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# ENHANCING DRILLING RIG EFFICIENCY IN DRILLING PROCESS

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**Abstract-** Generalized indicators, which do not consider the mechanism of real disintegration, the technique, and parameters of the process technology, are used only for classification purposes for the comparative evaluation of various rock formations. Providing more accurate information is to ensure statistically determined relationships between the parameters of specific disintegration processes and the characteristics of formations. Currently, a combination of impact and blasting methods is widely used in mining operations. In this situation, impact loads are continuously transmitted to the tool being blasted under high gas pressure. Based on the assumption that each type of stress is equal in the disintegration process of formations, the article presents theories and concepts for the technical, technological, and economic problem-solving in the mining mechanics (ore) field of formation mass in the process of drilling wells for various methods (impact, blasting, impact and blasting). Theoretical and experimental research results have been discussed and analyzed in the article. Regarding drilling, guidelines have been provided and compared based on various parameters of drilling speed, which act as a key indicator reflecting the efficiency of the process. For instance, the drilling speed for perforation is correlated with the characteristics of the formation as well as considering the construction features of the drilling tool. In perforated drilling, new guidelines for drilling speed have been introduced, considering each impact and velocity. Guidelines for drilling speed have also been established by considering the degree of fragmentation of rock formations during drilling. Specifically, in mechanical drilling methods, drilling speed is determined by considering the contact strength of the drilled formation. Additionally, the distribution of stress conditions in the drilling zone has been determined. Additionally, the formation and development characteristics of fractures occurring in the formation during the use of drilling tools (especially dynamic perforations of the tool in the bottom zone of the well) have been investigated. It is worth mentioning that by studying the subsequent stages of breaking down the formation's coherence, the energy intensity of the drilling process has been determined. The technical and economic indicators of drilling operations have been evaluated. Corresponding mathematical formulas have been presented as reliable calculation schemes for drilling rates. The relevant mechanical and geophysical properties of the drilled formations have been considered. Based on the drilling method, the physical-mechanical properties of formations, and the geological conditions of the formation mass, drilling tools have been selected in the article. The results of the research can be used in the design of technological parameters of drilling operations.
The results obtained in the article are theoretical and practical in nature.

**Keywords:** Rock Formations, Compression Stress, Tensile Stress, Rock Strength, Drilling Speed, Hardness Index of the Rock Formation.

## 1. INTRODUCTION

In world practice, the drilling process is carried out by means of drilling rigs. After the well is fully dug, filling works are carried out in the well. After the completion of the work, the process of establishing a connection between the oil layer and the well begins. This process is called perforation. The most important issue in the performance of perforation work is to correctly make the pores and distributed. To ensure that the decomposition is carried out within a specific distribution, it is necessary to study the nature of the formation rocks. Perforation is the opening of holes in the casing, cement ring and surrounding environment to create flow from the bedrock into the production well. Figure 1 shows the perforation device. To choose the method of perforation to be carried out in the wells, the following should be taken as a basis:

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1. It is considered appropriate to apply the cumulative perforation method in solid rocks, in which it is relatively more difficult to create a reservoir-well connection.
2. It is recommended to apply the bullet perforation method in fragile and weakly cemented sandstones.
3. Torpedo (projectile) perforation method is appropriate to be applied in rocks with relatively high density and low permeability.

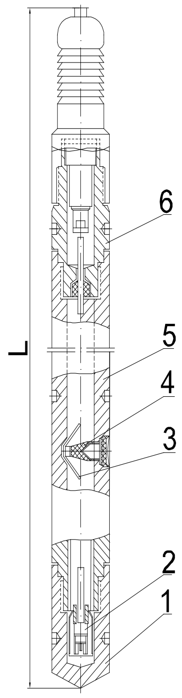
It should be taken into account here that bullet and torpedo perforators deform the production line during the perforation process, create cracks in the cement ring and the rock itself, although in some cases these cracks in the rocks in the formations are a factor that positively affects the flow of oil and gas from the productive formation to the well. In general, the disintegration of rock formations occurs under complex stress conditions, characterized by the combination of compression, tensile, and shear stresses. Obtaining objective information is possible by considering the physical laws of the disintegration process.

However, the development of rigorous analytical calculation methods, in relation to the complexity and uncertainty of the real mechanism of rock disintegration, which is often associated with some (sometimes controversial) assumptions and idealization of the rock formation object. This often leads to significant discrepancies between calculated indicators and actual data. Nevertheless, the analytical approach is superior because it allows for consideration of objective laws operating in nature. The theory relies on considering the forces system when introducing a conical tool into the formation. In this case, the physics of disintegration of the formations under the tool is not taken into account.

The drilling mechanism with impact is presented as follows: Initially, with the dynamic application of the bit, initial disintegration volume is formed in the shape of a groove. Subsequent impact under a certain angle of the tool forms the secondary disintegration volume. In the bit's area, a cutting force T is applied, which disperses the rock within the sector's volume between the grooves. Such a cyclic process leads to the disintegration of the entire surface layer of the groove or the bottom of the well to a certain depth.

In underground operations, around the main rock mass, a closed area of deformed rocks is formed due to the combined effect of its strength, structure, and depth of location with plastic deformation. The dimensions of this area and the magnitude of displacement of the excavation contour determine its stability. Analytical solutions to elastic-plastic problems are generally limited by a simplified model of the environment (integral, isotropic, homogeneous) and the form of excavation (cylindrical).

The mathematical modeling of the elastic-plastic deformation of the non-uniform rock mass, resulting from complex underground operations, is achieved only through advanced methods such as the finite element method (FEM). This approach introduces a series of problems requiring special considerations and fundamental assumptions concerning the validation of the modeled deformed environment.




1- Special nozzle
2- Electric detonator
3- Detonation wire
4- Cumulative shells
5- Steel cylinder
6- Igniter head

Figure 1. Cumulative perforator with case "PK-65" [1]

Drilling methods are selected with different scientific approaches depending on the hardness and types of rock [15,17,18]. Determining the origin of the rocks and the porosity between the rocks in advance is the main condition for choosing the right methods of the drilling process. Conducted scientific studies show that the influence of the drilling zone (DZ) and a new drilling analysis model was created that takes into account the drilling-based measurement method (RCZ) for the c-φ parameter of the rock. The ultimate destructive force formula was proposed based on the limit equilibrium principle [16].

In the method, useful work coefficients resulting from drilling moment and friction angle are analyzed based on rock types (Figures 2, 3). One more issue remains open. This problem does not consider the rocks' hardness and porosity.

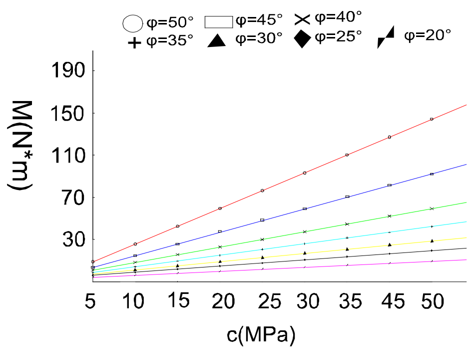



Figure 2. Drilling torque rates vs. cohesion [16]

In our presented research, our goal is to effectively increase the quality and speed of rock penetration works, considering the hardness and porosity of the rock.

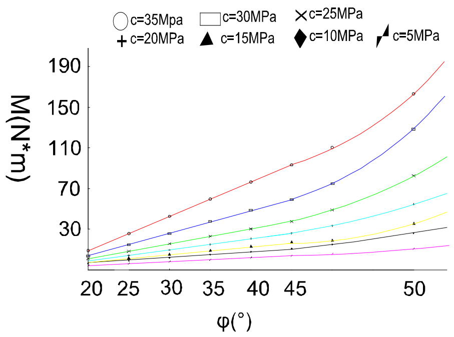



Figure 3. Drilling torque vs. internal friction angle [16]

## 2. THEORETICAL DESCRIBSION

Let us consider the stress-deformation state of a homogeneous isotropic elastic rock mass in the vicinity of a long (single) horizontal circular excavation located at a depth in the earth's surface and not subjected to the influence of mining activities (Figure 4) [2]. An evenly distributed load equal to the support force is applied to its contour. Within the influence zone of the excavation, we assume that the rock mass, which has a compressive strength limit, is stress-free. External evenly distributed loads are applied in the directions of and the axes to infinity, such that they can either be unequal to each other or equal (here, an example of unequal lateral pressure is provided). The magnitude of these loads is such that a plastic deformation zone is formed completely surrounding the contour of the excavation.

The deformation and disintegration of the rock mass occurs under specified deformation regimes within the elastic compressed portion of the mass. Both elastic and plastic zones maintain the integrity hypothesis of the environment. Considering that movement of the rock mass in the longitudinal direction of the excavation is not possible, a planar deformation state is assumed. As a result of solving the problem, it is necessary to determine the components of stresses, deformations, and displacements in both elastic and non-elastic zones, as well as the size and shape of the contour separating these zones. At an arbitrary point of the rock mass with coordinates and, the stress components ensure equilibrium with the slope gradients.

$$\frac{\partial \sigma_x}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}=0 \tag{1}$$

$$\frac{\partial \sigma_y}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}=0 \tag{2}$$

and the condition of compatibility of deformations

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\times\left(\sigma_x+\sigma_y\right)=0 \tag{3}$$

In addition, the physical consistency in the plastic deformation zones is determined by the following expression:

$$\sigma_\theta+\sigma_r=2k\left(\frac{A}{r^2}-B\right) \tag{4}$$

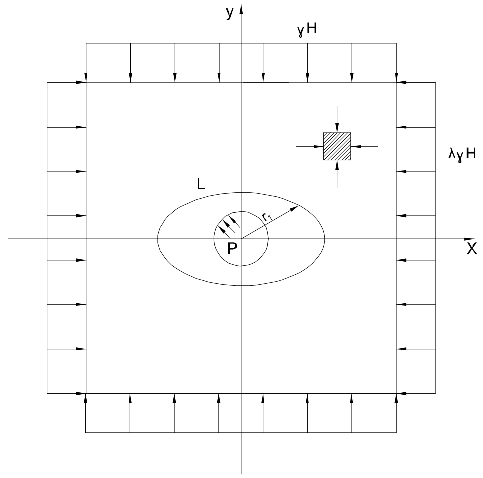



Figure 4. Calculation scheme for solving the problem of the slope of the rock mass in the vicinity of a horizontal excavation ($\lambda\neq 1$) [2]

Here and below, all quantities, including length and displacement, are referred to the excavation radius $R_0$. It is possible that there are no tangential stresses in the plastic zone $\tau_{r\theta}$=0. As a result, the stress state becomes axisymmetric. Let's denote the stress components in the plastic zone with subscript 1, and stress components in the elastic zone without subscript. Then, the boundary conditions take the following form:

- At the boundary of the excavation:

$$\tau^1_{r\theta}\Big|_{R=R_0}=0,\qquad \sigma^1_r\Big|_{R=R_0}=p_0 \tag{5}$$

- At infinity

$$\sigma_x^\infty=\lambda\gamma H,\quad \sigma_y^\infty=\gamma H,\quad \tau_{xy}^\infty=0 \tag{6}$$

Stresses at the boundary A between the plastic and elastic zones are continuous:

$$\sigma_x^1=\sigma_x,\quad \sigma_y^1=\sigma_y,\quad \tau_{xy}^1=\tau_{xy} \tag{7}$$

The principle of selecting an analytical expression for the function of decreasing strength is essentially the same by nature. For instance, in the "$\sigma-r$" coordinate system, experimental data is approximated by a monotonic curve, whose ordinates increase from some close or zero strength value at the excavation contour to the strength boundary between the untouched massif of $R_c$ and the plastic and elastic zones. Analytical formulations for the drop in strength function adhere to this idea for varied degrees of strength loss.

However, when initially constructing a physical model, the continuity of the rock mass should be considered, so the form of the function $f(r)$ must comply with this initial condition. Especially in the plastic and elastic regions, the stress function $F(r)$ must be biharmonic in the Polar coordinate system. Then, it will have a unique special expression. The following rule will be introduced to determine the type of decrease in strength function. Let's write the initial relations in the polar coordinate system as follows. The compatibility equations for slope and deformations are of the following form [3-5]:

$$\frac{\partial \sigma_r}{\partial r}+\frac{1}{r}\frac{\partial \tau_{r\theta}}{\partial \theta}+\frac{\sigma_r-\sigma_\theta}{r}=0 \quad (8)$$

$$\frac{1}{r}\frac{\partial \sigma_\theta}{\partial \theta}+\frac{\partial \tau_{r\theta}}{\partial r}+\frac{2\tau_{r\theta}}{r}=0 \quad (9)$$

$$\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r^2}\frac{\partial}{\partial \theta^2}\right)\times\left(\sigma_\theta+\sigma_r\right)=0 \quad (10)$$

where, $r,\theta$ are polar coordinates.

$$\left(\sigma_\theta-\sigma_r\right)^2+4\tau_{r\theta}^2=4k^2 f^2\left(r\right) \quad (11)$$

where, $k$ is a certain constant depending on the initial physical conditions involved in the strength condition.

Let's represent the stress function in such a way that the following relations are ensured in the plastic region:

$$\sigma_r=\frac{1}{r}\frac{dF}{dr}, \quad \sigma_\theta=\frac{d^2F}{dr^2}, \quad \tau_{r\theta}=0 \quad (12)$$

It is clear that in this form, the stress function always satisfies the equilibrium equations. To determine the analytical expression of the strength reduction function, we substitute Equations (8)-(10). Then, we obtain the following system of equations:

$$\frac{1}{r}\frac{dF}{dr}-\frac{d^2F}{dr^2}=\pm 2kf\left(r\right) \quad (13)$$

$$\nabla\nabla F=0 \quad (14)$$

where, $\nabla$ is the Laplace operator. By solving Equation (13) using the method of constant variation, we obtain the following expression for the stress function:

$$F\left(r\right)=kr^2\int f\left(r\right)\times r^{-1}dr-k\int rf\left(r\right)dr+C_1r^2+C_2 \quad (15)$$

where, $C_1$ and $C_2$ are arbitrary integral constants. To determine the stress field components in the plastic zone, we consider the stress function determined in accordance with the dependencies in Equations (9) and (10):

$$F\left(r\right)=2k\left[r^2\left(C_1+\frac{B}{4}\right)-\frac{B}{2}r^2\ln r-\frac{A}{2}\left(\ln r+\frac{1}{2}\right)\right]+C_1r^2+C_2 \quad (16)$$

Using the second boundary condition of Equation (1) at the excavation contour, we determine the values of the integral constants:

$$C_1=\frac{P_0}{2k}+\frac{A}{4}, \quad C_2=0 \quad (17)$$

Then, considering Equations (13) and (12) will take the following form:

$$F\left(r\right)=2k\left[\frac{r^2}{2}\left(\frac{A}{2}+\frac{B}{2}+\frac{P_0}{k}\right)-\frac{B}{2}r^2\ln r-\frac{A}{2}\left(\ln r+\frac{1}{2}\right)\right] \quad (18)$$

Using Equation (14) and the principle of Equation (12), we determine the stress components in the plastic zone:

$$\sigma_r^{(1)}=\frac{1}{r}\times\frac{dF}{dr}=2k\left[\frac{A}{2}\left(1-\frac{1}{r^2}\right)-B\ln r+\frac{P_0}{2k}\right] \quad (19)$$

$$\sigma_\theta^{(1)}=\frac{d^2F}{dr^2}=2k\left[\frac{A}{2}\left(1+\frac{1}{r^2}\right)-B\left(\ln r+1\right)+\frac{P_0}{2k}\right] \quad (20)$$

where, $\tau_{r\theta}^{(1)}=0$. The Kolosov-Muskhelishvili relations [4] for the elastic zone are as follows:

$$\sigma_x+\sigma_y=4\operatorname{Re}\Phi\left(z\right) \quad (21)$$

$$\sigma_x-\sigma_y+2i\tau_{xy}=2\left[\bar{z}\Phi'\left(z\right)+\Psi\left(z\right)\right] \quad (22)$$

$$2G\left(u+iv\right)=\left(3-4\mu\right)\int\Phi\left(z\right)dz-z\overline{\Phi\left(z\right)}-\int\Psi\left(z\right)dz \quad (23)$$

where, $\Phi\left(z\right)$ and $\Psi\left(z\right)-Z\left(Z=re^{i\theta}\right)$ are some analytic functions of the complex variable; $G=\frac{E}{2\left(1+\mu\right)}$, $E$ is Young's modulus, $\mu$ is Poisson's ratio, $u$ and $v$ are the displacements correspondingly have radial and tangential components; $z=x+iy$.

The $\tau_{r\theta}^{(1)}=0$ considering that, we will convert Equations (16) and (17) from Dekart coordinates to polar coordinates:

$$\sigma_x+\sigma_y=\sigma_r+\sigma_\theta \quad (24)$$

$$\sigma_y-\sigma_x+2i\tau_{xy}=\left(\sigma_\theta-\sigma_r\right)e^{-2i\theta} \quad (25)$$

Then, based on Equations (3), (15) and (19), the following relations will hold for the contour $L$:

$$4\operatorname{Re}\Phi\left(z\right)=2k\left[2A+\frac{P_0}{k}-B\left(1+2\ln r\right)\right] \quad (26)$$

$$\bar{z}\Phi'\left(z\right)+\Psi\left(z\right)=2k\left(\frac{A}{r^2}-B\right)e^{-2i\theta} \quad (27)$$

where, $\left|z\right|\to\infty$

$$\Phi\left(z\right)=\frac{1}{4}\left(\sigma_x^\infty+\sigma_y^\infty\right)+O\left(z^{-2}\right) \quad (28)$$

$$\Psi\left(z\right)=\frac{1}{2}\left(\sigma_x^\infty-\sigma_y^\infty\right)+O\left(z^{-2}\right) \quad (29)$$

To solve the boundary problem, we will use the method presented by Q.P. Cherepanov [5] For this, we will use the $Z=\omega\left(\xi\right)$ conversion to switch to the parametric representation of the complex variable $\xi$

$$\varphi\left(\xi\right)=\Phi\left[\omega\left(\xi\right)\right] \quad (30)$$

$$\psi\left(\xi\right)=\Phi\left[\omega\left(\xi\right)\right] \quad (31)$$

In the given expression, we obtain the following boundary problem in terms of $\xi$ to determine the three unknown functions $\varphi\left(\xi\right)$, $\psi\left(\xi\right)$, and $\omega\left(\xi\right)$ from the compatibility conditions at $L$ (3):

$$\varphi\left(\xi\right)+\overline{\varphi\left(\xi\right)}=k\left(A-B+\frac{2P_0}{k}\right)-2kB\ln\sqrt{\omega\left(\xi\right)\times\overline{\omega\left(\xi\right)}} \quad (32)$$

$$\frac{\overline{\omega\left(\xi\right)}}{\omega'\left(\xi\right)}\varphi'\left(\xi\right)+\psi\left(\xi\right)=2k\frac{A-B\left[\omega\left(\xi\right)\times\overline{\omega\left(\xi\right)}\right]}{\left[\omega\left(\xi\right)\right]^2},\left|\xi\right|=1 \quad (33)$$

where, $\left|\xi\right|\to\infty$

$$\varphi\left(\xi\right)=\frac{1}{4}\left(\sigma_x^\infty+\sigma_y^\infty\right)+O\left(\xi^{-2}\right) \quad (34)$$

$$\psi\left(\xi\right)=\frac{1}{2}\left(\sigma_x^\infty-\sigma_y^\infty\right)+O\left(\xi^{-2}\right) \quad (35)$$

$$\omega\left(\xi\right)=O\left(\xi\right) \quad (36)$$

Let us consider the functional equation in the extended formulation $\xi$

$$\frac{\varphi'(\xi)}{\omega'(\xi)}\bar{\varpi}\left(\frac{1}{\xi}\right)+\psi(\xi)=k\frac{A-B\left[\omega(\xi)\bar{\varpi}\left(\frac{1}{\xi}\right)\right]}{\left[\omega(\xi)\right]^2} \quad (37)$$

The solution of the problem is sought in the following form:

$$\omega(\xi)=C_3\xi+\bar{P}_v\left(\frac{1}{\xi}\right) \quad (38)$$

where, $P_v\left(\frac{1}{\xi}\right)$ coefficients are still undetermined $v$ th degree polynomials. It should be noted that concerning drilling, the indicator that fully reflects the efficiency of the process is the drilling speed $V_b$. Various authors [4, 6, 7] believe that for percussion drilling, the drilling speed is related to the rock properties as follows:

$$V_b=\frac{k^*}{\sigma_{cj}^{0.59}} \quad (39)$$

where, $k^*$ is a coefficient that considers the construction characteristics of the drilling tool. Considering the rock hardness factor, empirically, the following expression is given for the drilling speed $V_b$.

$$V_b=415-32f+0.65f^2 \quad (40)$$

where, $f$ is the rock hardness factor, $V_b$ (mm/min).

Considering Equations (29) and (30), we provide the following empirical expression for the drilling speed $V_b$ in the form of the following formula:

$$V_b=\frac{290N}{d^2\left(f_D+2.6\right)} \quad (41)$$

where, $N$ is the power of the perforator, kVt; $d$ is the diameter of the drilling crown, mm, and $f_D$ is the dynamic coefficient of strength. Taking into account all the expressions given for the drilling speed above, we provide the following more general expression:

$$V_b=\frac{k}{\sigma_{sj}\tau_{sdb}\times \text{tg}\left(\frac{\alpha}{2}+f_t\right)} \quad (42)$$

where, $\alpha$ is the angle of the tool blade thrust; and $f_t$ is the coefficient of friction between the tool and the rock.

Given the foregoing, we propose a new rule for drilling speed $V_b$ that takes into consideration every impact and its speed in percussion drilling.

$$V_b=\frac{AnV_{\max}^{0.85}}{d_j} \quad (43)$$

where, $A$ is the energy of a single impact, $C$; $n$ is the velocity of impact per minute; and $d_j$ is the diameter of the hole, mm.

Taking into account the degree of fragmentation of the rock during drilling, we present the following expression for the drilling speed $V_b$:

$$V_b=\frac{0.003AnV_{\max}}{d^2} \quad (44)$$

where, $V_{\max}$ is the fragmentation index according to the L.I. Baron.

Determining the drilling speed by considering the contact strength of the rock mass drilled in mechanical drilling methods is one of the interesting cases. Therefore, by taking into account the contact strength of the rock mass, the following expression is provided for the drilling speed:

$$V_b=\frac{1}{7.2\times 10^{-9}P_k-2.75} \quad (45)$$

where, $P_k$ is the contact strength of the rock mass.

During drilling, when the force $P_y$ acts along the $Y$ axis, the drill bit penetrates the rock mass to a depth of $h$. At this point, the rock's resistance to compression force $F_{sm}$ and the frictional force $F_{tr}$ must be overcome. Then, the failure condition is expressed as follows:

$$F_Y=F_{sm}+F_{tr} \quad (46)$$

During the application of the bit, perpendicular axis reactions occur in the rock mass. The vectorial sum of these forces $F_{sm}$ is represented by Equation (11):

$$F_{sm}=2N\sin\left(\frac{\alpha}{2}\right) \quad (47)$$

where, $F_{sm}$ is represents the vectorial sum of the normal axis reaction forces to the bit in the rock mass perpendicular to the bit. Formation rock fragmentation strength is determined by the following expression:

$$\sigma_{sm}=\frac{F_{sm}}{S_{sm}},\ F_{sm}=\sigma_{sm}S_{sm} \quad (48)$$

To understand the physics of drilling, it is necessary to consider the distribution of stresses when the tool enters the rock. In the simplest case, the model of the process can be influenced by the combined $P$ force in the elastic half phase. In such a model, the analysis of the stress condition is based on solving the Bussineski phase problem [6-8].

Let's consider an arbitrary point $A$ at a distance $R$ from the application point of the concentrated load. At this point, the total stress vector $\sigma_R$ coincides with the direction of the applied load $R$ (the origin of coordinates), and it points towards point $O$ under an angle $\beta$. If we draw a sphere with a diameter $k$ passing through the origin and point $c$, then the total stresses at all points on this sphere will be the same, and this stress is determined by the following principle:

$$\sigma_R=\frac{3P}{2\pi d^2} \quad (49)$$

In problems of equilibrium, the sphere of equal stresses is transformed into a circle. The total stress is divided into normal (to the loading surface) and tangential stress components, determined by the following principles:

$$\sigma_z = \frac{3P}{2\pi d^2} \times \cos\beta \tag{50}$$

$$\tau_{xz} = \frac{3P}{2\pi d^2} \times \sin\beta \tag{51}$$

In problems of equilibrium, the sphere of equal stresses is transformed into a circle. The total stress is divided into normal (to the loading surface) and tangential stress components, determined by the following principles:

The distribution of pressure on the contact surface between the cylindrical stamp with radius and the formations surface is not uniform, and it depends on the distance *x* from the stamp's axis [9, 10, 11]:

$$\sigma(x) = \frac{P}{2\pi a\sqrt{a^2 - x^2}} \tag{52}$$

Equation (42) when we examine the statement, it turns out that on the stamp axis, that $x = 0$ in this case, the pressure will be lower: $\sigma(x = 0) = \frac{P}{2\pi a^2}$ . At the contact contour, the pressure becomes infinitely large: $\sigma(x = a) \to \infty$

Both theoretical and experimental research indicate that the vertical and horizontal stresses on the stamp's contact surface with the ore are maximum and equal to each other: this means $\sigma_z = \sigma_x = \sigma_y = \max$, without tangential stresses: then $\tau = 0$ . Therefore, the surface of the formation rock is under equal biaxial compression conditions near the contact surface, meaning it cannot disintegrate. However, as we move away from the contact surface, i.e., when $z \geq 0$ , the normal stresses decrease. Furthermore, the horizontal stresses, $\sigma_x = \sigma_y$ , decrease more intensely than the vertical stress $\sigma_z$ . The difference in normal stresses leads to the formation of tangential stresses, according to Mohr's theory. As this difference increases, the tangential stresses increase. They reach a maximum at a depth corresponding to the radius of the stamp. These tangential stresses ensure the disintegration of the formation rocks beneath the stamp.

The compression nucleus $F$ , expanding under the influence of the free path $v$, works to separate its volume from the mass. This work is calculated through the following principle:

$$A = \frac{kV\sigma_p^2}{E} \tag{53}$$

where, $k$ is described as an analogy taking into account the difference between the real behavior of the mass and ideal elasticity; it is commented as a plasticity index.

On the other hand, the work of the compression nucleus is determined by the increase in its volume with the following statement:

$$dV = dV_F - dV_p \tag{54}$$

where, $dV_F$ and $dV_p$ are compression nucleus is determined by the increase in its volume due to the force $F$ and the return reaction $P$ .

The energy balance equation for a given distribution scheme, derived from the law of conservation of energy, is provided in the following principal form [12]:

$$\frac{kV\sigma_p^2}{E} = \frac{2\sigma_p V\nu F}{HBE} - \frac{3\sigma_p^2 V^2 b^2 \sigma_0 A_1 (1-2\nu)}{2H^2 FE} \tag{55}$$

where, $\nu$ is the Poisson coefficient of formation rock; $A_1$ and $B$ is the width and length of the tool blade; $\sigma_0$ is the strength of formation rock during isotropic compression; $\sigma_0 = 0.1E$ is assumed , $b - V$ the volume shape coefficient; For a rectangular shape $b = 1$ .

$$V = \frac{2H^2 F}{2\sigma_p b\sigma_0 A_1 (1-2\nu)}\left(\frac{2\nu F}{HB} - k\sigma_p\right) \tag{56}$$

It is certain that, if $V > 0$ , then the minimum force required for the tool causing the fragmentation of formation rock is determined by the following statement:

$$F\frac{k\sigma_{pHB}}{2\nu}_{\min} \tag{57}$$

In turn, the force on the tool is determined by the respective energy $Q$ , and the impact energy is given by the following statement.

$$F = \frac{2QE}{A_1\sigma_0} \tag{58}$$

where, $\sigma_0 = \frac{F}{A_1 B}$. If we consider that to be the case, then the formula:

$$F = \sqrt{2QEB} \tag{59}$$

and

$$\sigma_0 = \sqrt{\frac{2QE}{A_1^2 B}} \tag{60}$$

where, $q = \frac{Q}{V}$ knowing that scattering involves specific energy consumption, (46), (49), (50) considering the conditions, we can define the formula:

$$q = \frac{3k\sigma_p^2 b(1-2\nu)}{2E\nu^2} \tag{61}$$

From Equation (46), the dispersed volume of the rock depends non-linearly on the parameter $H$ . Often, $H$ is referred to as the thickness of the crushed layer. Then the extremum of the function at $\frac{dV}{dH} = 0$ will correspond to the optimal thickness of the crushed layer.

$$H_{opt} = \frac{\nu F}{k\sigma_p B} \tag{62}$$

or else (49) if we consider the Equation;

$$H_{opt} = \frac{2b\nu\sqrt{QE}}{k\sigma_p\sqrt{2b}} \tag{63}$$

The [12] as demonstrated in the scientific work; by substituting the force $F$ with the energy $Q$ in equation (45), it is possible to determine the volumetric fragmentation event with the following principle:

$$V = \frac{4v^2QE}{3k\sigma_p^2 b(1-2v)} \quad (64)$$

It is known from the theory of elasticity that the efficiency of the fragmentation process is determined by the following formula:

$$\eta = \frac{2v^2}{3(1-2v)} \quad (65)$$

It is the efficiency of the fragmentation process, i.e., the portion of the total energy transferred to the tool that is directly used for the fragmentation of the rock. Then we express the volume of rock fragmentation $V$ with the following principle:

$$V = \frac{2QE\eta}{k\sigma_p^2 b} \quad (66)$$

In this case, the linear fragmentation rate $V_b = \frac{V}{St}$ can be defined with this formula, $t$ is the time for a single fragmentation event. As applied to the drilling perforation process, $S = \frac{\pi d^2}{4} = \frac{\pi B^2}{4}$ and $t = \frac{1}{n}$, and $n$ is the rate of impact. Therefore, the drilling speed:

$$V_b = \frac{4Vn}{\pi B^2} \quad (67)$$

The application of Equation (49) with the limited area $s$ and the loading of the confined mass by the force $F$ results in the localized fragmentation of the formation rock. According to the scheme proposed by Yu.I. Protasov [12], the initial compression element $\Delta V_1$ acts in the direction of width to cause deformation $V_{01}$, which in turn triggers the rock reaction.

In this case, as the free surface expands in the direction of width, the second compression element $v$ acts to displace the volume of the rock, pushing it away from the mass. Following the same logical basis as in the compression situation, Yu.I. Protasov derives the following energy balance equation for drilling:

$$\frac{k\sigma_p V}{E} = \frac{2v^2F^3\eta}{3A_1B^2E(1-2vv)_0} \quad (68)$$

From Equation (38), the fragmentation event $v$ is determined by the following principle:

$$V = \frac{8H^2F}{3\sigma_p b^2\sigma_0 A_1(1-2v)}\left(\frac{vFb\eta}{HB} - k\sigma_p\right) \quad (69)$$

Accordingly, for $v = 0$:

$$F = \frac{k\sigma_p HB}{vb\eta} \quad (70)$$

The specific energy intensity of fragmentation is calculated using the following principle:

$$q = \frac{3k\sigma_p b(1-2vv)}{4Ev^2\eta^2} = \frac{k\sigma_p b}{2E\eta^3} \quad (71)$$

The function (52) possesses an extremum at $\frac{dV}{dH} = 0$ as well.

Then, the optimal depth of fragmentation is determined by the following expression:

$$H_{opt} = \frac{vFb\eta}{2k\sigma_p B} \quad (72)$$

For a single fragmentation, Equations (34)-(46) can be written similarly as follows:

$$V = \frac{16Q^3E^3v^2\eta^2}{3A_1^4B^2\left(1-2vvk\sigma_p b^2\sigma_0^4\right)} = \frac{8Q^3E^3\eta^3}{A_1^4b^2B^2k\sigma_p^2\sigma_0^4} \quad (73)$$

The maximum efficiency of the fragmentation mechanism will occur when the distance to the second exposure, corresponding to $H_{opt}$ reaches the maximum depth Equation (48). As this distance increases, the share of the fragmentation mechanism decreases, and at a certain critical distance, $H_{kr}$ equals zero, meaning that rock fragmentation is only possible through crushing. The value of $H_{kr}$ can be determined from Equation (46) for a given value of $V = 0$. In general, the value of $H_{kr}$ is determined by Equation (74) [13, 14].

$$H_{kr} = \frac{2vF}{k\sigma_p B} \quad (74)$$

or else (23) with following formula:

$$H_{kr} = \frac{2v\sqrt{2QE}}{\sqrt{k\sigma_p B}} \quad (75)$$

By comparing Equations (72) and (74), it is possible to observe that $H_{kr}$ is twice as large as $H_{opt}$ (Table 1).

Table 1. Difference table from $H_{kr}$, $H_{opt}$

| | | | | | | |
|---|---|---|---|---|---|---|
| $H_{kr}$ (mm) | 0.11 | 0.13 | 0.18 | 0.20 | 0.22 | 0.25 |
| $H_{opt}$ (mm) | 0.20 | 0.25 | 0.33 | 0.39 | 0.41 | 0.49 |

Based on Table 1, the following can be concluded. To choose the method of perforation to be carried out in the wells, the following should be taken as a basis:

1. It is considered appropriate to apply the cumulative perforation method in solid rocks, in which it is relatively more difficult to create a reservoir-well connection;
2. It is recommended to apply the bullet perforation method in fragile and weakly cemented sandstones;
3. Tor pedal (projectile) perforation method is appropriate to be applied in rocks with relatively high density and low permeability.

It should be taken into account that bullet and torpedo perforators deform the production line during the perforation process, create cracks in the cement ring and the rock itself, although in some cases these cracks formed in the rocks in the formations are a factor that positively affects the flow of oil and gas from the productive formation to the well.

## 3. CONCLUSION

This paper provides a complete description of the fragmentation process in rock mass drilling, combining theoretical concepts, empirical findings, and practical factors. We created a comprehensive framework that explains the basic principles regulating the drilling process by investigating the energy balance equations, stress distribution, and failure mechanisms. Analyzing the obtained principles, we can provide the following conclusions:

1. The structural organization is the same for both crushing and drilling. The main difference lies in the various degrees of $\eta$ exponent. In the real process of mechanical fragmentation of formation rock, there are always both crushing and drilling elements. However, the specific energy consumption of drilling is $\frac{1}{\eta^2}$ times greater than that of crushing. Therefore, the parameters of the fragmentation process should be chosen in such a way that the rock disperses as quickly as possible in the largest possible volume.
2. The efficiency of the fragmentation process is influenced by factors such as crushed layer thickness, tool characteristics, and rock properties.
3. It is considered appropriate to apply the cumulative perforation method in solid rocks, in which it is relatively more difficult to create a reservoir-well connection;
4. It is recommended to apply the bullet perforation method in fragile and weakly cemented sandstones;
5. Tor pedal (projectile) perforation method is appropriate to be applied in rocks with relatively high density and low permeability.

This study emphasizes the need of taking into account the individual geological formations and drilling circumstances while using the established theory. Future study should look into the effects of drilling parameters on wellbore stability, drilling fluid characteristics, and overall drilling performance. The oil and gas sector can make major advances in drilling efficiency and sustainability by addressing these research gaps and translating the results into practical implementations.

However, additional research is required to enhance the models and parameters utilized in this work, including aspects such as rock heterogeneity, tool wear, and downhole conditions. Experimental validation of theoretical discoveries is critical to ensuring their use in real-world drilling circumstances. In that case exploring the possibilities of modern materials, technology, and data analytics can lead to more innovative drilling procedures. Thus, a unified theory of drilling has not yet been developed. However, the theory and experience of the process, along with numerous studies, allow for the selection of the optimal drilling equipment and the planning of its operation in efficient regimes for given mining-geological conditions.

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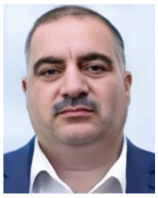

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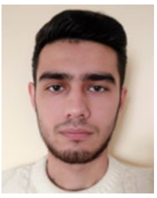

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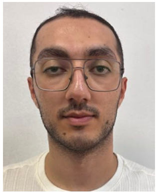

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