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Parameters determination of hydromechanization technologies for the dumps development as technogenic deposits

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Abstract

Purpose. Determination and substantiation of the hydromechanization technologies parameters and the hydraulic transport operation modes for mining the technogenic deposits formed as a result of the enrichment waste storing in tailing dumps of mining and processing enterprises.

Methods. A comprehensive multi-stage analytical approach has been used in a paper when performing research. Initially, in order to substantiate the hydromechanization technologies parameters, the parameters of the pulp-preparation unit have been analytically determined in this paper, which are limited by the value of the upper dam edge, taking into account the types of hydraulic mixture. At the second stage, dependences have been set for calculating the critical velocity of hydraulic transporting the pulps with different concentration (low, mean, and high). The next research stage was to determine the head and rate specification (HRS) of the hydrotransport pipeline and the required capacity of the hydraulic mixture, which will enable substantiating the parameters for the corresponding mining complex in the technogenic deposits development.

Findings. A critical pipeline diameter has been set with the prescribed parameters of the mining complex and the adopted pulp preparation system. Dependences have been found for calculating the critical velocity of hydraulic transportation of mean- and highly-concentrated pulps. The head and rate specifications have been determined of the tailing hydrotransport pipeline.

Originality. For the first time it has been revealed that the critical diameter value is determined by the product of two terms – the first one takes into account the effect of the mining complex productivity, and the second – the dependence on the pulp preparation system parameters. This makes possible to control the parameters and modes of hydromechanization technologies when mining technogenic deposits formed as a result of storing the enrichment waste in tailing ponds.

Practical implications. The "Recommendations for substantiating the parameters of the processes of accumulating capacity restoring of a pond with the use of hydromechanization devices" and "Methods for calculating the parameters for hydraulic transportation of highly-concentrated hydraulic mixtures", have been developed, which may be useful for design organizations and mining-metallurgical enterprises to provide additional volumes of raw material output and increase the tailing ponds lifetime.

Keywords: *hydraulic transport, technogenic deposits, hydraulic mixture, head and rate specification (HRS), high concentration*

1. Introduction

Technogenic mineral deposits formed in artificial waste dumps are the most promising for the immediate mining development [1]-[5]. Given the existing method of storing enrichment waste in the form of low-concentrated hydraulic mixtures, it follows that successful development of these deposits is not possible without the use of pulp preparation technology [6]-[9].

These technologies have become widespread during hydromechanization of surface mining operations, where they are most often used for low and mean-concentrated hydraulic mixtures [10], [11], also it is used during amber buoying by hydromechanical extraction [12]-[14].

A distinguishing feature of pulp preparation technologies, when mining technogenic mineral deposits of the studied type, is the use of highly-concentrated hydraulic mixtures, which is not typical for the primary placer deposits extraction [15]-[18]. Prior to this, the hydraulic transporting technologies of enrichment waste in the form of pastes and Bingham-Shvedov plastics were known. However, in accordance with them it is supposed to perform pulp preparation through special technological cycles, the application effectiveness of which was not studied in surface mining.

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It is not characteristic for these technologies to use hydromonitors to create the jets and supply water to the sump for adjusting the pulp concentration, as well as to the trammel for mixing the phases. The use of ejector technologies of pulp preparation, based on mixing the flows of two phases in the pipeline, is considered ineffective due to the high density and viscosity of the suspension being prepared, as well as its initial shearing stress. A certain perspective under these conditions the installations have, equipped with augers to supply solid particles or to mix the phases with subsequent supplying the finished hydraulic mixture into the pipeline [19]-[22].

The bunker technologies of pulp preparation are considered the most acceptable for these conditions, since they involve the process of mixing the liquid and solid phases of the pulp in a certain tank, which ensures the associated suspension thickening and the introduction of reagents into it [23]-[26]. For low and mean-concentrated hydraulic mixtures, the finished pulp density control in this type of devices is ensured by selecting the volumetric flowrate of phases, and the uniformity of mixing is provided by ways of their supply. For hydraulic transport systems transporting hydraulic mixtures with such a concentration, several designs of jet sumps are known that provide a stable value of the pulp concentration [27]-[30]. Water filtration and soil deformations under above mentioned conditions must be also taken into consideration [31]-[33].

Review of technogenic deposits accumulation and prospects of their developing in mining industrial regions in Ukraine shown in detail in [34]. At the same time, mo-dern technologies for mining technogenic deposits formed in artificial waste dumps are already oriented towards technologies and technical means of pulp preparation, which allow pulp formation with high concentrations at the current flood-breaking dam. There are no scientifically substantiated methods for determining the parameters of such hydromechanization technologies for enrichment waste storage conditions, and adaptation of the calculation methods used for low and mean-concentrated hydraulic mixtures requires studying the peculiarities and differences of the studied processes, taking into account the rheological characteristics of the suspension and possible hydrotransport modes.

The purpose of the work is to determine and substantiate the hydromechanization technologies parameters for mining the technogenic deposits formed as a result of the enrichment waste storing in tailing dumps of mining and processing enterprises.

2. Determination of the hydromechanization technology parameters for the development of technogenic deposits formed in dumps

To a large extent, the dimensions of the pulp-preparation unit, regardless of the selected technology, will be determined by the required capacity of the hydraulic mixture:

$$Q = Q_S + vQ_S + Q_w,$$

where:

Q – the volumetric flowrate of the finished hydraulic mixture;

Q_S – the volumetric flowrate of the technogenic placer;

v – the moisture content value of the technogenic placer;

Q_w – the volumetric flowrate of water supplied from the tailing pond.

In the case under consideration, when accepting the assumptions of the pulp formation process model proposed in [35], [36], the following formulas can be written for determining the parameters of the finished pulp:

$$Q = Q_S\left(1+v+q\right); G = \rho_S Q_S\left(1+\frac{v+q}{Ar+1}\right); C_V = \frac{1}{1+v+q}; \quad (1)$$

$$C = \frac{1}{1+\dfrac{v+q}{Ar+1}};\ \rho = 1+\frac{Ar}{1+v+q};\ q = \frac{Q_w}{Q_S};\ Ar = \frac{\rho_S-\rho_W}{\rho_W}, \quad (2)$$

where:

G – the freight flow;

C – the mass concentration of the pulp;

C_v – the volumetric concentration of the pulp;

A_r – the Archimedes' parameter of the transported material;

ρ_S – the weighted average of particles density of the transported material;

ρ_w – the water density;

q – the specific flowrate of water for the pulp formation [35], [36],.

If the moisture content value of the developed technogenic placer is negligible compared to the specific flowrate of water for pulp formation, then instead of the above formulas the following dependences can be used:

$$Q = Q_S\left(1+q\right);\ G = \rho_S Q_S\left(1+\frac{q}{Ar+1}\right);\ C_V = \frac{1}{1+q},$$
$$C = \frac{1}{1+\dfrac{q}{Ar+1}};\ \rho = 1+\frac{Ar}{1+q}. \quad (3)$$

The pulp flowrate determined by the formulas (1) and (3) is a characteristic of the pulp-preparation unit and does not take into account the flow regime of the slurry, which depends on the pipeline diameter (Table 1). It also does not take into account the head and rate specification (HRS) of the main pipeline, which at the obtained concentration values can provide some greater or less consumption than that of calculated.

Table 1. Classification of pulp flow regimes with different concentrations

Pulp classification by concentration	Classification of pulp flow regimes	
	Heterogeneous liquid	Homogeneous liquid
Low concentration Mean concentration	$V < 1.25V_{kp}$	$V \geq 1.25V_{kp}$
High concentration	Rod regime	Turbulent regime

Note: the following notations are used in the Table:
V – the average consumption velocity of the pulp flow;
V_{kp} – the critical velocity of hydraulic transportation [35]-[40].

In formulas (1)-(3), the value Q_S is determined by the selected mining equipment and is a constant within this task, and the value Q_w is determined by the head and rate specification of the water supply system and may change when passing from map to map, as well as when passing to a new alluviation layer. It can be seen from formulas (1)-(3) that, as the value Q_w changes, not only the pulp consumption, but also its concentration will change. Thereby, the operating mode and the type of a slurry delivered to the processing plant can be changed.

Thus, it is necessary to estimate the values of the specific water flowrate for pulp formation, at which the type of hydraulic mixture and its flow regime along the main pipeline will be changed.

3. Substantiation of delimitations for the pulp preparation unit

Appropriate delimitations on the specific water flowrate for pulp formation, at which the type of hydraulic mixture will be changed (Table 2). Considering together with the formula for C from (2) and the dependences, we obtain:

$$C_m = 0.2\frac{Ar+1}{Ar};\; C_P = \frac{1}{1+\dfrac{2.33}{Ar+1}};\; C_L = \frac{1+Ar}{\dfrac{3.33}{2-P_{0.1}}+Ar},$$

where:

C_m – the limiting value of mass concentration for low-concentrated pulps [35], [41]-[43];

C_p – the limiting value of mass concentration for mean-concentrated pulps [43];

C_L – the maximum possible mass concentration of hydraulic mixture, corresponding to dense packing of solid particles [39]-[44];

$P_{0.1}$ – the fraction in the transported material of particles with a diameter less than 0.1 mm [45]-[48].

Table 2. Delimitations of q values for pulps of different types

Pulp classification by concentration	Delimitations of q values	Limiting value of q parameter
Low concentration	$q_m < q$	$q_m = 4Ar - 1 - v$
Mean concentration	$q_P < q < q_m$	$q_P = 3.33 - 1 - v$
High concentration	$q_L < q < q_P$	$q_L = 3.33/(2 - P_{0.1}) - 1 - v$

In addition, for each type of hydraulic mixture, the certain dependences will be used to calculate the critical velocity for hydraulic transportation, as well as the formulas that predetermine various dependences for the pipeline diameter choice [35], [41]. The diameter of the pipeline providing the supply of the mined technogenic placer to the processing plant is chosen from the condition that at a given pulp flowrate the higher critical velocity of the flow will be provided:

$$Q = KV_{kp}\frac{\pi D^2}{4}, \tag{4}$$

where:

D – the diameter of the pipeline;

K – the parameter of hydraulic transportation, $K > 1$ [35].

It should be noted, that for low-concentrated pulps, the critical velocity of hydraulic transportation with account of the dependence of the relative pulp density on the indicators of the pulp formation process (2), is determined by the formula:

$$V_{kp} = 15\sqrt[3]{D}\sqrt[4]{w}\left(0.6+\frac{Ar}{1+v+q}\right),$$

taking this into consideration, as well as dependences (1), the value of the pipeline critical diameter will be:

$$D_{kp} = \left(\frac{ArQ_S}{4.24K\sqrt[4]{w}}\right)^{\frac{3}{7}}\left(\frac{x^2}{x+1}\right)^{\frac{3}{7}};\; x = \frac{0.6}{Ar}(1+v+q), \tag{5}$$

where:

D_{kp} – the critical diameter of the pipeline;

x – the value characterizing the dependence of the critical diameter on the parameters of the pulp formation process.

The value of the critical diameter is restricted by the values of the pipeline diameters, from the existing range, for which the regime of the hydraulic mixture flow will be supercritical. It is seen from the formula (5), that the critical diameter value is determined by the product of two terms – the first one takes into account the effect of the mining complex productivity, and the second – the dependence on the pulp preparation system parameters. To study this dependence, the formula (5) should be written in the following form:

$$\delta = \left(\frac{x^2}{x+1}\right)^{\frac{3}{7}};\; \delta = \frac{D_{kp}}{D_*};\; D_* = \left(\frac{ArQ_S}{4.24K\sqrt[4]{w}}\right)^{\frac{3}{7}}, \tag{6}$$

where:

δ – the relative critical diameter;

D_* – the fictitious technological diameter of the pipeline [35], [42]-[44].

The study of dependence (6) by methods of computational mathematics made it possible to offer the following approximation for a rational range of the pulp formation parameter changes:

$$\delta = 0.712x^{0.62}. \tag{7}$$

Thus it follows, that when there are more than five values of the pulp preparation parameter, that is, for low-concentrated pulps (Table 2), the following approximate formulas are valid:

$$x = q\frac{0.6}{Ar};\; \delta = 0.64\left(\frac{q}{Ar}\right)^{0.62}.$$

By the given parameters of the mining complex and the system of pulp preparation with the use of formulas (6) and (7), the critical pipeline diameter is determined, according to which the nearest smaller diameter is selected from the pipe assortment. After that, the density and concentration of the hydraulic mixture, the critical velocity of hydraulic transportation are calculated, and then, fixing these values, the hydraulic slope and the possible pulp supply are determined. The resulting supply value is compared with the value of the pulp supply, calculated by the formula (1). If the difference between the obtained values satisfies the calculation accuracy, then the calculations are terminated, if not, then the value q should be changed and the calculation is repeated anew.

Such an algorithm is not suitable for practical calculations in a production environment, as it involves an iterative calculation process, and the convergence of the computational process is dependent on the presence of certain pipes in the assortment. It is possible to simplify the use of formulas (6) and (7) in the case when the calculated values of the critical diameter would be in the range of used pipes. Then, it is possible to get the dependence of the value q on the relative critical diameter. The expression (6) after the change of variable is converted to a quadratic equation, the solution of which is as follows:

$$q = bD_{kp}^{\frac{7}{3}}\left[\sqrt{1+B}-1\right]-(1+v);$$

$$B = \frac{0.943ArQ_S}{K\sqrt[4]{w}D_{kp}^{\frac{7}{3}}}; \tag{8}$$

$$b = \frac{K\sqrt[4]{w}}{0.823Q_S},$$

and the expression (7) is converted to the formula:

$$q = 6.829Ar^{0.922}b^{0.691}D_{kp}^{1.613}-(1+v).$$

Having substituted the dependence (8) into the formulas (1)-(3), the expressions can be obtained for determining the parameters of pulp supplied from the designed unit of pulp preparation:

$$Q = abD_{kp}^{\frac{7}{3}};$$

$$Q_w = abD_{kp}^{\frac{7}{3}}-(1+v)Q_S;$$

$$\rho = 1+\frac{B}{a}; \tag{9}$$

$$C = \frac{Ar+1}{Ar+abD_{kp}^{\frac{7}{3}}};$$

$$a = \sqrt{1+B}-1.$$

4. Substantiation of dependences for calculating the critical velocity of hydraulic transporting the mean-concentrated pulp

In the formulas obtained, the diameter of the pipe existing in the assortment, which is rounded off to the nearest whole number is used as the critical diameter.

For pulps with mean concentration, the value of the critical velocity is somewhat reduced compared to the value it reaches at a concentration of C_m, and for the calculations with account of the dependence of the relative density of the pulp on the indicators of the pulp formation process (3), it is recommended to use the following formula [35]-[40]:

$$V_{kp} = 12.8\sqrt[3]{D}\sqrt[4]{w}\sqrt[3]{1+\frac{1+v+q}{Ar}}, \tag{10}$$

taking this into consideration, as well as dependences (1), it is recommended to use instead of the above formulas for calculating the critical diameter of the pipeline:

$$\delta = \left(\frac{x^3}{x+1}\right)^{\frac{1}{7}};$$

$$x = \frac{1+v+q}{Ar}; \tag{11}$$

$$D_* = \left(\frac{0.0995ArQ_S}{K\sqrt[4]{w}}\right)^{\frac{3}{7}}.$$

The form of the approximation function and the simplified formulas will be preserved, only the coefficients included into them will be changed:

$$\delta = 0.901x^{0.33};$$

$$x = \frac{q}{Ar};$$

$$\delta = 0.901\left(\frac{q}{Ar}\right)^{0.33}.$$

For the case of mean-concentrated pulps, the formula of the form (9) and (10) is invalid, since unlike the formula (6), when solving the dependence (11), a cubic equation is obtained relative to x from δ, and its solution form is determined by the discriminant sign:

$$x = \begin{cases} \sqrt[3]{\frac{\delta^7}{2}}\left[\sqrt[3]{1+\sqrt{1-\frac{4\delta^7}{27}}}+\sqrt[3]{1-\sqrt{1-\frac{4\delta^7}{27}}}\right], & \delta^7 < \frac{27}{4}; \\ \sqrt{\frac{4\delta^7}{3}}\cos\left[\frac{1}{3}\arccos\left(\sqrt{\frac{27}{4\delta^7}}\right)\right], & \delta^7 \geq \frac{27}{4}, \end{cases}$$

and the expression for the specific flowrate of water for pulp formation process is converted to the formula:

$$q = 1.372Ar\delta^{3.03}.$$

5. Substantiation of dependences for calculating the critical velocity of hydraulic transporting the highly-concentrated pulp

For pulps with high concentration, the concept of critical velocity of hydraulic transportation is absent. For such pulps, the value of the critical pressure drop at the ends of the pipeline is considered, at which the acting forces resist the force caused by the initial shearing stress (ISS) and the slurry begins moving [39], [43]-[44]:

$$\frac{4\tau_0 L}{D\Delta P} < 1,$$

where:

ΔP – the acting pressure drop;

L – the pipeline length.

Since for the considered hydraulic transport installations, the acting pressure drop is created by the geodesic difference:

$$\Delta P = \rho\rho_W gZ,$$

then the above formula takes the following form:

$$\frac{4\tau_0}{\rho_W gD} < \rho\frac{Z}{L},$$

where:

Z – the geodesic elevation difference of the beginning and end of the main pipeline.

Thereby, the critical diameter of the pipeline will be:

$$D_{kp} < D;\ D_{kp} = \frac{4\tau_0}{\rho_W g} \cdot \frac{L}{\rho Z}. \qquad (12)$$

It can be seen from formula (12), that for highly-concentrated pulps the actual diameter of the pipeline should be higher than the critical one, unlike the pulps with low and mean concentration, for which the actual diameter should be less than the critical one.

With account of the research results of the specialists from the Institute of Geotechnical Mechanics of National Academy of Sciences in Ukraine [39], [40], [48]-[52] and foreign scientists [43] on the study of the ISS dependence on the pulp concentration [48],[52], [53]:

$$\tau_0 = K_\tau \ln\left(k_\tau C\right),$$

and also dependences (1)-(3), we obtain the following expression for calculating the relative critical diameter of the pipeline for highly-concentrated pulps:

$$\delta = \left(1+y\right)\ln\left(\kappa y\right);\ y = \frac{Ar}{Ar+1+q+\nu};$$
$$\kappa = \frac{Ar+1}{Ar}k_\tau;\ D_* = \frac{4K_\tau L}{\rho_W gZ}, \qquad (13)$$

where:

K_τ, k_τ – the approximation parameters.

The study of dependence (13) by methods of computational mathematics made it possible to offer the following approximation for a rational range of pulp formation parameter changes (Figs. 1-3):

$$\delta = ay + b;\ a = 3.7605\kappa^{0.1272};\ b = 0.7169\kappa^{0.2783}.$$

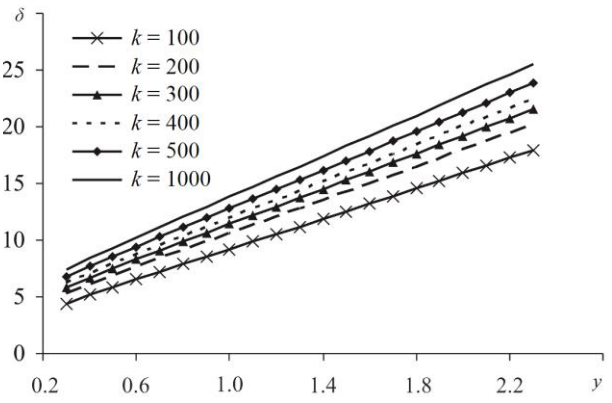

Figure 1. Dependence of the relative critical diameter of the pipeline for highly-concentrated pulps on the value characterizing the parameters of the pulp formation process

Having substituted the expressions for the approximation coefficients into the initial equation, and having made the conversion of the similar summands, we get:

$$\delta = 3.761\left(y + 0.191\kappa^{0.151}\right)\kappa^{0.127}.$$

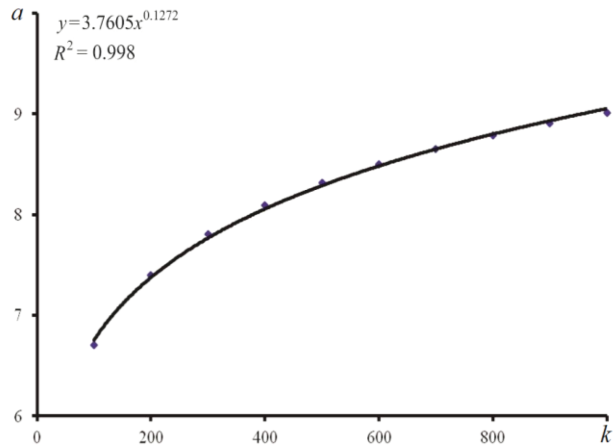

Figure 2. Dependence of the approximation coefficient a on the parameter k

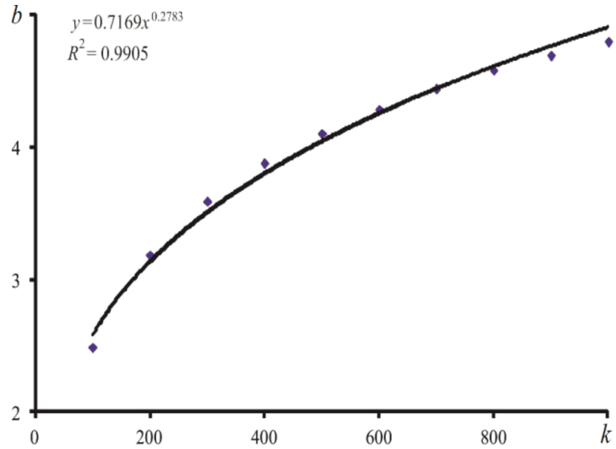

Figure 3. Dependence of the approximation coefficient b on the parameter k

After the replacement of the variable, the last expression is converted into the following dependence to determine the parameter of the pulp formation process:

$$q = \left(\frac{3.761\kappa^{0.127}}{\delta - 0.718\kappa^{0.278}} - 1\right)Ar - \left(1+\nu\right), \qquad (14)$$

and having substituted the dependence (14) into formulas (1)-(3), the expressions can be obtained for determining the parameters of pulp supplied from the designed unit of pulp preparation [54]-[56].

It is evident from the above formulas that, unlike low- and mean-concentrated pulps, the fictitious technological diameter of the pipeline for highly-concentrated pulps depends on the number of the dam being mined, since the values L and Z included into the formula are calculated depending on these parameters of the flood-breaking dams. Having substituted the expressions for L and Z into the formula (13), we obtain the following dependence:

$$D_* = \frac{4K_\tau}{\rho_W g i_Z} \cdot \frac{i_Z}{i_m}\left(1 + \frac{i_m - i_Z}{i_L}\frac{1}{n + \dfrac{i_Z}{i_L}}\right); \qquad (15)$$

$$i_g = \frac{i_m}{k_z}\left(1 + \frac{i_Z - i_m}{i_m + i_L n}\right);\ i_Z = \frac{Z_0}{L_0};\ i_L = \frac{h}{L_0};$$
$$i_m = \frac{1}{\beta + m};\ \beta = \frac{b}{h};\ m = \frac{1}{\sin\alpha},$$

from which it follows that the influence of the dam number on the value D_* will be less than 10%, starting from a layer, the number of which is determined by the formula:

$$n_0 = 0.1\frac{i_L}{i_m}\left(1 + \frac{i_Z - i_m}{k_z \dfrac{i}{\rho} - i_Z}\right),$$

where:

k_z – a coefficient of local hydraulic losses;

L_0 – the length of the horizontal pipes sections, which are laid in parallel to the perimeter of the waste dump along the dams, as well as the pipeline length from the persistent dam to the processing plant;

i_g – an effective geodesic slope of the pipeline;

i_L – the relative height of the flood-breaking dam;

i_m – dam profile parameter form;

i_Z – fictitious geodesic slope of the unchanged pipeline part;

n – dam number of the current layer;

β – the relative width of the flood-breaking dam top;

m – outer slope ratio of the flood-breaking dams;

h – the height of the flood-breaking dams;

Z_0 – the geodesic elevations difference of the beginning and end of the pipeline from the persistent dam to the processing plant;

b_0 –the width of the flood-breaking dam top;

α – outer slopes angle of the flood-breaking dams.

It can be seen from formula (15) that, depending on the ratio of values i_m and i_Z, an increase in the order number of the alluviation layer will lead to an increase or decrease in the value D_*. In the case when i_m is higher than i_Z, then with an increase in n the value D_* decreases, and when i_m is lower i_Z – it increases. If these two values are equal to each other or have similar values, then it can be assumed that the considered value D_* does not depend on the number of the current alluviation layer and for the entire period of the WD operation is equal to:

$$D_* = \frac{4K_\tau}{\rho_W g}(\beta + m). \tag{16}$$

When the condition $n \geq n_0$ is satisfied, the expression (16) will take the following form:

$$D_* = \begin{cases} 4.4\dfrac{K_\tau}{\rho_W g}(\beta + m),\ i_m > i_Z; \\ 3.6\dfrac{K_\tau}{\rho_W g}(\beta + m),\ i_m < i_Z. \end{cases}$$

From the above formulas it follows that at the final stage of WD filling, the value D_* does not depend on the number of the current alluviation layer.

6. Determination of the head and rate specifications of the hydrotransport pipeline

The pipeline diameter of the considered hydraulic transportation plants is selected from an assortment of available pipes according to the pipeline critical diameter, and also, based on the main pipeline ability to provide at a such a diameter the specified flowrate from the current alluviation layer, that is, in fact, at a given length and difference in the geodesic elevations of the main pipeline. To do this, it is necessary to construct the HRS of the main pipeline for the studied hydraulic transportation plant, to calculate its parameters for the selected diameter, to find the pulp supply at which the head losses will be equal to the geodesic elevation difference, with account of the relative density of the pulp, and then to compare this value with the required pulp flow rate.

Using the formula to determine the parameter of the hydraulic transportation mode:

$$K = \sqrt[3]{\frac{1.2\sigma}{\rho - 1}\cos^2\alpha},$$

we set in advance the supercritical mode of hydraulic transportation:

$$1 \leq K \leq 2,$$

that allows to choose freely from the assortment the diameter of the pipe, as the velocity margin, conditioned by the homogeneous liquid mode, is much higher than the critical velocity margin, conditioned by the lack of coincidence between the standard pipe diameters and their critical values.

Thus, having substituted the expressions for the critical velocity of hydraulic transportation and K in (4), and having made the appropriate conversions, it is easy to obtain a formula for determining the diameter of the pipeline, which provides the hydraulic mixture flow in the regime of a homogeneous liquid:

$$D = \left(\frac{Q}{\sqrt[4]{w}}\right)^{\frac{3}{7}} \cdot \frac{0.34U}{\sqrt[7]{\cos^2\alpha}};$$
$$U = \sqrt[7]{\frac{\rho - 1}{\rho^{1.5}(1 + 150d) - 1}} \cdot \frac{1}{(\rho - 0.4)^{\frac{3}{7}}}; \tag{17}$$
$$d = \frac{d_{cp}}{D},$$

where:

d – the relative coarseness of transported particles;

U – the value, which accounts the dependence of the pipeline diameter on the relative density of the hydraulic mixture, as well as on the relative coarseness of the transported particles (Fig. 4).

It can be seen from the Figure 4, that the value U varies slightly in the considered range of the relative pulp density, and its value is mainly determined by the value of the relative coarseness of the transported material. Numerical analysis shows that this dependence can be approximated with engineer accuracy by the following function:

$$U = 0.654\left(\frac{D}{d_{cp}}\right)^{0.046},$$

with allowance of which the expression for calculating the pipeline diameter will be:

$$D = \frac{0.207}{d_{cp}^{0.048}\cos^{0.3}\alpha}\left(\frac{Q}{\sqrt[4]{w}}\right)^{0.45}. \qquad (18)$$

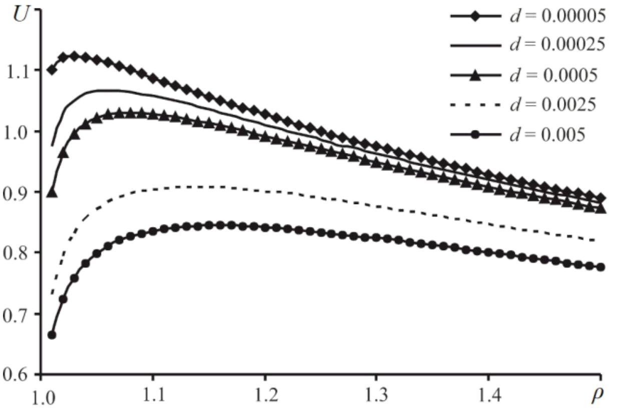

Figure 4. Dependence of the value U on the relative hydraulic mixture density at different values of the relative coarseness of the transported particles ρ

Having substituted the expression (7) into formula (18) and having made simple conversions, we obtain an equation for determining the value q for the pulp flow in the regime of a homogeneous liquid:

$$q = \frac{D^{2.2} d_{cp}^{0.107}\sqrt[4]{w}}{0.03 Q_S}\cos^{0.67}\alpha - (1+v).$$

Having substituted the dependence (18) into formulas (1) and (2), we obtain expressions for determining the parameters of the pulp supplied from the designed unit of pulp preparation in the regime of a homogeneous liquid [49]-[53].

Substituting the formula (18) into the equation for calculating the HRS of the main pipeline and equating it to zero, after simple conversions we obtain an expression for determining the possible flowrate of pulp through the main pipeline in the regime of a homogeneous liquid:

$$Q = \left(w^{0.113} d_{cp}^{0.048}\frac{\cos^{0.3}\alpha}{0.207}\right)^{m_1}\times$$
$$\times\frac{2^{m_2}}{\pi^{m_3}}\left(\frac{k_z N v_w^p}{g}\frac{L_0 + n[\beta + m]h}{Z_0 + nh}\right)^{m_4}; \qquad (19)$$

$$m_1 = \frac{5-p}{m_4};$$

$$m_2 = 2\cdot\frac{1.5-p}{m_4};$$

$$m_3 = \frac{2-p}{m_4};$$

$$m_4 = \frac{p+0.455}{1.82}.$$

Having substituted the expressions (1) into formula (19) and having made simple conversions, we obtain an equation for determining the value q for the flowing of pulp in the regime of a homogeneous liquid with account of the HRS of the main pipeline.

During the flowing of the highly-concentrated pulp, the pipeline departure angle does not affect the hydraulic slope. In the regime of a heterogeneous liquid for such pulps, the hydraulic slope is calculated in accordance with the solution of the Buckingham equation, which makes possible after some conversions to write the expression (4) in the following form:

$$Q = \left(i_g - \frac{c_0\tau_0}{\rho_w g D\rho}\right)\cdot\frac{\rho\rho_w g\pi D^4}{c\eta}, \qquad (20)$$

from which it is evident, that the flowrate of the highly-concentrated pulp will be higher than zero if the condition is being satisfied:

$$i_g > \frac{c_0\tau_0}{\rho\rho_w g D},$$

which means that for the pipeline diameter, besides the critical value conditioned by the pressure drop, formulas (12), there is a critical value conditioned by the hydraulic slope:

$$D > D'_{kp};\ D'_{kp} = \frac{c_0\tau_0}{\rho\rho_w g i_g}, \qquad (21)$$

where:

D'_{kp} – the critical pipeline diameter conditioned by the hydraulic slope.

When comparing the expressions (12) and (21), it is easy to verify that the value D'_{kp} exceeds by 26.38%. Thus, the choice of the pipeline diameter should be made according to the condition (21), which, with account of the corresponding safety factor, can be written in the following form:

$$D = \sigma_D\frac{c_0\tau_0}{\rho\rho_w g i_g}, \qquad (22)$$

where:

σ_D – the safety factor along the pipeline diameter.

Most of the values, included into the formula (20), depend on the hydraulic mixture concentration, so, in addition to the dependences (2) and (22), the following formulas are valid:

$$Q = Q_S\left(\frac{1+Ar}{ArC} - 1\right)Ar;\ \rho = \frac{1}{1 - \frac{Ar}{1+Ar}C};\ \eta = K_\eta e^{k_\eta C},$$

where:

η – the structural viscosity of the slurry;

K_η – the proportionality factor;

k_η – the exponent;

e – the base of the natural logarithm.

Having substituted these expressions into formula (20) and having made the appropriate conversions, we obtain the following equation for calculating the hydraulic mixture concentration, which provides the specified freight flow to the processing plant by gravity flow in a structural mode (Fig. 5):

$$F(x;k) = M;$$

$$M = \frac{(\sigma_D - 1)\sigma_D^3 \pi c_0^4 K_\tau^4}{c\left(\rho_w g i_g\right)^3 Ar Q_S K_\eta};$$

$$F(x;k) = \frac{e^{kx}}{x(1-x)^2 \ln^4(150kx)};$$

$$x = \frac{ArC}{1+Ar};\ k = \frac{1+Ar}{Ar} k_\eta .$$

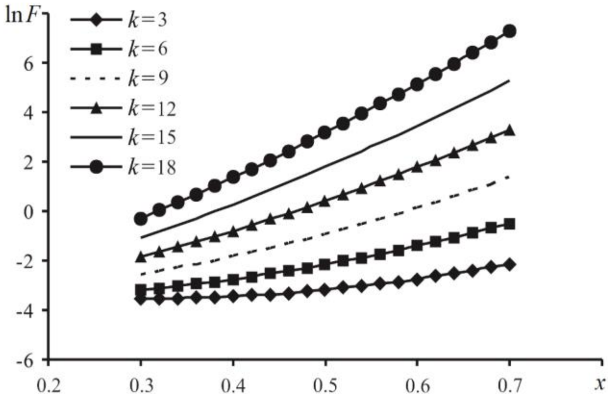

Figure 5. Dependence of the value lnF on x at different values of k

The function $F(x; k)$ is highly non-linear (Fig. 5) and, as it is shown by the results of numerical studies, can be approximated by exponential dependence (Figs. 6, 7):

$$F = A\mathrm{e}^{Bx};\ A = \frac{0.0179}{k^{0.7494}};\ B = 1.2537k^{0.9373}.$$

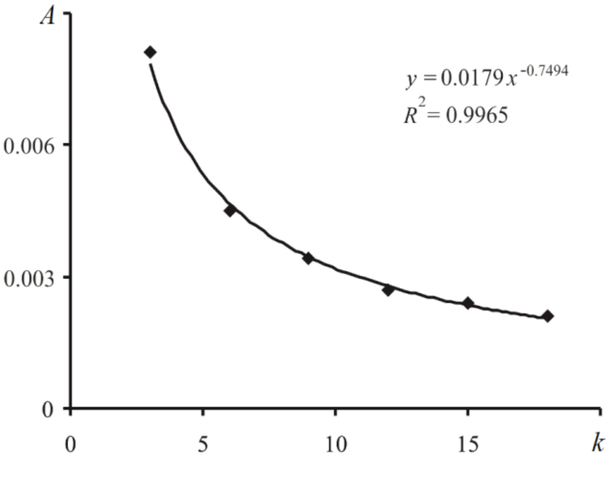

Figure 6. Approximation of the dependence of value A on k

Using the obtained formulas, it is easy to get an expression for determining the required hydraulic mixture concentration:

$$C = \frac{0.798}{k_\eta^{0.937}} \ln\left(\frac{E}{i_g^3}\frac{Q_*}{Q_S}\right);\ Q_* = \frac{c_0^4 K_\tau^4 k_\eta^{0.749}}{\left(\rho_w g\right)^3 c K_\eta};$$
$$E = \frac{(1+Ar)^{0.749}}{Ar^{1.7494}} \cdot \frac{(\sigma_D - 1)\sigma_D^3 \pi}{0.0179}. \qquad (23)$$

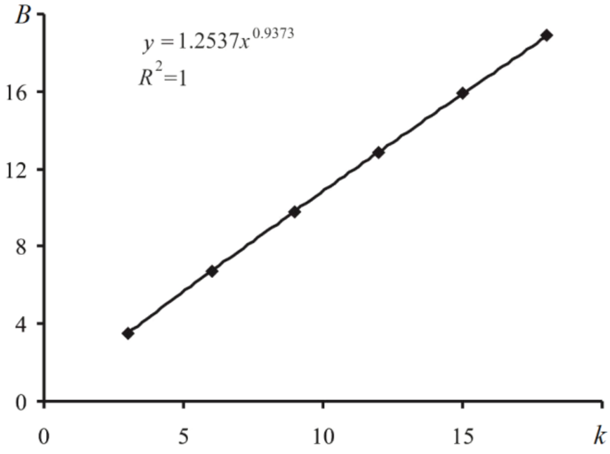

Figure 7. Approximation of the dependence of value B on k

Using the formulas (1), (2) and (23), an expression for calculating the value q can easily be determined:

$$q = (Ar+1)\left(\frac{1.253k_\eta^{0.9373}}{\ln\left(\frac{\Delta E}{i_g^3}\frac{Q_*}{Q_S}\right)} - 1\right) - v,$$

and then with the help of it, by the formulas (1)-(2), to determine all the parameters for the pulp preparation process.

With an increase in the flow velocity, the core of the flow is destroyed. After the complete destruction of the flow core, a turbulent flow regime occurs, in which, according to the well-known recommendations [40], [41], [54]-[57], the hydraulic slope of the pulp will be calculated by the formula:

$$i = 0.059\sqrt[8]{\frac{\eta_T \rho^7 Q^{15}}{g^8 D^{39}}}, \qquad (24)$$

where:

η_T – the Newtonian kinematic coefficient of the slurry viscosity.

As studies of the solution of the complete Buckingham equation [10], [11][11] have shown, the disappearance of the flow core occurs at pulp supply values, subjected to the following condition:

$$Q \geq \frac{25\pi}{8} \cdot \frac{D^3 \tau_0}{\eta}, \qquad (25)$$

that is, the actual pipeline diameter will depend on the flowrate of the slurry:

$$D \leq 0.467\sqrt[3]{\frac{\eta Q}{\tau_0}}. \qquad (26)$$

In the case under consideration, the HRS of the main pipeline can be written in the form, which, after the substitution of the formula (24) makes it possible to obtain an expression for calculating the pulp supply:

$$Q = 1.5\left(g i_g\right)^{\frac{8}{15}} \cdot \sqrt[15]{\frac{\rho}{\eta_T}} D^{\frac{39}{15}}. \qquad (27)$$

Therewith, the condition (25) will be satisfied for the following diameters:

$$D \le 0.07 \sqrt[6]{\frac{\left(g i_g\right)^8}{\eta_T}} \sqrt[6]{\rho} \left(\frac{\eta}{\tau_0}\right)^{\frac{15}{6}} .$$

Inequation (26) from the known parameters of the mining complex and pulp preparation system enables to assess the critical pipeline diameter. The actual pipeline diameter is selected from the pipes assortment like the closest diameter smaller than the critical value. When the pipeline diameter is known, the density and concentration of the hydraulic mixture, the initial shearing stress and the structural viscosity of the suspension can be determined. Thereafter, by the formula (27), the possible hydraulic mixture supply is calculated, the value of which is compared with the regulated supply value. If the difference between the obtained values satisfies the calculation accuracy, then the calculations are terminated, if not, then the value q should be changed and the calculation is repeated anew.

7. Conclusions

Based on the material above, the following peculiarities can be noted of calculating the hydromechanization technologies parameters for mining the technogenic deposits in the waste dumps of mining and processing enterprises when using highly-concentrated pulps.

For highly-concentrated pulps, the actual pipeline diameter should not be less than for low and mean-concentrated pulps, but greater than the critical value. Besides, unlike low and mean-concentrated pulps, the fictitious technological diameter of the pipeline for highly-concentrated pulps depends on the number of the dam being mined. The research results of the pipeline fictitious technological diameter value for highly-concentrated pulps from the number of the dam being mined indicate the complex nature of this dependence. This dependence nature is determined by the ratio of the fictitious geodesic slope of the unchanged pipeline part and the profile parameter forms of the flood-breaking dam. Thus, an increase in the order number of the alluviation layer will lead to a decrease in the fictitious technological diameter value of the pipeline for highly-concentrated pulps, in case when the value of the profile parameter forms of the flood-breaking dam is greater than the fictitious geodesic slope of the unchanged pipeline part. And vice versa, if the value of the profile parameter forms of the flood-breaking dam is less than the fictitious geodesic slope of the unchanged pipeline part, then the value of the fictitious technological diameter of the pipeline for highly-concentrated pulps will increase with increasing the order number of the alluviation layer. If these two values are equal to each other or have close values, then it is possible to assume that the considered value of the fictitious technological diameter of the pipeline for highly-concentrated pulps does not depend on the order number of the current alluviation layer, and for the entire period of the waste dumps exploitation.

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Визначення параметрів технологій гідромеханізації для розробки сховищ як техногенних родовищ

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Мета. Визначення й обґрунтування параметрів технологій гідромеханізації і режимів роботи гідротранспорту для розробки техногенних родовищ, сформованих при складуванні відходів збагачення у хвостосховищах гірничо-збагачувальних комбінатів.

Методика. У роботі використано комплексний багатоетапний аналітичний підхід до проведення дослідження. Першочергово в роботі для обґрунтування параметрів технологій гідромеханізації визначались параметри вузла пульпоприготування, які обмежуються величиною верхнього гребеню дамби з урахуванням типів гідросуміші. На другому етапі встановлювались залежності для розрахунку критичної швидкості гідротранспортування для пульп різної концентрації (низької, середньої і високої). Наступним етапом досліджень було визначення витратно-напірних характеристик гідротранспортної магістралі та необхідна продуктивність гідросуміші, що дозволять обґрунтувати параметри для відповідного заданого видобувного комплексу при розробці техногенних родовищ.

Результати. Встановлено критичний діаметр трубопроводу по заданих параметрах видобувного комплексу і прийнятої системи пульпоприготування. Визначено залежності для розрахунку критичної швидкості гідротранспортування пульп середньої і високої концентрації. Визначено витратно-напірні характеристики гідротранспортної магістралі хвостів збагачення.

Наукова новизна. Вперше встановлено, що величина критичного діаметра визначається добутком двох співмножників, перший з котрих враховує вплив продуктивності видобувної комплексу, а другий – залежність від параметрів системи пульпоприготування, що дозволяє управляти параметрами та режимами технологій гідромеханізації при розробці техногенних родовищ, сформованих у процесі складування відходів збагачення в сховища.

Практична значимість. Розроблено "Рекомендації з обґрунтування параметрів процесів відновлення акумулюючої здатності прудка з використанням засобів гідромеханізації" і "Методики розрахунку параметрів гідротранспортування висококонцентрованих гідросумішей", які можуть бути корисні для проектних організацій та гірничо-металургійних підприємств для забезпечення додаткових обсягів видобутку сировини і збільшення терміну експлуатації хвостосховищ.

Ключові слова: *гідротранспорт, техногенні родовища, гідросуміш, витратно-напірні характеристики, висока концентрація*

Определение параметров технологий гидромеханизации для разработки хранилищ как техногенных месторождений

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Цель. Определение и обоснование параметров технологий гидромеханизации и режимов работы гидротранспорта для разработки техногенных месторождений, сформированных при складированиии отходов обогащения в хвостохранилищах горно-обогатительных комбинатов.

Методика. В работе использован комплексный многоэтапный аналитический подход к проведению исследования. Первоначально в работе для обоснования параметров технологий гидромеханизации аналитически определялись параметры узла пульпоприготовления, которые ограничиваются величиной верхнего гребня дамбы с учетом типов гидросмеси. На втором этапе устанавливались зависимости для расчета критической скорости гидротранспортирования для пульп разной концентрации (низкой, средней и высокой). Следующим этапом исследований было определение расходно-напорных характеристик гидротранспортной магистрали и требуемой производительности гидросмеси, которые позволят обосновать параметры для соответствующего добычного комплекса при разработке техногенных месторождений.

Результаты. Установлен критический диаметр трубопровода по заданным параметрам добычного комплекса и принятой системы пульпоприготовления. Определены зависимости для расчета критической скорости гидротранспортирования пульп средней и высокой концентрации. Определены расходно-напорные характеристики гидротранспортной магистрали хвостов обогащения.

Научная новизна. Впервые установлено, что величина критического диаметра определяется произведением двух сомножителей, первый из которых учитывает влияние производительности добычного комплекса, а второй – зависимость от параметров системы пульпоприготовления, что позволяет управлять параметрами и режимами технологий гидромеханизации при разработке техногенных месторождений, сформированных в процессе складирования отходов обогащения в хранилища.

Практическая значимость. Разработаны "Рекомендации по обоснованию параметров процессов восстановления аккумулирующей способности прудка с использованием средств гидромеханизации" и "Методики расчета параметров гидротранспортирования высококонцентрированных гидросмесей", которые могут быть полезны для проектных организаций и горно-металлургических предприятий для обеспечения дополнительных объемов добычи сырья и увеличения срока эксплуатации хвостохранилищ.

Ключевые слова: *гидротранспорт, техногенные месторождения, гидросмесь, расходно-напорные характеристики, высокая концентрация*

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