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ASPECTS REGARDING THE DETERMINATION OF CHARACTERISTIC VALUES FOR THE ROCK DRILLING PROCESS

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Abstract: *This paper presents some aspects of the drilling process regarding stress conditions and how to determine certain parameters necessary for studying this process, drills, and determining the technical and economic indicators achieved during drilling.*

Key words:*rock drillingprocess, penetrationcoefficient, recoilcoefficient, drill-rock system, stresswaves, penetrationdepth, percussionforce, rock hardnesscoefficient*

1. INTRODUCTION

This paper addresses the issue of determining the depth of penetration of the drill bit into the rock following the impact between the hammer piston of the rock drill, the penetration and recoil coefficients required in the study of drilling, but also the drill-rock system. In these determinations, the complexity of the calculation is determined by the initial conditions and the limiting conditions due to the penetration of the drill bit into the rock. Furthermore, the wave process to which the drill bit is subjected includes not only its deformations but also its absolute displacements. All these factors significantly complicate the calculations and exclude the possibility of directly applying the results of classical percussion theory in the case under study.

2. THEORETICAL ASPECTS REGARDING THE DETERMINATION OF THE ROCK PENETRATION COEFFICIENTS OF THE DRILL BIT AND THE DRILL BIT RECOIL

Figure 1 shows a schematic representation of the drilling system-rock, in which the following are noted: 1 - drill; 2 - cutting crown; 3 - drill piston; 4 - rock being drilled; d, *l* - drill diameter and length; *v*, *a*- speed and linear acceleration of the hammer piston at the moment of impact; M - piston mass; ω - angular velocity of the drill.

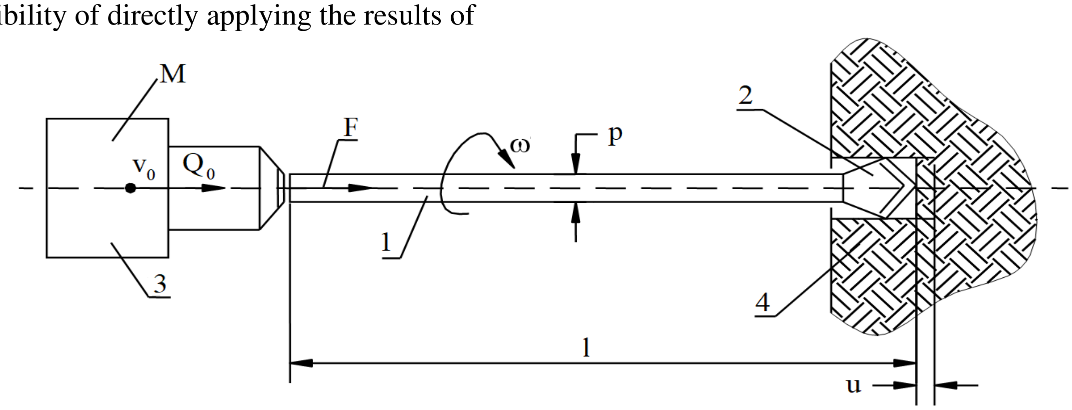

Fig.1 Drilling system-rock

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Under the action of the piston's percussive force, applied to the drill bit shank, the cutting edge of the crown penetrates the rock due to the compressive stress. As a result of repeated blows applied to the drill bit shank and its continuous rotation, the rock is broken up and evacuated from the mine hole with the help of pressurized water that reaches the bottom of the mine hole through a central hole in the drill bit, and the drill bit advances.

The expression of the depth of penetration into the rock of the chisel-type cutting edge of the drill bit, under the action of percussion, takes different forms according to various authors.

According to Pokrovski, I.S., the expression of depth and penetration has the form:

$$u=\frac{F}{2a\cdot\tau_r}\cdot\frac{sin^2\beta}{\left[1+\frac{2}{cos^2\beta}+\frac{tg(180-\beta)}{2\cos\beta}\right]} \quad (1)$$

where: F - is the magnitude of the percussion force; a - the length of the bit's cutting edge; τ_r- the rock's shear strength; β - the rock's internal friction angle.

To address the issues raised in this paper, equation (1) can be modified to highlight the penetration coefficient.

In this sense, relation (1) highlights the magnitude of the penetration coefficient k_p and the active area A of the crown cutting edge:

$$u=\frac{F}{k_pA} \quad (2)$$

where:

$$k_p=\frac{\tau_r}{u_m}\cdot\frac{1+\frac{2}{cos^2\beta}+\frac{tg(180-2\beta)}{2\cos\beta}}{tg\frac{\alpha}{2}\cdot sin^2\beta} \quad (3)$$

and

$$A=2u_m a\cdot tg\frac{\alpha}{2} \quad (4)$$

In relations (3) and (4) it was noted: *α/2* - the sharpening angle of the drill bit; u_m - the average penetration depth of the crown bit into the rock.

According to relation (2), it follows that when the drill penetrates the rock, the reactive force is proportional to the values *u*, $k_{(p)}$,and*A*.

$$F = k_p\cdot A\cdot u \quad (5)$$

In summary, it can be said that the penetration of the drill bit into the rock is directly proportional to the percussion force and inversely proportional to the penetration coefficient and the active area of the cutting edge. In turn, the value of the penetration coefficient depends on the critical stress $\tau_r$of the rock, the sharpening angle of the cutting edge, and the internal friction angle of the rock.

Similarly, it can be shown that when the drill recoils, the recoil force is proportional to the penetration depth, the active surface area of the cutting edge, and the recoil coefficient k_0.

$$F=k_0\cdot A\cdot u \quad (6)$$

The recoil coefficient $k_0$depends on the characteristics of the rock, as well as the dimensions and shape of the drill bit crown

$$k_0=\frac{E}{1-\mu^2}\cdot\frac{1}{\beta\sqrt{A}} \quad (7)$$

where *E* and *μ* are the modulus of elasticity and Poisson's ratio of the rock, and β is a coefficient that depends on the shape and dimensions of the bit.

During drilling, the displacement of rock from the massif occurs mainly due to compressive stress, at a stress value in the drilling direction:

$$\sigma_1=\sigma_x=(3...4)\cdot\sigma_c \quad (8)$$

Under axial stress on the drill, a spatial state of stress is generally achieved in the rock (Fig. 2).

According to the Huber–Henekky–Mises strength theory, the equivalent stress at point P at which rock fragmentation occurs is:

$$\sqrt{\sigma_1^2+\sigma_2^2+\sigma_3^2-(\sigma_1\sigma_2+\sigma_1\sigma_3+\sigma_2\sigma_3)}\geq\sigma_c \quad (9)$$

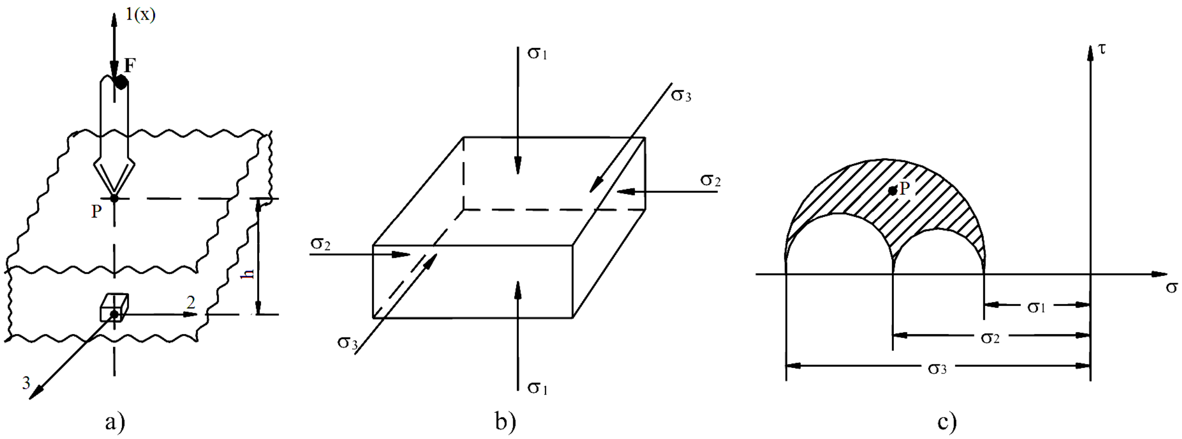

Fig. 2 Stress state in the rock under axial stress from the drill bit with impact force *F*
a. drill-rock interaction; b. stress state in the rock at a point P near the cutting edge of the bit;
c. Mohr's circles for the stress state at point P

Due to the symmetry of the stress $\sigma_2 = \sigma_3$ (Fig. 3), relation (9) becomes

$$\sqrt{\sigma_1^2+\sigma_3^2-2\sigma_1\sigma_3}= \sigma_1-\sigma_3 \geq \sigma_c \quad (10)$$

i.e., a relationship equivalent to Coulomb's theory.

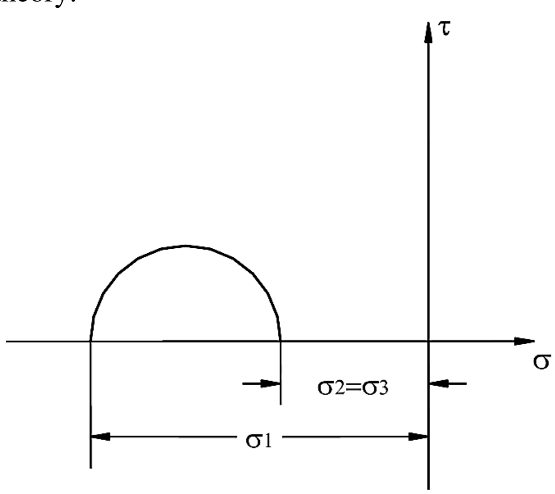

Fig.3 Stress state at point *P* for $\sigma_2 = \sigma_3$

It has been mentioned that in the case of stress in two directions, rock failure occurs at the stress value $\sigma_1$given by relation (8). Under intermediate stress conditions (between stress in three directions and stress in two directions), rock failure occurs for a stress:

$$\sigma_1=\sigma_x=(13...17)\sigma_c \quad (11)$$

3. RESULTS OBTAINED

If the coefficient$\xi=\frac{F}{m\cdot v_0}$ is introduced into relation (2), where$m=\frac{E\cdot A_s}{a}$, the following is obtained:

$$u=\frac{F}{k_pA}=\frac{\xi\cdot m\cdot v_0}{k_pA}=\frac{\xi\cdot E\cdot A_s\cdot v_0}{k_p\cdot a\cdot A} \quad (12)$$

where: m- oscillating mass; A_s- cross-sectional area of the drill bit; v_0- piston velocity at the moment of impact (equal to the velocity of the impacted section of the drill bit).

In [4], it is demonstrated that at the end of the first half-phase of the stress waves in the drill bit ($\tau=\frac{L}{a}$, i.e., the time during which the stress wave traveled the length of the drill bit), the dimensionless quantity ξ is defined by the relation:

$$\xi_1= 2e^{-\frac{G_s}{2G_p}}\left(1-e^{-\frac{k_p\cdot A\cdot L}{2E\cdot A_s}}\right) \quad (13)$$

where: G_s- drill weight, and G_p- piston weight.

Taking into account (13), from (12) we obtain the penetration depth of the drill bit during one percussion, in the first half-phase:

$$u=\frac{2E\cdot A_s\cdot v_0}{k_p\cdot a\cdot A}e^{-\frac{G_s}{2G_p}}\left(1-e^{-\frac{k_pA\cdot L}{2E\cdot A_s}}\right) \quad (14)$$

Calculations show that the maximum penetration depth values usually occur in the first half-phase, less frequently in the second half-phase, and very rarely in the third half-phase.

For the second and third half-phases, the expressions for ξ are:

$$\xi_2=\xi_1\cdot\left(e^{-\frac{k_p\cdot A\cdot L}{2E\cdot A_s}}-e^{-\frac{G_s}{2G_p}}\right) \qquad (15)$$

$$\xi_3=\xi_1\cdot\left[\left(e^{-\frac{k_p\cdot A\cdot L}{2E\cdot A_s}}+e^{-\frac{G_s}{2G_p}}\right)^2-e^{-\frac{k_p\cdot A\cdot L}{2E\cdot A_s}}\cdot e^{-\frac{G_s}{2G_p}}\right] \qquad (16)$$

To simplify the writing of relations (13), (15), and (16), the dimensionless quantities $\omega=\frac{G_s}{2G_p}$ and $\eta=\frac{k_p\cdot A\cdot L}{2E\cdot A_s}$ are introduced, and the following is obtained:

$$\xi_1=2e^{-\omega}(1-e^{-\eta}) \qquad (17)$$

$$\xi_2=\xi_1\cdot(e^{-\eta}-e^{-\omega}) \qquad (18)$$

$$\xi_3=\xi_1\cdot[(e^{-\eta}+e^{-\omega})^2-e^{-\eta}\cdot e^{-\omega}] \qquad (19)$$

The limit value between ξ_1 and ξ_2 is obtained from relation (18), for $\xi_1=\xi_2$

$$e^{-\eta}+e^{-\omega}=1 \qquad (20)$$

from which the relationship between η and ω for this situation is obtained.

The relationship between ε and μ that defines the limit value between ξ_3 and ξ_1 is obtained from relation (19) for $\xi_3=\xi_1$:

$$(e^{-\eta}+e^{-\omega})^2-e^{-\eta}\cdot e^{-\omega}=e^{-\eta}+e^{-\omega} \qquad (21)$$

or

$$e^{-\eta}+e^{-\omega}-\frac{1}{e^{\eta}+e^{\omega}}=1 \qquad (22)$$

Relationships (20) and (21) are represented graphically in η-ω coordinates, obtaining curves I-I and II-II in Figure 4.

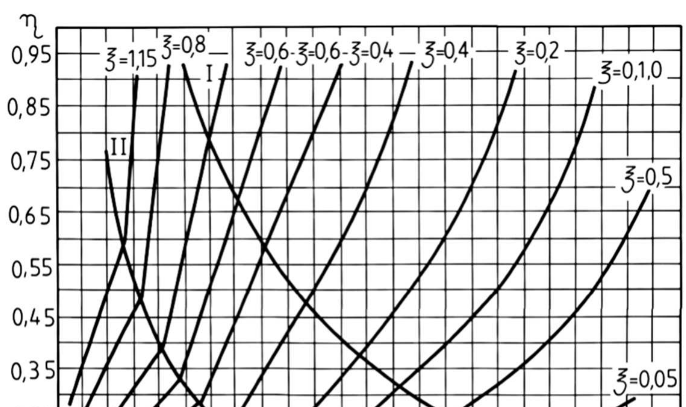

Fig.4 Graph of the penetration depth of the drill bit during piston percussion

According to relation (12), it was seen that the depth u of penetration of the drill bit into the rock during a percussion can be expressed as a function of the size ξ.

Also in the graph in Figure 4, starting from the top of the graph (from $\varepsilon = 0.95$) to curve I-I, function (17) is represented for $\xi_1 = 1.0; 0.8; 0.6; 0.5; 0.4; 0.3; 0.2; 0.15; 0.1; 0.05$.

Between curves I-I and II-II, which represent function (18), taking for ξ_2 the same values as for ξ_1 and finally, below curve II-II, function (19) is represented with the same values for ξ_3 as those taken for ξ_1 and ξ_2.

In the study, the penetration and rebound coefficients were determined for drilling in rocks of different hardnesses, using a drill bit used in practice.

For example, in the case of drilling in limestone, where the Protodiakonov hardness coefficient is known to be $f = 12$, the yield strength under compression $\sigma_c = 100\ N/mm^2$, the internal friction angle $\beta = 65^o$, the tensile strength under two directions of stress $\sigma_x = (3...4)\sigma_c = (300...400)\ N/mm^2$, the shear strength $\tau_r = (0,06...0,08)\sigma_c = = (18...32)\ N/mm^2$, and when using a drill bit with a cutting edge angle $\alpha/2 = 45^o$ the active area $A = a \cdot l = 36\ mm^2$, and $2\mu_m \cdot tg\ \alpha/2 = 1$ (for reinforced crowns), according to relation (3), the penetration coefficient $k_p = (0,596...1,060) \cdot 10^3\ N/mm^3$ is obtained.

Figure 5 shows the variation of the penetration coefficient k_p as a function of the rock hardness coefficient for the same drill characteristics.

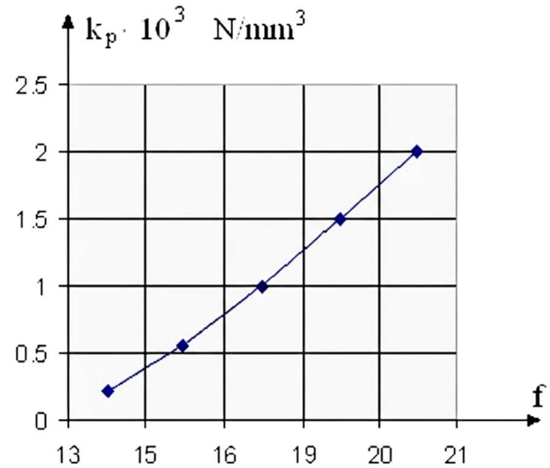

Fig.5 Variation of the penetration coefficient as a function of the rock hardness coefficient

For the case of an altered granite (calcite) with $E = 500\ N/mm^2$, $\mu = 0.295$ and $\beta = 0.4$, for the same drill bit with $A = 36\ mm^2$, according to relation (7) we obtain $k_0 = 216.48$.

When using heavy rotary percussion drills P125, manufactured by Independența Sibiu, with which the IMP-2 mobile drilling rigs are equipped, the following are known: $G_p = 68.5\ N$- weight of the drill piston; $d_s = 32 \cdot 10^{-3}\ m$ - the diameter of the drill bit; $A_s = 804.25 \cdot 10^{-6}\ m^2$- the cross-sectional area of the drill bit; $L = 3.41$- the length of the drill bit; $G_s = \gamma A_s L = 215.28\ N$- weight of the drill bit; $E = 2.1 \cdot 10^{11}\ N/m^2$ and $\gamma = 7.85 \cdot 10^4\ N/m^3$-modulus of elasticity and specific weight of the drill bit material; $A = 36 \cdot 10^{-6} m^2$ - active area of the drill bit crown; $k_p = 1.0 \cdot 10^{12}\ N/m^2$(for rocks with a hardness coefficient $f = 17$); $a = \sqrt{E/\rho} = 5,15 \cdot 10^3$ m/s- the propagation speed of the elastic wave in rods; $v_0 = 10\ m/s$- the speed of the piston at the moment of impact.

With these data, from relations (17) we obtain $\eta = 0.74$ and $\omega = 1.569$, and from the graph shown in Figure 5 we determine by interpolation the value $\xi_1 \approx 0.12$ at the intersection of the values η and ω, resulting in the maximum penetration of the drill occurring in the first phase. With the value of ξ_1, from (12) the value of the maximum depth u of the drill bit penetration into the rock during a percussion is determined. The same value for ξ_1 is also obtained from relation (13).

After determining the penetration depth, the drilling speed can be determined using the relation:

$$v_{perf} = u \cdot \frac{n\gamma_0}{360} \cdot c_0\ m/min$$

where n- drill rotation speed in revolutions per minute; c_0- coefficient that takes into account the type of drill bit (for chisel-type bit $c_0 = 2$, and for cross-type bit $c_0 = 4$) and γ_0- the angle of rotation of the drill bit after each percussion.

Taking into account the coefficients k_p and k_0, the drilling operation can be studied.

4. CONCLUSIONS

The mechanical characteristics of rocks are known with sufficient accuracy, as are the geometric characteristics of drill bits, which are correlated with the strength coefficient of rocks, the diameter and length of mine holes, and the technical characteristics of drills.

The study of the drilling operation involves determining the characteristic values of the drilling process, as well as the efficiency achieved in this operation. For this reason, it is necessary to determine the penetration and recoil coefficients by analytical calculation and experimentally. The paper presents a methodology for determining these values by calculation.

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Aspecte privind determinarea valorilor caracteristice pentru procesul de forare a rocilor

Rezumat: În lucrare sunt prezentați invarianții structurilor din bare articulate, static nedeterminate, analizați prin metoda forțelor. Acești invarianți demonstrează faptul că orice variație de ordin infinit mic a unui efort într-o bară r a structurii produce o variație de același ordin a dimensiunilor secțiunii barei s din cadrul aceleiași structuri. Studiul utilizează atât formularea clasică a metodei eforturilor, cât și abordarea matricială pentru identificarea și validarea acestor parametri intrinseci

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