from one end, and the opposite end is in contact with an obstacle, the magnitude of the axial impulse is not affected by the total charge mass, but by its active part (m_a), which has a conical shape (the Munroe effect or cumulative effect is the focusing of blast energy by a hollow or void cut on the surface of an explosive) [2]. The detonation products from this part of the charge are directed towards the base of the cone, that is, towards contact with the obstacle. The magnitude of the active mass depends on the location of the initiator in the charge; in the direction of the propagation of detonation, 4/9 of the total explosive energy is released. With increasing height of the cylindrical charge and at constant diameter, the active mass increases to a certain limit, after which the mass of the active part of the charge remains constant.

When using a cylindrical charge as an intermediate detonator, its initiating ability increases with increasing diameter. For actual deep-hole charges, the maximum effect is achieved when the diameter of the detonator is equal to the diameter of the deep-hole charge.

Due to the fact that the active mass of the cylindrical charge of the detonator has the shape of a cone, it is advisable to give the intermediate detonator a conical shape. All of the above relates to an open charge, in which there is no durable outer shell. In the presence of a shell, the possibility of lateral expansion of the detonation products is limited, and the brisance of this charge in the axial direction is simultaneously increased.

The aim of the present work was a practical and model investigation of the characteristics of the detonation decomposition, the shape and nature of the radiated energy field in the explosion of a concentrated charge of conical shape, which corresponds to the shape of the active mass of a cylindrical charge in its end part.

2 Materials

Before the statement of the computer simulation problem, field tests of two series of conical charges were carried out, Figure 1. Series No. 1 was a mixture

of trinitrotoluene (TNT) and ammonium nitrate, and series No. 2 was a mixture of ammonium nitrate (or potassium perchlorate) and nitromethane. The choice of such compositions of high-energy materials was determined by comparing the characteristics of conditionally dangerous and conditionally safe intermediate conical detonators [3]. If mixture No. 1 contains the classic brisant explosive TNT, the components of mixture No. 2 are not explosives but become an explosive composition only after mixing, which allowed us to consider independently the detonation processes determined by the geometry of the charge. The main indicator of the effectiveness of charges under field test conditions is brisance. Both compositions have demonstrated performance in field tests.



(a)



(b)

Figure 1. Conical detonators on a 5 mm steel witness plate

3 Test and Simulation Results

The study of the extremely fast decomposition of a detonation charge at the stage of the formation of the detonation front in the charge and its further transformation into a shock wave beyond the charge limit is possible through experimental studies requiring the use of modern measuring equipment. However, due to the significant cost of such experiments, modern science prefers computer modelling of the physical processes. A limited number of experiments is required only to establish the reliability of the simulation results. To develop ideas about the wave phenomena in the detonation products during the explosion of a conical-shaped explosive charge, simulation was performed using the “GEFEST” software package [4] based on the use of the two-dimensional “KOLDUN” hydrocode [5, 6].

Computer simulation of the decomposition process of a truncated conical explosive charge was carried out in axisymmetric Euler formulation [7] using equations in cylindrical coordinates ($r - z$):

$$\begin{aligned}
 \frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_r)}{\partial r} + \frac{\partial(\rho u_z)}{\partial z} + \frac{\rho u_r}{r} &= 0; \\
 \rho \frac{du_r}{dt} &= \rho \left(\frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} + u_z \frac{\partial u_r}{\partial z} \right) = \frac{\partial \sigma_{rr}}{\partial r} + \frac{D\sigma_{rz}}{\partial z} + \frac{1}{r} (2D\sigma_{rr} + D\sigma_{zz}); \\
 \rho \frac{du_z}{dt} &= \rho \left(\frac{\partial u_z}{\partial t} + u_r \frac{\partial u_z}{\partial r} + u_z \frac{\partial u_z}{\partial z} \right) = \frac{\partial \sigma_{zz}}{\partial z} + \frac{D\sigma_{rz}}{\partial r} + \frac{1}{r} (D\sigma_{rz}); \\
 \sigma_{rr} &= D\sigma_{rr} - p; \quad \sigma_{zz} = D\sigma_{zz} - p; \quad \sigma_{rz} = D\sigma_{rz}; \\
 \frac{dD\sigma_{rr}}{dt} &= 2G \left(\frac{\partial u_r}{\partial r} + \frac{1}{3\rho} \cdot \frac{\partial \rho}{\partial t} \right) + \delta_{rr}; \quad \frac{dD\sigma_{zz}}{dt} = 2G \left(\frac{\partial u_z}{\partial z} + \frac{1}{3\rho} \cdot \frac{\partial \rho}{\partial t} \right) + \delta_{zz}; \\
 \frac{dD\sigma_{rz}}{dt} &= 2G \left(\frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r} \right) + \delta_{rz}; \\
 \delta_{rr} &= \left(\frac{\partial u_r}{\partial z} - \frac{\partial u_z}{\partial r} \right) \cdot D\sigma_{rz}; \quad \delta_{zz} = \left(\frac{\partial u_z}{\partial r} - \frac{\partial u_r}{\partial z} \right) \cdot D\sigma_{rz}; \quad \delta_{rz} = \frac{1}{2} \cdot \left(\frac{\partial u_z}{\partial r} - \frac{\partial u_r}{\partial z} \right) \cdot (D\sigma_{rr} - D\sigma_{zz})
 \end{aligned} \tag{2}$$

where u_i is a component of the velocity vector of the medium; ρ is the density of the medium; G is the shear modulus (elastic modulus of the second kind); σ_{ij} is a stress tensor component; $D\sigma_{ij}$ is a component of the stress deviator. This formulation is based on the principle of mathematical movement of media through a fixed computational grid and allows the determination at a high level of the degree of deformation of the media, including various kinds of turbulence and twisting. Additionally, each design element may contain a mixture of several materials. In the present case, it is a mixture of detonation products and air. To conduct a thorough calculation through the contact boundaries

of the media, the concentration method was used, and the system of equations was supplemented by the concentration ratio:

$$\frac{\partial(\omega\rho)}{\partial t} + \frac{\partial(\omega\rho u_r)}{\partial r} + \frac{\partial(\omega\rho u_z)}{\partial z} + \frac{\omega\rho u_r}{r} = 0. \quad (3)$$

Within the flow field of the detonation products and air in the calculated Eulerian element, the appearance of one of two, or some part of the interacting media in it, was determined using the concentration parameter (ω), the value of which varied from 0 to 1. In this case, the value “0” corresponded to the complete filling of the calculated element with detonation products, and the value “1” corresponded to the complete filling of the calculated element with air.

The expansion of the detonation products was described by an isentropic in the form of Jones-Wilkins-Lee:

$$p = A \left(1 - \frac{\omega}{R_1 V}\right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V}\right) e^{-R_2 V} + \frac{\omega \bar{E}}{V} \quad (4)$$

where p , E_0 are respectively, pressure and internal energy of the detonation products; $\bar{V} = \frac{\rho_0}{\rho}$ is the relative volume of the detonation products; ρ_0 , ρ are respectively, the initial and current density values; A , B , R_1 , R_2 , ω are parametric constants, which depend on the type of explosive.

During the tests, a change in the characteristics of the explosion was observed with a different geometrical arrangement of the conical charges from both mixture No. 1 and mixture No. 2 [8]. The brisant characteristics of the same conical charge depend on its spatial location and significantly increase when it is installed on the wide surface of the cone. This was the basis for research and mathematical analysis of the energy field in the explosion of a conical charge.

The results of computer simulation are shown in the form of isolines of the density of the products of a conical-charge explosion when it is initiated from the narrow or the wide base (Figures 2(a) and 2(b), respectively). For comparison purposes, similar data are given for a cylindrical charge (Figure 2(c)).

An analysis of the dynamics of the development of the fields (isolines) indicated the following:

- the field shape of the isolines of the density of the explosion products is primarily due to the form of the charge, regardless of where it originates,
- according to the shape of the isoline field, when a charge is initiated from the narrow base (Figure 2(a)), a high concentration of energy \bar{E} is observed in the

axial direction (along the Z-axis) towards the wide base of the cone; when initiating a conical charge from the wide base (Figure 2(b)), the development of the field, and accordingly the flow of energy, occurs in the direction of the narrow base of the cone,

- during the explosion of a cylindrical charge, the superior directions of development of the energy field in the explosion products are practically oriented normal to each surface of the charge (Figure 2(c)); there is a displacement of the density field of the explosion products from the center of the charge in the direction opposite to the place of initiation,
- if the total area of the density field of the explosion products is associated with the total energy of the explosion, it is possible to redistribute the flow of energy due primarily to the orientation of the base and sides of the truncated conical charge, and then the place of its initiation,
- the conditions of initiation determine the prevailing direction of development of the energy flow, namely, along the normal to the base in the direction opposite to the place of initiation.

In confirmation of these observations, it is worth noting that the greatest distance between neighboring isolines is observed in the direction of the development of the detonation process.

In this sense, the shape of the energy field of an explosion of a short cylindrical charge initiated at the base is typical (Figure 2(c)). In this case, the development of the energy field to the opposite base of the charge also prevails. At the same time, the field develops symmetrically towards the side surface of the cylindrical charge, generally mirroring the charge geometry with a certain transverse displacement towards the development of the detonation process.

This means that control of the dynamics and direction of the development of the force field is possible by choosing the place of application of the initiating pulse, namely location of the detonator on the opposite base of the charge to develop the process in the desired direction of explosion energy concentration. In practice, the isolines diagram allows the spatial location of the conical detonator in the borehole to be changed. It also increases the crushing of the rock in the lower part of the mountain ledge. The problems of granite crushing in the lower part of a mountain ledge are a well-known and urgent problem.

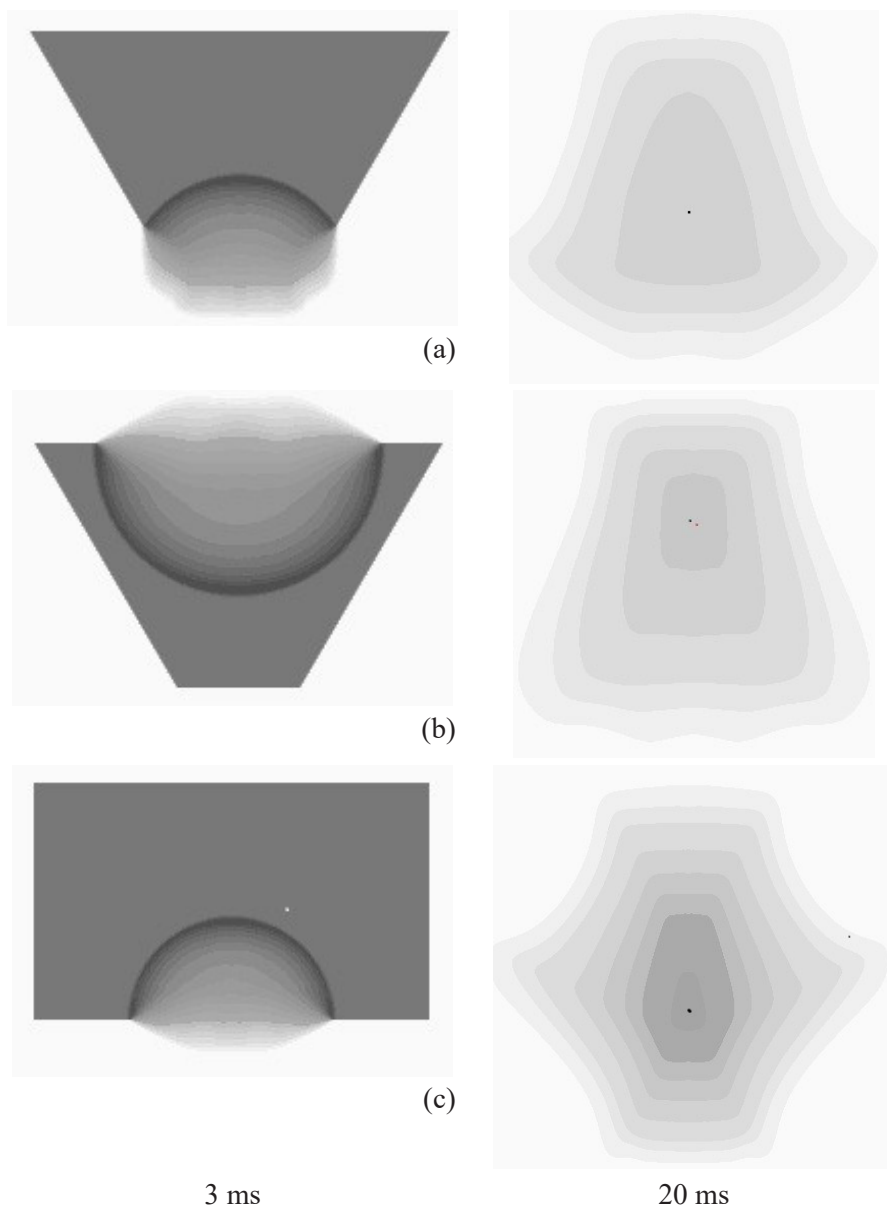


Figure 2. The initial (3 ms) and final (20 ms) moments of the development of the density field of the products of detonation of charges of contact action in the form of: (a) a truncated cone (initiation of detonation from above), (b) a truncated cone (initiation of detonation from below), (c) a cylinder

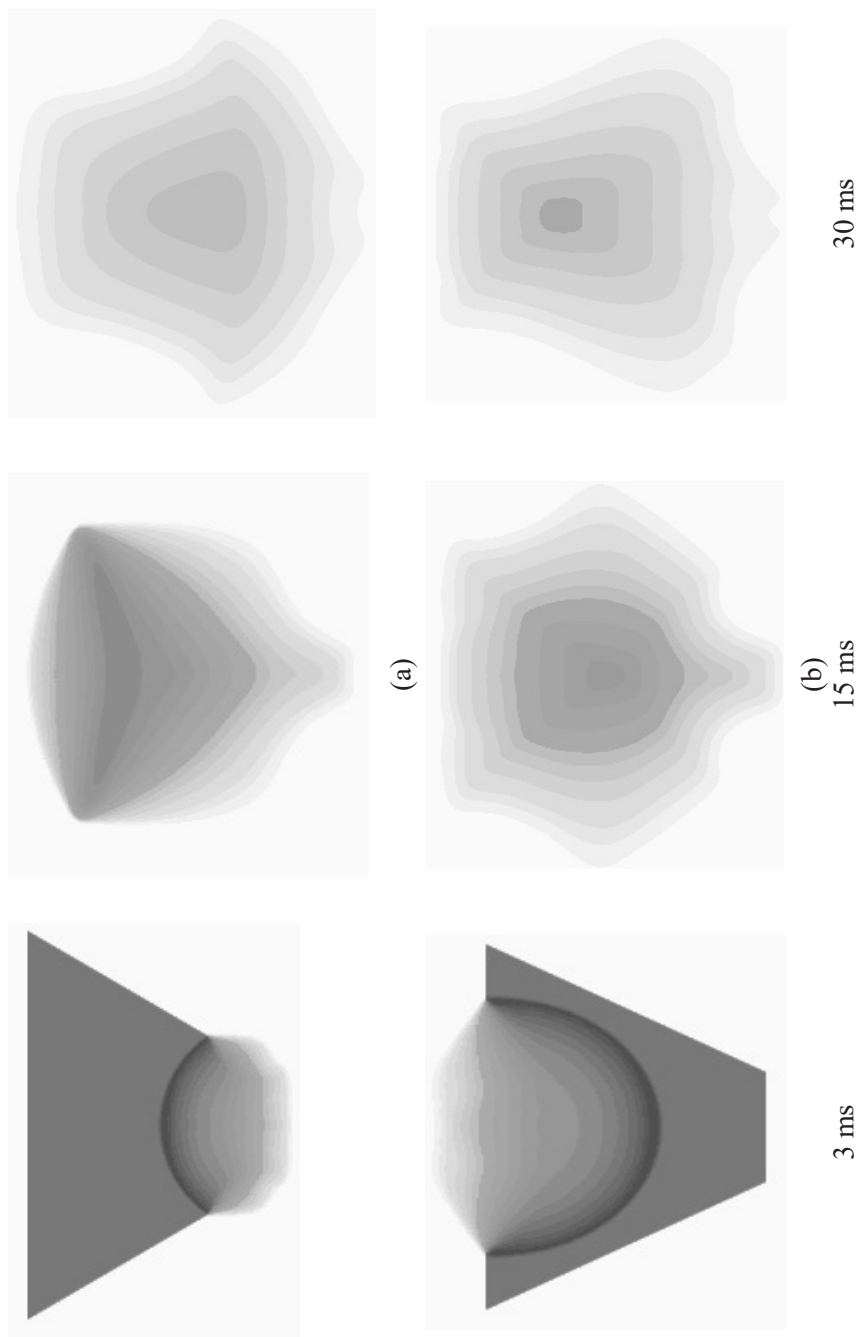


Figure 3. Intermediate shots of the process of developing a force field from an explosion of a conical shaped charge after 3, 15 and 30 ms, when it is initiated (a) from the narrow base, or (b) from the wide base

A characteristic element of the process is the formation of a force field along the axis of a conical charge. A preemptive pulse is first formed in the direction of propagation of the detonation process *vs.* time, in the force field along the axis of the cone, (Figure 3, time 3 ms). Later, this impulse and force field cease to develop along the axis and begin to expand in the lateral direction (time 15 ms). In fact, this process looks like a side wedging of power flow into a destructible medium in the area of the narrow base of the cone (time 30 ms).

In general, a frame-by-frame analysis of the development of a force field shows that its configuration is primarily determined by the form of the charge itself and is less dependent on the initiation conditions, having a central “burst” typical of this form of charge along the axis of the cone, which is different from the field shape during a cylindrical charge explosion.

However, according to Figure 3(b), the intensity of the field development from the explosion of a conical charge is also influenced by the place and direction of the detonation process. Initiation in each variant occurs from the wide base of the truncated cone in the direction of the narrow base. In this initiation variant, the effect of the lateral inclined charge surface is more pronounced. The features of the effects that are observed in this case can be used in technologies where the local mechanical effect of the explosion plays a dominant role.

4 Applied Aspects of the Results of the Theoretical Studies

An example of the technological application of the characteristics of the formation of a force field in the explosion of a conical charge is its use as an intermediate deep-hole charge detonator. Located at the bottom of the charge, such a detonator, when it is oriented with the wide base upwards, that is in the form of a reverse cone, can simultaneously solve problems of charge initiation and rock crushing depth.

First of all, such a conical intermediate detonator provides the optimal mode of initiation of the deep-hole charge due to the maximum contact of the detonator’s end surface with its wide base with the initiated charge. Ideally, the top wide base of the detonator in contact with the charge should be commensurate in area with the cross section of the charge (Figure 4(a)).

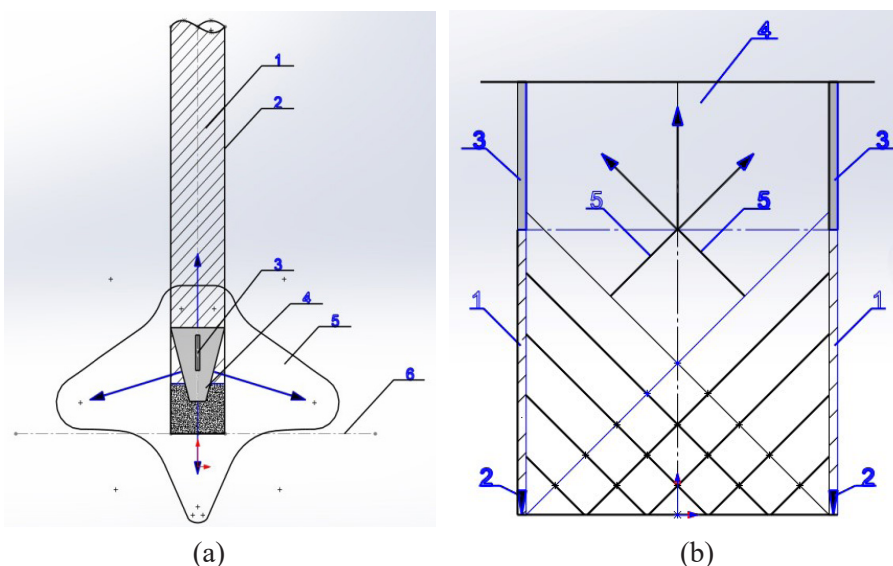


Figure 4. Interaction pattern of deep-hole charges for loosening: (a) the emergence of a force field at the bottom end of the deep-hole charge: 1) explosive charge, 2) deep-hole, 3) capsule, 4) intermediate detonator, 5) force field from a conical charge explosion, 6) horizon of the step ledge; and (b) the sequence of radiation of the voltage wave fronts in the interwell charge rock mass at $D = C_p$: 1) deep-hole charge, 2) intermediate detonator, 3) tamping (stemming), 4) rock layer at the tamping level, 5) displacement vectors of the interacting fronts

Due to the specific “pear-shaped” form of the radiated force field from the explosion of the conical detonator, the vector 5 of the stress wave front in the rock faces the surface layer located at the level of the tamping (Figure 4(a)). The area is located in the zone of action of the end part of the deep-hole charge, where the force field loses about 40% of the energy due to a change in symmetry [2] from axial to conditionally spherical.

The use of the initiation at the bottom part of the charge allows the front of the force field to be turned in the direction of the upper layer of the array and, accordingly, to strengthen the result of the interaction of adjacent charges in this layer, especially in the middle part of the interwell pillar. The greatest effect of such a reorientation of the force field can be achieved under the conditions of almost simultaneous explosion of adjacent charges (Figure 4(b)).

However, in fact, even within the same group (row) of adjacent charges, the detonation time of each next charge increases due to the time interval required for the detonation process in the shock-tube, the detonation velocity of which is close to 2000 m/s. For example, in a series of deep-hole charges, which conditionally explode simultaneously, with a distance between them of $a = 3$ m, the time for the course of a detonation pulse between the active and the next (still passive) charges will be 1.5 μ s. Since the speed of the stress wave in the rock mass generated by the explosion of the active charge is about 5000 m/s, its front will be removed along the array from the active charge to a distance of 7.5 m, that is, it crosses the influence zone of the neighboring charge that has not yet detonated. Thus, the ideal conditions for the interaction of stress fields in the total group of charges are almost impossible.

Only in the variant of simultaneous parallel initiation of neighboring groups of charges (Figure 4(b)) is such an interaction possible. Since the corresponding charges in adjacent rows explode simultaneously, the fronts of the stress fields will meet strictly in the inter-charge space, and the total force field vector in the case of such an interaction will be directed along the normal to the free surface of the block.

Technically, such conditions are quite difficult to achieve due to the high velocity of propagation of the stress waves, which is additionally affected by the system of cracks in the massif. Therefore, it is more realistic to rely on the known mechanism of interaction of rock masses, which move towards and are additionally similarly destroyed by the conditions of blasting with short decelerations along the cutting-edge scheme. In this case, the interaction mechanism is used at the level of a slower process – counter-movement of rock masses directed towards the upper free surface. In fact, in this case, the scheme of a wedge or trapezoidal cut is realized, but oriented instead of towards the lateral free surface but towards the ledge roof, which is the main source of oversized fractions.

This scheme of interaction of groups of charges contradicts the traditional methods of designing schemes of short-delayed blasting. It excludes the mechanism of horizontal movement of the rock mass and orients the movement of these masses in the vertical direction. To combine these movements, a switching circuit was tested, which consisted of the simultaneous parallel explosion of three adjacent rows of deep-hole charges, which are treated as one group, and in the subsequent short delayed explosion of an adjacent three-row group and beyond. The implementation of such a scheme makes it possible to use its advantages due to the combination of the mechanisms of mass movement in the vertical direction and the traditional movement with the collision of parts

of the array in the horizontal direction. The advantages of using a mixed network switching scheme have been demonstrated by industrial testing of the method.

As shown above, the “pear-shaped” form of the force field from the explosion of a conical initiator in the lower part of a deep-hole charge provides a controlled impulse load on the rock mass at the level of the bottom of the ledge, which allows, in certain rock conditions, partial or complete solution of the subdrilling problem. This method differs from the well-known ones [9] by the complexity of solving the issue of managing energy flows in a massive explosion.

The use of a conical detonator in the lower part of a deep-hole charge is aimed at providing a set of useful phenomena that can consistently and simultaneously deal with subdrilling, provide an optimal detonation process within the deep-hole charge and at the same time control the deformation phenomena in the surface layers of the block fractions being destroyed.

5 Conclusions

The following conclusions can be drawn:

- the mechanical effect of the explosion of conical detonators of substantially different composition was experimentally studied,
- as a result of numerical, theoretical and practical research, new data was obtained on the mechanism of development of a force field around a conical charge and the relationship of its form and intensity to the conditions of application of the initiating impulse,
- it was established that the shape of the family of isolines of the density of detonation products during a conical charge explosion does not depend on the initiation conditions and is associated only with the form of the charge, namely, the presence of characteristic surfaces in the cross section of the cone, normal to which the explosion product particles expand,
- the lower initiation of a system of adjacent deep-hole charges by conical detonators orients the total vector of mass displacements in the group of charges, that explode simultaneously, towards the surface layer of rocks at the level of tamping (stemming), intensifying in it the destructive effect of a massive explosion.

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