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SUBSTANTIATING PARAMETERS OF ZEOLITE-SMECTITE PUFF-STONE WASHOUT AND MIGRATION WITHIN AN EXTRACTION CHAMBER

Purpose. To substantiate parameters of zeolite-smectite puff-stone deposit hydromining method while analyzing dependences between physico-technological indices of hydromining equipment and rock mass characteristics, which will help optimize the extraction technique.

Methodology. Complex research approach (i.e. field observations, laboratory tests, and bench testing) is the methodological basis to solve the problem. The approach involves system analysis, physical modeling of hydrodynamic processes, and outcome analysis using MatLab mathematical software package.

Findings. Dependences of zeolite-smectite puff-stone failure upon a mouthpiece diameter, water pressure, washout radius, and gravity streaming hydraulic transportation within an extraction chamber have been determined. Effect of kinetic energy of a falling slurry stream on the decrease in the specific power consumption in the process of rock transportation over an extraction chamber floor has been identified. Power consumption dependence upon hydraulic monitor dimensions and working agent pressure is of quadratic nature: the increased pressure of a working agent in front of a mouthpiece, power consumption of the washout increases, and specific water consumption drops.

Originality. For the first time, an approach to describe zeolite-smectite puff-stone failure taking into consideration hydrodynamic puff-stone washout, hydraulic mixture migration within an extraction chamber, and transportation of the mineral has been applied. Relying upon power consumption to washout hydraulic mixture and transport it within a washout chamber, both linear nature and directly-proportional dependence of transport capacity upon hydraulic monitor loss and chamber floor slope has been determined. Power consumption dependence has been defined for different types of mouthpieces and working agent pressure in order to avoid cuts and layer-by-layer washout of a mineral.

Practical value. The obtained results can be applied to improve dominating parameters influencing the hydrodynamic process for zeolite-smectite puff-stone washout. For the purpose, rational efficiency of puff-stone failure has been identified as well as rotational angle of a lateral mouthpiece of a jet head at 15–20 m height in terms of layer-by-layer washout with rock migration over a distance being equal to a half of the washout diameter. Real conditions (for zeolite-smectite puff-stones) have been determined under which minor jet velocity variation from the determined parameters results in a cut or in a fall of the washout chamber.

Keywords: *puff-stone*, *washout, extraction chamber, slurry, power intensity, hydraulic fluid*

Introduction. During the recent decades, the world has been demonstrating heightened interest in volcanic puff-stones related to the proved zeolite puff-stone deposits being of essential sorbate, cation-exchange, and other characteristics. Forecast resources of such zeolite- containing volcanic puff-stones within Rivne-Volyn region of Ukraine are hundreds of millions of tons, i.e. they are almost inexhaustible [1] by the side of accumulation of technogenic waste of mining regions [2].

According to the data by Rivne and Kovel geological prospecting expeditions, the carried out analysis of the state of crude puff-stone deposit as well as the results of geological investigations has shown that open pit mining of the deposit is unacceptable since its major share is under the privatized agricultural lands; partially, it is under forests belonging to the area of special planning control [1]. Impossibility of open pit mining also depends upon extra flooding of the territory as well as down to 200 m north deepening of the puff-stone occurrence. Geotechnical methods, among which a well hydromining technique (WHM) is one of the basic and promising approaches, can be considered as an alternative to traditional mining of zeolite-smectite deposit.

A number of prospective deposits of late diagenetic zeolite puff-stones, connected with volcanogene-sedimentary rocks, are available at the territory of CIS. Tedzami and Dzegvi deposits (Georgia), Aidag deposit (Azerbaijan), Noemberyan deposit (Armenia), Tayjuzgen deposit (Eastern Kazakhstan), Pegas deposit (Kuzbas), Shivirtui deposit (Trans-Baikal), Hongoruu deposit (Yakutia), Chuguev deposit (Primorya), Lutog deposit (Sakhalin) and others are the most promising ones. Details are available concerning puff-stone deposits of Transcaucasia; less detailed data concern Kuzbas, Trans-Baikal, Yakutia, Primorya, and Sakhalin. Generally, the deposits are represented by clinoptilolite ores, mordenite-clinoptilolite ores, and heulandite-clinoptilolite ores. In terms of their zeolite content, ores are divided into high-grade (70–95 %), medium (40–70 %), and low-grade (10–40 %) ones in terms of their 12.73 and 15 % ratios respectively. Along with zeolites, whose content may vary from 10 to 95 %, the ores contain quartz, feldspar, hydromica, montmorillonite, and other minerals. Clinoptilolite, being the most popular component of natural zeolite puff-stones, occurs as three basic cation forms: potassic, sodium, and calciferous [3].

According to the data of deep mapping by *Pivnichheolohiia* SRGE (Ukraine), volcanic puff-stones in Rivne-Volyn region (Fig. 1) trace under Mesozoic-Cenozoic formations along western wing of Polissia anticline, and western slope of Ukrainian crystalline shield in the form of a ribbon with 1–10 km width at 5–300 m [1].

Literature review. Volcanic puff-stones were not analyzed as minerals by the specialized geological prospecting activities. Only crude data are available concerning their material composition, characteristics, and applicability. At the same time, technological experiments as well as a number of the studied bioactive, agrochemical, and conserving properties of puff-stones demonstrated their feasibility to be used in the context of various techniques and production operations (Tables 1 and 2).

Thus, according to the content of petrogenic minerals, the volcanic puff-stones are altered profoundly by zeolite-smectite rocks, which experienced significant secondary transformations, and hydrothermal mineralization [4, 5].

Possibilities of multipurpose use as well as availability of large amount of useful minerals within the rock, no toxic components, and convenient geographical location motivate further research concerning the use of basalt puff-stones in Rivne region.

Unsolved aspects of the problem. A number of papers concern the development of hydrodynamic models as for the slurry migration over a conic surface. Basically, the papers determine stationary parameters of the migration process [6, 7], analyze effect of different factors on the hydraulic mixture nonuniform motion [8] as well as surface soil reclamation [9]. However, the papers pay insufficient attention to dynamic characteristics of the process and ignore roughness parameters of hard border of the stream.

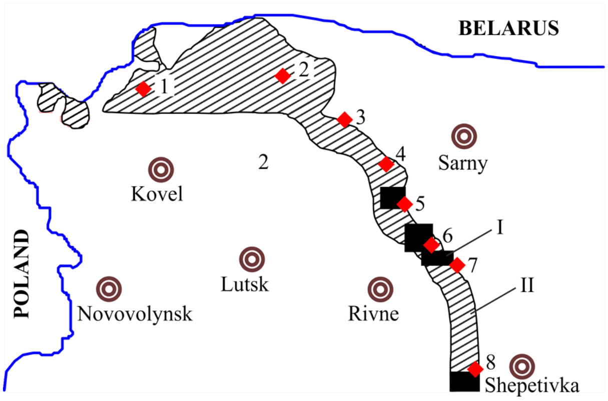

Fig. 1. Scheme of sampling and puff-stone outcrop in the context of operating open pits:

1–8 – sampling areas; I – puff-stone outcrops in open pits; II – puff-stone outcrop to Pre-Mesozoic– Cainozoic surface

Description of the methods. Experimental program for zeolite- puff-stone washout by means of water jet through mouthpieces with 15, 20, 25, 30, 35 mm and 1–3 MPa pressure is intended to determine efficiency, maximum washout radius, power intensity, and specific water consumption. Velocity of a breaking mouthpiece of a hydraulic monitor within a stope sector varied from 0.3 to 2.4 m/s. The mineral washout was performed gradually when bench height was 20–35 cm with its displacement to a boundary distance being equal to the washout radius. It was displaced with the help of a jet. Virtually, rock breakage and transportation were a single process implemented by means of a consistent jet action on a stope displaced constantly.

MatLab and Microsoft Exel softwares approximated the experimental data, and processed them statistically. The second order polynomials approximated the majority of the experimental data.

The measurement data, formed as some vector y in terms of certain values of argument shaping vector X of a length similar to vector y, were approximated polynomially by means of MatLab built-in polifit procedure (X, Y, Z), where Z is an order of the approximating polynom. A vector with (Z+ 1) length

Table 1

Economic use of basalt puff-stones in Rivne region

Application area for puff-stones			
Environmental measures	Agriculture	Construction industry	Binders
1. Reclamation of contaminated soils 2. Underground nuclear waste disposal 3. Sewage cleaning from NH^{4+}	1. Mineral fertilizer, plant nutrient stabilizer 2. Seed storage 3. Supplementary feeds for livestock and poultry	1. Manufacture of brick, roof tile, and ceramic tile 2. Manufacture of cement, and claydite 3. Pigments for staining agents, and integrally colored concrete	1. Ore balling 2. Fertilizer balling

Table 2

Chemical composition of puff-stones in Rivne region

Deposit	Basic minerals	Content of petrogenic oxides (%)													
		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3	V.P.P	H_2O^-
Polytske	Hectorite Saponite Analcime	47.2	1.98	13.9	11.9	1.7	0.17	7.0	2.79	4.87	1.48	0.14	0.03	6.65	–
Berestovetske	Montmorillonite Nontronite	61.9–66.2	1.18–1.34	8.61–10.7	9.59–10.6	0.93–2.59	0.092	2.82–3.74	1.32–1.67	0.5–0.59	1.73–2.43	0.16–0.21	0.04–0.43	4.19–5.12	3.38–3.81

of coefficients of the approximating polynom is the procedure result.

Microsoft Exel performed exponential approximation by adding a trend line function, which resulted in the construction of an approximating curve and its equation derivation within a graph of the data under study.

The data were processed statistically to verify the approximation and its quantitative evaluation; namely, a correlation coefficient and a mean square deviation between the experimental data and those, calculated according to approximation dependences, were determined.

The correlation coefficient was determined as follows

$$r = \frac{\sum (x_i - x_{ms})(y_i - y_{ms})}{\sqrt{\sum (x_i - x_{ms})^2 (y_i - y_{ms})}},$$

where *x, y* are experimental data and analytical data, respectively.

The mean square deviation was identified as follows

$$\delta = \frac{\sqrt{\sum (x_i - y_i)^2}}{n-1},$$

where *n* is the number of measuring points.

As for the quantitative evaluation of reliability of the determined mathematical dependences, maximum relative error between the experimental results and the analytical values has been identified for each measurement point

$$\gamma_i = \frac{x_i - y_i}{x_i} \cdot 100\,\%.$$

Washout radius dependence upon the working agent pressure and the diameter of the mouthpiece for zeolite-smectite puff-stones of Rafalivske deposit is approximated as follows

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

Depending upon the pressure and diameter of a hydraulic monitor mouthpiece, puff-stone washout efficiency is approximated using the following dependence

$$\Pi_p(d_0, H_0) = 0.07 H_0 \cdot e^{148 \cdot d_0} + 3.3 \cdot H_0 - 2.8.$$

During the process of derivation of analytical dependences according to the experimental data being complex functions of two variables (i. e. set of curves), approximation dependence of a certain type was constructed for each curve as a function of one variable [10]. Then, coefficient values within the curve equations were used to construct graphical dependences and approximation dependences being functions of a variable two. Substitution of the coefficients of approximation dependence one for variable two equations results in a function of the two variables [11].

Dependences of power intensity of puff-stone washout processes and specific loss of a working agent upon pressure and hydraulic monitor mouthpiece diameter were approximated by means of the following equations

$$\begin{cases} E_n = -a d_0^2 + b d_0 - c \\ a = 3174 \cdot H_0^2 - 11158 \cdot H_0 + 12\,755 \\ b = 134.8 \cdot H_0^2 - 448.1 \cdot H_0 + 546.1 \\ c = 1.09 \cdot H_0^2 - 3.465 \cdot H_0 + 3.26 \end{cases}; \quad \begin{cases} q = -a d_0^2 + b d_0 - c \\ a = -1983 \cdot H_0^2 + 4203 \cdot H_0 + 9209 \\ b = -174.2 \cdot H_0^2 + 525.3 \cdot H_0 + 192.3 \\ c = -2.71 \cdot H_0^2 + 10.5 \cdot H_0 - 8.3 \end{cases}. \qquad (1)$$

To verify reliability of the experimental data and full-scale data, we carried out theoretical studies of a washout process and slurry migration over a stope floor to an air-lift intake pump [12]. The study is based upon theoretical dependences derived by Professors Z. R. Malanchuk, O. H. Homon, B. O. Blius, and E. I. Cherniei listed in paper [13].

Results. Our basic studies were focused on the puff-stones of Rafalivske basalt open pit represented mainly by medium-fragmented and small-fragmented psammite types. Their thick layer (up to 100 m) occurs under basalts. When the basalts are mined out, the layer becomes seen within the open pit bottom and walls. Complete mineralogical analysis has helped determine high content of zeolites, smectites, and ferruginized disperse materials also being smectites in the puff-stones, drilled-out in the basalt open pit in the neighbourhood of basalt deposit Ivanchi (2 km southwest).

Table 3 represents the analyzed physical and mechanical characteristics of the puff-stone samples from the basalt open pit and wells.

According to the data of spectral analyses, average content of microelements, inclusive of environmentally hazardous, in the puff-stones from the site under study correspond to bulk earth values calculated for the basic lithosphere rocks as well as to the boundary allowable concentrations (BAC) in soils, which is represented in Table 4.

Puff-stones are characterized by thermostability, resistance to aggressive environment as well as to ionizing radiation, sufficient mechanical strength when they are dry, availability or nonavailability only in the trace amounts of poisons, and lack of contamination by microorganisms.

According to the data of X-ray diffraction analysis and thermal analysis (six determinations), samples of the puff-stones contain 65.0 (+16.0, –13.0) % of smectites of trio-ctahedral structure of hectorite-saponite series, and 28.17 (+14.83, –14.17) % of analcime on the average. At the mean, the puff-stones selected within Ivanchi basalt deposit (thirty-

Table 3

Physical and chemical characteristics of the puff-stones

Plasticity index	Bulk density, $*10^3$ kg/m^3	Specific surface, m^2/kg	Porosity, %	Water regain, %	Water adsorption in terms of weight, %	Water adsorption in terms of volume, %	Hardness, MPa
5–7	1–1.2	120	30	36	18	33	5

Table 4

Average contents of microelements in the puff-stones from Rafalivske deposit (42 samples, $1 \cdot 10^{-4}$ %)

Elements	P	Pb	Ba	Mo	Sn	Cu	Zn	Ni	Zr	Co	Cr	V	Mn	Ti
Average	670	5	350	0.8	5	103	46	34	140	31	47	116	1240	5480
Clarks	1500	6	330	1.5	6	87	105	130	110	48	170	250	1200	8000
BAC	–	30	–	–	–	100	100	100	–	–	100	150	1500	–

seven samples) contain 47.2 % of SiO_2; 1.98 % of TiO_2; 13.9 % of Al_2O_3; 11.9 % of Fe_2O_3; 1.7 % of FeO; 0.17 % of MnO; 7.0 % of MgO; 2.79 % of CaO; 4.87 % of Na_2O; 1.48 % of K_2O; 0.14 % of P_2O_5; 0.03 % of SO_3; and 6.65 % of в.n.n.

Bulk density of the fragmented puff-stone is 0.96–1.22 · 10^3 kg/m^3 and specific surface is 120–150 m^2/kg. Total porosity of the dispersed puff-stone material is almost 30 %; water regain is 36 %. If coagulant is available, it is 62 %. In terms of weight, water adsorption is about 18 %, and it is 33 % in terms of a volume.

In the process of washout, transportation capacity within a stope decreases significantly when the stope is distancing from the hydraulic monitor mouthpiece. The above was demonstrated in the fact that distance for which the rocks were thrown out per a cycle of a stream effect on the stope decreased; moreover, it took less time compared with larger fractions. At a certain distance from the mouthpiece, migration value of large fractions was practically equal to zero per a cycle of hydraulic monitor jet effect on the stope. Further, we consider maximum distance value, at which the jet transfers the largest rock fractions, as the washout radius.

Analysis of the rock washout process in terms of varying mouthpiece diameters and water pressure within a hydraulic monitor (Table 5) has shown that puff-stone washout by means of large-diameter jets results in the increased washout radii; moreover, the increase becomes more intensive depending upon the increase in working agent pressure in front of the mouthpiece (Fig. 2).

Analysis of the experimental data has helped determine that with increase in pressure in front of the mouthpiece, power intensity of washout increases as well and specific water consumption decreases.

Washout efficiency of puff-stones with similar physical and mechanical characteristics is influenced by a period of a jet action on a stope specified by the jet migration over the stope sector.

It has been identified that in the context of layer-by-layer washout of a mineral, the increased period of a jet influence on the rock mass results in a cut formation as well as in the decreased washout efficiency. The cut formation in the process of the mouthpiece hydraulic monitor rotation at $\omega = 1$ rot/min velocity was observed at 4–6 m distance from the mouthpiece. In this context, migration velocity of the jet over a stope varied from 0.3 to 0.9 m/s. Comparatively large value of the jet-surface impact value also favoured the cut formation. During the stope migration from 0 to 5 m, its value varied from 25 to 10° respectively.

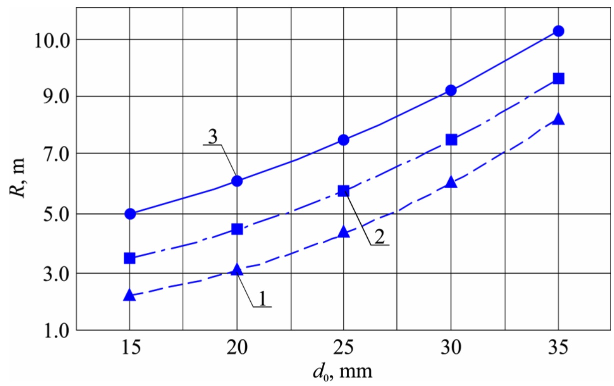

Fig. 2. Dependence of radius of zeolite-smectite puff-stone (R) upon a mouthpiece diameter (d_0) in terms of different pressures:

1 – $H_0 = 1$ MPa; 2 – $H_0 = 1.6$ MPa; 3 – $H_0 = 2.2$ MPa

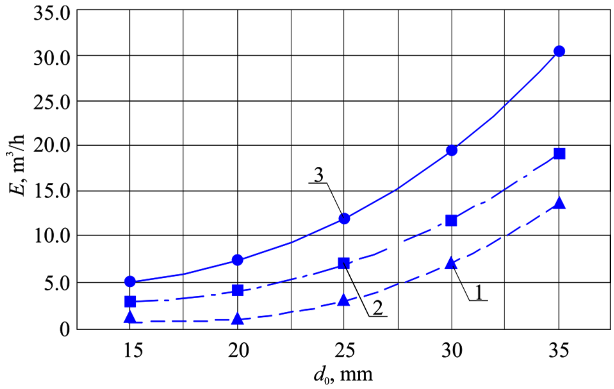

Fig. 3. Dependence of the averaged efficiency of puff-stone washout (E) at a distance of washout diameter (d_0) on the mouthpiece diameter in terms of different water pressure values:

1 – $H_0 = 1$ MPa; 2 – $H_0 = 1.6$ MPa; 3 – $H_0 = 2.2$ MPa

To improve the efficiency of mineral mining at up to 6 m distances from the hydraulic monitor mouthpiece, a slope angle of the jet to the washout surface should not be more than 5–7 %; in this context, jet velocity within a stope is limited down to 0.7–1.4 m/s and the stope height is

Table 5

Experimental data of zeolite-smectite puff-stone washout diameter while using a jet of a hydraulic monitor

Water pressure within a mouthpiece	Analysis		Mouthpiece diameter d_0, mm				
			15	20	25	30	35
$H_0 = 1$ MPa	1	A value of washout 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

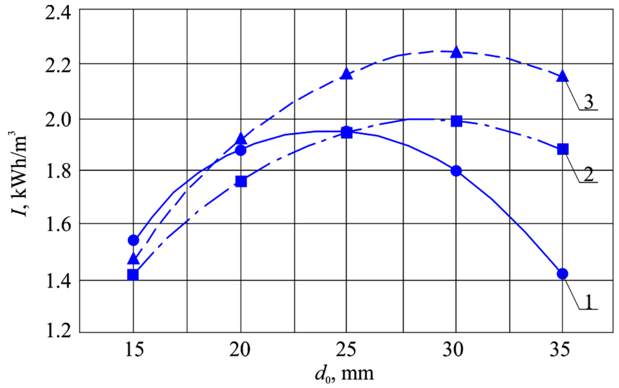

Fig. 4. Dependence of power intensity (I) of washout process upon a diameter (d_0) of a hydraulic monitor mouthpiece in terms of different pressures:

1 – H_0 = 1 MPa; 2 – H_0 = 1.6 MPa; 3 – H_0 = 2.2 MPa

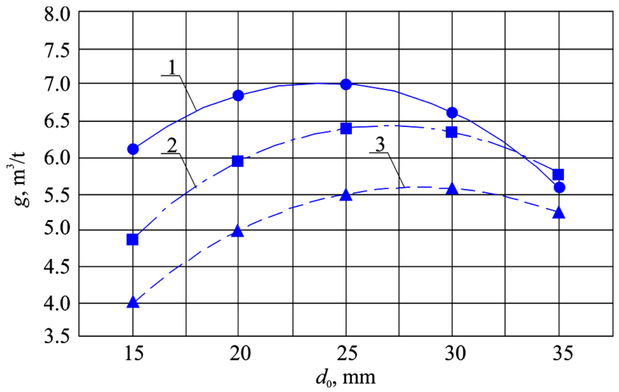

Fig. 5. Dependence of specific consumption (g) of working agent consumption upon a diameter (d_0) in different washout terms:

1 – H_0 = 1 MPa;2 – H_0 = 1.6 MPa; 3 – H_0 = 2.2 MPa

15–20 cm when washout through 25–35 mm mouthpieces takes place.

Taking into account the fact that volcanic puff-stones of Rivne-Volyn region occur in the form of seams, whose thickness is several meters up to 100 meters and more, such extraction chambers may be applied where floor is arranged within the mineral itself as well as within bedding rocks. Floor of an extraction chamber is a conic surface where a suction box with air-lift is located within a central part.

Diameter of an extraction chamber as well as its inclination angle is determined with the help of operation parameters of a well hydraulic mining; it varies during the process [14]. Floor roughness depends upon rock type, its fracture mode [15], and upon zonal disintegration [16].

To analyze slurry migration over an extraction chamber floor, we apply a model of homogeneous liquid migration within a thin layer assuming that velocity is similar in terms of the layer thickness and liquid-floor friction is taken into consideration with the help of empiric formulas [17, 18]. Such a model can be analyzed rather simply and solved analytically [19, 20].

To describe a process of a slurry layer over a conic surface, we select spherical coordinate system. Axle $0z$ of $0z\theta\psi$ spherical coordinate is compatible with symmetrical axis of the conic surface, and can be directed up vertically (Fig. 6).

Let us specify semiopening angle of an extraction chamber as β. We assume that liquid migrates over a surface in the form of a thin layer for which thickness, measured along internal normal up to the conic surface, $h/r \ll 1$ condition is met. In this context, the layer thickness, measured along the normal up to the conic surface, and thickness, measured along coordinate line θB lengthwise AB arc will differ insignificantly. Then, linear dimension, measured from a cone surface $\theta = \beta$ along AB meridian arc can be considered as the layer $h(r, \psi, t)$ thickness.

We select $ABCDA'B'C'D'$ element, limited by spherical surfaces of r and $r + dr$ radii, ψ = const and $\psi + d\psi$ = const planes, and area of conic surface $\theta = \beta$ $ADD'A'$ as well as area of free surface $BCC'B'$, as an elementary volume for which conservative laws will be applied.

In this context, the area of $ABCD$ element edge is $r\sin\beta d\psi h$ and $ABB'A'$ edges are $dr \cdot h$. The element volume will be $r\sin\beta h dr d\psi$.

Hence, flow through edges, being normal to $\vec{r}^{\,0}$, is equal to $-\frac{\partial}{\partial r}(\rho V_r rh)\sin\psi d\psi dr$ and it is following through edges, being normal to $\vec{\psi}^{\,0}$: $-\frac{\partial}{\partial\psi}(\rho V_\psi h) dr d\psi$, where V_r is a radial velocity component; V_ψ is a circular velocity component; ρ is the liquid density.

Since liquid inflow through free surface is not available within the problem, then the vertical velocity component V_θ in the layer may be neglected according to [3] research. In such a case, the liquid accumulation within $r\sin\beta h dr d\psi$ element per a time unit will be $\rho r \sin\beta \frac{\partial h}{\partial t} dr d\psi$.

Mass conservation law results in the equation

$$r\sin\beta\frac{\partial h}{\partial t} + \sin\beta\frac{\partial}{\partial r}(V_r rh) + \frac{\partial}{\partial\psi}(V_\psi h) = 0. \qquad (2)$$

If axially symmetric migration ($V_\psi \equiv 0$) takes place, we have

$$r\frac{\partial h}{\partial t} + \frac{\partial}{\partial r} = 0. \qquad (3)$$

We substitute r variable for x variable calculated counted off from the initial section of the layer: $u = -V_r$; $x = l - r$. Thus, instead of equations (2, 3), we will have

$$\frac{\partial h}{\partial t} + \frac{1}{l-x}\frac{\partial}{\partial x}\left[uh(l-x)\right] + \frac{V_\psi h}{(l-x)\sin\beta} = 0;$$
$$\frac{\partial h}{\partial t} + \frac{1}{l-x}\frac{\partial}{\partial x}\left[uh(l-x)\right] = 0, \qquad (4)$$

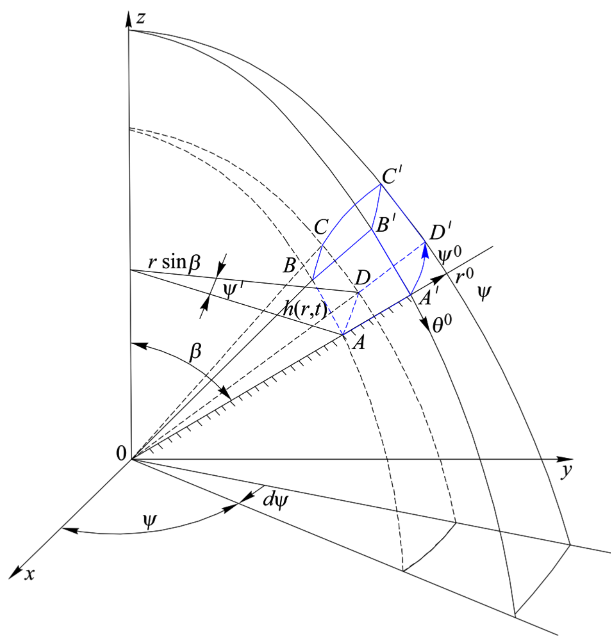

Fig. 6. Coordinate system and the liquid flow element

where l is a complete length of a floor formative of an extraction chamber.

Since the layer is thin, then consideration of an impulse equation, particle acceleration along the normal down to the flow bottom can be neglected as well as changes in a body force along the layer thickness [21, 22].

In such a case, motion equation in terms of the projection on $\overset{\to 0}{\theta}$ axis will be as follows

$$\frac{\partial p}{\partial \theta} = \rho g r \sin\beta.$$

After the equation integrating by θ within the layer, and taking into consideration the fact that over the free surface $y = h$ pressure is constant and equal to atmospheric pressure $p = p_a = \text{const}$, we express definitely a law of pressure distribution within the layer as

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

where $y = r(\beta - \theta)$ is a linear coordinate within the layer being counted off from a base through radius r arc.

While specifying a value of tangential stress of the layer floor, the following is obtained for an impulse equation within a projection on $\overset{\to 0}{r}$ for axially symmetric migration

$$\frac{\partial}{\partial t}\left(\rho h V_r\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(\rho V_r^2 h r\right) = \rho g \sin\beta h \frac{\partial h}{\partial r} - \tau_0 - \rho g \cos\beta h.$$

While combining the equation with a continuity equation, and transiting to x and u variables, we obtain impulse equations in the form of

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\sin\beta\frac{\partial h}{\partial x} = -\frac{\tau_0}{\rho h} + g\cos\beta,$$

which, together with (4), forms equation system for nonstationary migration of a slurry layer over the conic surface.

Taking into consideration specific features of the extraction chamber floor, which may consist of rocks with different roughness types, the well-known Chezy formula is applied to determine friction stress τ_0

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

where C is the Chezy coefficient whose value is determined depending upon material and relative roughness of an extraction chamber floor with the use of one of popular empiric formulas; for instance, formula by N. N. Pavlovsky may be applied.

Resulting from the research, maximum relative error in the process of rock washout calculation by working gent pressure, and mouthpiece diameter for zeolite-smectite puff-stones of Rafalivske open pit was 9.07 %; and maximum error in the process of puff-stone washout efficiency depending upon pressure and a mouthpiece of a hydraulic monitor was 12.3 %.

In the context of the approximation approach, proposed by formula (1), maximum divergence between analytical data and experimental data was far less, i.e. 2.14 % to determine washout power intensity, and 2.5 % for specific loss.

Conclusions. Compared with zeolite puff-stones of other deposits, zeolite-smectite puff-stones from Rivne region are characterized by lesser content of zeolite rock replaced by smectite minerals. While conserving useful sorption characteristics and cation-exchange ones, the above improves their technological properties from the viewpoint of washout within an extraction chamber and the use of a well hydraulic technology in the process of mining.

Increase in a mouthpiece diameter and water pressure results in washout radius increase while efficiency improves according to exponential laws. Power consumption dependences upon hydraulic monitor mouthpiece geometry and working agent pressure are of quadratic nature: increase in the working agent pressure in front of a mouthpiece results in the washout power intensity, and in the decrease of specific water consumption.

To avoid a cut formation and to improve the efficiency of puff-stone mining, at up to 6 m distances from the mouthpiece of a hydraulic monitor, a jet inclination angle should not be more than 5–7°. In this context, jet velocity along a stope is limited down to 1.4 m/s and during washout through 25–35 mm mouthpieces the stope height should not be more than 20 cm.

Processes have been analyzed and equation systems to calculate dynamic models of slurry migration over an extraction chamber floor have been determined. The research shows that parameters of slurry migration over an extraction chamber floor depend upon operation mode, and characteristics of a hydraulic monitor.

Surface of reliable hydraulic transportation is characterized by a curve radius whose values are constant for discrete intervals. Reliable hydraulic transportation at the surface of underlying rocks should involve certain mineral volume limited below by a surface of underlying rocks as well as wall cylinder surface whose diameter is determined with the help of washout radius or with the help of boundary overburden of extraction chambers.

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Обґрунтування параметрів розмиву й перетікання пульпи цеоліт-смектитового туфу у видобувній камері

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Мета. Обґрунтування параметрів технології гідровидобутку цеоліт-смектитових туфів шляхом аналізу залежностей між фізико-технологічними показниками гідровидобувного обладнання та характеристиками масиву породи, що дозволить оптимізувати процес видобування.

Методика. Методологічною основою рішення проблеми є комплексний метод досліджень (натурні, лабораторні, стендові дослідження), що включає системний аналіз, фізичне моделювання гідродинамічних процесів, аналіз результатів за допомогою математичного пакету MatLab.

Результати. Встановлені залежності процесу руйнування цеоліт-смектитового туфу від діаметра насадки, тиску води, радіуса розмиву й самопливного гідротранспортування у видобувній камері. Встановлено вплив кінетичної енергії падаючого потоку пульпи на зменшення питомих енергозатрат при транспортуванні породи по дну видобувної камери. Залежність енергозатрат від розмірів насадки гідромонітора й тиску робочого агента має квадратичний характер: зі збільшенням тиску робочого агента перед насадкою енергоємність розмиву зростає, а питома витрата води знижується.

Наукова новизна. Уперше використаний підхід для опису руйнування цеоліт-смектитового туфу з урахуванням гідродинамічного розмиву туфу, переміщення гідросуміші в умовах добувної камери та транспортування корисної копалини. Виходячи із показників енергозатрат на розмив та транспортування гідросуміші в камері розмиву, встановлені лінійний характер і прямо пропорційна залежність транспортної здатності потоку від витрати гідромонітору й ухилу дна камери. Для різних типів насадок гідромонітора й показників тиску робочого агенту встановлена залежність енергозатрат від цих параметрів з метою запобігання утворення врубу та пошарового розмиву корисної копалини.

Практична значимість. Отримані результати можуть бути використані для поліпшення домінуючих чинників, що впливають на процес гідродинамічного розмиву цеоліт-смектитових туфів. Для цього визначена раціональна продуктивність руйнування туфу, кут повороту бічної насадки гідромоніторної головки при пошаровому розмиві на висоту 15–20 см з переміщенням породи на відстань, що дорівнює половині радіуса розмиву. Отримані реальні умови (для цеоліт-смектитових туфів), в яких незначна зміна швидкості струмини від встановлених параметрів призводить до врубу або обвалу камери розмиву.

Ключові слова: *туф, розмив, видобувна камера, пульпа, енергоємність, гідросуміші*

Обоснование параметров размыва и перетекания пульпы цеолит-смектитового туфа в добычной камере

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Цель. Обоснование параметров технологии гидродобычи цеолит-смектитовых туфов путем анализа зависимостей между физико-технологическими показателям гидродобычного оборудования и характеристиками массива породы, что позволит оптимизировать процесс добычи.

Методика. Методологической основой решения проблемы является комплексный метод исследований (натурные, лабораторные, стендовые исследования), включающий системный анализ, физическое моделирование гидродинамических процессов, анализ результатов с помощью математического пакета MatLab.

Результаты. Установлены зависимости процесса разрушения цеолит-смектитового туфа от диаметра насадки, давления воды, радиуса размыва и самотечного гидротранспортирования в добычной камере. Установлено влияние кинетической энергии падающего потока пульпы на уменьшение удельных энергозатрат при транспортировании породы по дну добычной камеры. Зависимость энергозатрат от размеров насадки гидромонитора и давления рабочего агента имеет квадратичный характер: с увеличением давления рабочего агента перед насадкой энергоемкость размыва растет, а удельный расход воды снижается.

Научная новизна. Впервые использован подход для описания разрушения цеолит-смектитового туфа с учетом гидродинамического размыва туфа, перемещения гидросмеси в условиях добычной камеры и транспортирования полезного ископаемого. Исходя из показателей энергозатрат на размыв и транспортирование гидросмеси в камере размыва, установлены линейный характер и прямо пропорциональная зависимость транспортной способности потока от расхода гидромонитора и уклона дна камеры. Для различных типов насадок гидромонитора и показателей давления рабочего агента установлена зависимость энергозатрат от этих параметров с целью предотвращения образования вруба и послойного размыва полезного ископаемого.

Практическая значимость. Полученные результаты могут быть использованы для улучшения доминирующих параметров, влияющих на процесс гидродинамического размыва цеолит-смектитовых туфов. Для этого определена рациональная производительность разрушения туфа, угол поворота боковой насадки гидромониторной головки при послойном размыве на высоту 15–20 см с перемещением породы на расстояние, равное половине радиуса размыва. Определены реальные условия (для цеолит-смектитовых туфов), в которых незначительное изменение скорости струи от установленных параметров приводит к врубу или обвалу камеры размыва.

Ключевые слова: *туф, размыв, добычная камера, пульпа, энергоемкость, гидросмеси*

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