https://doi.org/10.31713/m1228

MODELING OF THE HYDROMECHANICAL PROCESSES OF SLURRY FORMATION AND MOVEMENT DURING HYDROMINING OF ZEOLITE-SMECTITE TUFFS

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Annotation

The materials of theoretical and practical researches are aimed at improvement of mathematical models of individual technological operations of the technology of underground development of zeolite-smectite tuff deposits of the Rivne-Volyn region by the hydraulic well method, taking into account the dominant factors of the hydraulic mining process.

The subject of the research is the parameters of hydrodynamic erosion of zeolite-smectite tuffs, the movement of the slurry in the conditions of the mining chamber and the transportation of the mineral. The work uses a comprehensive research method, which includes a system analysis and generalization of the experience of borehole hydromining, physical modeling of hydrodynamic processes, applied and bench research using industrial samples of technological equipment, as well as a mathematical modeling method - to establish dependencies between parameters well hydraulic mining.

During the research and development of hydrodynamic mathematical models, the method of analyzing the processes of pulp flow over a conical surface was used, in which the stationary parameters of the flow process were determined and the influence of various factors on the uneven movement of slurry was investigated. In the proposed mathematical models, the dynamic characteristics of the process are sufficiently fully considered, and the parameters of the roughness of the solid boundary of the flow are also taken into account.

On the basis of the conducted research, recommendations were developed for the use of well hydrotechnology depending on the state of the deposit and the composition of the rock, the method of selecting the parameters of the hydro-fracturing process and self-draining hydraulic transportation of zeolite-smectite tuffs along the bottom of the extraction chamber was investigated and improved. Proposed technological solutions for the installation of round-shaped mining chambers in thick layers of rock.

Introduction

Interest in volcanic tuffs, which is connected with the discovery of deposits of zeolite tuffs, which have valuable sorption, cation exchange and other properties, has been growing significantly in recent years. The ambiguity in the characteristics and diversity of volcanic tuffs (more than 40 varieties have been discovered in the world) is primarily related to the conditions of formation and the age of a particular deposit. Tuffs from different deposits may differ in color, strength, and physical and chemical properties. At the same time, for the same deposit, the difference in the composition of tuffs is manifested depending on the depth or location. To a large extent, this is the reason for the insufficient exploration and lack of reliable analytical and technological data on tuff slurry of some deposits [1, 2]. The estimated resources of such zeolite-containing volcanic tuffs in the Rivne region amount to hundreds of millions of tons, that is, they are practically inexhaustible.

The analysis of tuff deposits explored in the Rivne-Volyn region and their wide economic purpose encourage the rapid development of deposits of these minerals, and the impossibility of an surface method of mining, due to being confined to a nature reserve zone, the presence of highly productive agricultural land and excessive irrigation of the territory, requires the search for alternative mining methods. The increase in the depth of tuff in the northern part of the region, the presence of a reliable solid roof in the form of basalt layers, significant water absorption of the rock and the ability to self-destruct under prolonged exposure to moisture, favorable hydrogeological conditions, are indisputable arguments and grounds for using the underground method of developing zeolite-smectite tuffs in Rivne-Volyn region by the method of well hydrotechnology [3-7].

Smectite tuffs with a content of smectite minerals of more than 50%, which have a swelling crystal lattice and, in most cases, a high surface energy, which causes the active interaction of minerals with water, which can be absorbed or released through interlaminar spaces are suitable for borehole hydraulic production in terms of physical and mechanical properties. At the same time, minerals increase or decrease in volume, and become plastic when wet. The recommended smectite for hydraulic mining is montmorillonite, which can increase in volume by 20 times due to the absorption of water. During dehydration, the volume of the mineral decreases sharply.

As for zeolite tuffs, they are solid inorganic compounds of a frame structure that are strongly cemented, do not undergo hydraulic erosion and are not subject to hydromining.

The main studies of parameters of borehole hydrotechnology for tuff extraction were carried out at the Rafalivsky deposit, which is located in the Volodymyretsky district of the Rivne region and partially in the Manevytskyi district of the Volyn region.

The area of the field is 6,4 km^2, including the area of previous exploration - 1,2 km^2.

Administratively, the research area, which has the thickest layers of zeolite-smectite tuffs, is located within the Volyn and Rivne regions of Ukraine.

Taking into account the significant dependence of the chemical composition of tuffs on the deposit and its significant difference within one deposit, and the lack of detailed research in this direction at this time, it can be predicted that in the process of mining operations, the rational limits of the application of the development method in relation to the varieties of tuffs will be determined. Improved methods of its extraction and formulated general principles of complex processing.

Taking into account that the creation of a general model of well hydraulic production technology is practically impossible due to methodological and technological difficulties, studies were conducted for individual technological operations.

Mineral erosion

The main element of the system – the erosion of the mineral includes the reflection of the rock with a hydromonitor water jet and the supply of the pulp to the area of action of the suction nozzle or to the output product. The movement of liquid in a stream is characterized by the movement of water particles in the absence of solid boundaries of the channel. During the movement of a jet, when several liquids of different densities are mixed, as well as in multiphase, when the substance of the jet and the substance of the medium are in different physical states (gaseous or droplet), and sometimes with an admixture of solid particles in the boundary layer of the jet, phenomena occur are so complex that at the present stage there are no reliable methods of their analytical determination.

Determination of the features of the hydrodynamic erosion process was carried out under natural conditions at the basalt quarry of the village Ivanchi, Rivne Oblast, where overlying rocks were removed from the test site to expose the mineral. According to the data of geological studies, tuffs lie above the water saturation zone, therefore, in the studies, unflooded hydromonitor streams of medium (1MPa-4MPa) pressure were considered. In the calculation of the interaction of the stream with the rock massif, a scheme with a one-way output was used, which most fully corresponds to the technology of formation processing both from top to bottom and from bottom to top.

Erosion of the mineral was carried out layer by layer at a ledge height of 1-35 cm with its movement by the stream to a limit distance equal to the radius of erosion. The speed of movement of the shock nozzle of the hydromonitor in the sector of the blowout varied from 0,3 to 2,4 m/s. Breakout and transport of the rock represent a single process and were carried out by the sequential action of the jet on the constantly moving outcrop.

During the destruction of zeolite-smectite volcanic tuffs under the influence of the pulsating action of the jet, the connection between individual particles of the rock was broken. As a result of filtering part of the water into the pores, their moistening and wetting took place, which led to a cohesive force between the particles. In addition, in an unflooded blowout, the mass of stream water accumulated in the recess opened it up and, as a result, tensions arose in the massif, which contributed to the appearance of cracks and the detachment of individual pieces of rock.

Experimental data on the radius of erosion of zeolite-smectite tuffs by the jet of the hydromonitor are given in the table 1.

The experiment established that erosion of tuffs by jets of a larger diameter leads to an increase in the radius of erosion, and with an increase in the pressure of the working agent, the productivity of erosion increases significantly.

Table 1

Water pressure in the nozzle	No. of the experiment	Nozzle diameter d_0, mm				
		15	20	25	30	35

H_0=1 MPa	1	The value of the erosion radius *R*, m	2,2	3,3	4,25	6,0	8,1
	2		2,25	3,2	4,3	6,1	8,1
	3		2,2	3,4	4,5	6,2	8,3
	Average		2,22	3,30	4,35	6,10	8,17
H_0=1,6 MPa	1		3,5	4,4	5,5	7,4	9,5
	2		3,6	4,55	5,6	7,65	9,7
	3		3,5	4,5	5,6	7,5	9,7
	Average		3,53	4,48	5,57	7,52	9,63
H_0=2,2 MPa	1		5,1	6,0	7,3	9,1	11,5
	2		5,3	6,15	7,45	9,2	11,6
	3		5,1	6,05	7,4	9,15	10,9
	Average		5,17	6,07	7,38	9,15	11,33

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

$$R(d_0, H_0) = 0{,}9e^{0{,}064 \cdot d_0} + 2{,}5 \cdot H_0 - 2{,}5 \quad (1)$$

The maximum relative error of the calculation of the rock erosion radius according to the established dependence was 9,07%.

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

$$\Pi_p(d_0, H_0) = 0{,}07\mathrm{H}_0 \cdot e^{148 \cdot d_0} + 3{,}3 \cdot H_0 - 2{,}8 \quad (2)$$

The maximum error when calculating the erosion performance was 12,3%.

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

Dependence between the parameters

The process of hydraulic transportation of the pulp to the automated borehole hydromonitor or output products is a separate element of the system, therefore the reliability of the operation of each link determines the efficiency of the entire technological complex. Knowing the nature and basic laws of this element will allow you to choose the optimal conditions for transporting the hydraulic mixture.

It should be noted one more important circumstance: the research of hydraulic transportation in related industries was carried out, as a rule, with the constant flow of the working fluid, while the hydraulic transportation of the slurry in these conditions took place with a variable flow of water. In addition, all known studies were carried out during the transportation of material that does not have an initial speed (it lies motionless on the chamfer or on the bottom of the production), which is significantly different from the conditions of erosion and hydraulic transportation at the bottom of the chamber. Here, the mineral has a significant reserve of kinetic energy when it falls to the bottom of the chamber. With a certain flow rate of the working fluid and the slope of the bottom, the initial speed of movement of the hydraulic mixture can have a predominant effect on further transportation along the bottom of the chamber.

It is characteristic that most studies did not set the task of active intervention in the process of formation and preservation of the dynamics and kinematics of the movement of the slurry in order to obtain optimal conditions for self-flowing and forced hydraulic transportation. Solving the hydraulic transportation issues mainly came down to determining the transport capacity of the stream. This approach to the calculation of hydraulic transportation in the conditions of the technology of well hydraulic mining is unacceptable, since the ability of hydraulic transportation comes from the possibility of hydraulic fracturing.

The lack of analogues and the need for effective hydraulic transportation require the identification and establishment of the following dependencies: the influence of water consumption on the transport capacity of the stream; influence of the slope of the bottom of the chamber on the transport capacity of the flow; the effect of the roughness of the bottom of the chamber on the productivity of transportation; detection of the impact of the initial energy of particles on technological losses.

As a basis, for the study of the process of interaction between the destroyed tuff and the flow of liquid, the theoretical dependences established by many researchers and given in the literature [8-12] were used.

When the stream acts on the destroyed rock, particles of minerals are carried out of the zone of its influence and a trench is formed. What is more, the removed particles form a stream not only along the course of the jet, but also from the sides of the trench. The calculation of the process of rock washing in a submerged indentation is reduced to the determination of the geometric dimensions of the stream and the trench and the time of formation of the pit.

When the nozzle is immersed in the rock, erosion occurs against the foundation of the pit, that is, the eroded rock is carried away and stacked behind the upper edge of the pit. As the nozzle deepens, the length of the trench becomes shorter, and when the nozzle is lowered below a certain depth h_{cr} the process of pit formation stops and the lifting and movement of the rock mass begins with the formation of diffusion zone. Further immersion of the nozzle leads to the creation of a stationary volume of rock under the diffusion zone.

In the diffusion zone, the rock moves along a closed trajectory. At first, it, captured by the stream of water, moves horizontally. Then, having lost energy, it turns vertically upwards. The rock raised above the surface of the flow is pushed to the nozzle and is again included in the movement.

Research of the diffusion zone made it possible to establish the dependence between the parameters of the stream (r_0 and u_0) and the type of rock, the characteristics of which are the non-eroding speed and the dimensions of the erosion and diffusion zones. These dependencies have the following form

$$\frac{u_0}{u_{\text{нер}}} = \frac{0{,}0004}{r_0^2}[(a' - h_1) + 4K(h_1 + h_2)]^2 \quad (3)$$

$$\frac{u_0}{u_{\text{нер}}} = \frac{0{,}0064}{r_0^2}K^2(h_1 + h_2)^2\left[15\left(\frac{a'-h_1}{a'+h_2}\right)^2 - 1\right] \quad (4)$$

$$\frac{u_0}{u_{\text{нер}}} = \frac{0{,}008}{r_0^2}K^2(a' + h_1)^2\left[5\left(\frac{h_1+h_2}{a'+h_2}\right)^2 - 1\right] \quad (5)$$

where h_1 - is the height of the suspension zone above the surface; h_2 - depth of the suspension zone; K - is the average consistency of the pulp in the diffusion zone, which is defined as the ratio of the volume of the rock in its normal state to the volume of the pulp; r_0 - nozzle radius; a' - is the distance from the nozzle to the soil surface.

The width of the diffusion zone b is expressed in terms of h_1 and h_2 and is determined by the dependence b=1,3(h_1+h_2)–7.

Gravity hydraulic transport is possible only in the presence of a certain slope, and the pressure flow of liquid creates a hydraulic pressure gradient, as a result of which the rock mass moves with water.

At rest, stratification of the slurry occurs, and the rate of sedimentation mainly depends on the size and shape of the particles, their mineral composition. The presence of clay particles, as well as additives of surface-active substances, increase the stability of the slurry.

Depending on the hydraulic size of the transported particles, the critical speed of the hydraulic mixture is determined. When $u_s>u_m$ a jump-like movement of particles is observed, when $u_s>2u_m$ the movement of the solid occurs in a suspended state, when $u_s>(3\text{-}5)u_m$ solid deposition in the flow is not observed. The process of movement of a hydraulic mixture with pieces of rock is very complex, and its consideration begins with a simple case - the movement of individual pieces in an open turbulent flow of liquid. At the same time, it is important to determine the conditions of friction of the pieces against the solid boundaries of the flow, the speed of contact of different samples, and the relative speed of their movement in the fluid flow.

By the value of the contact speed, the conditions of the hydromechanical action of the flow on the tuff pieces at the time of the start of translational movement are judged. The relative speed of movement of solid samples in the liquid flow is the most important kinematic characteristic of the movement of the slurry, thanks to which the conditions of interaction of the liquid and solid bodies are determined. During gravitational transport of tuffs, the speed of contact and the relative speed of movement of pieces in the fluid flow largely depend on the value of the friction coefficient.

For a finely dispersed slurry at a flow rate $u_s>u_0$, the separation of small particles from the lower wall of the flow is observed; with $u_s>2u_0$ for a coarsely dispersed slurry, intermittent weighing of particles during transportation is practically completely ensured. At low flow saturations, it is enough to transport a hydraulic mixture with large pieces of rock so that the flow speed exceeds the speed of touching the pieces by 25-40%.

The productivity of transportation for all possible schemes is determined by the water consumption through the nozzle of the hydromonitor and the specific water consumption for washing 1 m^3 (or 1 ton) of rock.

The specific consumption of water for flushing is determined experimentally for each rock and depends significantly on the state of the pit.

Through the parameters of the hydromonitor, the performance is expressed by formula 2.

During borehole hydraulic mining of zeolite-smectite tuffs, pulp formation is carried out by a rotating hydraulic monitor. The hydromonitor erodes the formation by rotating with a certain angular velocity around the vertical axis of symmetry of the extraction chamber. Thus, the dimensions of the extraction chamber and the characteristics of the pulp flow process in it are determined by the performance and rotation frequency of the hydromonitor.

Alternatives to the choice of borehole hydrotechnology

At the preliminary stage, the choice is made within the framework of an increased technical and economic analysis. One or another method of hydraulic mining can be established based on the analysis of the indicators of the base deposit. At the same time, the choice is greatly influenced by the hydrogeological conditions of the deposit and the value of the mineral.

With regard to the development of powerful fields, when the time for working out the chamber is much higher than the limit value, an alternative is the system with the attachment of the cleaning space.

Mixing of rocks due to the structural design of the bottom of the extraction chambers occurs in systems in which hydraulic transport, as their element, within the chamber occurs by gravity. At the same time, the capacity of the system is determined by one unit of borehole hydraulic mining. Solving the problems of the completeness and quality of extraction makes sense only in the case when the underlying rocks are subject to hydromonitoring destruction, with the exception of systems with storage, the design of the bottom in which is carried out with the help of drilling and blasting.

The conducted studies are limited to the maximum exposure span of the roof of the extraction chambers L_{np}, in which during the period of time the chamber is fully worked out, there is no mixing of the superimposed rocks on one side, and natural phenomena associated, for example, with the removal of silt, as a result of which the chamber is blocked - on another side. System parameter M characterizes the depth of development of the underlying rocks at the value of the erosion radius R_{ni} and the limit span of the exposure of the roof of the extraction chamber L_{npi}.

The surface of reliable hydraulic transportation is characterized by the radius of curvature L_{ki}, the value of which is for discrete intervals $L_{npi}...L_{np2}$; $L_{np2}...L_{np1}$; $L_{np1}...0$ is permanent. With an increase in the parameters of the depth development of deposits the values of L_{np} and M are decreasing.

In general, the volume of mixed underlying rocks is determined by the formula

$$V_p = \pi \int_0^M [f(i)]^2 \, di \qquad (6)$$

where i - is the current parameter of the transportation surface.

For engineering calculation methods, a simplified formula for determining V_p is recommended

$$V_p = \frac{\pi \cdot L_{\text{пpi}}^2 \cdot M_i}{12} \qquad (7)$$

The structural unit of the deposits site, by which it is possible to estimate the coefficients of quantity, quality and extraction from the subsoil (K_{kil}, $K_{я}$ and $K_{н}$), is a rectangle ABCD (Fig. 1), which includes two worked out extraction chambers in the first and second stages, and the lost volume of mineral that remained between the contours of the chambers (shaded in the figure).

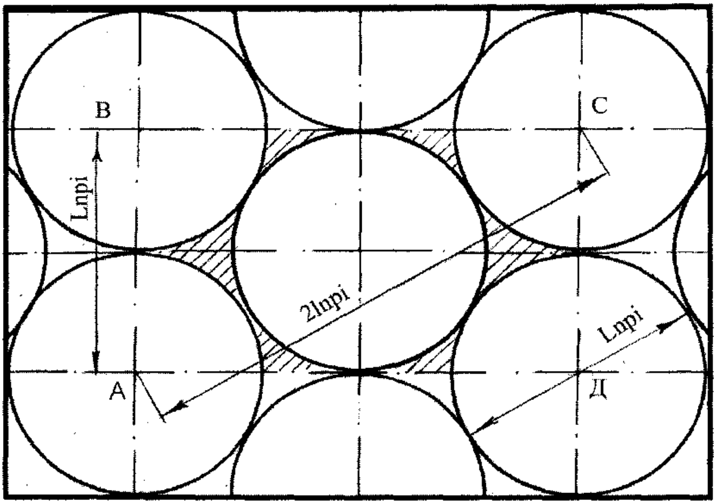

Fig. 1. The scheme for calculating the coefficients K_{kil}, $K_{я}$, $K_{н}$ of circular chambers

The coefficient of the amount of extraction for systems in which the bottom of the chamber is structurally made in the underlying rocks expresses the ratio of the mined mineral together with the rock mixed with it to the amount of balance reserves paid off during extraction.

The amount of mined mineral together with mixed underlying rocks (8) can be set as the sum of the volumes of the chamber made in the mineral with capacity m_i diameter L_{npi}, as well as mixed underlying rocks

$$V_k = \frac{\pi \cdot L_{\text{пpi}}^2}{4} m_1 \tag{8}$$

The amount of balance reserves paid off during mining is defined as the sum of the volumes: the chamber made in the mineral (V_k), that falls on the extracting chamber, for the case of inter-chamber mineral that are not subject to mining according to economic criteria.

The coefficient of change in quality is defined as the ratio of the content of useful components in the mined mineral and in the balance reserves paid off.

The coefficient of extraction from the subsoil expresses the ratio of the amount of mineral extracted from the subsoil to the amount of mineral that is in the calculated balance reserves and can be found according to the relationship: $K_{\text{н}} = K_{\text{kil}} \cdot K_{\text{я}}$.

For systems in which the bottom of the chamber is structurally made of minerals (Figs. 2 and 3), the schemes for calculating indicators of completeness and quality of production are presented on the example of systems with an open cleaning space.

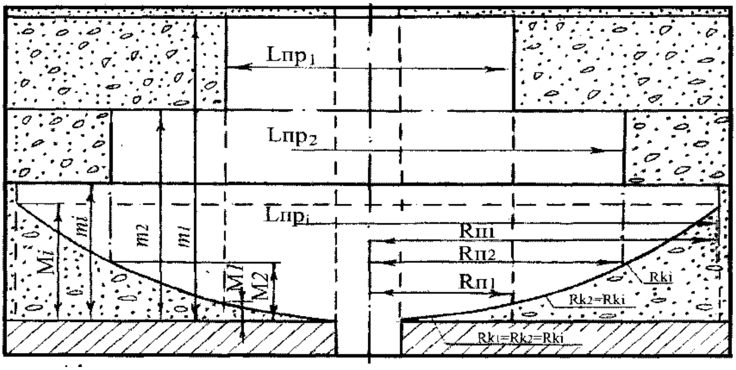

Fig. 2. The scheme for calculating the coefficients K_{kil}, $K_{\text{я}}$ and $K_{\text{н}}$ of circular chambers, the bottom of which is structurally made in the mineral itself, for development depths $H \leq 50$ m

Camera parameter M_i, which can be characterized as the depth of the graduation notch, is regulated by the factors discussed above.

Thus, in order to create reliable hydraulic transportation, it is necessary to leave some volume of mineral on the surface of the underlying rocks, limited from below by the surface of the underlying rocks and the side surface of the cylinder with a diameter set by the radius of erosion R_{ni} , or the limit span of exposure of the roof of the extraction chambers $L_{\text{пpi}}$. The volume of mineral lost in the extraction chamber

$$V_n = \pi \left(\frac{\mathbf{L}_{\text{пpi}}^2 \cdot \mathbf{M}_i}{4} - \int_0^{Mi} [f(i)]^2 \, di \right) \tag{9}$$

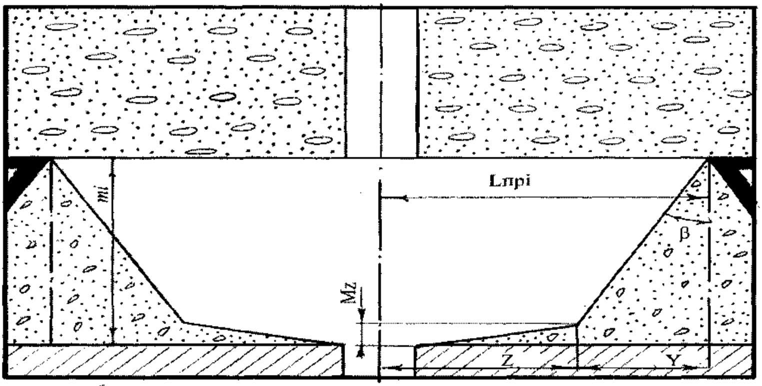

Fig. 3. The scheme for calculating the coefficients K_{kil}, $K_я$ and $K_н$ of circular chambers, the bottom of which is structurally made in mineral, for development depths H>50 m

For engineering calculation methods, it is recommended to use simplified analytical dependencies to determine the volumes of mineral extracted from the extraction chamber:

- deposit development depth up to 50 m

$$V_п = \mathbf{L}^2_{\text{прi}}(\mathbf{0,8}m - \mathbf{0,26M}_i) \tag{10}$$

- development depth over 50 m

$$V_п = 1{,}6\mathrm{L}_{\text{прi}} m(0{,}5\mathrm{L}_{\text{прi}} - m\tan\beta) - 0{,}54\mathrm{M}_z(\mathrm{L}_{\text{прi}} - 2m\tan\beta)^2. \tag{11}$$

Dependencies, which can be used to determine K_{kil}, $K_я$ and $K_н$ provided that the bottom of the mining chamber is structurally made in a mineral, are as follows:

- deposit development depth up to 50 m

$$K_{\mathbf{kil}} = \frac{\mathbf{L}^2_{\text{пр}}(\mathbf{0,8}m + \mathbf{0,54M}_i)}{\mathbf{0,8L}^2_{\text{пр}}m + m\left[\mathbf{0,87}(\mathbf{L}_{\text{пр}} + x)^2 + \mathbf{0,78L}^2_{\text{пр}}\right]},\ K_н = K_{kil}; \tag{12}$$

- development depth over 50 m

$$K_{kil} = 1 \cdot \frac{6m(0{,}5L_{np} - m\tan\beta)}{1} \cdot 6m(0{,}5L_{np} + x) - \frac{0{,}54M_i(L_{np} - 2m\tan\beta)^2}{1} \cdot 6m(0{,}5L_{np} + x),\quad K_н = K_{kil} \tag{13}$$

Coefficient $K_я$ we take equal to 1 for both cases.

Calculation of extraction chambers

After extracting the mineral, the massif, which was subjected to artificial irrigation, becomes unstable. It follows from this that a correctly constructed scheme for calculating the mechanical behavior of the roof of the extraction chamber must take into account both the time factor and the change in the conditions of the laying of underground structures - ceilings and the target. The first condition is ensured by linear extrapolation in time of modeling results on equivalent materials. Satisfiability of the second condition is achieved by adjusting the modeling results with theoretical calculations that allow taking into account the quantitative and qualitative change in the laying conditions. The calculation is based on the condition of equilibrium of external and internal forces in the roof of the extraction chamber in a steady state. The mechanical behavior of the massif under technological influence can be formally modeled by the state of the ceiling and wholes, as the main bearing elements.

The common goal inherent in mining equipment is to bring the mineral to a mobile state at the place of occurrence with the help of a working agent fed into the chamber, limited by the scope of the problems to be solved regarding the processes of clean extraction.

The existing designs of borehole hydraulic monitors allow to arrange the circuit of the chamber only with a circular cross section. Mining hydraulic monitors and units of borehole hydraulic mining allow mining of minerals by sectors.

For example, if the chamber is formed by one well hydraulic mining unit, then its cross-section will have the shape of a circle (Fig. 4).

The use of borehole hydraulic production systems for testing and development of a rock layer is theoretically possible up to the depths at which the amount of rock pressure becomes equal to the compressive strength of the rock massif

$$H \leq H_{гр} = \frac{\sigma_{ст} \cdot K_{ф}}{\gamma} \quad (14)$$

where $H_{гр}$ - is the limit depth of system application; $\sigma_{ст}$ - compressive strength limit of rocks; γ - rock density; $K_{ф}$ - coefficient of mineral shape: for ribbon $K_{ф}$ =1, for star-shaped $K_{ф}$=0,7.

With the average values of the compressive strength limit of rocks $\sigma_{ст}$=22,5·10^{5}Pa and density 2,08·10^4 t/m^3, the critical depth of application of borehole hydraulic production systems with left ribbon mineral will be 108 m, systems with star-shaped mineral - 76 m.

As a result of the mathematical analysis, the relationships between the limit span of the roof and the depth of development were established

$$L_{пр}=471\cdot H^{-0,76}. \qquad (15)$$

The calculated values of stability of the span of the roof of the extraction chambers for the limit case are in good agreement with the modeling results.

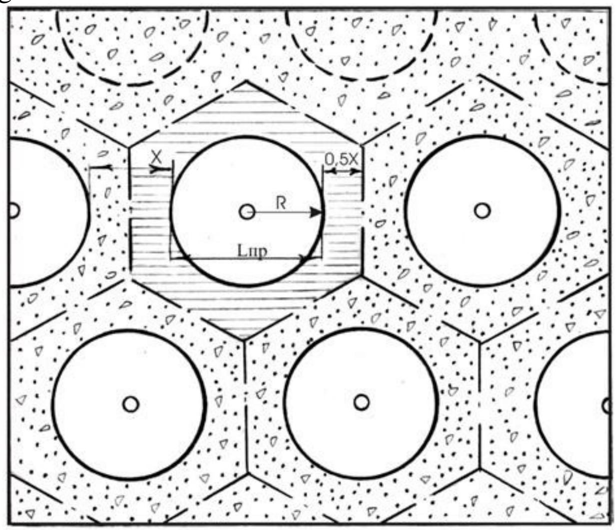

Fig. 4. Scheme for calculating parameters of extraction chambers of round shape and inter-chamber mineral without further loading of extraction space

In figure 5 shows the three-stage sequence of working out the mineral in the chamber for stable overlying rocks from the bottom to the top within the capacity of the formation.

According to its technological essence, the primary purpose of the mineral is to perceive the load from the overlying rocks. So, in a mechanical sense, the mineral material works on compression, that is, in the most favorable mode from the point of view of stability. However, the existence of free surfaces during uniaxial compression creates prerequisites for the occurrence of shaking tension along the sliding planes, which will be accepted as a criterion for the destruction of the mineral material. This concept is the basis of the theory of marginal equilibrium. The theory makes it possible to uniquely solve the system of equilibrium equations of the environment by including the limit state condition.

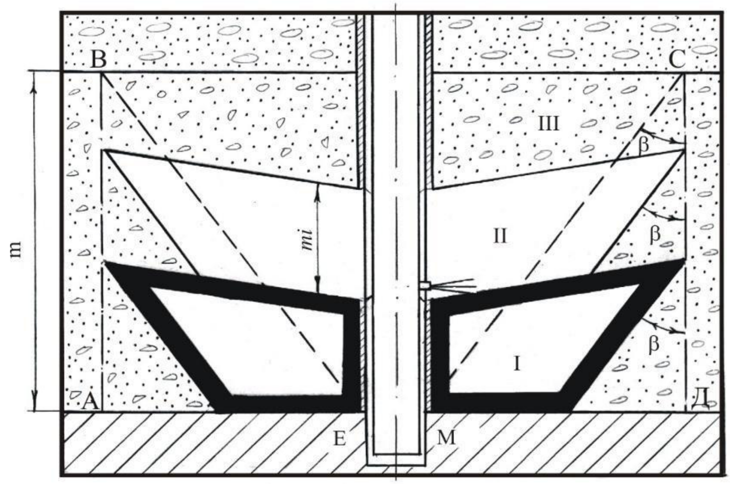

Fig. 5. The proposed technology of extracting a mineral of high capacity layer by layer from bottom to top: I, II, III – stages of extraction, respectively

In the preliminary approximation, we will consider the walls of the mineral to be vertical, along which there is no load, and the bursting pressure is created exclusively due to the cohesive forces of the rocks of the massif.

The maximum possible depth of formation of wholes with vertical walls with a height of $X_{ц}$ from the expression for active expansion

$$H_{пр} = \frac{\theta}{\lambda}\left(\frac{1+sin\varphi}{1-sin\varphi}\right) - X_{ц} \tag{16}$$

The change in the mechanical properties of the array over time is carried out through the environment parameter $\theta = C/tg\varphi$, in the formation of which φ and C participate.

On this basis, the dependence represented by the parameter θ on time t is recommended for use

$$\theta_t = 110{,}5 - 19t. \tag{17}$$

From formula (15), it is possible to estimate the degree of participation in the formation of the stability of the array of factors such as time and depth of testing (development). At the same time, a reserve of stability of 1 hour is equivalent to a decrease in depth by 19 m. Practically, this means that the previously performed calculations for stable parameters correspond to the initial moment of the camera's existence.

Taking into account the dependence of the θ indicator of the rocks on the angle of inclination of the walls of the target and to ensure stability for the required time at a certain depth (in the absence of other measures to strengthen the targets or improve their conditions), it is recommended to form the angle of the target's slope with the value

$$\beta = \frac{90\varphi \cdot}{\pi} \cdot \ln\ln\left[\frac{\gamma \cdot H}{\theta_т}\left(\frac{1 - sin\varphi}{1 + sin\varphi}\right)\right]. \quad (18)$$

At depths of more than 50 m, the volumes of the strengthening prism may be significant, which will call into question the feasibility of using well hydraulic production systems.

The shape of the extraction chambers of the same system, which are formed at different depths, can be represented by the figure of ABCD at $H \leq 50$ m and the figure of BCME at $H > 50$ m (Fig. 5).

The size of AE strengthens the prism and at β=60˚ and m=10 m will be 20 m, that is, it will exceed the limit span of the roof $L_{пр}$, which will not allow it to construct the chamber of the required dimensions.

In this regard, it is proposed to extract the mineral within the contours of the chamber in several stages with the division of the capacity of the bed of rock m into a certain number of segments with a rational height.

At the first stage, a part of the mineral with a capacity of m_i in the formation of which with the formation of a strengthening prism at an angle β. After the mineral is mined, the produced space is laid with a hardening material. The second and third stages repeat the operations of the first, with the exception of bookmarking at the third stage, which may not be performed.

Thus, working out extraction chambers with the proposed technology allows to significantly increase production from one well and reduce losses of minerals.

Mathematical model of the process of movement of slurry

Considering the fact that volcanic tuffs in the Rivne-Volyn region lie in layers with a thickness of several meters to 100 or more meters, in the process of erosion, depending on the area of work, mining chambers with the arrangement of the bottom can be used both in the mineral itself and in underlying rocks. The bottom of the extraction chamber is a conical surface, in the center of which there is a receiving box with a hydraulic elevator.

The diameter and angle of inclination of the bottom of the extraction chamber are determined by the technological parameters of the well hydraulic production and changes during the process. The roughness of the bottom depends on the type of rock and the nature of its destruction.

A small number of works [13-15] are dedicated to the development of hydrodynamic models of pulp flow over a conical surface, in which, mainly, stationary parameters of the flow process are determined and the influence of various factors on the non-uniform movement of the fluid mixture is investigated. However, these works do not sufficiently consider the dynamic characteristics of the process, and also do not take into account the parameters of the roughness of the solid boundary of the flow.

To confirm the reliability of experimental and natural studies, theoretical studies of the process of erosion and movement of the pulp from the bottom of the extraction chamber to the suction nozzle of the hydraulic elevator were conducted. The theoretical dependences developed by professors Z.R. Malanchuk, O.G. Gomon, and E.I. Chernya are taken as a basis [16-19].

To analyze the process of pulp flow through the bottom of the extraction chamber, we will use the model of the movement of a homogeneous liquid in a thin layer, assuming that the velocity is the same throughout the thickness of the layer, and the presence of friction between the liquid and the bottom is taken into account using empirical formulas. Such a model is relatively easy to analyze and, under certain assumptions, allows an analytical solution [20].

To describe the process of the movement of the pulp layer along the conical surface, we will choose a spherical coordinate system. Align the $0z$ axis of the spherical coordinate system with the $0z\theta\psi$ axis of symmetry of the conical surface and direct it vertically upwards (Fig. 6).

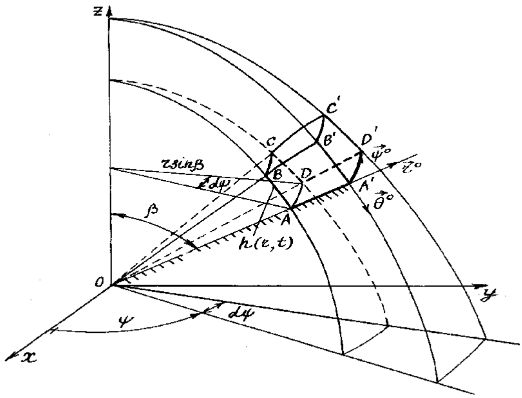

Fig. 6. Coordinate system and fluid flow element

Denote the angle of the half cut of the bottom of the extraction chamber by β. We will assume that the liquid flows over the surface in a thin layer, for the thickness of which, measured along the internal normal to the conical surface, the condition $h/r<<1$ is fulfilled. In this case, the thickness of the layer, measured along the normal to the conical surface, and the thickness, measured along the coordinate line θ along the arc *AB* will differ slightly. Therefore, the linear size measured from the surface of the cone $\theta=\beta$ along the arc of the meridian AB can be considered as the thickness of the layer $h(r, \psi, t)$.

As an elementary volume to which we will apply the laws of conservation, we will choose an element *ABCDA'B'C'D'*, bounded by spherical surfaces of radii r and $r+dr$, surfaces $\psi=const$ and $\psi+d\psi$=const, as well as the section of the conical surface $\theta=\beta ADD'A'$ and the area of the free surface *BCC'B'*.

At the same time, the area of faces *ABCD* of the element will be equal to: $rsin\beta d\psi \boldsymbol{h}$, and faces *ABB'A'* − $dr{\cdot}h$. The volume of the element in this case will be: $r \cdot sin\beta \cdot h \cdot dr \cdot d\psi$.

Accordingly, the flow through faces normal to $\vec{r}^{\,0}$, equal to

$$-\frac{d}{dr}(\rho \cdot V_r \cdot r \cdot \boldsymbol{h})sin\psi \; d\psi dr \tag{19}$$

and through faces normal to $\vec{\psi}^{\,0}$

$$-\frac{d}{d\psi}(\rho V_\psi \boldsymbol{h})drd\psi \tag{20}$$

where V_r - radial component of velocity; V_ψ - circular component of speed; ρ - is the density of the liquid.

Since in this task there is no inflow of matter through a free surface, then, according to studies [21], the vertical component of the velocity V_θ in the layer can be neglected. In this case, the accumulation of matter in the element with the above volume per unit of time will be equal to

$$\rho r sin\beta \frac{d\boldsymbol{h}}{dt} drd\psi \tag{21}$$

The law of conservation of mass leads to an equation

$$r \cdot sin\beta \cdot \frac{d\boldsymbol{h}}{dt} + sin\beta \cdot \frac{d}{dr}(V_r \cdot r \cdot \boldsymbol{h}) + \frac{d}{d\psi}(V_\psi \cdot \boldsymbol{h}) = 0 \tag{22}$$

In the case of axisymmetric flow ($V_\psi \equiv 0$), we have the equation

$$r\frac{d\boldsymbol{h}}{dt} + \frac{d}{dr}(V_r r\boldsymbol{h}) = 0 \tag{23}$$

Instead of the variable r, we will enter the variable x calculated from the initial section of the layer: $u=-V_r$; $x=l-r$. At the same time, instead of equations (22) and (23), we will have

$$\frac{d\boldsymbol{h}}{dt} + \frac{1}{l-x}\frac{d}{dx}[u\boldsymbol{h}(l-x)] + \frac{V_\psi \boldsymbol{h}}{(l-x)\sin\beta} = 0 \tag{24}$$

$$\frac{d\boldsymbol{h}}{dt} + \frac{1}{l-x}\frac{d}{dx}[u\boldsymbol{h}(l-x)] = 0 \tag{25}$$

where l - is the total length forming the bottom of the extraction chamber.

Since the layer is thin, when considering the momentum equation, the acceleration of particles along the normal to the bottom of the flow and the change in the mass force along the thickness of the layer can be neglected [21]. In this case, the equation of motion in the projection on the axis $\vec{\theta}^0$ will take the form

$$\frac{dp}{d\theta} = \rho g r \sin\beta \tag{26}$$

After integrating this equation by θ within the layer and taking into account that above the free surface $y=h$ the pressure is constant and equal to the atmospheric pressure $p=p_a=const$, finally the law of pressure distribution in the layer can be written in the form

$$p = p_a + \rho g \sin\beta\,(h - y) \tag{27}$$

where - is a linear coordinate in the layer counted from the base along an arc of radius *r*.

Denoting through τ_0 the value of the tangential pressure at the bottom of the layer, for the equation of impulses in the projection on the direction $\vec{r}^{\,0}{}_0$ for axisymmetric flow, we get

$$\frac{d}{dt}(\rho h V_r) + \frac{1}{r}\frac{d}{dr}(\rho V_r^2 h r) = -\rho g \sin\beta\, h \frac{dh}{dr} - \tau_0 - \rho g \cos\beta\, h \tag{28}$$

Combining this equation with the continuity equation (23) and moving to the variables *x* and *u*, we obtain the momentum equation in the form

$$\frac{du}{dt} + u\frac{dn}{dx} + g\sin\beta\frac{dh}{dx} = -\frac{\tau_0}{\rho h} + g\cos\beta \tag{29}$$

which, together with (25), forms a system of equations for the unsteady flow of the pulp layer over the conical surface.

Taking into account the peculiarities of the bottom of the extraction chamber, which can consist of rocks of different roughness, to determine the frictional pressure τ_0 at the bottom of the extraction chamber, we apply the well-known Chézy formula

$$\tau_0 = g\frac{\rho u^2}{C^2} \tag{30}$$

where *C* is the Chézy coefficient, the value of which is determined depending on the material and the relative roughness of the bottom of the extraction chamber.

Model of stationary pulp flow

For the stationary flow of destroyed tuff along the bottom of the extraction chamber, the theoretical model presented in the work of the authors O.H. Gomon and Z. R. Malanchuk is most suitable. [22, 23].

If the flow parameters at the beginning forming the bottom of the extraction chamber are stationary, then a stationary flow is realized on the conical surface, which, due to (25) and (29), satisfies the system of equations

$$\frac{d}{dx}[uh(l - x)] = 0$$

$$u\frac{du}{dx}+g\sin\beta\frac{dh}{dx}=-\frac{\tau_0}{\rho h}+g\cos\beta \tag{31}$$

$$uh(l-x)=q$$

where the value q is determined by the parameters of the mineral erosion process by the hydromonitor.

The system of equations (31) can be solved by obtaining the following equations for u and for h :

$$\frac{du}{dx}=\frac{[[g\cos\beta-\frac{gn^2}{q^m}u^{2+m}(l-x)^m-\frac{qg\sin\beta}{u(l-x)^2}\Big]u^2(l-x)}{u^3(l-x)-qg\sin\beta} \tag{32}$$

$$\frac{dh}{dx}=\frac{q\cos\beta h^3(l-x)^2-\frac{gn^2}{h^{m-1}}q^2-\frac{q^2h}{l-x}}{g\sin\beta\, h^3(l-x)^2-q^2} \tag{33}$$

Differential equations (32) and (33) are equivalent, and any of them together with (34) determines the distribution of flow velocities and heights along the forming bottom of the extraction chamber. Any of these equations can be solved by numerical methods if the initial data u_0 and h_0 at x=0 are given. We also note that the integral curves of equations of the type (32) and (33) have been sufficiently fully investigated in hydraulics.

Converting the denominator of the last equation to zero means that the flow reaches a critical depth at a given location, at which the velocity reaches a critical value

$$h_{kp}=\left[\frac{q^2\sin\beta}{g(R-x\sin\beta)^2}\right]^{\frac{1}{3}} \tag{34}$$

$$u_{kp}=\left[\frac{qg\sin^2\beta}{R-x\sin\beta}\right]^{\frac{1}{3}} \tag{35}$$

Value h_{H} , in which x^{y}=0 we will call it the local normal depth. The value of h_{H} satisfies the equation:

$$h_{H}^{2+m}-\frac{q^2\sin^3\beta}{g\cos\beta\,(R-x\sin\beta)^3}h_{H}^{m}-\frac{n^2q^2\sin^2\beta}{\cos\beta\,(R-x\sin\beta)^2}=0 \tag{36}$$

The peculiarity of equation (36) is that it can be solved without determining the speed from the solution of equations (32) and (33).

Nonlinear model of unsteady pulp flow

The system of equations (25) and (29), taking into account (30), describes the unsteady movement of the pulp along the bottom of the extraction chamber:

$$\frac{du}{dt} + u\frac{du}{dx} + g\sin\beta\frac{dh}{dx} = -\frac{gn^2u^2}{h^m} + g\cos\beta \quad (37)$$

$$\frac{dh}{dt} + h\frac{du}{dx} + u\frac{dh}{dx} - \frac{uh\sin\beta}{R - x\sin\beta} = 0 \quad (38)$$

The solution of system (37), (38) can be obtained numerically using the method of characteristics, if at some point in time $t=t_0$ the parameters forming the bottom of the extraction chamber are known $u^0(x)$ and $h^0(x)$, for example, from the solution of the stationary problem equations. At the same time, for a "calm" flow in the inlet and outlet sections, one of the functions $u(t)$ or $h(t)$, should be specified, and for a "turbulent" flow, both functions in the inlet section should be specified. Boundary conditions $u(t)$ and $h(t)$ can be arbitrary functions of time.

When applying the method of characteristics, it is necessary for system (37), (38) to find wave fronts and compatibility conditions on the surface of surface (x, t). At the same time, the characteristic directions x' on the plane (x, t) are determined from the condition that the determinant of the system is equal to zero

$$(u - x')\frac{du}{dx} + g\sin\beta\frac{dh}{dx} = A_1 \qquad h\frac{du}{dx} + (u - x')\frac{dh}{dx} = A_2 \quad (39)$$

where $A_1 = g\cos\beta - \frac{gn^2u^2}{h^m} - \frac{du}{dt}$; $A_2 = \frac{uh\sin\beta}{R - x\sin\beta} - \frac{dh}{dt}$.

From here we get $(u - x')^2 = gh\sin\beta$, that is, there are two characteristic directions $x_1' = u + \sqrt{gh\sin\beta}$, $x_2' = u - \sqrt{gh\sin\beta}$, or, in other words, two wave fronts moving at speeds

$$\frac{dx_1}{dt} = u + c_0 \; i \; \frac{dx_2}{dt} = u - c_0 \quad (40)$$

where $c_0 = \sqrt{gh\sin\beta}$ - own velocity of wave propagation.

The first wave front propagates downstream with velocity $u+c_0$, which is ahead of the current. The second wave front propagates downstream or upstream, depending on whether $u>c_0$ or $u<c_0$. If $u>c_0$ then the second front, just like the first, spreads downward and such a current is "turbulent". If $u<c_0$, then the second front spreads

upstream towards the first, and such a flow is called "tranquil". In a calm flow along the first front, disturbances are transmitted from the inlet section to the outlet section, and along the second front - vice versa. In a turbulent flow, disturbances are localized between the fronts and spread from the inlet section to the outlet section.

The trajectories of wave fronts in the plane (*x, t*) with velocities dx_1/dt and dx_2/dt will be called the first and second families of characteristics, respectively.

The characteristic ratios are based on the equality of the zero determinant

$$\begin{vmatrix} A_1 & g\sin\beta \\ A_2 & u-\dot{x} \end{vmatrix} = 0 \quad (41)$$

For the first family, this ratio has the form

$$g\sin\beta\frac{dh}{dt} + c_0\frac{du}{dt} = B_1 \quad (42)$$

and for the second family - the form

$$g\sin\beta\frac{dh}{dt} - c_0\frac{du}{dt} = B_2 \quad (43)$$

where $B_{1,2} = \dfrac{\sin^2\beta \; uh}{R - x\sin\beta} \pm c_0\left(\dfrac{gn^2u^2}{h^m} - g\cos\beta\right)$.

The numerical procedure of the method of characteristics is constructed by replacing the differential relations (40), (42) and (43) with finite difference relations and solving the resulting algebra equations step by step. Thus, the method of characteristics makes it possible to build a nonlinear solution of a non-stationary problem with any necessary accuracy and, in particular, to find the dependence of the output parameters on the input parameters.

Dynamic model of pulp flow

To describe the process of pulp flow over a conical surface, flow models in the form of two liquid layers with different densities are known [24]. Similar models, based on averaging over a live section of hydrodynamic parameters, with one or another modification, are widely used in the hydraulics of open channels. However, during borehole hydraulic extraction of tuffs, the flow of pulp along the bottom of the extraction chamber must be described by a model of single-layer flow of a liquid of variable density, which changes as a result of particles of solid material falling to the bottom. At the same time, we believe that the deposited material does not form a mobile layer, as it accumulates in the pores, cracks and roughness of the bottom of the extraction chamber and refers to rock losses.

According to this model, the layer is a mobile pulp, from which, during its movement along the channel, solid rock particles continuously settle to the bottom of the stream. The concentration of rock particles in the upper layer changes continuously, so that its density is considered as a function of the longitudinal coordinate and time. Let us also assume that in the pulp layer, solid particles are transported along the forming channel without sliding.

The equation of laws of conservation of mass and momentum shall be written in a spherical system of coordinates, assuming that the layer of pulp is sufficiently thin. The equation of the law of conservation of mass will be written separately for the carrier liquid and for solid particles. The normal rate of solids deposition to the bottom surface is w.

If we consider only axisymmetric flows along the conical surface (V_ψ=0), then the equations of conservation of liquid and solid phases in the pulp layer will have the form

$$\frac{d}{dt}[(1-\varphi)\boldsymbol{h}]+\frac{1}{r}\frac{d}{dr}[(1-\varphi)\boldsymbol{h}rv]=0 \quad (44)$$

$$\frac{d}{dt}(\varphi\boldsymbol{h})+\frac{1}{r}\frac{d}{dr}[\varphi r\boldsymbol{h}v]=-\varphi\mathbf{w} \quad (45)$$

$$\rho=\rho_l(1+Ar\varphi),\ \rho_l=\rho_0(1+Ar_l\sigma) \quad (46)$$

$$Ar=\frac{\rho_s-\rho_l}{\rho_l},\ Ar_l=\frac{\rho_s-\rho_0}{\rho_0} \quad (47)$$

where h - is the layer thickness; v - layer velocity averaged over the live section; ρ - current pulp density; φ - volume fraction of the rock in the pulp; ρ_s - density of rock particles; ρ_l - is the density of the carrier mixture; σ - volume fraction of the rock in the carrier mixture; ρ_o - is the density of water.

Combining equations (44) and (45) and replacing parameters $r=l-x$ and $u=-v$, let's write the previous system in the form

$$\frac{d\boldsymbol{h}}{dt}+\frac{1}{l-x}\frac{d}{dx}[(l-x)\boldsymbol{h}u]=-\varphi\mathbf{w} \quad (48)$$

$$\boldsymbol{h}\left(\frac{d\varphi}{dt}+u\frac{d\varphi}{dx}\right)=-\varphi(1-\varphi)\mathbf{w}\ . \quad (49)$$

Equation (49) is used to determine the current, averaged over the thickness of the layer, fate of the solid φ due to the sedimentation of the rock from it in the cracks of the surface of the bottom of the extraction chamber.

System (44), (45) also allows one to write down one general equation of the law of conservation of mass of the mixture in the upper layer:

$$\frac{d}{dt}(\rho \boldsymbol{h}) + \frac{1}{l-x}\frac{d}{dx}(\rho u \boldsymbol{h} r) = -\varphi \mathbf{w} \rho_s \, . \quad (50)$$

Let's write the momentum equation for the pulp layer, considering it as a homogeneous mixture. At the same time, we will assume that there is hydrostatic pressure in the thickness of the layer, which is determined according to (50)

$$p = \rho_a + \rho_l g(\delta - y)\sin\beta \, , \quad (51)$$

and the thickness of the layer δ and the ordinate y are measured along the normal to the side surface of the extraction chamber. In the momentum equations, the frictional stress on the bottom τ_0 is taken into account and rolling force $g\cos\beta$

$$\frac{d}{dt}(\rho u \boldsymbol{h}) + \frac{1}{r}\frac{d}{dr}(\rho u^2 \boldsymbol{h} r) = -\rho_l g \boldsymbol{h}\frac{d\boldsymbol{h}}{dx}\sin\beta - \frac{g n^2 \rho u^2}{\boldsymbol{h}^{2y}} - g\rho \boldsymbol{h}\cos\beta - \varphi \mathbf{w} u \rho_s \quad (52)$$

Combining equation (52) with the continuity equation, we arrive at the following equation for single-layer pulp flow along the bottom of the extraction chamber:

$$\frac{du}{dt} + u\frac{du}{dx} = -\frac{\rho_l}{\rho} g \frac{d\boldsymbol{h}}{dx}\sin\beta - \frac{g n^2 u^2}{\boldsymbol{h}^m} + g\cos\beta \quad (53)$$

To close the system of equations (50), (53), the particle sedimentation rate w must be specified in the function of the parameters sought.

For the stationary case, this system of equations has the form

$$\frac{d}{dx}[(l-x)\boldsymbol{h}u] = -\varphi \mathbf{w}(l-x) \quad (54)$$

$$\frac{d\varphi}{dx} = \frac{\varphi(\varphi-1)\mathbf{w}}{hu} \quad (55)$$

$$u\frac{du}{dx} = -\frac{g\sin\beta}{1+Ar\varphi}\frac{d\boldsymbol{h}}{dx} - \frac{g n^2 u^2}{\boldsymbol{h}^m} + g\cos\beta \quad (56)$$

Rock particles that fell from the pulp flow into rock cracks at the bottom of the extraction chamber constitute rock losses. The system of equations allows you to determine these losses depending on the parameters of the bottom of the extraction chamber and the characteristics of the pulping process. The mass of rock that falls out of the annular segment in width *dx* per unit of time is equal to

$$dM = 2\pi\varphi\rho_s \mathbf{w}(l - x)\sin\beta dx \tag{57}$$

Thus, the volume fraction of rock particles that fell out of the moving layer will be described by the following equation:

$$\frac{d\Pi}{dx} = \frac{2\pi\varphi \mathbf{w}(l - x)\sin\beta}{q_0(1 - \varphi)} \tag{58}$$

where $q_0=2\pi q\sin\beta$ - pulp productivity.

Solving the obtained equations relative to the derivatives, we will obtain the final system of equations for single-layer pulp flow, taking into account rock losses:

$$\frac{d\mathbf{h}}{dx} = \frac{gh\cos\beta - \frac{gn^2u^2}{h^m} - \frac{hu^2\sin\beta}{R - x\sin\beta} + \varphi uw}{\frac{hg\sin\beta}{1 + Ar\varphi} - u^2} \tag{59}$$

$$\frac{du}{dx} = \frac{\frac{gn^2u^3}{h^{2y}} + \frac{ghu\sin^2\beta}{(1 + Ar\varphi)(R - x\sin\beta)} - \frac{\varphi wg\sin\beta}{(1 + Ar\varphi)} - ug\cos\beta}{\frac{gh\sin\beta}{(1 + Ar\varphi)} - u^2} \tag{60}$$

$$\frac{d\varphi}{dx} = \frac{\varphi(\varphi - 1)w}{hu} \tag{61}$$

$$\frac{d\Pi}{dx} = \frac{\varphi w(R - x\sin\beta)}{q(1 - \varphi)\sin\beta} \tag{62}$$

For the obtained equations, the inherent speed of wave propagation depends on the density and volume fraction of the rock in the pulp flow and is determined by the formula

$$u_c = \sqrt{\frac{gh\sin\beta}{1 + \varphi Ar}}.$$

The initial conditions for solving the Cauchy equation for the system (59)...(62) at the place where the pulp enters the bottom of the extraction chamber (x=0) are as follows $h=h_0$, $u=u_0$, $\varphi=\varphi_0$, where values are h_0 and u_0 are determined by the parameters and mode of operation of the hydromonitor, φ_0 is the concentration of the rock in the ore.

To solve the equations of the system (59)-(62) hydraulic size of rock particles is determined by the formula

$$w = w_0(1-\varphi) \tag{63}$$

where w_0 - is the hydraulic particle size in an infinite liquid at rest.

The hydraulic particle size in an infinite liquid at rest is calculated depending on the flow regime [23].

Taking into account the formula (63), the system takes the following form

$$\frac{dh}{dx} = \frac{(1+Ar\varphi)}{h^m}\,\frac{(gh^{2y+1}\cos\beta - gn^2u^2 + \varphi(1-\varphi)uh^{2y}w_0)(R - x\sin\beta) - u^2h^{2y+1}\sin\beta}{(gh\sin\beta - u^2(1+Ar\varphi))(R - x\sin\beta)} \tag{64}$$

$$\frac{du}{dx} = \frac{[(gn^2u^3 - ugh^m\cos\beta)(1+Ar\varphi) - \varphi(1-\varphi)w_0gh^m\sin\beta](R - x\sin\beta) + gh^{m+1}u\sin^2\beta}{(gh\sin\beta - u^2(1+Ar\varphi))(R - x\sin\beta)h^m} \tag{65}$$

$$\frac{d\varphi}{dx} = -w_0\frac{\varphi(1-\varphi)^2}{hu} \tag{66}$$

$$\frac{d\Pi}{dx} = \varphi\frac{(R - x\sin\beta)}{\sin\beta}\frac{w_0}{q}. \tag{67}$$

To solve the system of equations (64)-(67), the initial values of the thickness of the pulp layer, velocity and concentration at x=0 (at the place of the pulp entering the bottom of the extraction chamber) are necessary.

The stream of the hydromonitor with the flow Q_w when hitting the wall of the breakout it reflects, loosens and erodes a certain amount of rock, which is characterized by the specific consumption of water on 1 м^3 the rock. Thus, the volume of washed rock per unit of time and the consumption of pulp entering the bottom of the extraction chamber will be equal

$$Q_p = \frac{Q_w}{A(1-m_p)} \tag{68}$$

$$q_0 = Q_w\frac{1-m_p+A}{A} \tag{69}$$

where Q_p - performance of the hydromonitor on solid; A - specific water consumption for erosion of this type of rock [23]; m_p - porosity of the rock in the residual state of extraction.

For a unit of time, the jet of the hydromonitor escribes an angle equal to $\omega=2\pi/T$, which on the surface of the breakout corresponds to an arc of a circle with a radius of R equal to $S_T=\omega R$. If at the point of contact of the jet with the wall of the breakout, the diameter of the jet is equal to *d*, then the total length of the perimeter of the contact of the jet with the rock is

$$L_T = S_T + d = \omega R + d \tag{70}$$

The value L_T is the width of the stream flowing down the wall of the breakout with the total flow rate q_0 in the initial section of the inclined surface of the bottom of the extraction chamber.

The flow of the pulp along the breakout wall before it reaches the bottom of the extraction chamber will be close to vertical. Therefore, the speed of the pulp at the moment it hits the bottom of the extraction chamber, if the effect of friction on the hole wall is neglected, can be determined by the formula

$$u_0 = k_U\sqrt{2g\Delta Z} \tag{71}$$

where ΔZ - is the distance between the point of contact of the jet axis with the breakout surface and the upper edge of the bottom surface of the extraction chamber; k_U - is an empirical coefficient that takes into account the influence of friction and other physical and mechanical factors.

Layer thickness h_0 can be obtained from the consumption equation

$$h_0 = \frac{Q_w}{(\omega R + d)} \frac{1 - m_p + A}{A k_U \sqrt{2g\Delta Z}} \tag{72}$$

Values u_0 and h_0, calculated by formulas (71) and (72), serve as initial values *u* and *h* for the system of equations (64)-(67).

From formulas (34)-(36) and (64)-(72) that the parameters of pulp flow along the bottom of the extraction chamber are largely determined by the operating mode and characteristics of the hydromonitor. Research has established that the flow of the pulp is most influenced by the feed of the hydromonitor, the radius of erosion, the area of the jet at the moment of contact with the rock.

Natural modeling of processes in the extraction chamber

The movement of the tuff hydromonitor destroyed by the jet to the suction device of the issuing device occurs in the flow along the bottom of the chamber by gravity or pressure flow of water. In addition, gravity delivery can be effectively used on the surface, from production wells to washout maps or pumping dredges [16-20].

Erosion of the chamber is carried out by sectors, which determines the presence of different specific consumption 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 consumption 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 breakout 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 breakout progresses. Over time, this leads to the impossibility of transportation of mined minerals 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 [20]. This significant difference is the basis of research on hydraulic transport during borehole hydraulic production.

The reserve of potential energy of the open flow of the pulp is spent on the interaction of: the working agent with the bottom and walls of the chamber; liquid particles with each other (friction in the liquid); particles of the transported rock with each other and overcoming local resistances. It is not possible to quantify the energy consumption separately for each interaction, so the method of total evaluation of the flow work is adopted. The total work is expressed by the maximum transport capacity of the flow through the solid at a given slope of the bottom of the extraction chamber and the consumption of the working agent [25].

It is extremely difficult to study the parameters of the technology for extracting minerals from the chamber under natural conditions, so the experiments were conducted in the laboratory on a model stand (Fig. 7). It is practically impossible to carry out an absolutely appropriate simulation of well hydraulic extraction of tuffs, therefore the research results are only quantitative in nature.

The purpose of the studies on the selection of the working chamber scheme was to determine the most effective method of destruction and extraction of the rock, the selection of the extraction method, as well as the determination of the characteristics of the mining equipment. Three schemes of working out of the chamber were studied: oncoming, passing blowout and circulating flow.

According to the first scheme, mining operations were carried out in sectors around the mining well.

In the second scheme, development initially took place by driving mining wells through a channel with its subsequent expansion. At the same time, well hydromonitors work on each other, creating favorable conditions not only for destruction, but also for rock transportation in the chamber, since the energy of the hydromonitor stream is used most rationally when the directions of movement of the hydraulic mixture and the advancement of the hole coincide.

The third scheme is close to the first one and provided for the formation of the primary chamber not over the entire radius of effective action of the jet. The gradual and continuous rotation of the nozzle of the hydromonitor forms a circular circulation of the hydraulic mixture in the near-bump zone of the chamber. In this case, the energy of the stream is also used to transport the hydraulic mixture to the dispensing device.

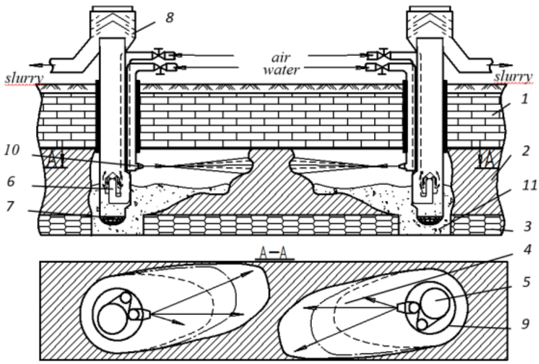

Fig. 7. Scheme of the stand for studying the technology of working out extraction chambers: *1* - roof rock; *2* - layer of zeolite-smectite tuff; *3* - underlying rock; *4* - extraction chamber; *5* - airlift; *6* - airlift nozzle; *7* - suction pipe; *8* - air separator plate type; *9* - column of casing pipes (well); *10* - hydromonitor; *11* - slurry

The experiments were carried out with the diameters of the nozzles of the hydromonitor d_0 equal to 4,2 and 6,0 mm, the change in water pressure H_0 from 0,2 to 0,7 MPa, and the thickness of the formation 0,08-0,19 m. Productivity of the airlift *5* and the density of the aqueous mixture *11* was measured with measuring containers. Model layer *2* is represented by zeolite-smectite tuffs from the basalt quarry of Ivanchi, taken from a depth of 15,2 m. The roof *1* and sole *3* of the layer were made of basalts and lava breccias, respectively. The walls of the laboratory installation were made of transparent glass to accurately determine the shape and dimensions of the chamber *4*. Pressure pads created an opportunity to load the formation.

Studies have shown that increasing the diameter of the nozzle and water pressure increase the washing rate and increase the efficiency of the extraction chamber, but the increase in efficiency is limited by the performance of the dispensing device. An increase in water pressure in the nozzle of the hydromonitor creates an increase in the density of the water mixture only up to a certain limit (ρ=1,3 g/cm^3).

The analysis of the research results showed that working out the formation in layers from top to bottom with a one-well production scheme creates favorable conditions for the flow of the hydraulic mixture to the discharge device. The scheme of working out the chambers with a passing hole is promising only for extracting the rock in the residual of extraction. A limitation to its use is a small angle of deviation from the axis of erosion.

Erosion of the layer and working out of the chambers by the circulation flow showed that regardless of the power of the spent rock layer, water pressure and diameter of the nozzle, the development stopped when the nozzle was rotated 25° from the initial position.

The process of working out the chamber with undercutting of the layer on the sole turned out to be less effective due to the collapse of the ore and disruption of the circulation flow. In the case of a working circulation scheme, it is better to increase the pressure on the nozzle to increase the flow rate. Flooding the camera dramatically reduces the efficiency of working out. Layer-by-layer mining with a circulating flow, all things being equal, reduces the working time of a chamber of the same size by about 25%.

The circulation scheme is very sensitive to changes in the operating modes of the hydromonitor and airlift, and therefore it is advisable to use it for rock with a uniform granulometric composition. Due to the limitation of the size of the product and the low stability of the circulation in the outcrop zone, the circulation scheme is less effective in comparison with the previous two. Its effectiveness was noted only at the beginning of the formation of the extraction chamber.

Thus, as a result of the conducted research, it was established that the most effective and promising application for borehole hydromining of zeolite-smectite tuffs is a single-well mining scheme with a counter strike, in which erosion occurs in sectors and round-shaped extraction chambers are formed. And taking into account that the roof of zeolite-smectite tuffs is thick layers of basalts, the most rational development system is a chamber system with an open cleaning space, in which tuff mining will be carried out in layers. The layers must be designed with a slope sufficient for gravity movement of the destroyed rock.

During the research, it was also established that for large particles (8-10 mm in size), the influence of the increase in flow occurs only until the liquid level rises to the height of the particle, that is, until it is completely immersed in the liquid. A further increase in the flow creates a much smaller effect in terms of the intensity of the effect on the particle, since the surface of the liquid does not come into contact with the plane of the particle, perpendicular to the vector of the speed of movement, and affects only the flow pattern. It can be assumed that with a further increase in the cost, the transportation range will increase, but the increase in the cost will lead to only a slight increase. This allows us to conclude that there is a limit to the influence of the increase in the cost of transporting particles of destroyed tuff.

In the experiment, the impact of the falling pulp flow on the transport capacity of the flow was also investigated. It was found that the initial energy of the falling pulp during washout intensifies the turbulence of the flow in the near-bump space and thereby reduces 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 become turbid, the density of the pulp increases and, as a result, the pushing force increases, which reduces 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 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.

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, it is necessary to create a rational, scientifically based profile of the bottom of the extraction chamber, which must meet the following requirements: - create an optimal (effective under the conditions of turbulence) flow depth in the hole. 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:

- 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.

Conclusions

1. It has been established that the stability of the chamber workings required for supporting the roof rocks is ensured by layer-by-layer working of the mineral within the chamber with the simultaneous formation of inter-chamber the residual of extraction at full capacity, and their strengthening with a supporting prism made of the mineral for development depths of more than 50 m.

2. The surface of reliable hydraulic transportation is characterized by the radius of curvature L_{ki} , the value of which for discrete intervals $L_{npi}.L_{np2}$; $L_{np2}.L_{np1}$; L_{np1}...0 are constant. With an increase in the parameters of the depth of deposit development, the values of L_{np} and M are decreasing To create reliable hydraulic transportation on the surface of the underlying rocks, it is necessary to leave some volume of mineral, limited from below by the surface of the underlying rocks and the side surface of the cylinder with a diameter set by the erosion radius R_{ni}, or the limit span of the opening of the roof of the extraction chambers L_{npi}.

3. At depths of more than 50 m, the volumes of the reinforcing

prism may be significant, which will call into question the feasibility of using well hydraulic drilling systems. In this regard, it is proposed to extract the mineral within the contours of the chamber in several stages with the division of the capacity of the bed of rock *m* into a certain number of segments with a rational height. Thus, working out extraction chambers with the proposed technology allows to significantly increase production from one well and reduce losses of minerals.

4. Researched processes and established systems of equations for calculating dynamic models of pulp flow along the bottom of the extraction chamber. It can be seen from the formulas that the parameters of pulp flow along the bottom of the extraction chamber are largely determined by the operating mode and characteristics of the hydromonitor.

5. As a result of natural studies of the transportation process, it was established that the pulp falling to the bottom of the extraction chamber intensifies the turbulence of the flow in the near-excavation space by creating the initial speed of the pulp movement to the suction nozzle of the device, thereby reducing the sedimentation of tuff particles in the flow, the maximum height of which should not exceed more than twice the size of the largest fractions of the destroyed rock.

6. It was established that the dependence of the transport capacity of the flow on the flow rate of the hydromonitor and the slope of the bottom of the chamber for the destroyed zeolite-smectite tuff is linear and directly proportional to the specified parameters.

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