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DESTRUCTION OF ROCK UPON BLASTINGOF EXPLOSIVE AGENT

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ABSTRACT

In order to provide the most efficient indices of development of underground excavations the main attention is paid to blasting operations, namely, to determination of optimum parameters of drilling and blasting operations. Development of new and reconstruction of existing mines require for extended scope of excavating works, their length can reach some tens of kilometers. Up till now excavations at most of mines are developed using drilling and blasting operations. Improvement of drilling and blasting operations is one of trends to increase efficiency of excavation development. Reliability extent of calculated parameters of drilling and blasting operations can influence on technical and economical performances of excavation development. At present numerous existing procedures are empiric dependencies, they are based on primary determination of specific consumption of explosive. The main drawback of such procedures is the application of coefficients of specific consumption, which vary in wide range, their values depend on the qualification of experts who perform such calculations. As a consequence, the parameters of drilling and blasting operations are set on the basis of averaged values, which impair efficiency of blasting operations. We believe that calculations of parameters of drilling and blasting operations should account for the most complete range of factors playing important role in impact of blasting energy on destructing massif. In addition, the proposed engineering approach should enable improvement of efficiency of blasting operations with desirable decrease in material and non-material expenditures. This work describes briefly tock destruction by blasting of explosives, highlights main factors influencing on efficiency of drilling and blasting operations upon development of excavations. The work analyzes calculation procedures of main performances of drilling and blasting operations, recommendations are given for development of pattern of drilling and blasting operations on the basis of calculation of destruction zones of rock massif.

Keywords: rock defragmentation, blasting, detonation, blast hole pressure, shear zone, cracking zone.

1. INTRODUCTION

Increasing the depth of mining and the load on the working faces results in uncreased volume of gas in the goafs. In these cCapital investment into developed mining companies can significantly increase future economic potential of Russia as a result of enormous attempts of numerous workers.

Since the old days resource mining was the basis of economic stability, power and welfare of state. Advances of machinery and engineering made it possible to substitute resource mining using stone implements, iron hammers and other ancient tools with mining operations using black powder and then to dynamite when it was invented by Alfred Nobel in 19th century.

Nowadays mining is comprised of numerous fields, each of them being gradually modernized, which leads to increase in production output and, hence, of earnings after sales of these mineral resources (Figure-1) [[36]].

Blasting is one of key fields of mining, since the issues related with blasting operations are among the most disputed in mining. Up till now there is not single theory which would completely explain rock destruction upon blasting. This work presents generalized data on the aspect of rock destruction by impact of blasting energy.

2. EXPERIMENTAL

Rock deformation upon blasting of explosive is one of the main results of blasting impact, which in its turn leads to numerous mechanically irreversible modifications occurring in the vicinity of blast source, such as generation of camouflet cavity, medium destruction, cracking and so on [0].

Initial theory of essence and mechanism of rock destruction by blasting energy was proposed by Lomonosov [[7]], who was the first who determined main parameters of explosives. Then the problem of rock destruction by blasting was studied by Russian researchers Vlasov, Drukovannyi, Kutuzov, Mel'nikov, Pokrovskiy, and Khanukaev [[4], [10], [12], [16], [20], [23]]. The efforts of these and other researchers resulted in development of numerous theories and fundamental knowledge regarding the mechanism of rock destruction by blasting.

Blasting is characterized by most researchers as very rapid chemical oxidation with evolution of high amount of heat resulting in transformation of explosive into gases.

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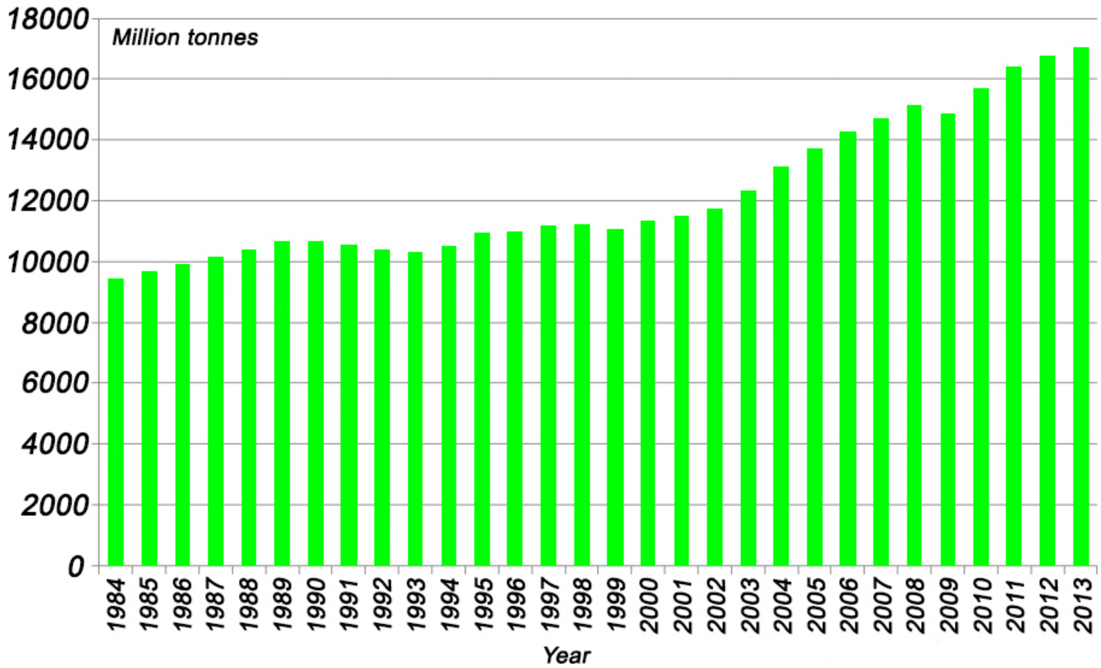

Figure-1. Global mining.

Blasting is initiated by the influence of external source, known as initiator. Subsequent propagation of blasting via explosive bulk from initiation point is referred to as detonation. The boundary between the segment not covered by blasting and the fragment where a portion of explosive transforms into gases is referred to as detonation front (Figure 2, a).

Then, in rock near blast hole with explosive, shock waves originate, forming the so called shear zone (squeezing zone), where intensive fine fragmentation of rock occurs. With distance from blasting center these shock waves are dampened and transferred into cracking zone (Figure-2, a, b).

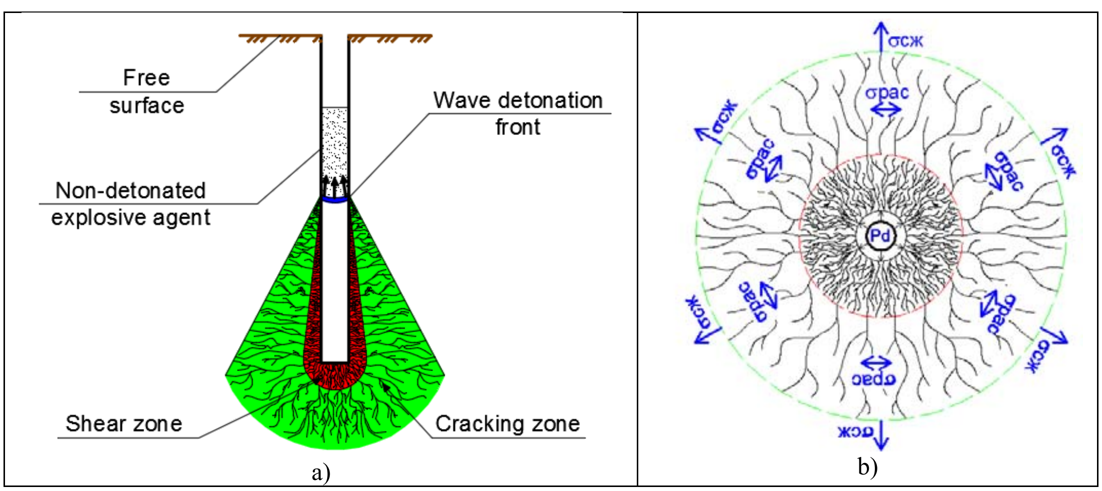

Figure-2. Rock destruction by blasting.

Let us consider some of these processes more thoroughly.

Detonation

Detonation velocity is highly important property of detonation and is described in numerous works.

Detonation in gases was discovered in 1881 independently by some French researchers: Berthelot and Vieille [[24]], as well as by Le Chatelier [[32]] while researching flame propagation in tubes [[3], [8]]. Then the first

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hydrodynamic theory of detonation was developed by Soviet physicist Mikhelson [[18]].

Numerous methods of detonation detection are available (Table-1), however, taking into account modern state of science the most frequently applied are specialized tools: photorecorders, magnetic and cathode oscillographs [[15]].

Table-1. Equations of detonation velocity upon blasting of explosive.

Equation	Remarks	Author and reference
$D = D_{Ch} \cdot \frac{l}{2 \cdot \Delta h}$, m/s	D_{Ch} - chord detonation velocity, m/s; l - distance between blast hole ends; Δh - distance between chord middle and blast impact point.	Dotrish[[2]]
$D = f(\rho) \cdot \sqrt{2Q(n^2 - 1)}$, m/s	ρ - density of explosive; Q - heat of explosion; n - polytropic index.	Kucheryavyi [[15]]
$D = \left(N \cdot M^{0.5} \cdot Q^{0.5}\right)^{0.5} \cdot (1.011 + 1.312 \cdot \rho)$, km/s	N - moles of gas per gram of explosive; M - mean molar weight of detonation products; Q - heat of explosion; ρ - density of explosive, g/cm^3.	KamletandJacobs [[28]]
$D = D^0 \cdot \left(1 - 0.74\left(1 - \frac{\rho}{\rho^0}\right)\right)$, km/s	D^0 - detonation velocity at density of single crystal; ρ - density of explosive, g/cm^3; ρ^0 - density of single crystal.	BorzykhandKondrikov [[2]]

While studying the main blasting parameters Dremin [[9]] established that at any charge diameter increase in density of explosive ρ from 1.0 to 1.45 g/cm^3 leads to significant increase in detonation velocity (up to 6000 m/s).

Bhandari and Lowrie [[25], [31]] determined that the detonation properties of industrial explosives are related with diameter of charged blast hole and density of explosive, which influence on pressure of detonation products in blast hole.

Pressure of detonation products in blast hole

Chemical reactions are initiated by pulse to explosive (for instance, detonating charge).

Chemical reactions occur after detonation wave where the explosive from its initial state is transferred to final decomposition products.

It is known that blasting decomposition of explosive is accompanied by release of high amount of heat and gases. Due to pressure in blast hole created by the chemical reaction the rock massif is destructed.

Pressure of detonation products defines the work of explosive expansion upon rock destruction. This index determines direct transfer of blasting energy to destructed massif and, hence, it can be applied for estimation of explosive efficiency [[26], [38]].

Despite the importance of this parameter direct measurement of pressure of detonation products are not actually performed due to unavailability of allowable procedures and tools, instead, empirical equations are applied for its determination (Table-2). Nevertheless, accuracy of such estimations is unknown [[26], [34]].

Table-2. Equations of pressure of detonation products upon blasting of explosive.

Equation	Remarks	Author and reference
$P_b = \frac{P_0 V' T}{(V - \alpha) \cdot 273}$, кg/cm^2	P – pressure of blast gases, кg/cm^2; P_0 - normal ambient pressure of 1.033 кg/cm^2; V' - volume of blast gases of 1 kg of explosive at normal conditions, dm^3; T - temperature of explosion, °K; V - volume of blast cavity, dm^3; α - volume of gas molecules of blasting, dm^3.	vanderWaals [[15]]
$P_b = \frac{\rho \cdot D^2}{8}$, Pa	ρ – density of explosive, kg/m^3; D – detonation velocity, m/s.	Persson [[35]]

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Therefore, the most reliable determination of pressure of detonation products in blast hole used for estimation of blasting efficiency and forecasting of blasting results are urgently required in modern mining.

Shear zone

After the processes described above there occurs direct destruction of rock massif, which starts from fine defragmentation of rock in the so called shear zone (Figure-3).

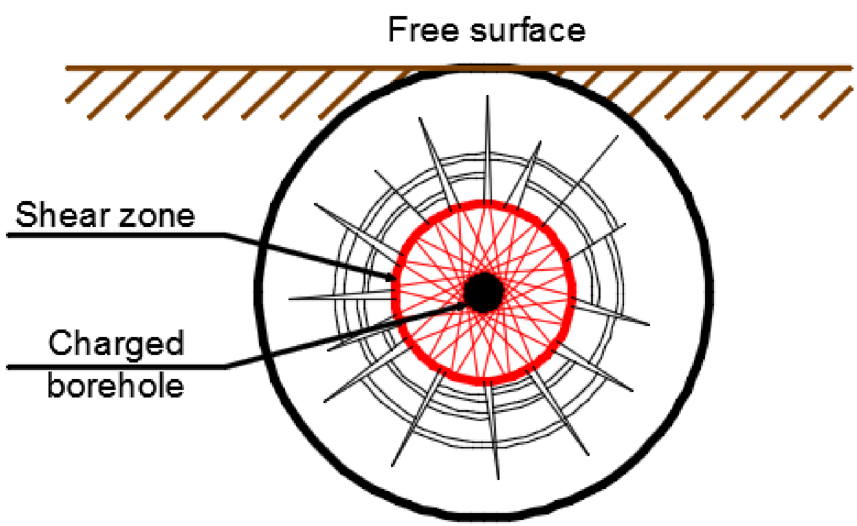

Figure-3. Schematic view of shear zone formation.

Contrary to detonation velocity, shear zone cannot be readily determined by instruments. Several researchers proposed various procedures for determination of shear zone radius (Table 3).

Table-3. Equations for determination of shear zone upon blasting of explosive.

Equation	Remarks	Author and reference
$R_{CM} = \sqrt{\frac{C_S}{C_P}} \cdot \sqrt[3]{q}$, m	C_P - propagation velocity of longitudinal waves in massif, m/s; C_S - propagation velocity of transversal waves in massif, m/s; q - charge weight in TNT equivalent, kg.	Mosinets [[33]]
$R_{CM} = \sqrt{\frac{2r_b^2 \rho Q_{EF}}{\sigma_{СЖ}}}$, m	r_b - blast hole radius, mm; ρ - density of explosive, kg/mm^3; Q_{EF} - effective energy of explosive; $\sigma_{сж}$ - ultimate compression strength of rocks, Pa.	Szuladzinski [[37]]
$R_{CM} = 810 \cdot \sqrt{\frac{\rho \cdot e}{\tau_{сд}} \cdot \frac{1-2\upsilon}{1-\upsilon}} \cdot d_b$, m	d_b - blast hole radius, м; ρ - packing degree, kg/m^3; e - relative power (capacity) of explosive; υ - Poisson coefficient of rock; $\tau_{сд}$ - ultimate shear strength of rock, Pa	Kuznetsov [[11]]
$R_{CM} = d_b \sqrt{\frac{\rho \cdot D^2}{8 \cdot \sigma_{comp}}}$, m	ρ - density of explosive, kg/m^3; D - detonation velocity, m/s; σ_{comp} - ultimate compression strength of rocks, Pa;	KutuzovandAndrievskiy [[13]]

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The most accurate determination of shear zone upon blasting makes it possible to reliably determine the size of cracking zone, which in its turn would facilitate calculations of optimum parameters of drilling and blasting operations (DBO).

Cracking zone

Then the rock destruction becomes more and more intensive, generation of cracking zone is initiated (Figure-4).

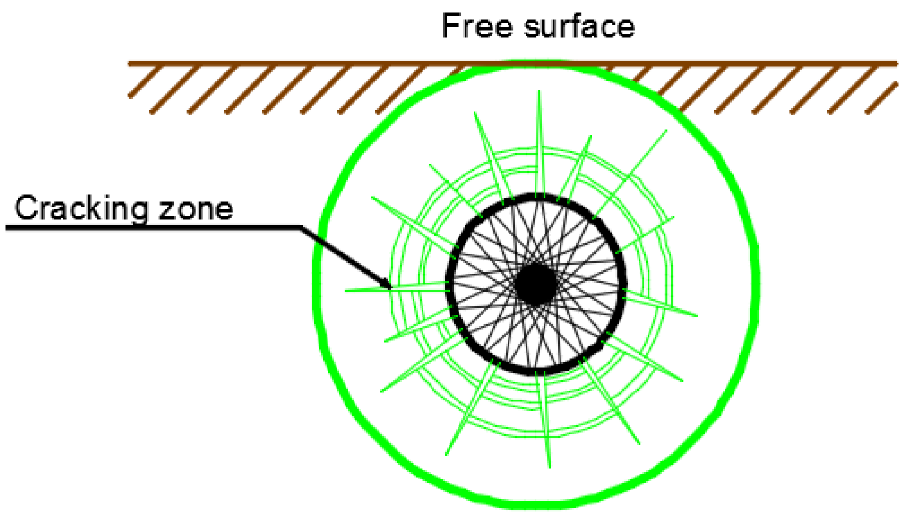

Figure-4. Schematic view of cracking zone formation.

Some of existing procedures of determination of cracking zone radius around blasted massif are given below (Table-4). These approaches quite often demonstrate blasting impact in ideal detonation medium, confidence estimation of impact calculated by the proposed procedures is possible only on practical level.

Table-4. Equations for determination of cracking zone upon blasting of explosive.

Equation	Remarks	Author and reference
$R_{TP} = \sqrt{\frac{C_P}{C_S}} \cdot \sqrt[3]{q}$, м	C_P - propagation velocity of longitudinal waves in massif, m/s; C_S - propagation velocity of transversalwaves in massif, m/s; q - charge weight in TNT equivalent, kg.	Mosinets[[33]]
$R_{TP} = 55 \cdot d_b \cdot \sqrt{\frac{\rho \cdot e}{\sqrt{f}}}$, m	d_b - blast hole radius, м; ρ - relative density of explosive; e - coefficient of relative capacity of explosive.	Erofeev[[21]]
$R_{TP} = 96 \cdot \left(\frac{G}{10\sigma_{comp}}\right)^{\frac{1}{8}} \cdot (10E)^{\frac{1}{6}}$, mm	$\sigma_{сж}$ - uniaxial compression strength of rocks, MPa; E – elasticity modulus (Young modulus), MPa; G - charge length, kg/m.	Kexin [[29]]
$R_{TP} = 0,7 \cdot R_{CM} \cdot \sqrt{\frac{\rho \cdot D^2 \cdot d_b}{8 \cdot \tau_{sh} \cdot R_{CM}}}$, m	$\sigma_{сж}$ - ultimate compression strength of rocks, Pa; τ_{cp} - shear strength of destructed massif (for most rocks τ_{sh} is not higher than 20 MPa. τ_{sh} can be approximately defined as (0.1-0.02)·σ_{comp} [[14]]), Pa.	Kutuzov and Andrievskiy [[13]]

We believe that the most promising procedures of calculation of radii of shear and cracking zones are described in [[13], [27]].

Iverson *et al*. [[27]] developed procedure on the basis of detection and application of actual destruction zone, whereas Kutuzov and Andrievskiy [[13]] determine

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consecutively at first shear zone and then cracking zone, afterwards blast hole arrangement over the area of face is based on calculations involving final values of these zones. In addition, in [[13]] the development of final DBO pattern includes such index as *line of least resistance*, which accounts for blasting impact on additional free surface.

Line of least resistance

Line of least resistance (LLR) is the minimum distance from charge center to free surface (Figure-5) [[6]]. Currently it is established that the charge LLR depends on the type of applied explosive, properties of destructed massif, as well as diameter of charged blast hole and packing degree.

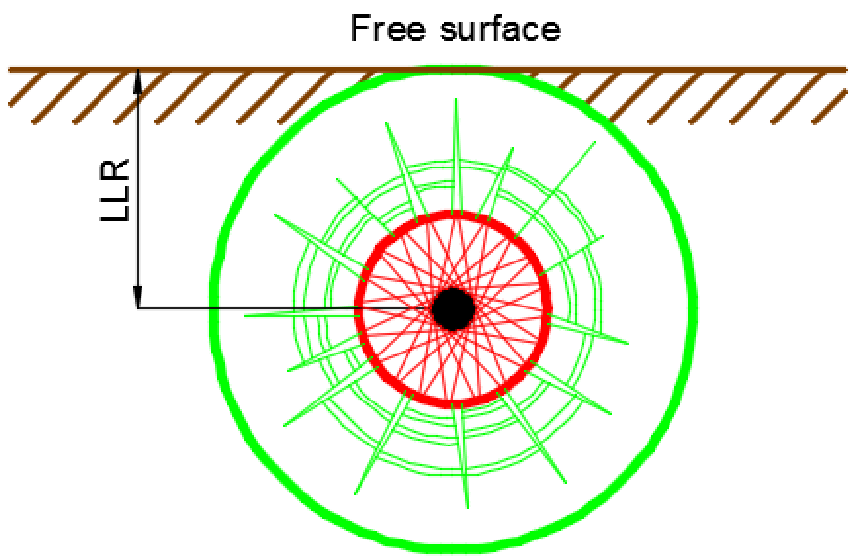

Figure-5. Schematic view of formation of lineof least resistance.

Numerous equations are available for calculation of LLR, some of them are summarized in Table-5.

Table-5. Equations for determination of line of least resistance upon blasting of explosive.

Equation	Remarks	Author and reference
$W = \left(\frac{P_b}{\sigma_{tens}}\right)^{\frac{2}{3}} r_b$	P_b - detonation pressure in blast hole, kgc/cm^2; σ_{tens} - ultimate tensile strength of rocks, kgf/cm^2; r_b - blast hole radius, cm.	Mindeli[[17]]
$W = \left(\frac{\rho Q}{10 f}\right) d_b$	ρ - packing degree, kg/dm^3; Q - heat of explosion, kJ/kg; d_b - diameter of explosive, m.	Zabudkin[[19]]
$W = R_{TP} \cdot \cos(0.5\alpha)$	α – minimum angle of blasting cone.	Kutuzov and Andrievskiy [[13]]
$W = 53 K_T \cdot d_b \sqrt{\frac{\rho \cdot e}{\gamma}}$	K_T - cracking factor; d_b - blast hole radius, м; ρ- density of explosive, g/cm^3; e - relative capacity of explosive; γ-density of rocks g/cm^3.	Davydov [[22]]

Therefore, reliable determination of LLR is one of major indices characterizing penetration distance between blast hole walls and free surface e.

3. RESULTS AND DISCUSSIONS

The above mentioned processes upon blasting of explosive can be considered as key ones, since exactly their action determines blasting efficiency. Calculation of each process can be characterized as initial step upon development of calculation procedure of reasonable parameters of drilling and blasting operations during excavations.

On the basis of analysis of above mentioned calculation procedures of destruction zones it can be noted that they all consider individual cases and can be applied under certain conditions. Many procedures can be applied only for solid massifs.

As already mentioned, reliably calculated destruction zones can be applied for development of blasting patter for mining excavation. On the basis of procedure proposed by Kutuzov and Andrievskiy [[13]], which includes numerous mining geological and engineering factors, we proposed its improved model [[5], [30]].

The main provision of this procedure is that it applies graphical analytical approach to development of DBO pattern. It means that instead of calculation of number of blast holes and distance between them by means of various equations it is possible to determine initially shear and cracking zones, and LLR, their dimensions are applied for draft pattern (Figures 6, 7).

Development of DBO pattern: charged blast holes are located so that the radius of cracking zone of each blast hole intersects with the middle of neighboring blast hole. Finally, there are no non-processed areas after completion of arrangement of blast holes. This provides good destructing action of blast energy with good obtained results.

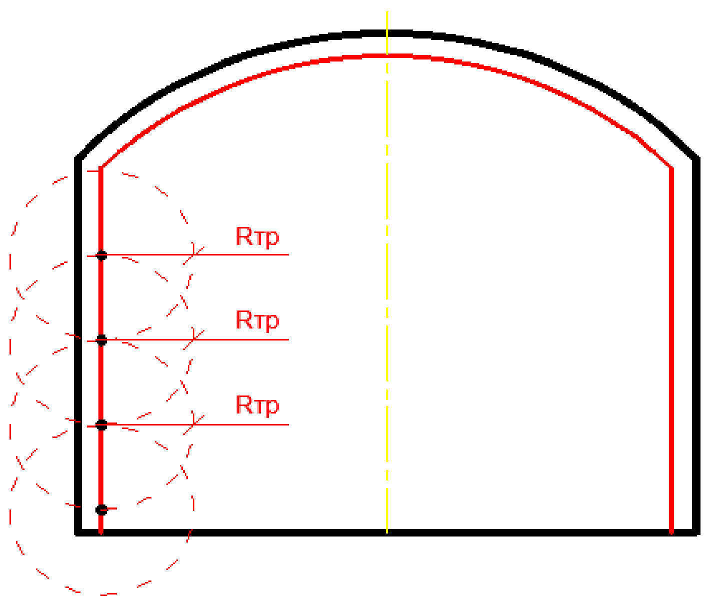

Figure-6. Schematic view of blast holes in cracking zones.

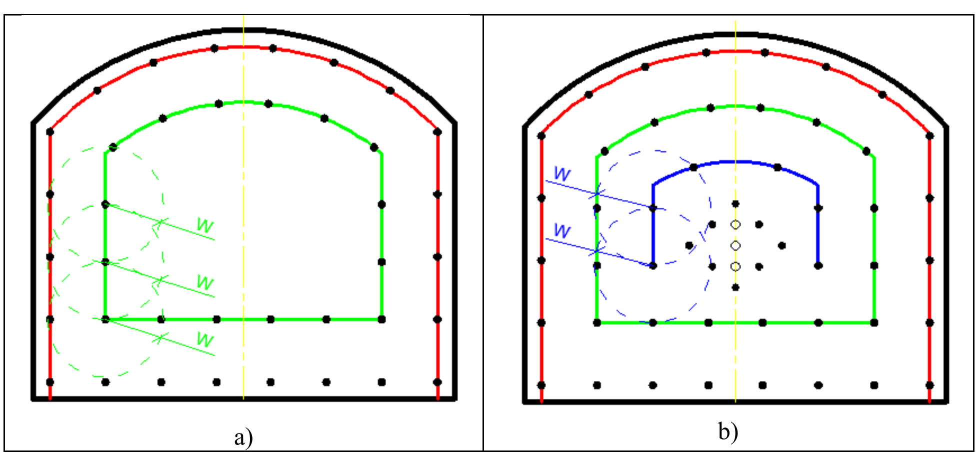

Figure-7. Schematic view of blast holes along line of least resistance.

While summarizing, it is possible to state that determination of reasonable parameters of DBO is hindered by the fact that it is necessary to consider for high amount of mining geological and engineering condition of excavation development. Any developed procedure of determination of reasonable parameters of

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DBO should be advantageous both in terms of efficiency of resource utilization and in terms of safety and economics of mining company.

4. CONCLUSIONS

This study is performed by the team of authors of Chair "Mine and underground development", Siberian Federal University aiming at investigation into impact of blasting of explosive and, hence, its potential influence on peripheral massif of excavations. Analysis of the considered materials reveals that at present there are numerous and various methods of determination of both single blasting variables (detonation velocity, pressure of detonation products, shear and cracking zones, and others), and integral procedures on the basis of which it is possible to calculate drill pattern in bottom hole using specified consequence.

We attempt to develop a software package for reliable forecasting of destruction zone of rock massif around explosive on the basis of initial key parameters of mining geological and engineering data, and to define blasting pattern for subsequent commercial application. As evidenced by approbation of such patterns on commercial scale at mines of Norilsk Nickel Mining Company and Dzhusinkiy underground mine, such patterns significantly decrease specific consumption of explosives and drilling operations without deterioration of blast quality and mapping of excavations, herewith, the coefficient of blast hole operation increases in average by 5-10%.

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