MATHEMATICAL MODELS OF THE NODE OF TECHNOGENIC INFLUENCE, TAKING INTO ACCOUNT THE MAIN DIRECTIONS OF MATERIAL FLOWS IN THE LOGISTICS OF MINING ENTERPRISES

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ABSTRACT. The aim of the work is to create a mathematical model of liquid waste storage that accumulates processed products and mine waters simultaneously from many mining and processing plants, taking into account technological constraints on waste volumes and climatic factors depending on the season. The proposed mathematical model of node of technogenic influence is based on the balance of material flows in and out the node. A typical node of technogenic influence is an accumulation node. In the problem considered in this paper, the accumulation node is a waste storage facility where liquid man-made deposits are stored. The model of this node includes a system of equations describing the height of the water mirror and the bottom level depending on the volume of placers and water in and out for the analysed period of operation, taking into account the geometric features of the storage. The main directions of material flows can be formed from two or three nodes of technogenic influence. The first case is typical for underground mining, and the second one is typical for open pit mining. In the second case, the main direction is formed from the node of extraction of primary deposits, the node of processing or separation, and the node of accumulation or the node of storage of man-made deposits. The mathematical model makes it possible to determine the level of the free surface mirror in any month of the year, as well as to calculate the change in the current height of the water mirror in storage for any period of the year, such as spring months or all year round.

Key words: node of technogenic influence, liquid waste storage.

Introduction

According to the research results of hydraulic systems logistics, it is determined that some of their nodes perform a leading and system-creating function (Semenenko, 2011). A system of material flows is created around such nodes, and other logistics and production subsystems play an additional function and ensure the continuity of material flows operation. Such nodes are formed together with the mining enterprise, developing together with it, but after the closure of the enterprise the nodes need further maintenance, as a technogenic load on the environment.

Some experts (Kovalskýa and Mičieta, 2017; Bulat et al., 2020; Espinoza et al., 2020; Petrova, 2021) suggest to name such logistics nodes as nodes of technogenic influence. Examples of such nodes are places of accumulation of mine waters, quarry dumps, mineral waste, and reverse fluid reservoirs. Nodes of technogenic influence create the main direction of material flows through consistent connections with each other. The main volumes of ore, primary and man-made placers, technical and return fluid, labour force, equipment and machinery for mining work move along this main direction. Perpendicular to the main direction, relatively speaking, there are material flows that move commodity concentrates, finances, additional raw materials, energy, etc.

The main directions of material flows can be formed from two or three nodes of technogenic influence (Kovalskýa and Mičieta, 2017; Bulat et al., 2020; Espinoza et al., 2020; Brodt, 2023). The first case is typical for underground mining, and the second one is typical for open pit mining. In the second case, the main direction is formed from the node of extraction of primary deposits, the node of processing or separation, and the node of accumulation or the node of storage of man-made deposits. In the first case, the node of extraction of primary deposits is considered absent, because underground mining has almost no man-made effects on the surface.

The places of accumulation of mine waters and storages of the liquid waste from ores enrichment, so-called storage of industrial waste (SIW) are the most threatening technogenic impact on the environment of Prydniprovsk region. In most cases, the liquid stored in these storages has high acidity and contains harmful chemicals and heavy metals, which makes it impossible to dispose industrial waste in any of the known ways. However, without SIW, the mining enterprises of the region cannot operate, so, SIW have high social significance and impact on sustainable development (Bulat et al., 2020; Petrova, 2021; Collivignarelli et al., 2022).

The enterprises of Prydniprovsk region, like the mines of Kuzbass and Western Donbass, are characterised by joint operation of the place of accumulation of mine waters and storage of the liquid waste from ores enrichment, when several mining enterprises drain liquid waste and mine water into one liquid waste storage. At the time of putting into service, these storages were able to accumulate the significant volumes, but at the beginning of the XXI century, when the volume of liquid coming from enterprises increased and free volume of the storage decreased, quotas began to be introduced for storage of liquid technogenic waste.

The volume of mine waters to be stored on the surface and the volume of the liquid waste from ores enrichment is directly proportional to the amount of primary minerals extracted, and is determined by the mining and geological conditions of the deposit and the features of mining and processing technology. Increasing the depth of mineral extraction and increasing the

production capacity of mining enterprises steadily lead to an increase in the storage of liquid technogenic waste on the surface. The storage capacity of these waste facilities is limited by the volume of existing storages, as the construction of new ones is impossible and the construction of dams is environmentally unsafe. The only way to renew the storage capacity is to discharge some liquid waste into rivers every year during floods in the three spring months (Kovalskýa and Mičieta, 2017; Bučkováa et al.,2019; Espinoza et al.,2020; Petrova, 2021;). So, today the capacity of mining enterprises and their stable operation are limited by the ability of waste storage to accept liquid technogenic deposits.

This situation is unforeseen and has arisen due to certain circumstances, so the management of liquid waste for each enterprise in the region is "random", "manual" and "by mutual agreement". That is, today there are no models for the operation of such logistics systems and scientific methods for determining parameters that can ensure environmentally friendly operation of mining enterprises in the industrial region.

The aim of this paper is to create a mathematical model of liquid waste storage that accumulates processed products and mine waters from some mining enterprises, taking into account technological constraints on waste volumes and climatic factors. Additionally, this mathematical model is aimed to determine the level of free surface mirror in any month of the year.

Model development and approbation

The mathematical models of node of technogenic influence are based on the balance of material flows in and out the node. A typical node of technogenic influence is an accumulation node (Ilchev and Davcheva–Ilcheva, 2021; Andreas et al., 2021). Its model includes a system of equations describing the height of the water mirror and the bottom level depending on the volume of technogenic placers and water in and out for the analysed period of operation, taking into account the geometric features of the liquid waste storage. In this case, by analogy with the terms used in the calculation of water storage dams, the integral volume of solid particles accumulated during operation of the storageis called sediment load, the corresponding volume of water is called liquid effluent and the following equations can be used (Bučkováa et al., 2019; Kaykov and Koprev, 2020; Bulat et al., 2020; Ge Heet al., 2020):

$$G = m\int_0^{H_S} F_S(z)dz \tag{1}$$

$$W = \int_0^{H_W} F_w(z)dz + (1-m)\int_0^{H_S} F_S(z)dz$$

$$G = \int_0^{T} Q_X^S(t)dt - W_0^S \tag{2}$$

$$W = \int_0^{T} Q_X^W(t)dt + \int_0^{T} Q_{OS}^W(t)dt - \int_0^{T} Q_{lS}^W(t)dt - W_0^W$$

where G – volume of sediment load in accumulation node, m^3; W – volume of liquid effluent in accumulation node, m^3; T– current period of operation; Q_X^S – consumption of solid particles entering the storage with waste; Q_X^w – consumption of water, entering the storage with processing waste; Q_{OS}^W – generalised precipitation flow; Q_{lS}^W – generalised liquid consumption from the surface of SIW due to evaporation; W_0^W – the volume of clarified water from the accumulation node; W_0^S – the volume of technogenic placers taken from the accumulation node; t – time; m – porosity of enrichment waste after warehousing; H_S – the height of the current bottom, the interface between the solid and liquid phases; $F_S(z)$ – function that describes the dependence of current cross-sectional area of the accumulation node occupied by solid fraction on the height of the water mirror; H_W – current height of water mirror (or free water surface in SIW); $F_W(z)$ – function that describes the dependence of current cross-sectional area of the accumulation node occupied by liquid fraction on the height of the water mirror; z– depth of SIW.

The values in formulas (1) and (2), according to literature (Bučkováa et al.,2019; Kaykov and Koprev, 2020; Bulat et al., 2020; Ge Heet al., 2020; Batur andBabii, 2022), are determined by the following equations:

$$Q_{OS}^W(t) = 2{,}31\cdot 10^{-8} q_{OS} F_w(H_W(t)) \tag{3}$$

$$Q_X^W = (1 - C_0'(t))Q_{OF}(t),$$

$$Q_{lS}^W(t) = 0{,}007\Sigma_+ F_w(H_W(t)), \tag{4}$$

$$Q_X^S(t) = C_0'(t)Q_{OF}(t), W_0^S = C_P W_0^W,$$

where C_0' – the volumetric concentration of the hydraulic mixture coming from processing plant (PP); Q_{OF} – consumption of industrial waste (IW) entering the storage; q_{OS} – precipitation rate for this region (Table 1) (Patterson et al., 2016; Bučkováa et al., 2019; Ge He et al., 2020; Batur and Babii, 2022;); $\sum_+$ – sum of air temperature norms for the months of the warm period of the year; C_P – the maximum allowable volume concentration of solid particles in the liquid extracted from the SIW.

Table 1. *Climatic characteristics of the Dnipro region*

The month of the year	Precipitation rate, mm
January	43
February	35
March	33
April	37
May	44
June	59
July	53
August	38
September	37
October	33
November	42
December	46

Considering formulas (1) and (2) together with (3) and (4), we obtain the following equations for modeling the accumulation node parameters:

$$(1-m)\int_0^{H_S} F_S(z)dz = \int_0^{T} Q_X^S(t)dt - W_0^S; \tag{5}$$

$$\int_0^{H_W} F_w(z)dz + m\int_0^{H_S} F_S(z)dz = \int_0^{T} Q_X^W(t)dt + \int_0^{T} Q_{OS}^W(t)dt - \int_0^{T} Q_{lS}^W(t)dt - W_0^W. \tag{6}$$

Given that the concentration of solid particles in the liquid waste from ores enrichment does not exceed 5 % by weight, and that in the liquid entering the storage of acidic waters the concentration is even less (Bulat et al., 2020), the second integral in the left part of formula (6) can be replaced by the right part of formula (5). After the corresponding transformations, we obtain the following equation:

$$\int_0^{H_W} F_w(z)dz = W_{OF} - W_{AT} - W_E; \quad (7)$$

$$W_E = \left(1 - \frac{m}{1-m} C_P\right) W_0^W;$$

$$W_{OF} = \int_0^T \left(1 - \frac{C_0'(t)}{1-m}\right) Q_{OF}(t)dt; \quad (8)$$

$$W_{AT} = 0{,}007\Sigma_+ \int_0^T \left(1 - \frac{\alpha_* q_{OS}}{\Sigma_+}\right) F_w(H_W(t))dt;$$

where W_{OF} – the volume of liquid technogenic waste that comes to storage from mining enterprises; W_{AT} – the volume of liquid, which comes to storage from the atmosphere; W_E – the volume of liquid technogenic waste, which is removed from storage during the spring months; α_* – the coefficient of proportionality equal to 0.0004 (Bulat et al., 2020).

The value of IW consumption entering the storage used in formulas (7) and (8) is calculated according to the capacity of all mining companies that send liquid waste to the storage, as follows:

$$Q_{OF}(t) = \sum_{i=1}^{N} Q_{OF}^{(i)}(t); \qquad Q_{OF}^{(i)}(t) = \mu_i G_{OF}^{(i)}(t), \quad (9)$$

where i– serial number of the i-th mining enterprise that directs liquid waste to storage; μ_i – coefficient of processability of the i-th mining enterprise that directs liquid waste to storage; $G_{OF}^{(i)}$ – capacity of the i-th mining enterprise for saleable concentrates; N – number of mining enterprises, that direct liquid waste to storage.

The coefficient of processability of mining enterprise shows how many cubic meters of liquid enrichment waste and mine waters are generated during the production of one ton of saleable concentrate, and integrally characterises the efficiency of the technology used. For more advanced and efficient technologies, the value of this coefficient is less, due to which mining enterprises have the opportunity to make more profit by storing the same amount of liquid waste compared to enterprises with higher value of this coefficient.

Considering formulas (5) - (8), taking into account (9), with a frequency of one month, to calculate the current height of the water mirror, we can use the following recurrent formulas:

$$\int_{H_W^{(i-1)}}^{H_W^{(i)}} F_w(z)dz = \left(1 - \frac{C_0'}{1-m}\right) Q_{OF}^{(i)} t_i - k_{AT}^{(i)} \int_{T_{i-1}}^{T_i} F_w(H_W)dt - W_E \frac{i}{3} \delta(i,1,3) \quad (10)$$

$$\delta(k,i,j) = \begin{cases} 1, & i \le k \le j \\ 0, & k < i, \quad k > j \end{cases}; \quad (11)$$

$$T_i = \sum_{j=1}^{i} t_j; \qquad k_{AT}^{(i)} = 0{,}007\Sigma_+ \left(1 - \frac{\alpha_i}{\Sigma_+}\right),$$

where $k_{AT}^{(i)}$ – the parameter that takes into account the impact of precipitation (Table 2) (Bulat et al.,2020); α_i – the value of norms of air temperatures for the month; δ – the function of determining the interval of floods on the local rivers; T_i – the time interval.

In the calculations according to formulas (10) and (11), the initial value of the current height of the water mirror $H_W^{(0)}$ is considered equal to the height of the water mirror at the end of February.

Table 2. *Values of α_i during the year for the Dnipro region (Bulat et al.,2020)*

The month of the year	The month number	Value
January	1	0.013
February	2	0.015
March	3	0.018
April	4	0.024
May	5	0.021
June	6	0.015
July	7	0.015
August	8	0.013
September	9	0.017
October	10	0.018
November	11	0.017
December	12	0.014

The use of formulas (10) and (11) means determining the type of function $F_w(z)$, which describes the dependence of the current cross-sectional area of the accumulation node occupied by the liquid fraction on the height of water mirror. The results of the analysis of scientific studies of local researchers (Bulat et al., 2020) indicate several possible functions that describe the surface of the internal slopes of storage of liquid technogenic waste (Table 3).

Table 3. *Formulas for calculating the right side of equation (10) for different types of function $F_w(z)$*

Type of Function	Formulas for calculation $\int_{H_W^{(i-1)}}^{H_W^{(i)}} F_w(z)dz$
$F_w(z) = a$	$a\left(H_W^{(i)} - H_W^{(i-1)}\right)$
$F_w(z) = a + bz$	$a\left(H_W^{(i)} - H_W^{(i-1)}\right) + \frac{b}{2}\left(H_W^{(i)2} - H_W^{(i-1)2}\right)$
$F_w(z) = a + b\sqrt[n]{z}$	$a\left(H_W^{(i)} - H_W^{(i-1)}\right) + \frac{bn}{1+n}\left(H_W^{(i)\frac{1+n}{n}} - H_W^{(i-1)\frac{1+n}{n}}\right)$
$F_w(z) = a + bz^n$	$a\left(H_W^{(i)} - H_W^{(i-1)}\right) + \frac{b}{1+n}\left(H_W^{(i)1+n} - H_W^{(i-1)1+n}\right)$
$F_w(z) = a + b\mathrm{e}^{cz}$	$a\left(H_W^{(i)} - H_W^{(i-1)}\right) + \frac{b}{c}\left(\mathrm{e}^{cH_W^{(i)}} - \mathrm{e}^{cH_W^{(i-1)}}\right)$
where a, b, c – approximation constants; n – degree indicator	

As can be seen from other types of function, the first type of the function from Table 3, is a part of the others since it describes the volume of the main part of the storage, which does not change with the height of the water mirror (Figure 1). Therefore, the parameter of approximation *a* is equal to the area of the bottom of the storage, and can be represented as follows (Figure 2):

$$a = kR^2 , \quad (12)$$

where k – the coefficient of geometric shape of perimeter of the storage, for square is 1, and for a circle – 3.14; R – the nominal storage radius of the bottom (Figures 1, 2).

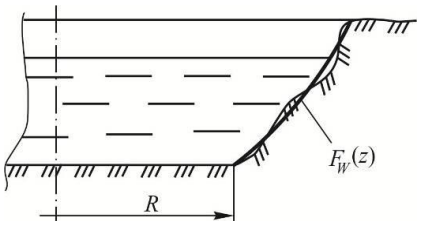


Fig. 1. The structure of internal slope of the storage

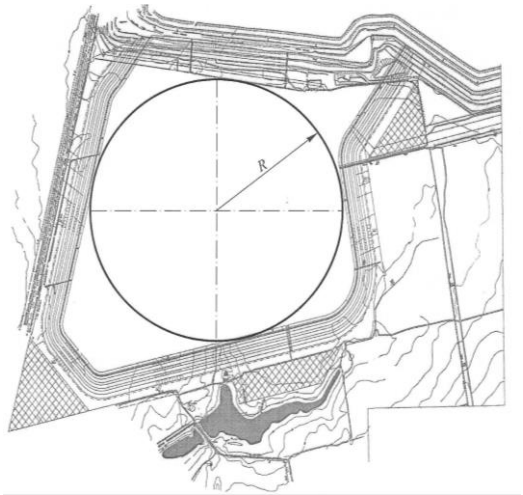


Fig. 2. Scheme of the storage of industrial waste for the calculation of parameter *a* (Table 3)

The parameters of the storage of liquid technogenic waste at Kryvbas mining enterprises, presented in the studies (Bulat et al., 2020), clearly indicate the possibility for introducing the following postulate for these tasks solving (Table 4):

$$\frac{\max\{H_W\}}{R} << 1 , \quad (13)$$

where $\max\{H_W\}$ – the maximum possible value of current height of water mirror in the storage.

Taking into account the formula (12), the data from Table 4 and the probable estimate (13), as well as the records of the formulas from Table 3 in the forms given in Table 5, it can be said that for calculations with engineering accuracy we can use the following in equation (10):

$$\int_{H_W^{(i-1)}}^{H_W^{(i)}} F_w(z)dz \approx 1{,}1a\left(H_W^{(i)} - H_W^{(i-1)}\right); \quad (14)$$

$$\int_{T_{i-1}}^{T_i} F_w\left(H_W(t)\right)dt = at_i .$$

Replacing formulas (14) in equation (10), and performing the corresponding transformations, we obtain the dependence for calculating the change in the current height of the water mirror in the storage relative to the previous value:

$$H_W^{(i)} = H_W^{(i-1)} + \left(1 - \frac{C_0'(t)}{1-m}\right)\frac{Q_{OF}^{(i)}}{1{,}1a}t_i - \frac{k_{AT}^{(i)}}{1{,}1}t_i - \frac{W_E}{1{,}1a}\frac{i}{3}\delta(i,1,3) , \quad (15)$$

Formula (15) focuses on calculating the change in the current height of the water mirror in storage for one month, but based on this formula one can get dependencies for calculating the change in the current height of water mirror in storage for any time of year, such as spring or all year:

Table 4. *Parameters of liquid technogenic waste storages of Kryvbas mining enterprises (Bulat et al.,2020)*

Storage	Dam height, m	Bottom area, ha	*R*, m		H_w/R	
			k =1,00	*k* =3,14	*k* =1,00	*k* =3,14
«Voikoho» Pivdennyi mining and processing complex	50	250	1581	892	0.032	0.056
	74	250	1581	892	0.047	0.083
«Obiednane» Pivdennyi mining and processing complex	40	350	1871	1056	0.021	0.038
«Obiednane» Arcelor Mittal	59	550	2345	1323	0.025	0.045
«Myroliubivske» Arcelor Mittal	55	324	1800	1016	0.031	0.054
Pivdennyi mining and processing complex	76	1293	3596	2029	0.021	0.037
mine «Pivnichna» named after V.A. Valavko	10	300	1732	977	0.006	0.010

Table 5. *Formulas for calculation the right-hand side of equation (10) for different types of function $F_w(z)$*

Type of function	Formulas for calculation $\int_{H_W^{(i-1)}}^{H_W^{(i)}} F_w(z)dz$
kR^2	$kR^2\left(H_W^{(i)} - H_W^{(i-1)}\right)$
$kR^2\left(1+\frac{b}{kR^2}z\right)$	$kR^2\left(H_W^{(i)} - H_W^{(i-1)}\right)\left[1+\frac{b}{2kR^2}\frac{H_W^{(i)2} - H_W^{(i-1)2}}{H_W^{(i)} - H_W^{(i-1)}}\right]$
$kR^2\left(1+\frac{b}{kR^2}\sqrt[n]{z}\right)$	$kR^2\left(H_W^{(i)} - H_W^{(i-1)}\right)\left[1+\frac{n}{1+n}\frac{b}{kR^2}\frac{H_W^{(i)\frac{1+n}{n}} - H_W^{(i-1)\frac{1+n}{n}}}{H_W^{(i)} - H_W^{(i-1)}}\right]$
$kR^2\left(1+\frac{b}{kR^2}z^n\right)$	$kR^2\left(H_W^{(i)} - H_W^{(i-1)}\right)\left[1+\frac{1}{1+n}\frac{b}{kR^2}\frac{H_W^{(i)1+n} - H_W^{(i-1)1+n}}{H_W^{(i)} - H_W^{(i-1)}}\right]$
$kR^2\left(1+\frac{b}{kR^2}e^{cz}\right)$	$kR^2\left(H_W^{(i)} - H_W^{(i-1)}\right)\left[1+\frac{b}{kR^2c}\frac{e^{cH_W^{(i)}} - e^{cH_W^{(i-1)}}}{H_W^{(i)} - H_W^{(i-1)}}\right]$

$$H_W^{(4)} = H_W^{(0)} + \frac{cQ_{1,4}}{1{,}1a} - \frac{k_{1,4}}{1{,}1} - \frac{W_E}{1{,}1a}; \quad (16)$$

$$H_W^{(12)} = H_W^{(0)} + \frac{cQ_{1,12}}{1{,}1a} - \frac{k_{1,12}}{1{,}1} - \frac{W_E}{1{,}1a};$$

$$c = 1 - \frac{C_0'}{1-m};\ \ Q_{i,j} = \sum_{k=i}^{j} Q_{OF}^{(k)} t_k\ ;\ k_{i,j} = \sum_{k=i}^{j} k_{AT}^{(k)} t_k\ , \quad (17)$$

where $H_W^{(4)}$ – the height of water mirror in storage after the spring months; $H_W^{(12)}$ – the height of water mirror in storage in early March of current year; $H_W^{(0)}$ – the height of water mirror in storage in early March last year; $Q_{i,j}$– volume of IW, received in storage, for a period between the month with *i* number and the month with *j* number; $k_{i,j}$ – the integral value of the parameter taking into account the influence of precipitation for a period between the month with *i* number and the month with *j* number.

Conclusions

A mathematical model of liquid waste storage has been developed, based on the dependences (1) - (14), data from Tables 1 - 5 and taking into account Figures 1 and 2. Such storages accumulate processed products and mine waters from several mining enterprises, taking into account climatic factors of influence and technological restrictions on waste storage volumes. This model makes it possible to determine the level of the free surface mirror in any month of the year (formula (15)), and to calculate the change in the current height of the water mirror in storage for any time of the year, such as spring months or all year (formulas (16) and (17)).

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