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RESISTANCE OF ROCKS TO CRUSHING DURING WELL DRILLING

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The paper presents properties of the rocks according to their resistance to drilling. The effects of differential pressure on the rock drillability and changes in rocks strength depending on the depth of their occurrence and crushing conditions are examined. The interlinkage between technological processes for rock crushing at the borehole bottom and breaking stresses has been analyzed. The interlinkage between the breaking loads and deformations of rocks with account of their structural changes and rate of loading has been assessed. The relevance and applicability of identified regularities between stresses, deformations and differential pressure for solving practical tasks of efficient rock crushing in the course of drilling have been assessed. Issues of providing theoretical evidence for the rock breakage with the rock cutting tools in the bottom-hole conditions have been reviewed. It is proven that the rock destruction effect of drilling depends not only on the value of the breaking load but also on the rate of its application.

Key words: *borehole, differential pressure, breaking stress, drillability, drilling mud.*

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Introduction. The major factors determining operational efficiency during borehole drilling are rock drillability, breaking loads at the borehole bottom and composition of the drilling mud. Over the recent years various research organizations conducted numerous studies exploring rocks mechanics with regard to deep well drilling conditions in different oil and gas fields of the country. As experience of many companies shows when choosing rock cutting tools they are guided by the physical, mechanical and deformation properties of the rocks in the drilling intervals with account of the drilling mud effect on the borehole bottom, the bit drilling intensity is increased by 20-25 % both in terms of footage drilled and mechanical speed of drilling.

The aforesaid highlights a need for comprehensive research targeting a broad range of matters related to exploration of the regularities behind deep drilling processes aimed at efficient breakage of the rocks at the borehole bottom.

Analysis of the Current State of the Issue. A method for determining the optimal drilling mud composition and the sealant fractional composition is described in detail in the studies of G.G.Ishbaev, M.R.Dalmiev, S.Vikers and others [2-4, 8, 9, 17, 20]. The analyses of the said studies revealed, that the basic method of calculating the fractional composition is the Abrams' rule, according to which drilling mud shall contain the plugging material with a particle diameter equal to or larger than one third of the size of rock average pore, at a concentration of at least 5 % of the total solids in the drilling mud. Only in such a case the breaking stress is created. The main shortcoming of this method is that maintaining a certain particle size distribution in a dispersed phase only allows to start the sealing process but cannot guarantee a complete clogging of the rock pores.

In order to overcome this shortcoming S.Vickers [6, 20] developed a method based on a theory of perfect clogging. According to this theory perfect clogging occurs when a dependency of the aggregate particle content in the mud as a percentage of the square root of the particle size is linear. In this case the drilling mud creates a filter cake with the lowest permeability. The perfect clogging theory though commonly used in the oil industry has its drawbacks, the main of which is that it is generally based on estimation of the pore average size by invoking a square root of the permeability. The theory accuracy could have been ensured if the pore size distribution in the rock was a linear dependency. In practice no linear dependency is observed, and the pore size most frequently found in the rock will not be equal to the average size. The research findings do not give an answer to the question of efficiency of rock breakage at the bottom of the drilled borehole.

The use of drilling mud reducing the borehole fluid penetration and the pressure front in the bottomhole formation zone will not lead to the expected rock crushing efficiency at the bottom unless optimum technical and technological parameters are ensured to produce a necessary effect on the rocks. In discussion of problems associated with the borehole stability and the efficiency of rock crushing at the bottom, the primary focus is usually on the interaction between the rocks and the drilling mud. Still many literature sources agree that drilling parameters have a major influence on the stability of the drill string, leading to a significant increase in the rate of penetration [14-16].

The well drilling process means its deepening by transmitting a torque to the bit with the help of a drill string or a mud motor, with the energy transmitted from the surface spent on the rock crushing. In

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order to determine the amount of energy required to crush the rock at the bottom of the well, R.Theale [19] has introduced a concept of specific mechanical energy. The specific mechanical energy is described as a force required to remove a certain amount of rocks, which is a function of drilling parameters, properties of cuttings and dynamic impact of a bit on the rock.

In laboratory conditions the energy required for rock crushing remains relatively constant and equal to ultimate rock resistance to the uniaxial compression [19]. While in the field conditions with the use of the drilling rig the efficiency factor is added. Analysis of drilling shows that 30-40 % of energy is efficient, while 70-60 % of energy is wasted [5, 10, 13, 18]. The main reasons behind the loss of efficiency are drilling vibrations, which can be longitudinal, torsional and bending, lithology, along with design of drill string lower part, borehole geometry, trajectory, friction coefficient, etc. Thus when the value of specific mechanical energy is exceeded, it causes increased vibrations, leading to excessive contact between the drilling tool and the borehole walls, irrational use of energy and destabilizing the host rock and the filter cake.

The effect of the drill string vibrations on the borehole stability and rock crushing efficiency is fairly fully described in the literature. In particular V.A.Dunaevsky [12] and M.V.Dukstra [11] report that the drill string is exposed to a significant influence of vibration, the main source of which are interactions between the bit and the rock, the drill string and the borehole wall. The authors indicate that the vibrations ultimately lead to fatigue failure of the drill pipes and, in particular, to the rock breaking at the borehole bottom.

As it follows from the above the efficiency of rock crushing at the bottom of the borehole and its drillability are a function of many variables and depend on natural, technological and technical factors. Due to this the issue of rocks drillability in the context of deep drilling has not yet been sufficiently addressed.

Generally either a drilling footage or rate of drilling in various rocks under certain conditions is viewed as an indicator of drillability, while the effect of destructive stresses, depending in particular on the borehole parameters and a quality of the borehole mud is excluded.

The research insights help to better handle a task of effective selection of technical and technological solutions for well drilling.

Rock Crushing Efficiency Parameters in Drilling Process. In the drilling process, the same as in any other technological process, a certain amount of energy is spent on crushing a certain volume of rock. But the energy spent on crushing is determined not by one particular mechanical property, but by an aggregate combination of physical and mechanical properties of the rocks.

In this case specific destruction work per volume unit is the most objective indicator for rocks ranking by their drillability. Here it is important to bear in mind that the rock properties determining the ultimate destruction work shall be assessed in conditions accounting for the rock and hydrostatic pressure.

To date a clear relationship between physical and mechanical properties of the rocks and their drillability categories is revealed [6], making it possible to choose rock cutting tools and drilling operational parameters appropriate for specific geological profiles.

The deeper the rock, the higher resistance to destruction it has. This is due to both the increased rock pressure and compacting. Therefore with the borehole deepening a sharp increase in energy required for crushing is observed, i.e. the rock drillability is worsening. Analysis of the impact of the rock depth on the energy intensity of crushing showed that the higher the hydrostatic pressure at the hole bottom is, the faster the rock crushing energy intensity increases with the depth.

The impact of the rock depth on the intensity of its crushing can be judged by the results of field observations made by the report authors in the course of drilling at Usinskaya and Vozeyskaya fields (Figure 1). As is seen in the Figure 1, with the increased depth the rock drillability sharply drops. Examination of the drilled rocks' mechanical properties has revealed, that changes in their hardness and plasticity with the depth are minor and cannot be a reason of such a significant decrease in the rocks drillability.

The increase in hydrostatic pressure due to increased depth is about 1.0 kPa per every 1000 m. The hardness of the rocks under study was about 25 kPa, which also cannot explain a several-fold change in the rock drillability.

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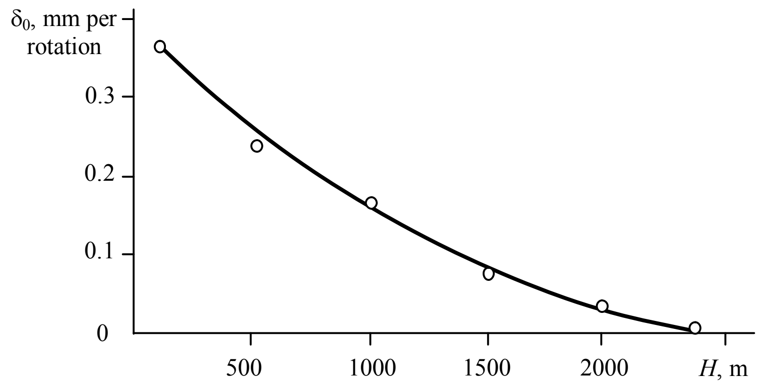

Fig.1. Dependency between crushing intensity and borehole depth

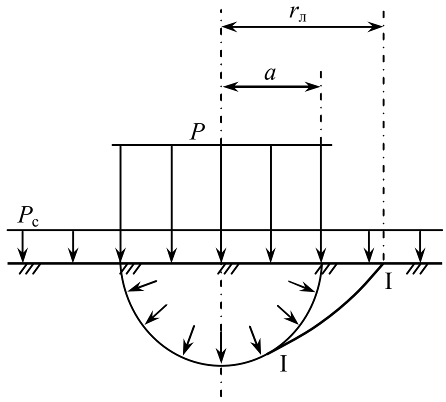

Fig.2. Diagram explaining mechanism of well pressure impact on the rock destruction

Analysis of literature sources [1, 6] and generalization of field research findings in the area of interest revealed that a decisive impact on the reduction of drillability is exerted by the rock compaction λ and difference in pressures in the well $P_с$ and in the drilled stratum $P_п$, known as differential pressure $P_д$:

$$P_д = P_с - P_п.$$

With account of data presented in papers [7] and analysis of field observations the impact of differential pressure on the rock drillability can be explained through examination of patterns of indentor pressing into the rock (Figure 2). Due to pressure on indentor a destruction nucleus is created in the rocks, generating pressure on the surrounding media. The pressure component directed upwards for lifting up the rocks around the indentor is about 4-7 % of total pressure on the indentor. When the tensile crack is formed (I-I in Figure 2) a cavity appears in the dense rocks with zero pressure inside. The crack is prevented from opening by pressure P_w, which creates a counter load on the lifted part of the rocks. Then

$$P_п = \pi P_с(r_л^2 - a^2). \tag{1}$$

Expression (1) demonstrates that the higher is the well pressure, the higher its impact is on the final stage of the rock crushing upon indentor pressing.

If the stratum is porous and pore fluid pressure is equal to $P_п$, then pressure in the crack can be also assumed to be equal to $P_п$. In this case the expression (1) will take the following form

$$P_п = \pi(P_с - P_п)(r_л^2 - a^2),$$

i.e. the impact on the final stage of crushing is exerted by difference in pressures of the well and of the stratum.

As a rule the porous strata are permeable. Fluid filtering from the high pressure area to the low pressure area leads to formation of a transition zone where pressure is gradually changing from $P_с$ to P (Figure 2).

It is obvious that in the dense rocks the transition zone thickness is equal to zero and the pressure difference at the depth of destruction $\delta_р$ will be equal to well pressure (Figure 3, *a*).

If the stratum is porous, and the transition zone thickness is less than $\delta_р$, the resultant pressure drop is equal to differential pressure (Figure 3, *b*). And only in case if the transition zone thickness is more than $\delta_р$ the resultant change is less than the differential pressure (Figure 3, *c*).

Reduction in the pressure change is greater with the higher permeability of the rock and filtration and the higher fluid filtering capacity. The filtration time is greater the lower the rotational speed of the cutting tool is.

If the pressure in the stratum is greater than the pressure in the well, then the pressure change has the opposite sign (Figure 3, *d*) contributing to the efficient separation of particles from the rock face.

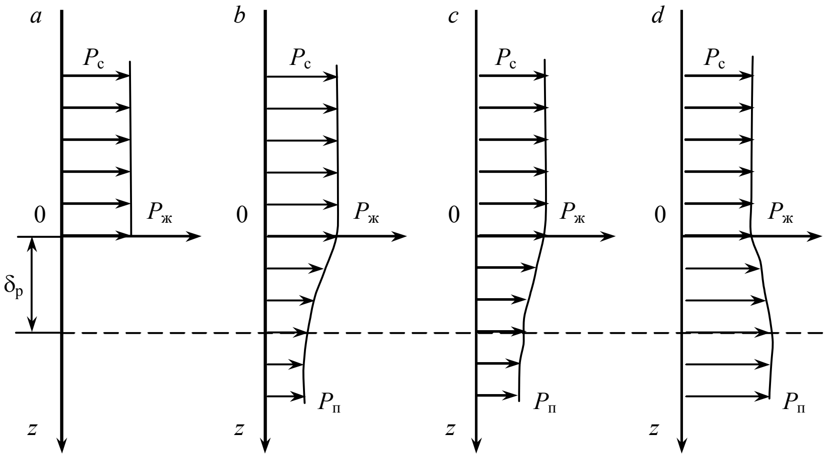

Fig.3. Changes in virtual differential pressure with rock crushing at the depth δ_p: *a* – dense rocks; *b* – low-permeability rocks; *c* – high-permeability rocks; *d* – rocks with $P_п \geq P_c$

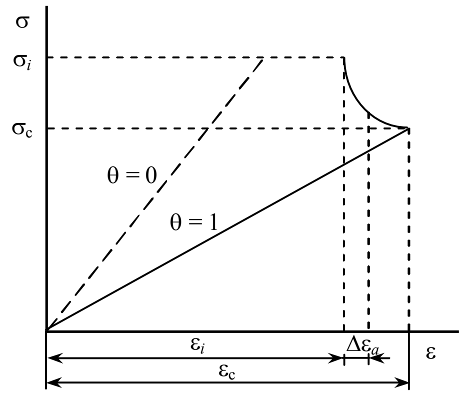

Fig.4. Change in relationship (σ – ε) at different values of structural coefficient θ

Efficiency of the rock crushing at the bottom of the borehole in addition to the pressure change is significantly affected by the breaking stress.

In the course of drilling with flushing the breaking stress in the rocks is increased due to the effect on the borehole bottom of the drilling mud hydrostatic pressure.

The rock compaction coefficient λ due to increase in depth of drilling with mud present in the well is expressed as a below dependency

$$\lambda = 1 + \gamma_p H_0 / 10\delta_p,$$

where γ_p is a density of the flushing fluid; H_0 is a depth of well; δ_p is an ultimate compression strength of the rock.

A considerable increase in the rock breaking stress at the depth is observed with low δ_p, whereas in case of hard rocks drilling an increase in λ is insignificant. Thus, for instance, for Usinskoye field with $H_0 = 1000$ m, drilling mud density $\gamma_p = 1.3$ g/sm^3 и $\delta_p = 0.1$ MPa, coefficient $\lambda = 2.3$, and with $\delta_p = 1{,}0$ MPa coefficient $\lambda = 1{,}1$.

With account of structural changes in the rock upon its loading a dependency between stress σ and deformation ε may be expressed as

$$\sigma = 2E\varepsilon / (1 + \theta),$$

where *E* is a modulus of natural elasticity with no permanent deformation; θ is a structural coefficient that varies with the load on solid body from 1 (elastic state) to 0 (plastic state).

Structural coefficient can be determined using the below dependency

$$\theta = 1 - \tau / t, \tag{2}$$

where τ is a period of relaxation; *t* is deformation time.

Figure 4 demonstrates a change in relationship (σ – ε), showing that when θ = 1 the rock manifests only elastic properties, i.e. $\sigma_c = E\varepsilon$, and when θ = 0 the rock plasticity is exerted, i.e. τ = t.

In order to determine dependency between the rock breaking stress and the rate of load application, let's define the relationship between stress σ_i when θ < 1 and σ_c when θ = 1 using the below expression

$$\sigma_i / \sigma_c = 2\varepsilon_i / (1 + \theta)\varepsilon_c.$$

as

$$(1 + \theta) = 2 - \tau / t = 2[(t - 0{,}5\tau) / t],$$

$$\sigma_i / \sigma_c = \varepsilon_i t / (t - 0{,}5\tau)\varepsilon_0 = V_i / V_c,$$

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where V_i and V_c are the rates of load application.

Due to rock porosity the value of rock deformation before destruction is increased by $\Delta\varepsilon$ and that's why stress σ_i is reduced by the value of porosity coefficient $K_п$, thus,

$$\sigma_i = \sigma_c(1 - K_п)V_i / V_c.$$

So with increase in the speed of deformation the rock resistance to crushing grows. With higher rock porosity and fracture intensity the impact of speed on the value of breaking stress reduces.

As stress required for plastic or viscous state of solid body at a constant loading rate is determined based on relationship $\sigma_i = \mu V_i$, where μ is viscosity coefficient. Comparison of this dependence with equation (2) helps to build the below expression

$$\mu_c = (1 - K_п)\sigma_c / V_c,$$

where μ_c is a coefficient of initial or natural viscosity of the rocks.

Specific destruction work or breaking stress δ_p is a physical measure and pursuant to decision of the International Bureau of Rock Mechanics for determination of δ_p the rate of load application $V_н$ shall be in a range between 5θ and 10θ, and then

$$\delta_p = V_н t_0 = (5\div10)\theta t_0,$$

where t_0 is a rock sample deformation time before its destruction.

Conclusion. The decisive impact on the efficiency of rock crushing at the bottom of the drilled borehole is exerted by the differential pressure, which depends on the physical and mechanical properties of the rocks, specific weight of the drilling mud, its viscosity and breaking stress at the borehole bottom.

Therefore, when planning technical and technological parameters of rock crushing during drilling not only physical, mechanical and deformation properties shall be taken into account, but also the nature of technical and technological interactions between the cutting tool and the rock.

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