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Scientific Research Support for the Construction and Operation of Inwashed Tailing Dumps at Operating Sites

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Abstract: Accidents at mining enterprises, including tailing dumps, pose significant threats to human lives, structures, and the environment. This study focuses on designing, constructing, and operating tailing dumps in Siberia's northern region. To ensure safety and minimize environmental impacts, comprehensive scientific monitoring and research were conducted at all stages, including design, construction, operation, and disposal. The aim was to create a uniform mass within the dam body, requiring understanding of the tailing structure and technological characteristics during placement. Parameters like particle size, distribution, density, and moisture content were considered to assess the physical and geometric properties of the tailings. Estimated monitoring was introduced as a permanent model to quickly assess the stability of hydrotechnical constructions. This involved monitoring changes in exploitation properties, structure height, beach length, and water levels. A controlled inwashing technology for subsequent dam layers was developed. Complex research facilitated the formulation of an estimated monitoring methodology and an algorithm for tailing dam formation. Practical application demonstrated high reliability and confirmed load-bearing capacity, allowing for the forecast of dam stability and safe execution. Findings led to alterations in work techniques, ensuring safe and efficient operation of tailing dams.

Keywords: tailing dump; tails; stability; inwash; scientific monitoring; consolidation; microstructure; algorithm

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1. Introduction

Accidents at mining enterprises, including tailing dumps, occur almost every year in various countries. The reported damages highlight a significant threat posed by reservoirs of various origins to human lives, engineering structures, and the surrounding environment [1].

Currently, the mining industry plays a key role in meeting humanity's needs for valuable minerals. However, along with the process of extracting natural resources, there is a need for effective processing and disposal of the waste generated by this activity. Tailings storage facilities become a central element in addressing this issue, providing a place for the collection and storage of mining industry waste [1–6].

However, the construction and operation of tailing storage facilities present complex and multifaceted challenges that require a scientific approach and research efforts to ensure their safety and sustainability. Scientific research in this field plays an important role in developing optimal methods and technologies for constructing tailings storage facilities, as well as finding ways to minimize their negative impact on the environment [1].

Scientific monitoring is necessary at all stages:

- design;
- construction;
- operation;
- disposal.

For inwashed tailing dumps, tailings serve as a valuable construction material used in the creation of such dumps. By processing and compacting the tailings, it is possible to form engineering structures such as dams, embankments, or protective barriers. This enables the efficient utilization of available resources and reduces the need for additional construction materials, thus minimizing costs.

Issues of environmental safety for the existing industrial waste storage facilities are of particular importance, since almost all tailings are long-term sources of negative impacts on the atmosphere, hydrosphere, soil and vegetation cover, and change existing landscapes. The assessment of the degree and scale of pollution of the territory and water resources (specific surface watercourses) is carried out on the basis of geoinformation mapping of the environment for various territories both in our country and abroad. However, due to the uniqueness of each tailing facility due to the specifics of production and characteristics of the territory (relief, location, climate, etc.), these results are of limited use. Each tailing dump requires its own research [1].

Assessing the impact of tailing storage facilities on the environment is also a crucial aspect of scientific research in this field. Research allows us assessing the potential risks to human health and the environment, determining optimal ways to minimize the impact on natural resources, and developing measures for restoring the natural environment.

In recent years, numerous studies have been conducted to investigate the processes of waste formation and containment, analyze potential risks, prevent accidents, develop efficient monitoring systems, and control the condition of tailing storage facilities. These studies help optimize the selection of materials for building tailing storage facilities, improve methods and technologies for their construction, and develop reliable systems to prevent leaks and environmental accidents [1,4,7].

The work presented provides an overview of our recent scientific research aimed at supporting the construction and operation of tailing storage facilities at active industrial sites. It discusses methods and technologies for building tailing storage facilities, analyzes research findings on waste processing, evaluates the impact of tailing storage facilities on the environment, and considers measures to prevent accidents.

The significance of scientific research in the field of tailing storage facilities cannot be underestimated. These studies not only improve the technologies and methods of constructing tailing storage facilities, but also develop new approaches to waste processing and disposal in the mining industry.

We hope that this article contributes to raising awareness about the need for scientific and technical support in the field of tailing storage facilities and stimulates further research on this important and relevant topic. Understanding and applying the results of scientific research will help engineers, designers, and environmentalists develop more efficient and safe systems for storing and disposing of mining industry waste, thereby promoting sustainable development in this industry sector.

2. Case History

The set objectives were successfully achieved in several significant projects where all the mentioned stages were carried out [1,7–9].

The objects of research of the present work are the following tailing dumps: Tailing dump "Lebyazhye" and Tailing Dump №1. They are located on the territory of the Norilsk industrial region (North of Siberia).

In the northern regions of Russia, in the areas of large mining and metallurgical enterprises, dozens of million cubic meters of different deposits have been accumulating for a long time in the tailing dumps.

The tailing dam inwashing processes are produced in spring and summer, when the average daily temperature is above −5 °C [1]. Based on the operating conditions of alluvial storage in permafrost, it should be noted that the increase in the annual capacity of alluvial layer may not provide its complete consolidation process during short spring–summer period (3–4 months) before freezing in winter, and thus it reduces the stability of the structure. In order to optimize the inwash technology of the tailing dam, it is necessary to determine the time of the tail's consolidation [8,9].

During the design, construction and operation of tailing dumps located in the North of Siberia, comprehensive scientific monitoring and research were conducted. Scientific studies and monitoring were carried out to ensure the safety of the structures and minimize their negative impact on the environment (Figure 1).

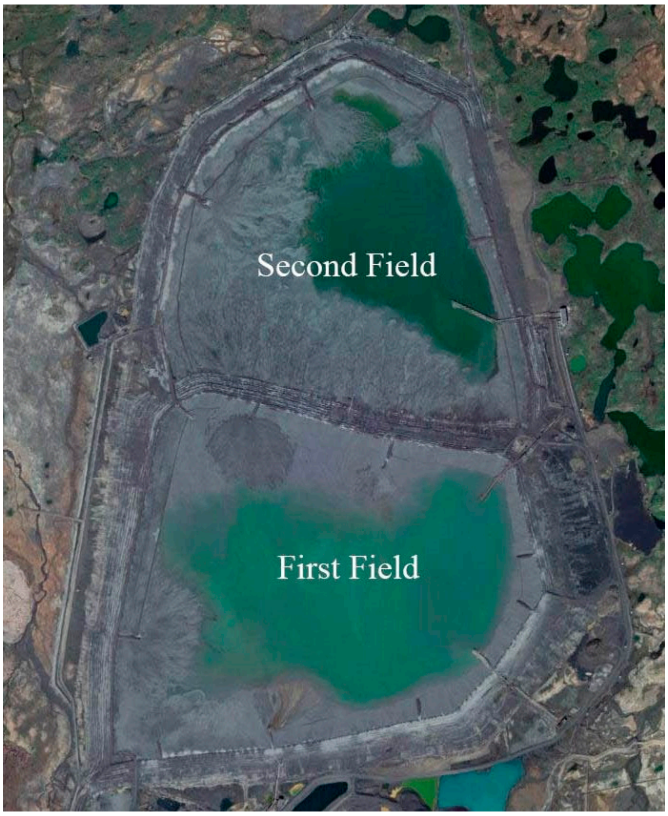

Figure 1. Tailing dump "Lebyazhye" of Norilsk industrial region (69°23′19.28″ N; 88° 6′36.91″ E).

The utilization of the disposal area started in 1983, marking the beginning of its operation. At that time, the first pond's dam was constructed, reaching an approximate height of 70 m. Several years later, in 2006, to accommodate additional waste, a second tailing pond was introduced to the existing tailing dump. This second pond is still undergoing construction. Its dam stands at a height of approximately 50 m. As a result, the tailing dump now consists of a cascade arrangement of multiple dumps, with dams having a height difference of about 20 m between them. It is planned that the tops of both dams will eventually reach a height of 90 m, allowing for effective containment and management of the waste materials [1,9].

The tailing dams of both fields are constructed as a persistent drainage prism using metallurgical slag. The constructive characteristics of the first and second dams and ponds are presented in Table 1 [1,9].

The disposal process for tailing dump№1 (Figure 2) was accompanied by comprehensive monitoring and scientific support [9].

Table 1. The constructive characteristics of the tailing dump "Lebyazhye" first and second fields.

№	Characteristics	Units	First Field	Second Field
1	The disposal area	km^2	4.02	2.4
2	The width of the prism	m	8	8
3	The length of the prism	m	8500	4313
4	The capacity of the disposal area	$mln.m^3$	16.7	14.7
5	The height of the dam	m	39.3	20.3
6	The inclination of the top drain level	-	1:50	1:50–1:100
7	The inclination of the bottom slope	-	1:4	1:4–1:5
8	The maximum depth of the pool	m	4.7	5.2
9	The average depth of the pool	m	2.5	2.9
10	The expected operational lifespan	year	20	15

Figure 2. Tailing dump №1 (69°20′33.86″ N; 88°7′37.93″ E).: 1—tailing dump №1; 2—the pond; 3—local tailing dam; 4—spillway channel; 5—magnetic pyrite depository №2.

The constructive characteristics of the dam are presented in Table 2.

The basis of the pool and the dam is layered by frozen artificial, alluvial and moraine soils with gravel and pebble with sand, loam and loam additions. The thickness of the stratum is of 5–60 m. The underlaying layer is heterogeneous rock.

Problems of stability of the structure are connected with the fact that the levee of the tailing dump was erected by the principle I (frozen condition), with application of freezing columns as the basic method of structure protection. During the operation and preservation of the damp the freezing system has failed, and now the maintenance of the stability of object consists in passing the flood waters and keeping safe water level in the pond zone. Thus during the summer–autumnal period on downstream side of a dam egresses and separate earthflows are observed.

Table 2. The constructive characteristics of the tailing dump №1.

№	Characteristics	Units	Tailing Dump №1
1	The disposal area	km^2	0.715
2	The length of the tailing dam	m	4410
3	The height of the dam	m	56.7
4	The inclination of the top drain level	-	1:20–1:30
5	The inclination of the bottom slope	-	1:3
6	The maximum depth of the pool	m	4.0
7	The average depth of the pool	m	0.4

In the tailing dump №1 the tails had been stored from 1948 to 1975. After commissioning of the tailing dump №2 in 1976, the dump №1 had been used from 1976 to 1987 as a backwater basin.

Since 1987, the tailing dump has served as a construction for the reception of drain, regulation and passing of flood waters and for the accumulation of surface-water flow arriving to the water-collecting area of the tailing dump in the form of atmospheric precipitation.

Now, on the tailing dump №1, the hydromechanized lifting and reprocessing of stale tails with extraction of non-ferrous metals and precious metals is carried out. In the magnetic pyrite depository №2 which is located in the basis of a downstream side of the tailing dump №1, the works on lifting of magnetic pyrite concentrate with the help of hydromechanization are being conducted [9].

The condition of the local dam of the tailing dump №1 in the place where it adjoins the magnetic pyrite depository is unsatisfactory. Lifting of stale concentrate and tails in a hydromechanized way can entail destruction of the local dam, filling of the worked-out area of the magnetic pyrite depository №2 and loss of valuable raw materials.

3. Methods

3.1. Design

In the conventional approach, stability calculations for the tailing dam are typically conducted during the design phase with a certain level of safety margin considered [9].

As already noted since 1997, a controlled inwash technology has been implemented for the dam. This method includes constructing a retaining prism using metallurgical slag on top of which a metal distributing slurry pipeline is installed. Furthermore, a ring slag fill is built in the beach zone, positioned at a specific distance from the axis of the distributing slurry pipeline. This fill serves the purpose of retaining solid particles within the beach zone while also allowing for water to flow into the pool with increased illumination.

The scheme of the dam inwash is shown in Figure 3.

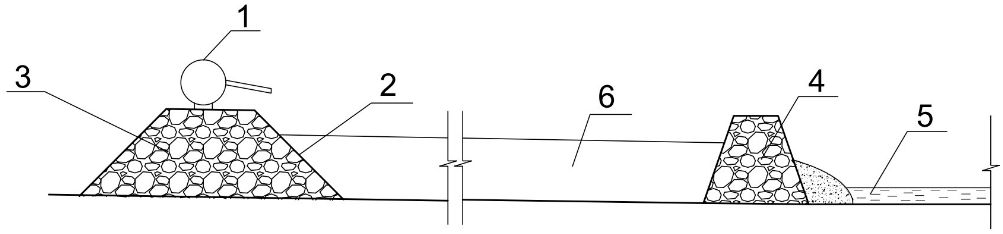

Figure 3. The scheme of the dam inwash: 1—distributive slurry pipeline; 2—geotextile anti-filtration screen; 3—the retaining slag prism of a dam; 4—slurry collecting slag prism; 5—pool; 6—inwashed tails.

Further, during the construction of the dam through collaborative research and production investigations, a technology for controlled inwash of subsequent layers of the dam has been developed [10]. It includes the following operations:

- the construction of the retaining prism of metallurgical slag. The metal distributing slurry pipeline is laid on it;
- the construction of ring slag fills in the beach zone at the specific distance from the axis of the distributing slurry pipeline. It retains the solid particles in the beach zone and simultaneously it clearing the water coming into the pool.

The scheme of the dam inwash is shown in Figure 4.

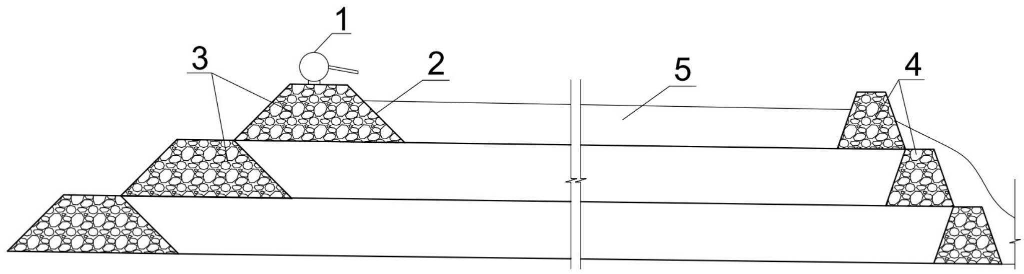

Figure 4. The scheme of the dam inwash: 1—distributive slurry pipeline; 2—geotextile anti-filtration screen; 3—a retaining slag prism of a dam; 4—slurry collecting slag prism; 5—inwashed tails.

The functions of a slurry collecting prism in operation of an inwash are the following:

- placing of prism on various distances from distributive slurry pipeline allows regulating intensity of an inwash;
- slurry collecting prism promotes more intensive consolidation of hydraulic fill tails and increase of stability of a dam;
- it allows operating of bottom contour formation in pond zone that is rather an important factor that provides winter storing of tails under ice;
- it promotes more intensive frost penetration in an inwash massif that raises its static and filtration stability and in that way provides environmental safety of the tailing dump;
- it carries out reinforcing a body of a levee function.

However, it is important to note that additional calculations can only be carried out in specific cases where there are modifications made to the mining or extraction technology. Unfortunately, this means that issues pertaining to industrial and environmental safety concerning tailings often lack consistent monitoring, which can contribute to unforeseen accidents. As a consequence, the implementation of permanent monitoring is not practiced, leaving potential risks unattended to. This highlights the need for more rigorous and continuous monitoring practices to ensure the overall safety and sustainability of tailing management.

3.2. Construction

Carried out complex researches allows formulating a methodology of the estimated monitoring for the tailing dam's stability [11]. The algorithm is shown in Figure 5.

Along with the standard set of observations, the methodology of the estimated monitoring includes the tailing dam's stability calculations under changing technological parameters of exploitation, observing geometric characteristics of construction and the properties of the inwashed tails [11].

The technique includes a number of successive operations.

At the first stage after receiving the research data on the structure and the properties of the composing inwashed soils, the preliminary calculations for the most typical cross-section and average values of physical and mechanical properties are conducted. The result is accepted as the baseline.

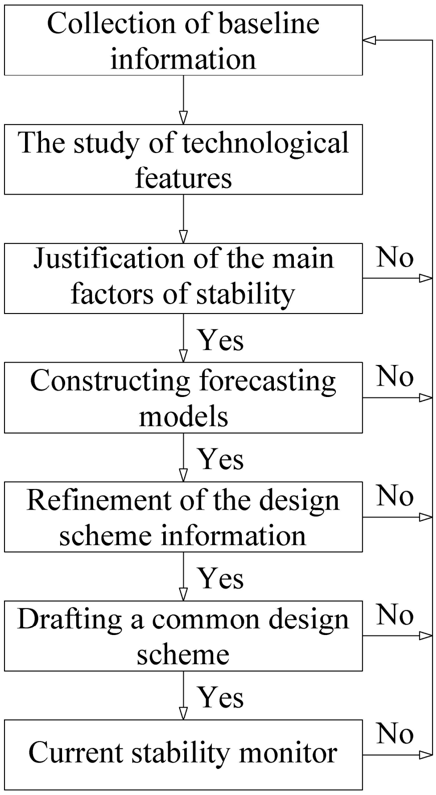

Figure 5. Algorithm of the methodology of the estimated monitoring for the tailing dam stability.

As the initial data for the calculation, the following materials should be used [11,12]:

- geology, geocryological and hydrogeological conditions, physical and mechanical properties of natural and artificial soils taken according to engineering studies, research and direct definitions and observations in the field and laboratory conditions;
- geometrical parameters of structures defined by the direct geodetic works [8].

At the second stage, while changing the values of soil characteristics, increasing and decreasing them, the influence of the physico-mechanical properties of soils on the construction stability is investigated.

At the third stage, the influence on the tailing dam's stability of the design parameters of height of dam and of angle of the foundations under constant values of physical and mechanical properties are tested.

At the fourth stage, the changes of physico-mechanical properties of inwashed soils during alluvion and subsequent consolidation are tested. It is recommended to study the physical and mechanical characteristics by microstructural analysis and modeling.

At the final stage, the multivariate calculations of the dam's stability are conducted using all the above-installed patterns. The calculations were carried out by means of the UniFos program. The UniFos program is a part of the UWay complex and it is intended for calculations of the stability of soil constructions. It is written in the object-oriented C++ language with the usage of optimising compiler Borland C++ Borland International v.5.02 with library OWL usage v.5.0 [13].

The results are recorded in the database and can be replaced in the process of obtaining new data on the structure. The estimation of the maintenance of the tailing dam stability consists in comparing the information obtained as a result of standard monitoring of hydraulic structure safety with that of the existing database. And if at least one of the parameters varies from the normalized values, the calibration calculations must be carried out and engineering activities must be designed to eliminate deviations.

Thus, the idea of estimated monitoring the stability of hydrotechnical constructions is presented as a permanent model intended to quickly check the state of buildings when changing technology exploitation properties of alluvial soils, height of structures, length of the beach, water level in the body of the enclosing constructions, etc.

Taking into account the significant difference in the elevation between the dams of the first and second fields, which amounts to almost 20 m, it can be said that they form a cascading tailings storage facility.

The technology for dam inwashing considers various factors such as the height of the dam inwashed during one cycle and throughout the year, the width of the inwash front, the quantity of inwashed tails, and the schedule of operations, among others. The inwashing process is performed in sections, where after the formation of a layer of tails with a capacity of approximately 0.5 m, a hydraulic fill section is left for a period of "rest" lasting 10–15 days. This method of inwashing allows for the gradual growth of the dam. Figure 6 and Table 3 present the beach sectoring for determining the volume of inwashed tails and the order in which the sections of the tailing dump are inwashed [8].

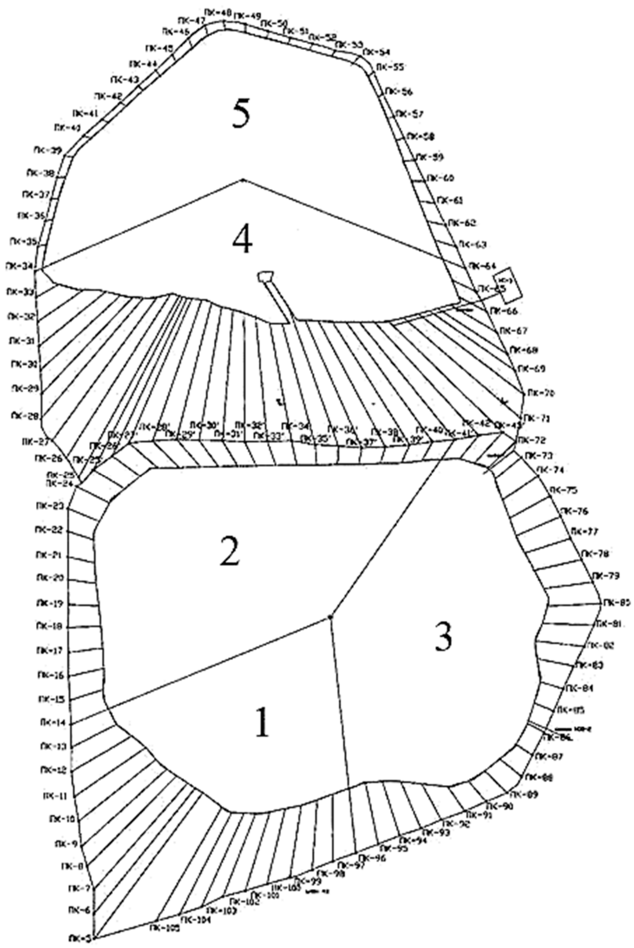

Figure 6. Beach sectoring: 1–5—inwash sectors.

The schedule for the inwash works is planned for the entire year. This comprehensive planning approach enables the determination of the duration of dam operation until it reaches its intended design elevation.

The dam undergoes alternating washing in the first and second fields, taking into account an average daily air temperature above −5 °C [1].

Through a series of experimental studies, a complex algorithm for the formation of the tailing dam was developed, as depicted in Figure 7 [14].

Table 3. Alluvium process options.

№ of Field	№ of Sector	Area of Plots, m^2	Accepted Height of the Alluvium, m	Volume of Plots, m^2	Distance between Pickets, m	Volume of Single Layer of the Alluvium, m^3
I field	1	634,436.5	1.0	634,436.5	1800.0	317,218.2
	2	305,490.7	1.0	305,490.7	2700.0	152,745.3
	3	426,747.2	1.0	426,747.2	2700.0	213,373.6
II field	4	728,976.3	2.0	1,457,953	3200.0	364,488.1
	5	689,924.7	2.0	1,379,849	3000.0	344,962.4

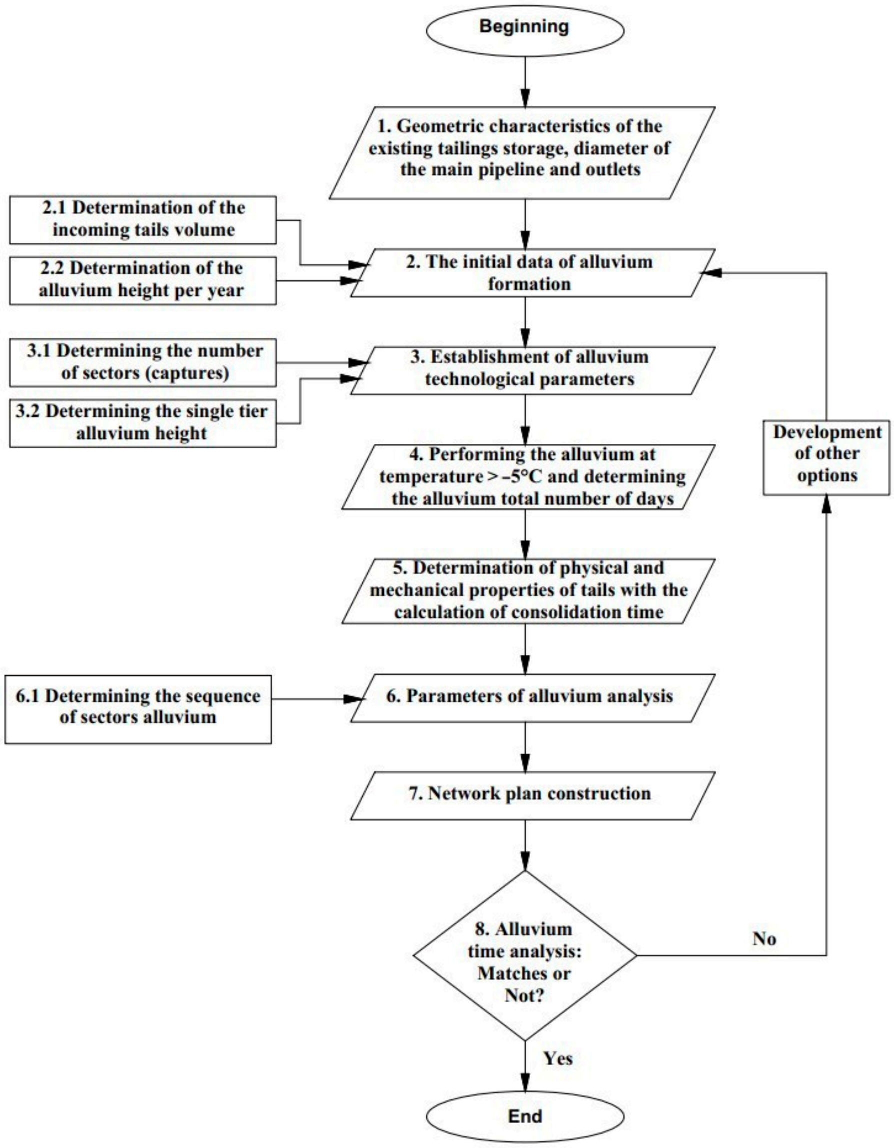

Figure 7. The algorithm of tailing dam forming.

In the first stage of the study, it is necessary to prepare initial data for further calculations. This includes determining the geometric characteristics of the existing tailing dump, such as the areas involved, and obtaining the diameter of the main pipeline. Additionally, the number of outlets and their respective diameters need to be defined.

During the second stage, the volume of incoming tails must be determined, and the height of the annual alluvium layer should be calculated based on the actual areas of alluvium.

In the third stage, the required number of outlets, the width of the alluvium sector, and the total number of sectors for storing tailings must be determined based on the daily volume of tails and the throughput of each outlet.

In the fourth stage, the alluvium of the tailing dump needs to be performed, and it is necessary to indicate the total time of the inwash onto the beach (the number of days per year with a temperature above −5 °C), which can be determined according to the climatic conditions of the region [1,15].

Furthermore, it is important to set a limit on the height of the annual inwash, especially for dumps located in the cryolithozone. The maximum permissible height of alluvium per year should ensure the freezing conditions of the alluvial mass, and it depends on the climate, chemical composition, and physical and mechanical properties of the tails. To determine the value of the maximum permissible height of annual alluvium, separate studies should be conducted for each specific case.

In the fifth stage, the physical and mechanical properties of the tails need to be determined. This involves conducting a series of individual soil tests for compaction, with a gradual increase in moisture content. The results of these tests should be presented in the form of a graph, which shows the dependency of the soil's skeleton density on its moisture content. It is recommended to conduct at least six individual tests, or a sufficient number to identify the maximum value of the soil's skeleton density [15].

Moreover, it is necessary to determine the plasticity limits of the tails. The ratio of filtration and rheological phenomena in the process of soil consolidation varies depending on factors such as density, humidity, characteristics of the soil structure, and the magnitude of the load. The upper limit of humidity is the moisture at the yield point [15].

The process of consolidation is typically divided into two phases: primary or seepage consolidation and secondary consolidation due to the creep of the soil skeleton. The completion time of the seepage consolidation stage (C_v) can be determined using consolidation curves constructed in the coordinates of displacement (s) and the logarithm of time (lgt) according to the Casagrande method. The consolidation curves provide valuable information about the settlement and time-dependent behavior of the soil, allowing for the prediction of consolidation settlement over time [15].

Furthermore, the coefficient of secondary consolidation (C_α) needs to be determined. This can be achieved by measuring the tangent of the angle between the linear segment of the consolidation curve in the secondary consolidation area and a straight line parallel to the abscissa axis [8,14–17].

It is possible to determine the consolidation time by altering the geometric properties of the samples in controlled laboratory conditions [8,14–17]:

$$t = \frac{F}{C_v} \times \frac{h}{h - s}, \tag{1}$$

where t is the consolidation time, min; F is the cross-sectional area of the sample, cm^2; C_v is the consolidation coefficient, cm^2/min; h is the initial height of the layer, cm; s is the displacement, cm.

In order to determine the time of tailing consolidation at known design values of humidity and density, it is necessary to prepare a regression polynomial Equation (2). This equation should be arranged in ascending powers of the studying factor while ensuring linearity for all coefficients [14–17].

$$y = f(x) = b_0 + b_1 x_1 + b_2 x_2 + \ldots b_n x_n. \tag{2}$$

The alluvium process for the storage area needs to be conducted in multiple stages. Additionally, there should be a technological break established between the completion of alluvium for one lower tier and the commencement of alluvium for the subsequent tier.

During the sixth stage, an analysis of the parameters of the alluvium structure is conducted. It is important to note that in the permafrost zone, increasing the annual capacity of the layer may not result in complete consolidation before freezing during the short spring–summer period. This incomplete consolidation could potentially reduce the stability of the structure.

Considering the operational conditions of alluvial storage in permafrost areas, it is important to note that increasing the annual capacity of the layer may not allow for complete consolidation within the short spring–summer period before freezing. This can compromise the stability of the structure. To optimize the inwash technology of the tailing dam in such conditions, it is crucial to accurately determine the time required for tailings consolidation. This factor plays a crucial role in optimizing the inwash technology in the permafrost zone.

In order to guarantee sufficient time for the tailings consolidation process, it is necessary to establish the sequence of all-in sectors.

During the seventh stage, the network planning method needs to be employed to meet the regulatory requirements for optimizing the inwash process. This method helps in organizing and coordinating the various activities involved in the process, ensuring efficient and effective execution.

Upon construction and calculation of the network plan, the duration of the critical path is determined in terms of days. This critical path duration provides insight into whether the entire volume of all inwashed tails can be completed within the required time frame. By assessing the duration of the critical path, it becomes possible to evaluate whether the project timeline aligns with the necessary timeframe for placing the entire volume of the inwashed tails [18].

In the final stage, it is crucial to verify whether the obtained number of days required for tailings inwash is compliant with the established standards. If the obtained duration does not meet the requirements, it is necessary to revisit the stage of determining the initial data.

The objective of our technological operations is to create a uniform and homogeneous mass of material. To achieve this goal, knowledge about the structure of tailings and the technological characteristics of their placement within the dam body is necessary. Studying the structure of tailings will help us understand their physical and geometric properties, such as particle size, particle size distribution, density and moisture content [19,20].

In the laboratory, the research of technogenic soils–tails was carried out according to the methodical scheme developed in the laboratory of soil science of the Institute of Earth Crust of the Russian Academy of Sciences by Ryashchenko T.G. [21] and including the definition of a set of indicators that are divided into four groups:

- structural (characterizing structural elements, type of structural connections and types of structures);
- chemical (indicators of chemical composition and physical–chemical properties);
- physical (indicators of physical condition and properties);
- mechanical (indicators of deformation and strength properties).

Air-dry samples of tails of the disturbed build were used. The selected samples were gray samples, stain hands; small aggregates and clay fractions (clay sand) were clearly present.

Granulometric analysis was carried out in three ways of sample preparation: microaggregate (shaking in water), standard (boiling with ammonia), and dispersed (boiling with sodium pyrophosphate).

Tables 4 and 5 shows the accepted indices of indicators with their decoding.

When determining the parameters of the microstructure, the number of aggregates (A) and primary particles (M), their size distribution (A_i, M_i) and the coefficients of freedom of fractions (F_i) representing the share (%) of primary particles in their total amount (primary plus those in aggregates) special calculations were performed.

The type of the soil structural model was set on the size of the prevailing elements ($A_i + M_i$) and special factor G according to the classification [21]. Coefficient G—the share of primary particles in the total sum of structural elements (primary particles plus aggregates), %; *x*—the size of primary particles and aggregates, microns.

Table 4. Accepted indexes.

Index	Parameter, %
A	Total amount of aggregates
A_1	Aggregates—1.00–0.25 mm
A_2	Aggregates—0.25–0.05 mm
A_3	Aggregates—0.05–0.01 mm
A_4	Aggregates—0.01–0.002 mm
A_5	Aggregates—0.002–0.001 mm
M^1	Primary (free) particles—1.00–0.25 mm
M^2	Primary particles—0.25–0.05 mm
$M^{2\text{-}A}$	Particles in aggregates—0.25–0.05 mm
M^3	Primary particles—0.05–0.01 mm
$M^{3\text{-}A}$	Particles in aggregates—0.05–0.01 mm
M^4	Primary particles—0.01–0.002 mm
$M^{4\text{-}A}$	Particles in aggregates—0.01–0.002 mm
M^5	Primary particles—0.002–0.001 mm
$M^{5\text{-}A}$	Particles in aggregates—0.002–0.001 mm
M^6	Primary particles—< 0.001 mm
$M^{6\text{-}A}$	Particles in aggregates—< 0.001 mm
M^7	The real fraction content < 0.001 mm
M^8	The real fraction content < 0.002 mm
M^9	Fraction content < 0.002 mm according to standard granulometry
K_{cl}	Clay coefficient (M^8/M^9)
M^{11}	The total fraction content 0.05–0.002 according to standard granulometry
F^1	Fraction freedom coefficient—1.00–0.25 mm
F^2	Fraction freedom coefficient—0.25–0.05 mm
F^3	Fraction freedom coefficient—0.05–0.01 mm
F^4	Fraction freedom coefficient—0.01–0.002 mm
F^5	Fraction freedom coefficient—0.002–0.001 mm
F^6	Fraction freedom coefficient—<0.001 mm

The method proposed by A.K. Larionov [22] and expanded by T.G. Ryashchenko [23,24] was used for the microagregency ratio calculation. These coefficients represent the difference between the fraction contents determined during dispersed sample preparation and microaggregate preparation. They are used to assess the degree of aggregation and determine the size of aggregates and their structure, i.e., it is possible to find out what smaller particles they consist of. In addition, the degree of freedom of fine-grained particles (less than 0.001 mm) particles in the size of K_{ma}^{1-2} is determined.

Micro-aggregate ratios are defined as follows:

$$K_{ma}^{1-2} = M_s^2\,(d) - M_s^2(ma), \tag{3}$$

$$K_{ma}^{1-1} = M_s^1\,(d) - M_s^1(ma), \tag{4}$$

$$K_{ma}^{2-2} = M_d^2\,(d) - M_d^2(ma), \tag{5}$$

$$K_{ma}^{2-1} = M_d^1\,(d) - M_d^1(ma), \tag{6}$$

$$K_{ma}^{3-2} = M_c^2\,(d) - M_c^2(ma), \tag{7}$$

$$K_{ma}^{3-1} = M_c^1\,(d) - M_c^1(ma), \tag{8}$$

where (d)—the content of the relevant faction in a dispersed way of sample preparation, %; (ma)—the same with microaggregate mode of preparation, %.

Table 5. Accepted indexes.

Indicator	Decoding	Unit	Coarseness
M_s^1	content of coarse sand fraction	%	more than 0.25 mm
M_s^2	content of fine sand fraction	%	0.25–0.05 mm
M_d^1	the content of coarse dusty fraction	%	0.05–0.01 mm
M_d^2	the content of fine dusty fraction	%	0.01–0.002 mm
M_c^1	content of coarse clay fraction	%	0.002–0.001 mm
M_c^2	content of fine clay fraction	%	less than 0.001 mm

where M_s, M_d, M_c—the total content of sandy, dusty and clay fractions, %; ^{1,2}—indices.

The lower this coefficient, the greater the degree of freedom, that is, clay particles are not part of aggregates, but are primary. When all fine clay particles are free, they do not participate in the formation of aggregates K_{ma}^{1-2} greater than or equal to zero. K_{ma}^{3-1} is always negative if coarse-grained particles are aggregates and is zero if all of them are primary. The other four coefficients can have arbitrary values.

When determining the parameters of the microstructure, the number of aggregates (A) and primary particles (M), their size distribution (A_i, M_i) and the coefficients of freedom of fractions (F_i), representing the share (%) of primary particles in their total amount (primary plus those in aggregates), special calculations were performed [24,25]. Depending on the number of aggregates, the type of microstructure was determined according to the classification Table 6.

Table 6. Classification of microstructure types of clay soils.

Total Number of Aggregates (A), %	Microstructure	Conditional Index
A < 10	skeletal	sk
10 < A < 25	aggregated-skeletal	ag-sk
25 < A < 40	skeletally aggregated	sk-ag
A > 40	aggregated	ag

The type of the structural model of the soil was set on the size of the prevailing elements ($A_i + M_i$) and special factor G according to the classification Table 7 [24].

Table 7. Classification of types of structural models of clay and loess soils.

The Size of the Prevailing Elements	Model Type	G = Mx/Ax + Mx	Model Type
$A^1 + M^1$	Medium coarse sand (250–500 microns)	80 < G < 100	Elementary
$A^2 + M^2$	Fine-grained (50–250 microns)	20 < G < 80	Mixed
$A^3 + M^3$	Coarse dusty (10–50 microns)	G < 20	Aggregated
$A^4 + M^4$	Fine dusty (2–10 microns)		
$A^5 + M^5$	Coarse clay (1–2 microns)		

Coefficient *G*—the share of primary particles in the total sum of structural elements (primary particles plus aggregates), %; *x*—the size of primary particles and aggregates, mm.

Strength indicators were determined on specially prepared samples with humidity varying in the range from 2% to 40%. Such humidity regime is due to a small difference (5.2%) between the limits of plasticity and fluidity; it is needed to assess the strength at low humidity, which corresponds to the humidity of the soil during the rest of the beach.

Tests were conducted on the automated test complex "ASIS" (Figure 8) which is intended for carrying out the mechanical tests of natural and industrial building materials at various sorts of a stress condition and loading paths. Special software ASIS was applied to the management of the test process. The software exercises in the automated mode administration of the test process, recording and transfer of results of the test to other software packages for further processing [26].

Figure 8. Test complex ASIS.

When the structure of the tailings is determined, the technological process for laying a homogeneous and dense structure of the massif needs to be simulated. For this, model tests were performed on a specially designed installation. The study of the influence of the technological parameters of the alluvium on the formation of a stable tailings dam was carried out using physical modeling.

For research, a laboratory stand was developed and manufactured [27] consisting of a tray, organic glass, with the possibility of changing the slope, a slurry distribution sump (distribution slurry pipeline), and distribution outlets through which alluvium is carried out (Figure 9). When designing the alluvium model for the tailing dam in accordance with the conditions of the theory of similarity, the chosen geometric scale was 1:100.

3.3. Operation and Disposal

As mentioned earlier, during the construction of a tailings storage facility, it is crucial to ensure a uniform and compact state of the tailings mass. The deposition process is carried out according to a specific technology or methodology, which dictates the manner in which the tailings are placed and distributed within the storage facility. This process aims to achieve a consistent and stable structure that minimizes the risk of environmental contamination and ensures the long-term integrity of the facility (see Figure 4).

Figure 9. The design of a laboratory setup for modeling the alluvium of the tailing dam.

During operations involving the filling of the tailing dump, there may arise a need to either increase the capacity of the dump or implement measures to address a decrease in the stability coefficient of specific sections of the dam. To tackle this issue, a compaction method and a secondary dike dam were developed and implemented. These measures are aimed at improving the stability and integrity of the tailing dump during the filling process.

During the process of tail development and its subsequent disposal, ensuring safety measures and preventing the collapse or loss of stability of the enclosing dam is of the utmost importance. Safety precautions must be carefully followed to mitigate any risks and safeguard the structural integrity of the dam.

4. Results and Discussion

4.1. Design and Construction

At the design and construction stage, the construction technology of the tailing dam was changed to form an impervious screen to prevent seepage from the tailings through the dam and increase its stability.

The technical solution consists of placing sleeves made of nonwoven geotextile filtering material in layers perpendicular to the flow propagation, with the sleeves filled with tails to form an earth dam in a bay from the side of the tailing pond (Figure 10). On the side of the enclosing dam, an impermeable screen made of non-filtering geotextile material is installed to prevent filtration from the tailing pond. The impermeable screen is directed towards the inner slope of the enclosing slag prism of the next layer, it is folded until the next layer is deposited, and then unfurled on top of the deposited tails, covering at least the width of the supporting part of the prism of the next layer for clamping [28].

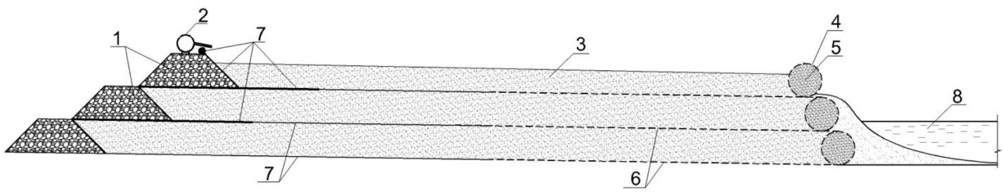

Figure 10. The scheme of the dam inwash: 1—enclosing dam in the form of slag prisms; 2—slurry pipeline; 3—tailings beach; 4—separating earth dam in a bay; 5—tails; 6—geotextile filtering material; 7—geotextile non-filtering material; 8—pond.

The method of constructing a tailing dam is carried out as follows: the construction of the enclosing dam in the form of slag prisms and a dividing dam, the installation of main and distribution pipelines, and the layer-by-layer dispersed deposition of tails on the inner beach. The dividing dam is constructed by placing a sleeve made of nonwoven geotextile filtering material perpendicular to the flow propagation, filling the sleeve with tails to form an earth dam in a bay from the side of the tailing pond. On the side of the enclosing dam, an impermeable screen made of non-filtering geotextile material is installed to prevent filtration from the tailing pond. The impermeable geotextile material is placed along the bottom of the tailing pond, directed towards the inner slope of the enclosing slag prism of the next layer, folded until the next layer is deposited, and then unfurled on top of the deposited tails, covering at least the width of the supporting part of the prism of the next layer for clamping. The diameter of the sleeve made of filtering geotextile material is determined based on the desired thickness of the deposited layer. Upon reaching the desired thickness of the layer, a new sleeve made of geotextile material is laid. The same operations are repeated for each subsequent layer.

During the tests, the influence of technological parameters of inwash on the characteristics of tailings distribution along the beach of the tailings storage facility was investigated.

The inwash technological parameters were as follows:

- values of the weighted average particle diameter—0.05—0.63 mm;
- the pulp pace—3.91; 4.05 and 4.31 m/s;
- the solid phase to liquid phase ratio—1:2; 1:2.5; 1:3.5 and 1:4.

The laboratory experiments were conducted on laboratory-scale plant made according to the requirements of the similarity theory criteria [11,29]. In accordance with the conditions of the theory of similarity, the geometric scale was chosen to be 1:100 (Tables 8–10).

Table 8. Tails distribution % at a fixed speed of the pulp 3.91 m/s.

Speed of the Pulp, m/s	Liquid to Solid Ratio	Distance from the Distribution Pipeline, m	Sieve Sizes, mm		
			0.63	0.2	0.05
3.91	1/2.5	10	1.20	22.98	75.82
		50	32.74	29.40	37.86
		100	7.62	6.82	85.56
	1/3.5	10	2.66	10.63	86.71
		50	7.94	26.22	65.84
		100	4.90	20.30	74.80
	1/2	10	3.67	17.64	78.69
		50	21.51	25.95	52.54
		100	4.80	19.25	75.95
	1/4	10	10.99	21.98	67.04
		50	17.54	22.53	59.93
		100	9.77	3.52	86.71

Table 9. Tails distribution % at a fixed speed of the pulp 4.05 m/s.

Speed of the Pulp, m/s	Liquid to Solid Ratio	Distance from the Distribution Pipeline, m	Sieve Sizes, mm		
			0.63	0.2	0.05
4.05	1/2.5	10	10.41	9.33	80.26
		50	11.18	8.74	80.08
		100	16.27	16.16	67.56
	1/3.5	10	3.08	4.95	91.97
		50	11.30	15.84	72.87
		100	14.13	43.59	42.28
	1/2	10	2.82	5.12	92.06
		50	8.66	7.65	83.68
		100	8.56	36.28	55.16
	1/4	10	2.92	8.80	88.28
		50	4.61	8.66	86.74
		100	9.87	15.47	74.66

Table 10. Tails distribution % at a fixed speed of the pulp 4.31 m/s.

Speed of the Pulp, m/s	Liquid to Solid Ratio	Distance from the Distribution Pipeline, m	Sieve Sizes, mm		
			0.63	**0.2**	**0.05**
4.31	1/2.5	10	0.78	20.59	78.63
		50	12.44	18.15	69.40
		100	4.89	10.24	84.87
	1/3.5	10	2.10	10.77	87.13
		50	5.37	21.26	73.38
		100	3.56	18.39	78.04
	1/2	10	2.65	15.85	81.51
		50	11.35	18.95	69.70
		100	3.51	17.13	79.36
	1/4	10	7.80	18.82	73.38
		50	13.03	20.13	66.84
		100	7.27	1.49	91.24

The tails distribution along the beach zone with optimum pulp quality depending on the pulp speed is presented in Table 11.

Table 11. Tails distribution % with optimum pulp quality.

Speed of the Alluvium, m/s	Distance from the Enclosing Dam, m		
	10	**50**	**100**
3.91	22.25	22.22	22.15
4.05	25.83	26.75	24.27
4.31	23.80	24.92	26.42

As a result of the experiments, polynomial trend lines of tails distribution along the beach area were obtained with optimum pulp consistency (liquid to solid ratio) depending on the speed of the pulp (Figure 11).

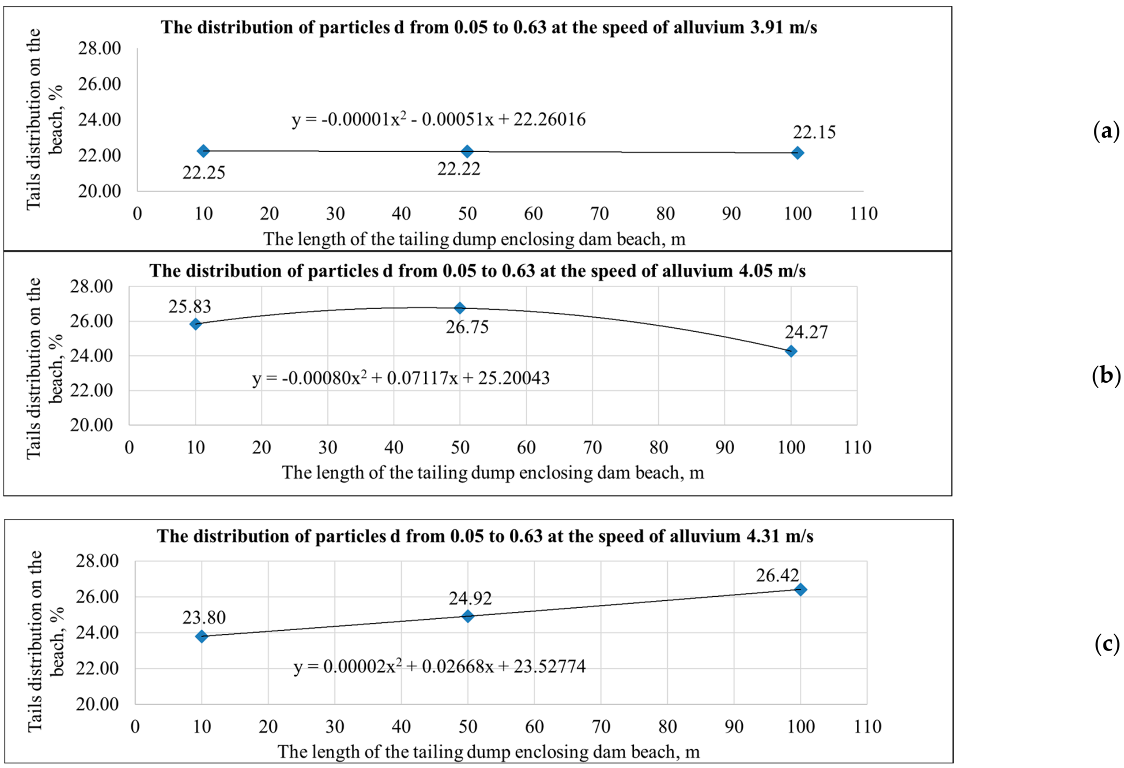

Figure 11. The distribution of tails on the beach at speed: (**a**) v = 3.91 m/s; (**b**) v = 4.05 m/s; (**c**) v = 4.31 m/s.

Figure 12 shows a summary graph of the tails distribution along the beach at a distance of 10, 40 and 70 m from the distribution slurry pipeline.

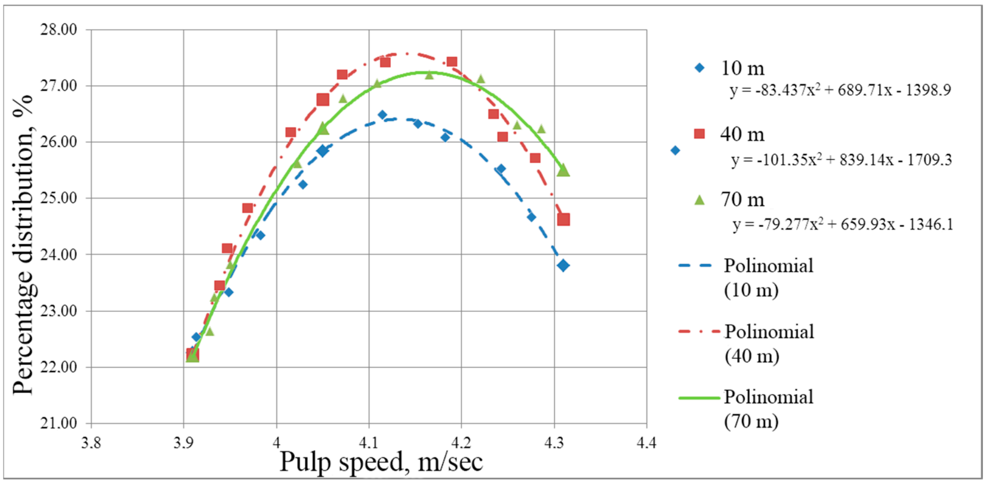

Figure 12. Tails distribution along the beach.

According to the data in Figure 12, the tails distribution along the beach has quadratic dependence on the pulp velocity, the height of the pulp axis, and the weighted average particle diameter [11,29].

In the aggregate, these parameters are dominant for any task of increasing the stability of a certain part of the beach due to the redistribution of tails.

To determine the influence of geometric characteristics on the stability of the tailing dam, three variants of calculations were performed with beach lengths of 50, 100, and 150 m.

Regularities of changes in the coefficient of stability (k_{st}) of the dam against its design parameters—the height and steepness of the bottom slope and the length of the beach—are shown in Figure 13.

The results of calculations show that with the same initially given data, an increase in the height of the dam leads to a significant decrease in its stability coefficient.

The results indicate that raising the height of the dam and the bottom slope layout decreases its stability coefficient substantially. But the raising the duration of the shore from 50 to 150 m increases the stability coefficient.

The influence of physical and mechanical properties was studied using physical modeling of the enclosing tailing dam formation. Through the change in such criteria for assessing the accident and stability—such as the strength characteristics of tails—the angle of internal friction and specific adhesion were investigated.

To establish the effect of changes in the physical and mechanical properties on stability, the values of specific adhesion and angle of internal friction of the soils composing the dam body were changed in the design scheme (Figure 14).

Analysis of the results showed a proportional dependence of the change in the stability coefficient on the soils' physical and mechanical properties, while the specific adhesion is a more important parameter determining stability than the angle of internal friction.

In order to control the strength characteristics and, accordingly, the stability of the enclosing dam, the process of the tailings' inwash on the beach area with the use of a compactor of dynamic action was modeled. The values of the stability coefficient are shown in Figure 15.

From the analysis of the test results, it can be concluded that the coefficient of the tailing dump enclosing dam stability linearly depends on the geometrical parameters of the dam, the strength characteristics of the inwashed deposits, and the degree of their compaction [29].

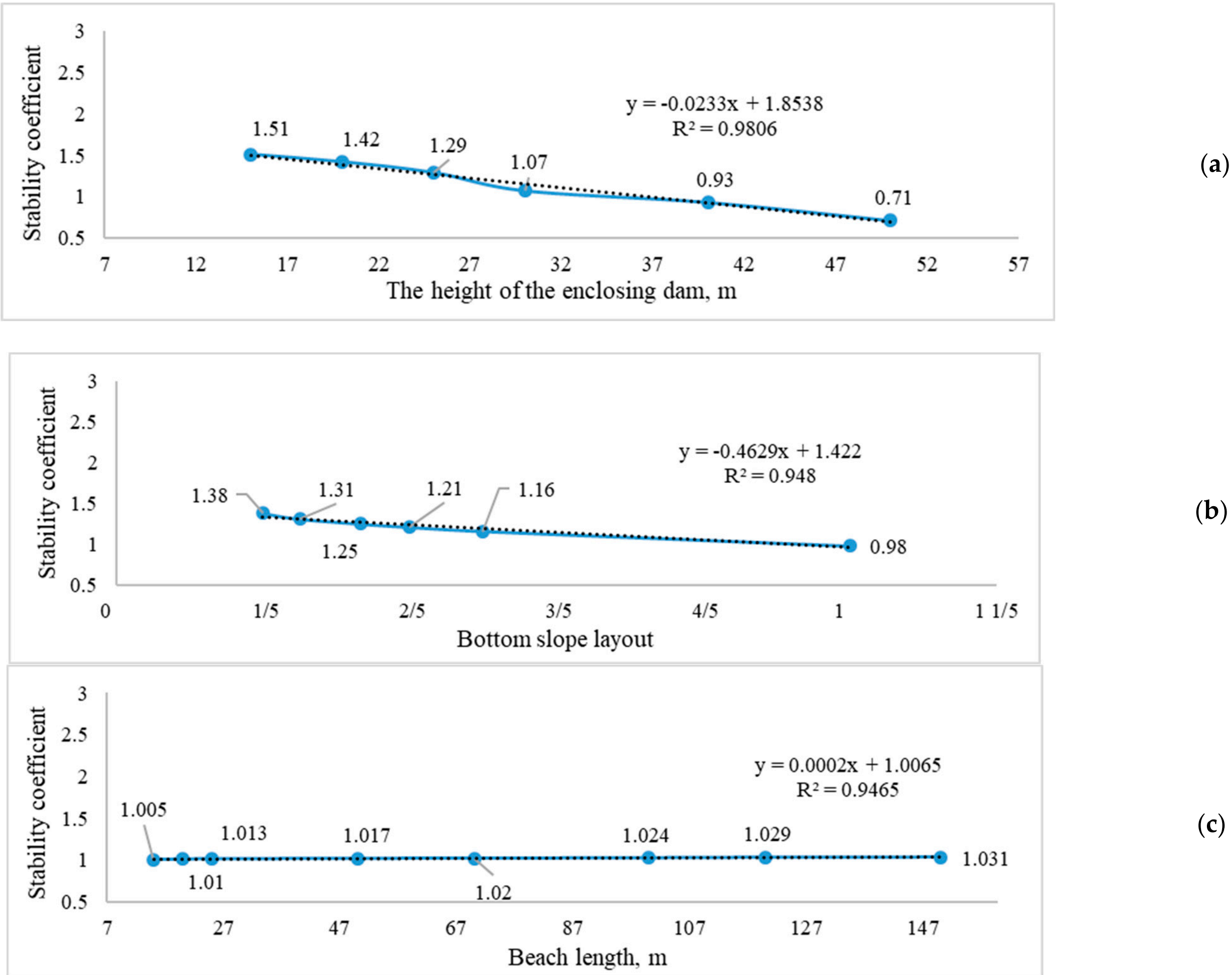

Figure 13. The k_{st} value depending on the geometrical parameters: (**a**) the influence of the height of the dam; (**b**) the bottom slope layout; (**c**) beach length effect.

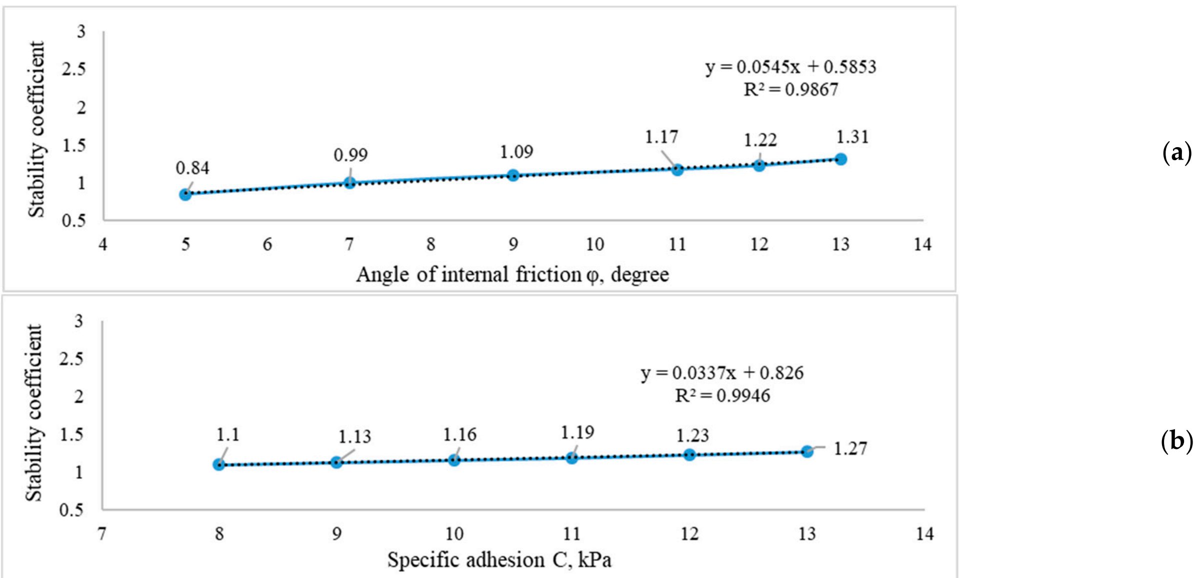

Figure 14. Influence of tailings strength characteristics on the dam's stability coefficient: (**a**) angle of internal friction; (**b**) specific adhesion.

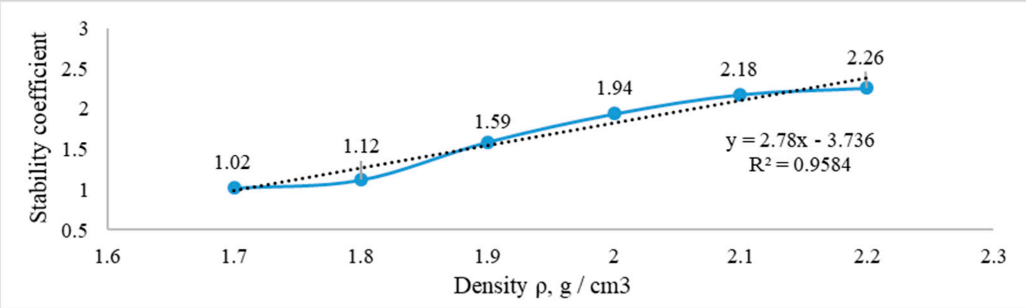

Figure 15. The density effect on the dam's stability factor.

4.2. Operation

4.2.1. Optimisation of Inwash Technology

The developed method of estimated performance monitoring the stability of the tailing dam was tested and implemented in a number of design decisions for the tailing dumps of the mining and non-ferrous metallurgy industrial enterprise in the North of Siberia.

The results of calculations were used for zoning and to visualize the state of the tailings of the tailing dump. Normally, the legend to the map serves as a table in which different colors mark the values that are valid, invalid, and above the permissible safety factor of sustainability, as indicated in Table 12 [29].

Table 12. The legend to the map of the tailing dump stability.

Combination of Loads and Effects	Class of Structure			
	I	II	III	IV
Basic				
Above the allowable (Stable)	>1.3	>1.2	>1.15	>1.1
Allowable (Boundary)	1.3–1.25	1.2–1.15	1.15–1.1	1.1–1.05
Invalid (Unstable)	<1.25	<1.15	<1.1	<1.05
Special				
Above the allowable (Stable)	>1.1	>1.1	>1.05	>1.05
Allowable (Boundary)	1.1–1.05	1.1–1.05	1.05	1.05
Invalid (Unstable)	<1.05	<1.05	<1.05	<1.05

The scheme is represented as a cartographic model with dedicated clearing blocks by color the status of the tailing dam stability (Figure 16).

According to the results of calculations, the following is established:

- plots along areas 1, 5 and 8 are in a steady state—slope condition is stable;
- plots along areas 2, 6, 7, 11 and 12 should be operated with careful observance of the requirements of the project for the operation of the tailing dump—slope condition is boundary;
- dam sites along cross-sections 3, 4, 9, and 10 need urgent measures to increase the bearing capacity of the dam—slope condition is unstable.

In these areas (3, 4, 9, 10), various methods must be applied to prevent an accident.

It is possible to do by technological ways. We will consider the results of approbation of some of them [30].

Technological ways of increasing the tailing dump volume:

- arrangement of a secondary banking dam with the help of excavating equipment;
- the compacting of the inwashed tails;
- replacement of a retaining prism by the filter screen from a geotextile.

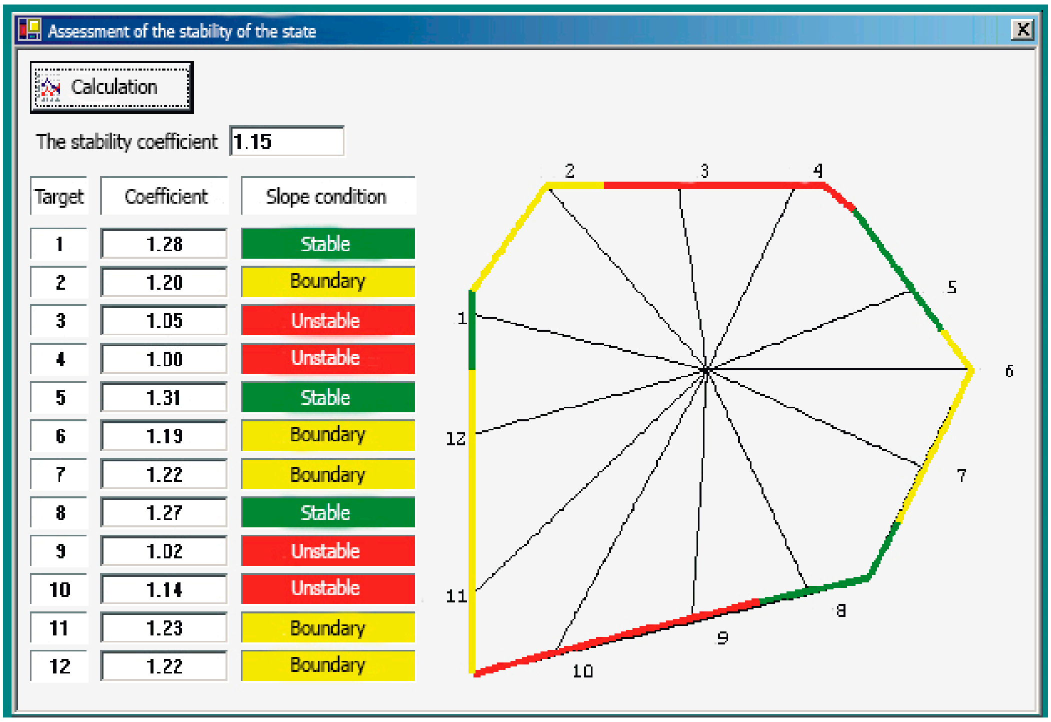

Figure 16. Tailing dam stability monitoring.

The intensity of the inwash process increases on the sites where the secondary coating of tails of the beach area at a distance of 5 m were carried out by tails with the help of excavating equipment. The schematic circuit of banking is shown in Figure 17.

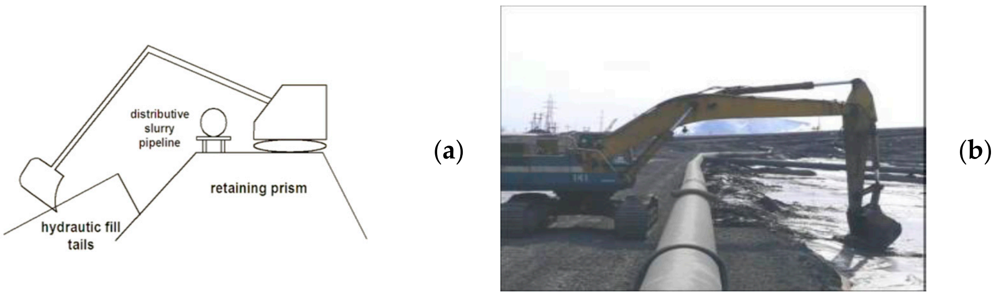

Figure 17. Arrangement of a secondary banking dam of hydraulic fill tails with the help of excavating equipment: (**a**) elementary diagram of arrangement; (**b**) in situ tests.

This allows forming an additional embankment dam, which in turn leads to a change in:

- geometric parameters of the dam with an increase in the size of the dam along the top;
- processes of consolidation of inwashed tailings, their acceleration and natural improvement of the dam base.

Creation of a secondary dam with the help of an excavator showed high efficiency.

Average speed of arrangement of a secondary dam from stale tails with the help of an excavator comes to ~10–30 m per hour.

At realization of the technology with the use of banking by excavating equipment, the following operations are being occasionally excluded from the technology used now:

- dismantling of a distributive slurry pipeline;
- overlifting of a distributive slurry pipeline.

Using the technology of levee embankment allows increasing its volume to up to 6%.

The next technological way of compression process and dump volume increase has been used by compacting of the inwashed beach zone by rollers (Figure 18).

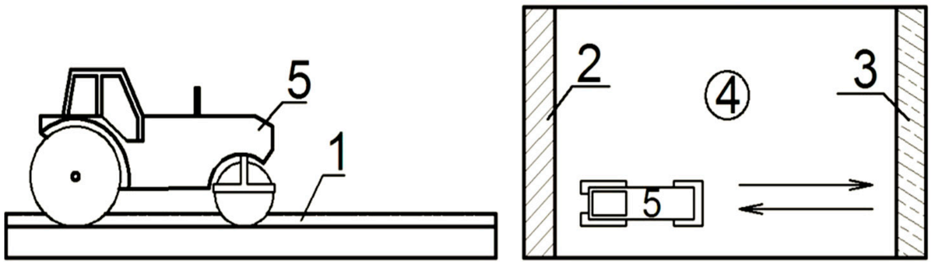

Figure 18. The scheme of the compacting process: 1–compacting lay of tails; 2–a retaining prism of a dam; 3–slurry collecting slag prism; 4–a beach zone; 5–roller.

During compaction process of tails, the following rules were observed:

- The selection of the type of the roller was carried out under the average characteristics of compacting tails;
- The compacting was performed with keeping of a technological pause for two weeks after inwashing of the next layer of tails and achieving the optimum humidity of 15 ÷ 20%;
- Each subsequent compacting trace of roller overlapped the previous one by 20 ÷ 30 cm;
- The direction of the movement of the road-roller was chosen from a retaining prism of a dam to a slurry collecting slag prism;
- The number of one-trace passes was defined depending on the weight characteristics of the roller, initial density, humidity of tails, and based on the demanded final density of tails.

As a result of compacting, it is possible to receive the reserves of volume of depositing tails up to 25 ÷ 30%.

The parameters of the compression process depend on humidity, density, and the grain size composition of tails.

Compacting was carried out in two weeks after the completion of an inwash of the next sector. The use of compacting allows increasing the capacity of a beach to up to 30%. In addition, due to compacting, the filtration factor reduction of a body of a dam is observed, and the value of stability factor increases.

The results of the obtained data were compared with the results of the basic version of the calculation of the stability of the structure. They show the dynamics of changes in the properties of soils which affects the stability coefficient, proving the legitimacy of the technology application (Table 13).

Table 13. Comparative results of the tailing dam stability calculation.

№ of Site	k_{st} Value, before Applying the Proposed Technology	k_{st} Value, after Applying the Proposed Technology
3	1.05	1.28
4	1.00	1.26
9	1.02	1.31
10	1.14	1.43

Thus, the approach to the accident factors allows for monitoring construction in the process of exploitation and to implement urgent measures in hazardous areas surrounding the tailing dam.

4.2.2. Consolidation Tests and Inwash Duration

When choosing a technological scheme of construction and operation, the influence of climatic conditions on the geotechnical massif technological scheme forming process is of particular importance.

Fifteen sets of samples were generated from the available tail samples in order to obtain moisture content and density data for conducting subsequent trials. The quantity of experiments was determined using the methods from the probability theory and mathematical statistics during the planning phase. The conclusion derived from these methods was used to establish the number of tests required for the predetermined parameters of the experiment. Table 14 shows the physical properties of the tested samples [29,31,32].

Table 14. Physical properties of samples.

№ Exp	Humidity W, %	Density ρ, g/cm³	Soil Particle Density ρ_s, g/cm³	Void Ratio e	The Degree of Saturation S_r	Flow Index I_L	Variety in Terms of Yield
1	4	1.05	2.63	1.60	0.07	<0	Solid
2	6	1.01	2.63	1.76	0.09	<0	Solid
3	8	1.09	2.63	1.61	0.13	<0	Solid
4	10	1.12	2.63	1.58	0.17	<0	Solid
5	12	1.16	2.63	1.54	0.21	<0	Solid
6	14	1.18	2.63	1.54	0.24	<0	Solid
7	16	1.12	2.63	1.72	0.24	<0	Solid
8	18	1.15	2.63	1.70	0.28	<0	Solid
9	20	1.34	2.63	1.36	0.39	<0	Solid
10	22	1.3	2.63	1.47	0.39	<0	Solid
11	24	1.44	2.63	1.26	0.50	<0	Solid
12	26	1.51	2.63	1.19	0.57	<0	Solid
13	28	1.94	2.63	0.74	1.00	0.15	Plastic
14	30	1.87	2.63	0.83	0.95	0.54	Plastic
15	32	1.87	2.63	0.86	0.98	0.92	Plastic

Figure 19 depicts the compression curves of the tail samples, showcasing their behavior at different moisture content and density levels. The data reveal that the behavior of the tails remains consistent across various moisture content and density conditions. This observation indicates that the factor of consolidation can be applied to determine the consolidation characteristics of the tails, resulting in a significant reduction in labor requirements.

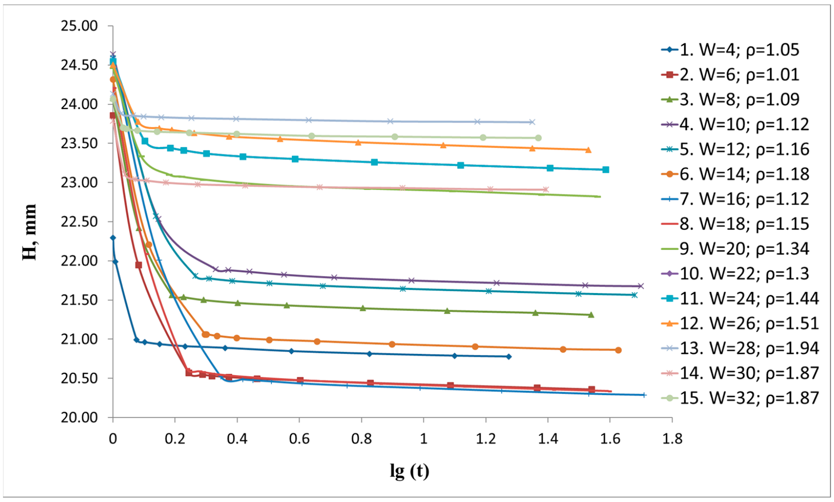

Figure 19. Compression curves for the tails samples with specified moisture content and density.

Equation (1) was used to determine the time required for the consolidation of the layer, as well as to describe the process of sample deformation in height based on its deformation properties. The results of these calculations and observations are presented in Table 15.

Table 15. The time of layer consolidation.

№ Exp	Filtration Consolidation Coefficient C_v, cm^2/min	Time, min	The Coefficient of Secondary Consolidation C_α, cm^2/min	Time, Days
1	6.89	10.38	0.0083	6.01
2	3.90	18.69	0.0117	4.34
3	580	12.03	0.0112	4.32
4	2.81	24.41	0.0090	5.27
5	5.36	12.86	0.0102	4.67
6	5.21	13.66	0.0091	5.43
7	5.22	14.02	0.0114	4.48
8	5.17	14.14	0.0125	4.07
9	5.92	10.99	0.0132	3.43
10	5.41	12.63	0.0141	3.37
11	5.52	11.61	0.0124	3.59
12	6.54	9.70	0.0124	3.55
13	17.16	3.64	0.0022	19.87
14	12.32	5.26	0.0045	9.90
15	15.23	4.14	0.0035	12.61

As is commonly understood, the process of tailings inwash can be divided into two distinct stages: tails inwash and consolidation of inwashed tails.

The respective values for the inwash and tails consolidation times were obtained and are documented in Table 16.

Table 16. The time of alluvium and consolidation of tailings.

<table>
<tr><th>The Volume of Pulp Alluvium on the Area per Day, m^3</th><th>The Time of the Alluvium of One Full Layer, Days</th><th>Required Humidity W, %</th><th>Required Density ρ, g/cm^3</th><th>The Time of Consolidation of One Complete Layer, Days</th></tr>
<tr><td>23,972</td><td>14</td><td rowspan="5">20</td><td rowspan="5">1.65</td><td>12</td></tr>
<tr><td>23,972</td><td>7</td><td>12</td></tr>
<tr><td>23,972</td><td>9</td><td>12</td></tr>
<tr><td>23,972</td><td>16</td><td>12</td></tr>
<tr><td>23,972</td><td>15</td><td>12</td></tr>
</table>

Based on the obtained results, it can be concluded that with successive washing of sectors, the duration of the inwash decreases.

$$(\mathrm{H1} + \mathrm{K1}) \cdot 2 + (\mathrm{H2} + \mathrm{K2}) \cdot 2 + (\mathrm{H3} + \mathrm{K3}) \cdot 2 + (\mathrm{H4} + \mathrm{K4}) \cdot 4 + (\mathrm{H5} + \mathrm{K5}) \cdot 4 =$$
$$= (14 + 12) \cdot 2 + (7 + 12) \cdot 2 + (9 + 12) \cdot 2 + (16 + 12) \cdot 4 + (15 + 16) \cdot 4 = 368 \text{ days}.$$

H—the inwash process; K—the consolidation process of the tails; 1–5—the sector numbers.

Based on the climate conditions in the area, it is possible to wash the tailings for a duration of 195 days.

In order to meet the regulatory requirements, optimization of the process of reclamation was applied to network planning (Figure 20).

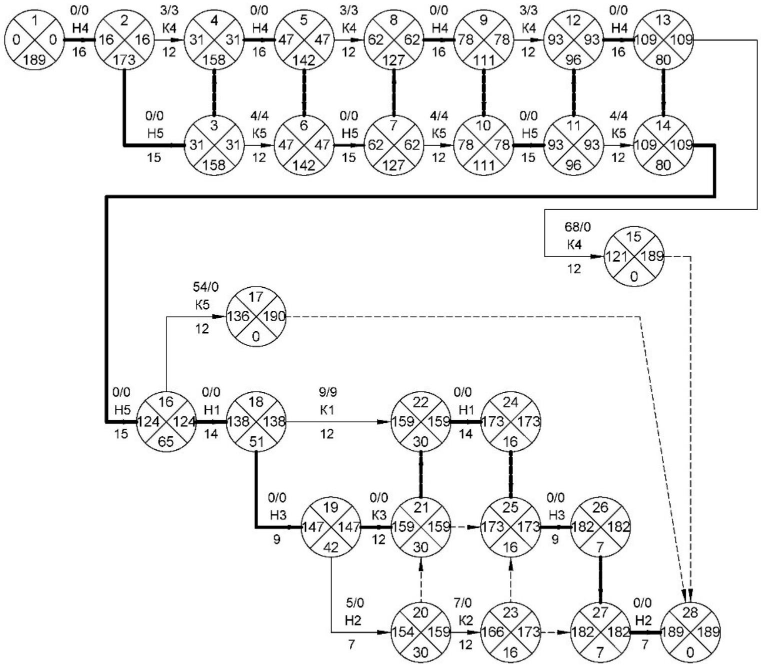

Figure 20. Network graph of tailings inwash.

To ensure efficient utilization of time, it is suggested to initiate the inwash process from the fourth sector of H4. This particular sector requires 16 days, which is the longest duration for inwashing. Once the inwash of H4 is completed, the consolidation process of K4 can commence. Simultaneously, the fifth sector of H5 can undergo inwashing for a duration of 15 days.

Furthermore, it is recommended to complete all stages of reclamation and consolidation in one field before moving on to the next in the case of multiple fields. This approach is considered more rational and ergonomic, especially when dealing with longer distances.

Upon constructing and evaluating the network schedule, it was determined that the critical path's duration is 189 days. This finding indicates that the required timeframe for laying the entire volume of tailings will be met.

4.2.3. Determination of Microstructure

Further, complex studies of the composition, structure and properties of tailings were carried out for the engineering and geological justification of the formation of alluvial technogenic massifs.

The results of the research showed that tailings have their own characteristic features of structure, composition and properties.

The results of the analysis of the granulometric composition of soils obtained by microaggregate, standard and dispersion methods are presented in Table 17.

Table 17. Results of granulometric soil analysis.

№ Tests	Sample Preparation Type	M_s^1	M_s^2	M_d^1	M_d^2	M_c^1	M_c^2
Lebyazhye tails	Aggregate	60.1	28.1	6.1	1.9	2.1	1.7
	Semi-dispersed	51.4	26.9	12.2	1.1	5.7	2.7
	Dispersed	49.2	30.1	8.3	2.4	6.8	3.2

The content of fractions (%): M_s^1—medium and coarse-sand (250–500 microns), M_s^2—fine sand (50–250 microns), M_d^1—coarse dusty (10–50 microns), M_d^2—fine dusty (2–10 microns), M_c^1—coarse clay (1–2 microns), M_c^2—fine clay (<1 microns) (according to Ryashchenko).

The results of determining the granulometric composition were used to calculate the microaggregate coefficients (K_{ma}) for six fractions based on the difference in their contents during dispersed and aggregate sample preparation, presented in Table 18.

Table 18. Obtained microaggregate coefficients.

№ Tests	K_{ma}^{1-2}	K_{ma}^{1-1}	K_{ma}^{2-2}	K_{ma}^{2-1}	K_{ma}^{3-2}	K_{ma}^{3-1}
Lebyazhye tails	1.5	4.7	0.5	2.2	2.0	−10.9

K_{ma}—microaggregate coefficients (%), calculated accordingly for M_c^2, M_c^1 (K_{ma}^{1-2}, K_{ma}^{1-1}), M_d^2, M_d^1 (K_{ma}^{2-2}, K_{ma}^{2-1}) and M_s^2, M_s^3 (K_{ma}^{3-2}, K_{ma}^{3-1}).

A negative coefficient indicates the number of aggregates of the corresponding value. The coefficient of microaggregates with a positive sign—an increase in particles of smaller sizes that released from the aggregates.

Thus, during dispersion, a natural process occurs: larger elements are destroyed, and the smallest ones are collected in a fraction of less than 0.001 mm.

The degree of soil aggregation and the size of their aggregates and particles is determined by the microaggregationality coefficients. Experiments and calculations made it possible to determine the features of tailings microstructure, types of microstructures and structural models of soils (Table 19).

Table 19. Types of microstructures and structural models of soils–tails.

Sample	A (%)	Mic.-st. Type	Structural Models of Soils				M^7	F^6	M^8
Lebyazhye tails	10.9	Ag-Sk	X^1	60.1	G^1	82	3.2	53	10.0

A—total number of aggregates, including A^{1-5}—250–500, 50–250, 10–50, 2–10, 1–2 μm; M^{1-5}—number of primary particles of the same size, M^6—number of primary particles < 1 μm; $M^{2\text{-}A}$—$M^{6\text{-}A}$—number of particles 50–250, 10–50, 2–1 and <1 μm as part of aggregates; M^7—total number (primary and in aggregates) of particles < 1 μm; M^8—total number (primary and in aggregates) of particles <2 μm_M; F^1–F^6—coefficients of freedom calculated for fractions 250–500, 50–250, 10–50, 2–10, 1–2 and <1 μm.

The next step is to obtain the total content of primary particles + particles in the composition of the aggregates (Table 20).

Table 20. Total content (primary particles + particles in aggregates).

Sample	M^{2A}	F^2	M^{3A}	F^3	M^{4A}	F^4	M^{5A}	F^5	M^{6A} / (M^7)	F^6
Lebyazhye tails	30.1	93	8.3	73	2.4	79	6.8	31	3.2	53

M^{2A}—fine–fine sandy, M^{3A}—coarse silty, M^{4A}—fine dusty, M^{5A}—coarse clay and M^{6A}—fine clay fractions and their coefficients of freedom F (%).

The degree of soil aggregation and the size of their aggregates and particles is determined by the microaggregationality coefficients. Experiments and calculations made it possible to determine the features of tailings microstructure, types of microstructures and structural models of soils (Table 21).

Table 21. Types of microstructures and structural models of soils.

№ Tests	Microstructure Type	The Model Type According to the Size of the Prevailing Elements	Type of Structural Model (G, %)
Unal tails	Skeletal	Fine grained [$A^2 + M^2$]	Elementary (93)
Fiagdon tails	Skeletal-aggregated	Medium coarse sanded [$A^1 + M^1$]	Mixed (56)
Tyrnyauz tails	Skeletal	Fine-grained [$A^2 + M^2$]	Elementary (85)
Lebyazhye tails	Aggregated-skeletal	Medium coarse sanded [$A^1 + M^1$]	Elementary (82)

Air-dry samples were used to determine indicators of physical and physical–chemical properties of soils. The research results are presented in Table 22.

Table 22. Indicators of Physical and Physical–Chemical Properties of Soils.

№ Tests	ρ_s	W_L	W_P	I_P	V	φ_1	φ_2	D_j	E_{ce}
Lebyazhye tails	2.62	31.9	27.6	4.9	2.5	19.2	15.8	7.2	12.3

ρ_s—density of the mineral part of the soil, g/cm^3; W_L, W_P, I_p—upper and lower limits of plasticity, number of plasticity, %; V—sedimentation volume, cm^3; φ_1, φ_2—angle of natural slope in air and under water, deg.; D_j—angle change, deg.; E_{ce}—cation exchange capacity of the soil, mg-eq per 100 g of substance.

Due to the specific values of the strength of technogenic soils which are associated with their specific composition (ore dressing wastes), it is not possible to use any recommendations of regulatory documents and reference calculated values "*c*" and "φ". Experimental data are required for calculations.

According to dispersed granulometry (boiling with sodium pyrophosphate) and on the basis of the calculations performed, the following information can be provided.

The tailings of the tailing dump are sandy loams, the content of the medium coarse sandy fraction (>0.25 mm) is 49.2%, the fine-fine sandy fraction (0.25–0.05 mm)—30.1%. The amount of clay particles is 10.0%. According to the total number of aggregates, an aggregated-skeletal (A = 9.5%) microstructure was established. The type of structural model is medium coarse sandy (medium coarse sandy structural elements prevail), elementary (G^2 = 82%).

4.3. Disposal

Mathematical modelling of various schemes of refining tails and magnetic pyrite concentrate, with the forecast of stability of frame fillings, was performed in order to develop an effective technique. Drilling and maintenance of the inspection equipment, as well as the measuring of temperatures and water levels in a dam body were executed. Exploration drilling including full testing of core samples was carried out on the territory of the magnetic pyrite depository №2.

To forecast the levee stability, a number of programs was used. The UWay program complex FEM package was applied to calculate the temperature condition on the basis of finite elements. To forecast the levee stability, the UniFos program was used [13].

The UWay program complex permits to forecast the stress-strained state of soil and rocky massifs, the change of temperature and hydrological modes of soil massif.

The UWay program performs the following types of calculations:

- changes in the geometry of the settlement area (for example, the registration of phases of buildings);
- changes in properties of materials;
- changes in boundary conditions (both power and displacement);
- operation of materials according to various models of behaviour of soils under load.

At the first stage, calculations of the temperature conditions in the tailing dam's massif for winter and summer periods were conducted. The results of calculations are shown in Figure 21.

The given results were used for the appointment of physical and mechanical characteristics of soils composing the dam's body and have formed the basis of the calculations of the dam's coefficient stability. The calculations were carried out by means of the UniFos program.

The UniFos program is a part of the UWay complex and is assigned for calculations of stability of soil constructions. It is written in the object-oriented C++ language with the usage of optimizing compiler Borland C++ Borland International v.5.02 with the library OWL usage v.5.0 [13].

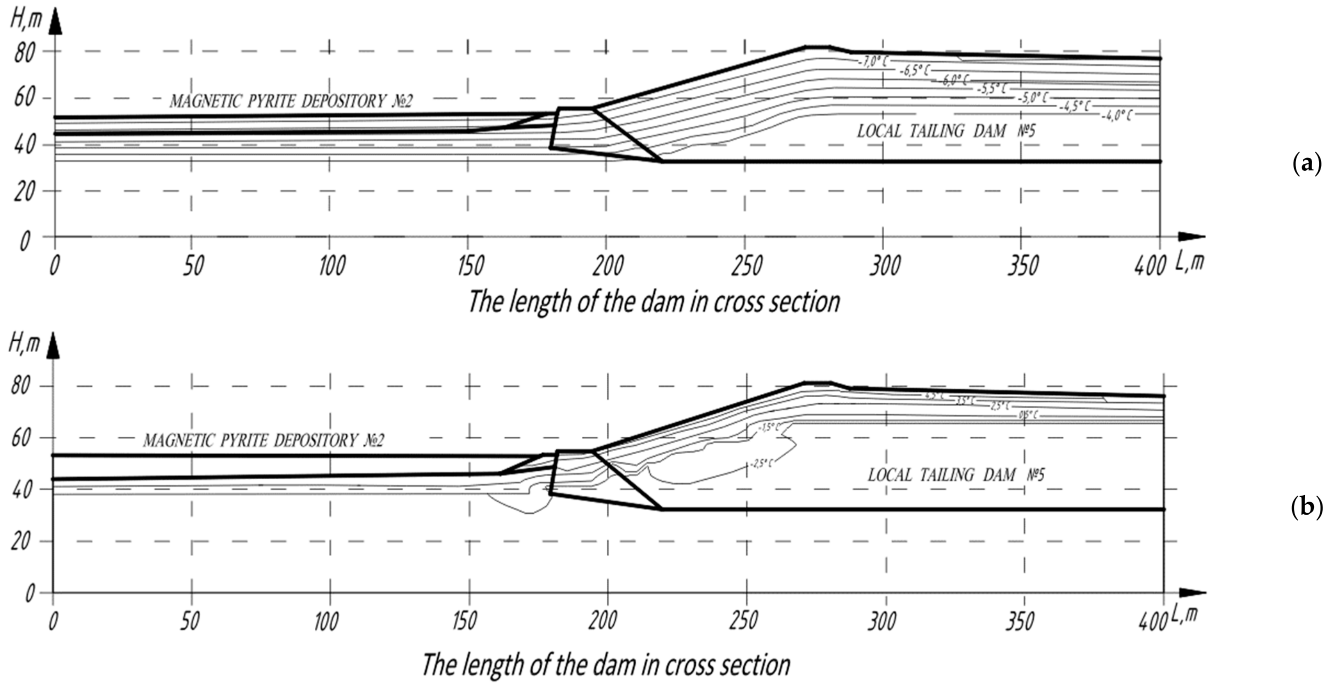

Figure 21. Results of calculations of the temperature conditions: (**a**) in winter time; (**b**) in summer time.

At the next stage, the calculations of the stability coefficient of the tailing dam were carried out for four conditions:

(a) in winter time before excavating works;
(b) in winter time on termination of excavating;
(c) in summer time on termination of excavating works and flooding by water;
(d) in summer time without flooding by water.

The results of calculations of the dam's stability coefficient are shown in Figure 22.

The analysis of results of mathematical modeling shows that the dam stability is not provided during the summer period (stability coefficient is less than 1.0) when the earlier-suggested technology of magnetic pyrite concentrate excavating is used. This result helped to form the basis for changing work technique that provided, in its turn, a safe and effective execution phase.

The justification of the minimum sizes of the security zone and the development of the concentrate excavating technology were executed at the following stage of modelling.

At this stage, various options of concentrate refining were considered:

- with preservation of a security zone of various width (20, 50, 75, 100 m),
- with the backfilling and without it,
- with a thawing assumption, etc.

The results of calculations of the stability coefficient for the various sizes of a security zone width permit to draw a conclusion that its optimum equals 50 m. This conclusion is based on the development of the excavating technology of magnetic pyrite concentrate.

The excavating technology of the pyrite concentrate is offered to be carried out in the following sequence:

- 1 turn: To excavate the concentrate from the whole area of the pyrite depository №2 up to the border of the security zone (about 50 m);
- 2 turn: To excavate the concentrate within the security zone during the winter period;
- 3 turn: To substitute the excavated volume within the security zone for soil material from the local tailing dam using slope flattening (at the beginning of the summer period).

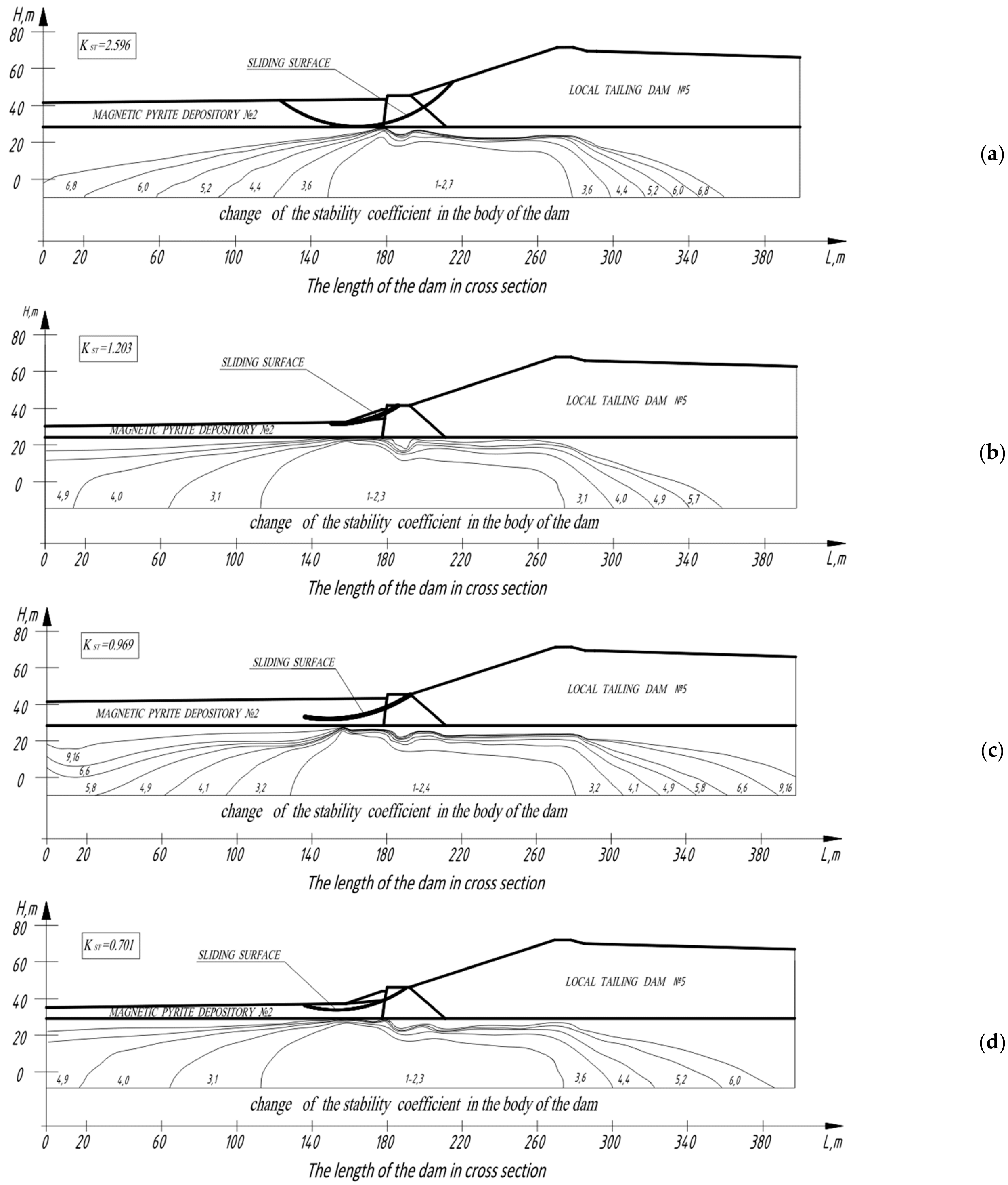

Figure 22. Results of stability coefficient calculations: (**a**) in winter time prior to the beginning of excavating; (**b**) in winter time on termination of excavating; (**c**) in summer time on termination of excavating and flooding by water; (**d**) the same without flooding by water.

The crest of a dam is cut off by 2 m, i.e., to the mark 121.0 m (under the condition of preservation of minimum admissible excess of dam crest level over the level of a pond mirror (mark—117.2 m). The slope inclination decreases to 1:4, that improves dam stability.

The stability coefficient grows to the 3.0 value, which testifies to a steady condition of the tailing dam (Figure 23).

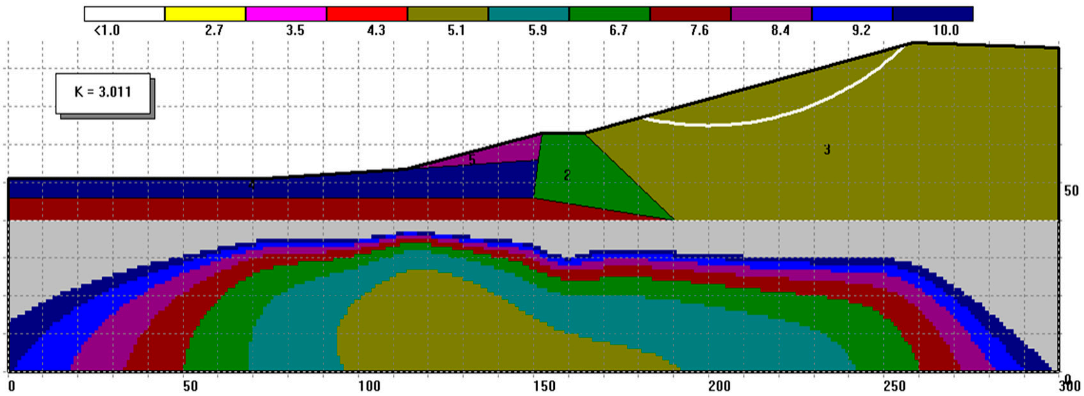

Figure 23. The stability coefficient of the enclosing dam after completion of works.

The program complex UWay FEM package has been applied to the dam's temperature condition calculation on the basis of finite elements.

Forecasting of stability of a levee was executed by means of the UniFos program.

The carried out calculations permitted to forecast the stability of the tailing dam and formed the basis for the alteration of the work technique that provided a safe and effective execution phase.

5. Conclusions

The comprehensive research carried out provided both theoretical and practical justification for several directions of effective and safe operation of the tailing dump in the coming years:

- The use of the proposed method of alluvial enclosing dam with the formation of an impermeable screen to prevent filtration from the tailing dump improves the technology of inwash processing of tailings of enrichment enterprises on soils of the tailings bed of different water permeability, and also increases the stability of the enclosing dam;
- The conducted experiments yielded polynomial trend lines for tails distribution along the beach area. These trend lines are dependent on the optimum pulp consistency, which is determined by the liquid-to-solid ratio, as well as the speed of the pulp. The summary graph shows the tails distribution at the distances of 10, 40, and 70 m from the distribution slurry pipeline. Based on the data, it can be observed that the tails distribution along the beach exhibits a quadratic dependence on the pulp velocity, the height of the pulp axis, and the weighted average particle diameter;
- The analysis of the test results leads to the conclusion that the stability coefficient of the tailing dump enclosing dam is directly influenced by the geometric parameters of the dam, the strength characteristics of the inwashed deposits, and the level of compaction they undergo;
- Implementing the technology of banking by excavating equipment eliminates certain operations like dismantling and overlifting of a distributive slurry pipeline. Additionally, utilizing the dam embankment technology enables an increase in its volume by up to 6%;
- The compaction process of tails involved selecting the appropriate type of roller based on average compacting characteristics. Compacting was performed with a two-week technological pause, allowing for inwashing and achieving the desired humidity. The roller's movement overlapped previous traces, and the direction was chosen accordingly. The number of passes was determined based on weight, initial density, humidity, and desired final density. Overall, compacting increased the volume of deposited tails by 25–30%;
- The compaction process carried out two weeks after cleaning the beach was proven to be effective. It significantly increased the beach capacity by up to 30%. Additionally,

this process improved the filtration and stability factors of the dam. The comparison of data with initial stability calculations confirms the positive impact of compaction on soil properties, supporting the use of this technology;

- Accurate determination of consolidation time is essential when optimizing technological parameters for tailings. Consolidation time plays a crucial role in determining the sequence of sector inwash;
- Network planning methods improve the accuracy of determining technological parameters, resulting in cost reduction during the construction and operation of facilities. By constructing and calculating the network schedule, the duration of the critical path is determined;
- The tailings of the Lebyazhye tailing dump are sandy loams, the content of the medium-coarse sandy fraction (>0.25 mm) is 49.2%, the fine-fine sandy fraction (0.25–0.05 mm)—30.1%. The amount of clay particles is 10.0%. According to the total number of aggregates, an aggregated-skeletal (A = 9.5%) microstructure was established. The type of structural model is medium coarse sandy (medium coarse sandy structural elements prevail), elementary (G^2 = 82%);
- The carried out calculations played a crucial role in predicting the stability of the tailing dam. These calculations served as the foundation for modifying the work technique, ensuring the safe and efficient execution of the project. The knowledge gained from these calculations enabled the team to make informed decisions and implement necessary changes to enhance the stability and safety of the tailing dam. Ultimately, these alterations in the work technique contributed to achieving a successful and secure execution phase.

Accidents at mining enterprises, particularly those involving tailing dumps, present a significant threat to human lives, engineering structures, and the surrounding environment. This underscores the urgent need for effective measures to address the risks associated with reservoirs of various origins.

Scientific research is essential in developing optimal methods and technologies for constructing these facilities while minimizing their negative impact on the environment.

Scientific monitoring is crucial throughout all stages of tailings storage facility management, including design, construction, operation, and disposal.

Thus, the practical application of the developed method of estimated monitoring for tailing dam stability demonstrated high reliability of the obtained results and confirmed the actual load-bearing capacity of the tailing dam.

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