Simulation of Hydro-Mechanical Processes of the Formation and Movement of a Hydro-Mixture During Hydro-Production

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Abstract

The article highlights the results of research and modelling of the processes of development of tuff deposits by geotechnological mining methods, in particular, the method of borehole hydrotechnology.
When modelling geo-technological mining processes, physical modelling methods were used and natural studies, allowed us to reproduce and study in the laboratory and natural conditions certain phenomena and physical mechanisms of processes. The conducted research concerns individual technological operations.
Erosion and transportation of mineral in the stream, namely, the impact of the rock by the jet from the hydro monitor and the supply of pulp to the area of action of the suction nozzle at different water pressures and different speeds of movement of the impact nozzle of the hydro monitor in the outcrop sector, the influence of the flow rate of the working agent (water) and the slope of the bottom of the extraction were studied cameras on the transport capacity of the stream.
As a result of research, it was established that in the case of an increase in the diameter of the nozzle and water pressure, the erosion radius increases, and productivity increases according to the exponential law. At a certain distance from the nozzle, the rate of advancement of the blowout remains unchanged (for different diameters of the nozzles), therefore, when developing the technology for working out chambers in dense tuffs, it is necessary to focus on the operating characteristics of the initial section of the jet. In order to prevent the formation of a notch and increase the efficiency of mining, at distances of up to 6 m from the nozzle of the hydromonitor, the angle of inclination of the jet to the erosion surface should not exceed 7°, the speed of the jet along the outcrop is limited to 1.4 m/s, and the height of the outcrop does not exceed 15 cm when washing through nozzles with a diameter of up to 35 mm.

Keywords: *zeolite-smectite tuffs, hydromonitor, geotechnological mining processes, erosion radius, flow transport capacity, extraction chamber*

1. Introduction

Volcanic tuffs are the main types of pyroclastic rocks and are characterized by a dense rock formed by direct deposition of solid products of a volcanic eruption, baked, compacted and cemented by various geological processes. Tuffs from different deposits can differ in colour, strength, and physicochemical properties, and for the same deposit, the composition of tuffs varies depending on the depth or area of occurrence, which is largely the reason for the insufficient study and the lack of reliable analytical and technological data for the development of such deposits [1, 2, 43-50].

In the zeolite-smectite tuffs of the Rivne-Volyn region, discovered by wells near the quarry, in the area of the "Ivanchi" basalt deposit (2 km to the southwest), a complete mineralogical analysis established high contents of zeolites, smectites and ferruginous dispersed minerals, which are also smectites [3, 73-82].

Tuff samples extracted from wells near the quarry, according to X-ray structural and thermal analyses (6 determinations), on average contain 65.0 (+16.0, −13.0) % smectites of the trioctahedral structure of the hectorite-saponite series and 28.17 (+14.83, −14.17) % analcime [1, 4, 51-64].

Freshly quarried tuffs are well-cemented, semi-rocky rocks, but when exposed to moisture for a long time, they easily decompose to form a loose mass [6-10, 65-68].

The bulk density of crushed tuff is within 0.96...1.22 · 103 kg/m^3, and the specific surface is 120...150 m^2/kg. The total porosity of the dispersed tuff material reaches about 30%; swelling in water – 36%, and in the presence of coagulant – 62%. Water absorption is about 18% by mass and 33% by volume [11-15, 69-72].

Therefore, the development of such tough deposits by geotechnological mining methods, in particular by well hydrotechnology, is promising and requires detailed research [16-31].

The movement of the tuff hydro monitor destroyed by the jet to the suction device of the dispensing device occurs in the

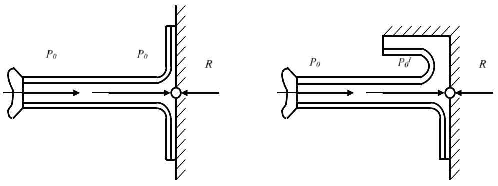

Fig. 1. Schemes of the interaction of a pressure water jet with different types of walls: is a flat wall; b) is a wall with a one-way exit

Rys. 1. Schematy oddziaływania strumienia wody pod ciśnieniem z różnymi typami ścian: a) ze ścianą płaską; b) ze ścianą z wyjściem jednokierunkowym

flow along the bottom of the chamber by gravity or pressure flow of water [32-34].

The novelty and distinguishing features of the technique of gravity hydraulic transport along the bottom of mining chambers is that the calculation is based on the condition of determining the qualitative and quantitative parameters of the erosion process: the amount of working agent required for erosion; mineral erosion performance, bottom roughness coefficient; radius and angle of the erosion sector.

Erosion of the chamber is carried out by sectors, which determines the presence of different specific costs of the working agent along the length of transportation and leads to variability of flow rates. In the end, the factor of variability of specific flows and velocities affects the transport capacity of the flow, which is minimal near the outcrop and increases in the direction of the output production. On the other hand, the amount of destroyed mineral is maximum near the extraction chamber and minimum near the outlet. Therefore, mineral losses near the pit are quite large even in the first few meters of the erosion radius of the mining chamber, increasing (due to the superimposition of previous under-washes) as the pit progresses. Over time, this leads to the impossibility of transporting the reflected mineral without repeated erosion of the entire area of the sector. Increasing the transport capacity of the flow near the hole by increasing the flow rate of the working agent will lead not only to its significant overspending but also to an increase in the productivity of hydraulic washing. In this way, the same problem arises - the impossibility of arranging such flow velocities on the periphery of the extraction chamber (near the outcrop) that would allow transporting the entire amount of reflected mineral. This significant difference is the basis of research and calculations of hydraulic transportation during borehole hydraulic production.

Given that the creation of a general model of well hydrotechnology is practically impossible due to methodological and technological difficulties, the conducted research concerns individual technological operations [35-42].

2. Study of processes of erosion and hydraulic transport

Mineral erosion. The main element of the system – the erosion of the mineral includes the reflection of the rock with a jet from the hydromonitor and the supply of the pulp to the area of action of the suction nozzle or to the output product.

According to the data of geological studies, tuffs lie above the zone of water saturation. In this regard, in our studies, we will consider unflooded hydromonitor streams of medium (1MPa...4MPa) pressure.

The pressurized unflooded water jet, which was created by the hydro monitor in the air environment during surface development of the rock, at the exit from the nozzle with a diameter d_0 of was characterized by the following parameters: consumption Q_0, by effort H_0, speed V_0, the live cross-sectional area ω_0 and impact force P_0 (specific pressure p_0). Formulas of connection between Q_0, H_0 and ω_0 or (d_0) the following:

$$V_0=\varphi\sqrt{(2gH_0)} \quad (1)$$

$$Q_0=\mu\omega_0 \sqrt{(2gH_0)} \quad (2)$$

$$\omega_0=\pi d_0\text{^}2/4 \quad (3)$$

as well φ – speed coefficient; μ – is the cost factor.

As for the impact force of the jet at the exit from the nozzle, its value depends on the initial parameters of the jet, the nature of the obstacle (wall) and the mutual location of the jet and the obstacle (Fig. 1).

When the jet acts on a flat wall located perpendicular to its axis (Fig. 1, a), the impact force is calculated by the formula:

$$P_0=\rho_w\ \omega_0\ V_0^{\ 2} \quad (4)$$

as well ρ_w – water density.

In the researched erosion chambers, the jet acts on a flat wall with a one-way outlet (Fig. 1, b). The impact force of the jet in this case:

$$P_0^{\ I}=P_0\ K' \quad (5)$$

as well K' – coefficient (according to the Institute of Hydrodynamics, it is accepted within 1.3...1.4).

The specific pressure of the stream on the obstacle was determined in all cases by the formula:

$$p_0^{\ i}=P_0^{\ i}/\omega_0 \quad (6)$$

For the destruction of rocks, the pressure of the stream in contact with the rock must be greater than the shear resistance.

For cemented tuffs, shear resistance is expressed by the Coulomb formula:

$$\tau=c+(\sigma-p_h)\cdot tg\varphi_I \quad (7)$$

as well σ – full normal voltage; p_h – neutral voltage, equal to the hydrostatic pressure of water in the pores; c – adhesion coefficient (for loose tuffs, you can take: c = 0); φ_I – angle internal friction.

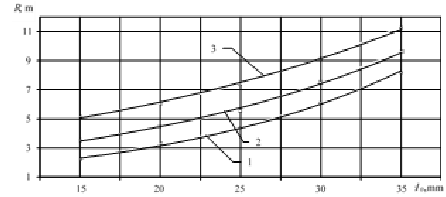

Fig. 2. Experimental dependences of the radius of erosion of zeolite-smectite tuffs by the jet of the hydro monitor on the diameter of the nozzle at different pressures: 1 – H_0 = 1 MPa, 2 – H_0 = 1.6 MPa, 3 – H_0 = 2.2 MPa

Rys. 2. Zależności eksperymentalne promienia erozji tufów zeolitowo-smektytowych strumieniem hydromonitora od średnicy dyszy przy różnych ciśnieniach: 1 – H_0 = 1 MPa, 2 – H_0 = 1.6 MPa, 3 – H_0 = 2.2 MPa

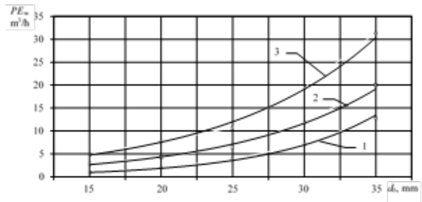

Fig. 3. Dependence of the average erosion performance of tuffs at the distance of the erosion radius on the diameter of the nozzle at different values of water pressure: 1 – H_0 = 1 MPa, 2 – H_0 = 1.6 MPa, 3 – H_0 = 2.2 MPa

Rys. 3. Zależność średniej wydajności erozji tufów w odległości promienia erozji od średnicy dyszy przy różnych wartościach ciśnienia wody: 1 – H_0 = 1 MPa, 2 – H_0 = 1.6 MPa, 3 – H_0 = 2.2 MPa

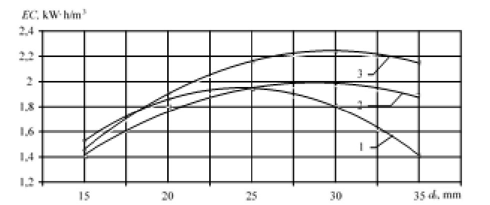

Fig. 4. Dependence of the energy consumption of the washing process on the diameter of the nozzle of the hydro monitor at different pressures: 1 – H_0 = 1 MPa, 2 – H_0 = 1.6 MPa, 3 – H_0 = 2.2 MPa

Rys. 4. Zależność zużycia energii w procesie mycia od średnicy dyszy hydromonitora przy różnych ciśnieniach: 1 – H_0 = 1 MPa, 2 – H_0 = 1.6 MPa, 3 – H_0 = 2.2 Mpa

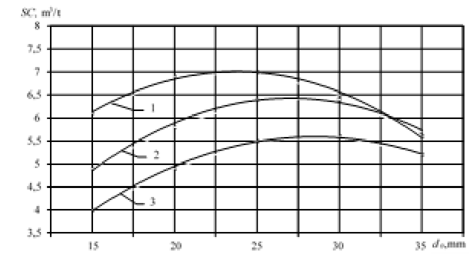

Fig. 5. Dependence of the specific consumption of the working agent under different washing conditions: 1 – H_0 = 1 MPa, 2 – H_0 = 1.6 MPa, 3 – H_0 = 2.2 MPa

Rys. 5. Zależność jednostkowego zużycia czynnika roboczego w różnych warunkach mycia: 1 – H_0 = 1 MPa, 2 – H_0 = 1.6 MPa, 3 – H_0 = 2.2 MPa

A decrease in the shear resistance of zeolite-smectite tuff rocks under vibrational influence occurs due to a change in the stress state, as well as a change in the angle of internal friction or the coefficient of friction. As a result, the structure of the rock is disturbed due to the displacement of individual unstable particles. During the vibrational impact, the process of permanent rarefaction first occurs: during the first pulses, the upper layer changes, which in turn causes the unloading of the lower layers and their transition to a rarefied state during further vibrations. The rarefaction zone is constantly moving, spreading into the depth of the layer. The time spent in a rarefied state is determined by the capacity of the layer, its water permeability, the change in the volume of pores during compaction, the placement of drains and the duration of the action of the dynamic load that destroys the structure.

In order to carry out on-site research in the Rafaliv basalt quarry (Ivanchi village), overlying rocks were removed from the experimental site to expose the mineral. The hydromonitor was installed at the top of the erosion sector. A trench was used at a certain distance from the top of the sector as a compensatory working, imitating the suction zone or the mouth of the exhaust working. The basis of the research methodology is the time required for erosion and removal of the mineral by power hp from the sector with an angle a. The test was carried out in accordance with the current instructions for geological maintenance.

The speed of movement of the shock nozzle of the hydromonitor along the sector of the blowout varied from 0.3 to 2.4 m/s. Erosion of the mineral was carried out layer by layer at a ledge height of 20...35 cm with its jet moving to a limit distance equal to the radius of erosion. Breakout and transport of

Tab. 1. Value of constant approximations
Tab. 1. Wartość przybliżeń stałych

SC
$\begin{cases} a = 3174 \cdot H_0^2 - 11158 \cdot H_0 + 12755 \\ b = 134.8 \cdot H_0^2 - 448.1 \cdot H_0 + 546.1 \\ c = 1.09 \cdot H_0^2 - 3.465 \cdot H_0 + 3.26 \end{cases}$
EC
$\begin{cases} a = -1983 \cdot H_0^2 + 4203 \cdot H_0 + 9209 \\ b = -174.2 \cdot H_0^2 + 525.3 \cdot H_0 + 192.3 \\ c = -2.71 \cdot H_0^2 + 10.5 \cdot H_0 - 8.3 \end{cases}$

the rock essentially represented a single process and were carried out by the sequential action of the jet on the constantly moving outcrop.

The transporting capacity of the jet in the process of erosion when the blowout was moved away from the nozzle of the hydro monitor noticeably deteriorated. This was expressed in the fact that the distance to which the rocks were thrown during one cycle of the impact of the jet on the hole decreased, and much faster for larger fractions. At some distance from the nozzle, the amount of movement of large rock fractions during one cycle of the impact of the hydromonitor jet on the outcrop was practically zero. In the future, the erosion radius will be understood as the maximum value of the distance over which the stream moves the largest rock fractions.

Studies of the process of rock erosion with different diameters of nozzles and for different values of water pressure in the hydromonitor (Fig. 2) showed that the erosion of tuffs by jets of a larger diameter leads to an increase in the radii of erosion, and with the increase in the pressure of the working agent in front of the nozzle, this increase becomes more significant.

In an unflooded depression, the mass of stream water, accumulated in the recess, distended it and, as a result, tensions arose in the massif, which contributed to the appearance of cracks and the detachment of individual pieces of rock.

Average washout performance PEw within the set radii of erosion, and depending on the diameter of the nozzles shown in Fig. 3.

The study of energy consumption for mineral erosion is presented in Fig. 4 and 5.

The dependence of the erosion radius on the pressure of the working agent and the diameter of the nozzle for zeolite-smectite tuffs of the Rafalovsky quarry is approximated by the following equation:

$$R(d_0,H_0)=0.9e^{0.064 \cdot d0} +2.5 \cdot H_0-2.5 \qquad (8)$$

The maximum relative error in the calculation of the rock erosion radius was 9.07%.

Next, the axial dynamic pressure of the jet at the distance of the radius of erosion is checked:

$$P_m=H_0 (l_n/R)^t \qquad (9)$$

as well l_n – the length of the initial section of the stream; t – an indicator that for distances of 5...7 m is recommended to be taken equal to 0.25 m.

The productivity of tuff erosion, depending on the pressure and diameter of the hydro monitor nozzle, is approximated by the following relationship:

$$PE_w (d_0, H_0)=0.07H_0 \cdot e^{148 \cdot d0} +3.3 \cdot H_0-2.8 \qquad (10)$$

The maximum error when calculating the erosion performance was 12.3%.

The specific consumption of the working agent and the energy consumption during the leaching of the mineral:

$$EC, SC=-ad_0^2+bd_0-c \qquad (11)$$

as well a, b, c – constant approximations, the values of which are given in the table 1.

The working time of the mining chamber is set as a fraction of the volume of the mining chamber divided by the productivity of mineral erosion determined by formula (10).

The working time of the extraction chamber must also be compared with the time of the roof collapse. If the working time of the chamber exceeds the time of collapse, then a downward correction of the span is necessary with the provision of measures to strengthen the wholes at depths of less than 50 m, or the division of the reservoir capacity into layers with the subsequent laying of the cleaning space.

The proposed method is universal in its range of use, both from the point of view of mining and geological conditions of objects and deposits and for determining the structural, qualitative and quantitative parameters of systems in which erosion is the main element (for example, in the exploration and development of deposits in which the stability factor plays a secondary role).

When deriving analytical dependencies based on experimental data, which are complex functions of two variables, that is, for families of curves, an approximation dependency of a certain type was constructed for each curve as a function of one variable. Further, graphic and approximation dependencies, which are functions of the second variable, were constructed based on the values of the coefficients in the equations of these curves. Replacing the coefficients of the first approximation dependence with the equations of the second variable gives a function of two variables.

Hydrotransportation of rock. The graphs (Figs. 6, 7, 8, 9) show the dependence of the transport capacity of the stream Qn from the flow of water from the nozzle of the hydromonitor and other parameters of gravity hydraulic transportation. Analyzing the results of the studies presented in these graphs, it was established that with an increase in flow, the transport capacity of the flow increases, and with a constant slope – directly proportionally (Fig. 6). The transport capacity of the stream also increases with increasing slope i the bottom of the extraction chamber (Fig. 7).

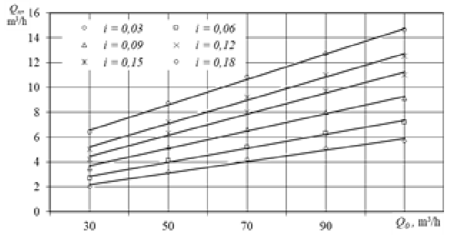

Fig. 6. Dependence of the transport capacity of the stream Q_n from the flow from the nozzle of the hydro monitor at different values of the slope of the bottom of the chamber

Rys. 6. Zależność przepustowości strumienia Q_n od przepływu z dyszy hydromonitora przy różnych wartościach nachylenia dna komory

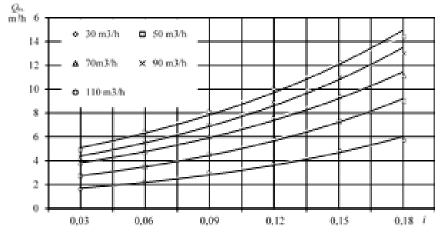

Fig. 7. Dependence of the transport capacity of the flow on the slope of the bottom of the extraction chamber for different values of the water flow rate from the hydro monitor nozzle

Rys. 7. Zależność wydajności transportowej strumienia od nachylenia dna komory ekstrakcyjnej dla różnych wartości natężenia przepływu wody z dyszy hydromonitora

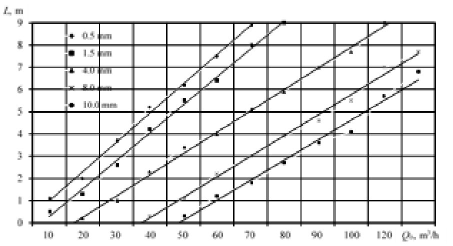

Fig. 8. Dependence of the transportation distance of rock of different hydraulic size k the bottom of the extraction chamber from water flow when: N = 0.016; i = 0.012

Rys. 8. Zależność odległości transportu skały o różnej wielkości hydraulicznej k dna komory wydobywczej od przepływu wody, gdzie: N = 0.016; i = 0.012

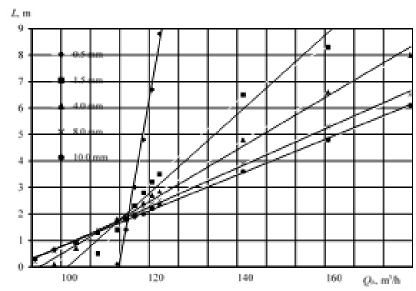

Fig. 9. Dependence of the transportation distance of tuff of different hydraulic size k the bottom of the extraction chamber from water flow when: N = 0.020; i = 0.012

Rys. 9. Zależność odległości transportu tufu o różnej wielkości hydraulicznej k dna komory ekstrakcyjnej od przepływu wody, gdzie: N = 0.020; i = 0.012

Change in roughness coefficient N of the bottom of the extraction chamber significantly affects the process of sedimentation of the mineral (Figs. 8 and 9).

In the experiment, the impact of the falling pulp flow on the transport capacity of the flow was also investigated. The analysis of the research results showed that the initial energy of the falling pulp during washout is significantly greater than the energy of the same flow during the washout of the useful component from the sloping bottom. The pulp falling to the bottom of the extraction chamber intensified the turbulence of the flow in the near-hole space and thereby reduced the probability of particle settling, creating the initial velocity of the falling particle. As a result of the impact, the particles of the reflected tuff became turbid, the density of the pulp increased and, as a result, the pushing force increased, which reduced the forces of adhesion of the particle to the bottom.

When the level of the pulp in the cavity of the chamber was high enough (the phenomenon was observed at small angles of inclination), the energy of the falling particle was extinguished by this layer and the settled particles could not move. In other words, there should be a turbulent movement on the periphery of the extraction chamber and a pulp level that is optimal for particle wear conditions.

Analyzing the research data, it was found that the transport properties of the flow in most cases are described by exponential dependencies or polynomials of the first order, i.e. linear functions, and the study of the transport ability of the flow when the flow rate of the hydro monitor and the slope of the bottom of the extraction chamber change, indicate that this process is approximated by an equation of this type:

$$Q_п\ (i,Q_0)=0.41 \cdot Q_0 \cdot i+0.032 \cdot Q_0+15.7 \cdot i+0.3 \quad (12)$$

The maximum permissible relative error of approximation does not exceed 10%.

The distance over which particles of destroyed tuff are transported, in addition to water consumption and hydraulic grain size, depends significantly on the roughness of the bottom of the chamber and, for certain values, is determined by the dependencies:

at N = 0.016 $L(Q_0,k)=(-0.0064 \cdot k+0.1301) \cdot Q_0-0.2804 \cdot k-0.3347$ (13)

at N = 0.020 $L(Q_0,k)=0.1682 \cdot Q_0 \cdot k^{-0.4188}-17.066 \cdot k^{-0.4982}$ (14)

The maximum approximation error does not exceed 14.3%.

Approximation and statistical processing of experimental data was carried out in Mat Lab and Microsoft Excel software packages. Most of the experimental data were approximated by second-order polynomials.

Polynomial approximation of the measurement data, formed as a certain vector Y at certain values of the argument, which form a vector X of the same length as the vector Y, was carried out using the "polifit" (X, Y, Z) procedure built into Mat Lab, where Z is the order of the approximating polynomial. The result of this procedure is a vector of length (Z+1) of the coefficients of the approximating polynomial [3].

Exponential approximation was carried out in Microsoft Excel using the function of adding a trend line, the result of which is the construction of an approximating curve and the output of its equation on a graph of experimental data.

To check the reliability of the approximation and its quantitative assessment, statistical processing of the data was carried out, namely, the value of the correlation coefficient and root mean square deviation between the experimental data and the data calculated according to the approximation dependences was found.

The correlation coefficient was determined by the formula:

$$r = \frac{\Sigma(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\Sigma(x_i-\bar{x})^2(y_i-\bar{y})}} \quad (15)$$

as well x, u – experimental and calculated data, respectively.

The root mean square deviation was determined by the formula:

$$\delta = \frac{\sqrt{\Sigma(x_i-y_i)^2}}{n-1} \quad (16)$$

as well n – the number of measurement points.

For the quantitative assessment of the reliability of the established mathematical dependencies, the maximum relative error between the experimental results and the calculated values for each measurement point was determined:

$$\gamma_i=(x_i-y_i)/x_i \cdot 100\% \quad (17)$$

To create the same conditions of transportation along the entire length of the section of movement of the reflected mineral in the extraction chamber, it is necessary to maintain a constant flow rate equal to the speed of reliable transportation. In this connection, there is a need to create a rational, scientifically based profile of the bottom of the extraction chamber, which must meet the following requirements:

- to create an optimal (effective under the conditions of turbulence) flow depth in the pothole. If the depth of the pulp in the extraction chamber is large enough (which is observed at small angles of inclination of the bottom), then the energy of the reflected rock particle will be extinguished when it falls and the deposited particles will not be able to be pulled into motion;
- to create the maximum rolling force;
- to have the optimal length of transportation of the reflected mineral.

Therefore, a rational profile should provide:

- the constancy of the flow rate, equal to the speed of reliable transportation;
- the minimum consumption of mineral resources during structural design;
- the impossibility of sedimentation of the mineral to the bottom of the extraction chamber.

The main criterion for the formation of the required profile is the constancy of the speed along the entire length of transportation. To do this, it is necessary to create such an initial speed that is capable of transporting the reflected mineral, and then, with the help of profiling along the length of the transport, maintain a speed that will ensure the effective movement of the destroyed mineral.

3. Conclusion

As a result of the analysis of the material composition, properties and conditions of occurrence of tuffs, it was found that the tuffs of the Rafalivka node are the most suitable for hydraulic mining, namely their zeolite-smectite varieties with a smectite component content of more than 50%. For these varieties of rock, the porosity of the dispersed tuff material reaches about 30%; swelling in water – 36%, and in the presence of coagulant – 62%. Water absorption is about 18% by mass and 33% by volume.

To ensure maximum destruction productivity, it is necessary to use a hydro monitoring head with central and lateral rotating nozzles that rotate around its axis and with the necessary use of a braking device that will allow you to adjust the speed of the jet movement along the hole. When the diameter of the nozzle and the water pressure increase, the erosion radius increases, and the productivity increases, and with the increase in the pressure of the working agent in front of the nozzle, this increase becomes more significant. The analysis of research results showed that at a certain distance from the nozzle, the rate of advancement of the punch remains unchanged (for different diameters of the nozzles). Therefore, when developing the technology for working out chambers in dense rocks, it is necessary to focus on the operating characteristics of the initial section of the stream.

In order to prevent the formation of a notch and increase the efficiency of tuff extraction, at distances of up to 6 m from the nozzle of the hydromonitor, the angle of inclination of the stream to the surface of erosion should not exceed 5...7˚. At the same time, the speed of the jet along the hole is limited to 2.2 m/s, and the height of the hole when washing through nozzles with a diameter of 25...35 mm does not exceed 15 cm.

It was established that when working out the formation in layers from top to bottom with a one-well production scheme, favourable conditions are created for the inflow of the hydraulic mixture to the discharge device. A conical sump is formed around the suction, and the jet acting from above does not prevent the flow of the hydraulic mixture.

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Symulacja procesów hydromechanicznych powstawania i ruchu hydromieszaniny podczas hydroprodukcji

W artykule przedstawiono wyniki badań i modelowania procesów rozwoju złóż tufowych metodami górnictwa geotechnicznego, w szczególności metodą hydrotechniki otworowej. W modelowaniu procesów górnictwa geotechnicznego wykorzystano metody modelowania fizycznego oraz badania przyrodnicze, które pozwoliły odtworzyć i zbadać w warunkach laboratoryjnych i naturalnych zjawiska i mechanizmy fizyczne procesów. Przeprowadzone badania dotyczą poszczególnych operacji technologicznych: erozja i transport minerału w strumieniu, a mianowicie uderzenie skały strumieniem z hydromonitora i dopływ pulpy do obszaru działania dyszy ssącej przy różnych ciśnieniach wody i różnych prędkościach ruchu dyszy uderzeniowej hydromonitora w sektorze odsłonięcia, wpływ natężenia przepływu czynnika roboczego (wody) i nachylenia dna wydobycia kamer na zdolność transportową strumienia.
W wyniku badań ustalono, że w przypadku zwiększenia średnicy dyszy i ciśnienia wody promień erozji wzrasta, a wydajność wzrasta zgodnie z prawem wykładniczym. W pewnej odległości od dyszy szybkość postępu wydmuchu pozostaje niezmienna (dla różnych średnic dysz), dlatego przy opracowywaniu technologii wydobycia komór w gęstych tufach należy skupić się na charakterystyce pracy początkowej sekcji strumienia. Aby zapobiec tworzeniu się karbu i zwiększyć wydajność eksploatacji, w odległości do 6 m od dyszy hydromonitora kąt nachylenia strumienia do powierzchni erozji nie powinien przekraczać 7˚, prędkość strumienia wzdłuż odsłonięcia jest ograniczona do 1,4 m/s, a wysokość odsłonięcia nie powinna przekraczać 15 cm przy przemywaniu przez dyszę o średnicy do 35 mm.

Słowa kluczowe: *tufy zeolitowo-smektytowe, hydromonitor, procesy geotechniczne górnictwa, promień erozji, wydajność transportu przepływu, komora ekstrakcyjna*