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Interdisciplinary Approach as Basis for Enhancing Construction and Operation Safety of Industrial Hydraulic Structures

Regina E. Dashko  and Darya L. Kolosova * 

Department of Hydrogeology and Engineering Geology, Empress Catherine II Saint Petersburg Mining University, 199106 Saint Petersburg, Russia; regda2002@mail.ru

* Correspondence: daryakolmot@yandex.ru

Abstract: This article analyses the necessity of employing an interdisciplinary approach in the geotechnical practice of designing, constructing, and operating industrial hydraulic structures—tailings dams of processing plants. Tailings dam failures often lead to irreversible consequences for the ecological state of the environment. The interdisciplinary approach involves treating the foundation soils of structures and anthropogenic tailings deposits as a multicomponent system. In this system, soil acts as a medium hosting groundwater of varying compositions and contamination levels, containing biotic components and their metabolic products, including the gaseous phase. It has been demonstrated that the justified application of this approach increases the operational safety of existing structures and the long-term stability of starter and tailings dikes built on weak clay foundation soils. Particular emphasis is placed on the biotic component and the dual role of sub-surface microorganisms. These bacteria negatively impact the strength and load-bearing capacity of water- and water-gas-saturated clay soils in the foundation of the structures under consideration. The diverse biocenosis in groundwater simultaneously facilitates self-purification from petroleum hydrocarbons to undetectable levels. This aspect holds fundamental importance, as groundwater discharges into river systems.

Keywords: water- and water-gas-saturated clay soils; industrial hydraulic structures; tailings storage facilities; stability of starter and tailings dams



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1. Introduction

Mining is almost always accompanied by processing to extract the target component from the ore [1]. The use of various processing methods requires the construction of industrial hydraulic structures, such as sludge and tailings storage facilities. These structures are typically built in areas with relatively unfavourable engineering–geological conditions to save productive land resources for other purposes [2]. Depending on the geomorphological features of the terrain, such structures may be situated within drainage divides (plains), river and stream valleys, ravines, or lake and sea basins. Excavation pits and depleted quarries are also repurposed for waste storage. It is established that the lower the concentration of the target component in the ore, the greater the number of tailings storage facilities needed. These facilities can span hundreds to thousands of hectares, with dam heights reaching tens of metres [3].

The foundation soils of industrial hydraulic structures include various types of rocks and soils, ranging from fractured rocks to sandy clay deposits of different genesis, strengths, and stabilities. Notably, the continuous deposition of tailings pulp results in a system where the pressure on the foundation steadily increases. This pressure is typically constrained

by the load-bearing capacity of foundation soils and the potential for slope instability or landslide deformation in sandy clay soils.

Current regulatory frameworks, developed with contributions from the United States of America, Canada, Switzerland, Russia, and other nations, address a broad range of tailings storage facility safety factors requiring consideration throughout their lifecycle [4–6]. Existing provisions encompass, among other critical aspects, monitoring of environmental, engineering–geological, and hydrogeological parameters—including groundwater physicochemical composition (pH, chemical oxygen demand, total dissolved solids, etc.). Nevertheless, they lack predictive methodologies for assessing adverse transformations in foundation soils beneath operational tailings storage facilities. Such transformations may arise from alterations in redox conditions, groundwater chemical composition (particularly organic compounds), and activity of both indigenous and introduced microbial taxa.

The operational safety of tailings and sludge storage facilities must be ensured throughout their lifecycle [7]. It is necessary to consider their long-term operation under evolving geotechnical conditions, where the underlying rocks and soils undergo transformations due to continuous interactions with process effluents. The composition of these effluents is governed by the processing technology employed—specifically, the use of organic and inorganic reagents [8,9]. Accordingly, the operational safety challenges of such facilities, which accumulate significant volumes of process wastes with complex chemical compositions, should be addressed through two research stages:

1. Ensuring the long-term stability of starter and tailings embankments, taking into account the load-bearing capacity of the foundation soils and their transformation over time, in close interaction with the tailings deposition technology of the disposed crushed ‘waste’ rock and the composition of the pulp’s liquid phase [10,11];
2. Under conditions of guaranteed stability of dams and foundation soil structures, it is essential to organise and conduct comprehensive monitoring of the adverse environmental impacts caused by tailings storage facilities at the local and regional levels. This includes, but is not limited to, impacts on groundwater and surface water, soils, air quality (particularly during wind erosion of deposited tailings containing clay particles), vegetation, and other components of the natural environment [12–14].

2. Suggested Methodology for Enhancing the Operational Safety of Industrial Hydraulic Structures

The conducted experimental studies and comprehensive monitoring results form the body of scientific–practical experience. This experience has demonstrated that enhancing the safety of construction and long-term operation of industrial hydraulic structures can be achieved only through an interdisciplinary approach. Its key principles are discussed below.

A comparative assessment of the actual conditions affecting the stability of starter and tailings dams at tailings storage facilities across various regions of Russia, as well as abroad, led to the conclusion that industrial hydraulic structures built on sandy clay soils pose the greatest risk in terms of prefailure and failure scenarios [15,16].

In the design practice of sludge and tailings storage facilities, the primary focus is on ensuring the stability of structures by accounting for the pressure exerted by deposited tailings, changes in the stress–strain behaviour (SSB), and consolidation processes of the foundation clay soils [17]. However, the negative impacts of incoming industrial (flotation) effluents on soil, groundwater, and surrounding areas are often overlooked.

Geotechnical engineers and engineering geology specialists also disregard the reduced load-bearing capacity of foundation soils beneath starter and tailings dams—a key factor controlling stability and operational safety of structures. It is essential to account for the high susceptibility of clay soils to water and, in particular, industrial effluents that are

characterised by varying compositions of organic and inorganic compounds and mineralisation levels, including brines (potash salt processing) [18]. The key factors determining the long-term stability of industrial hydraulic structures built on clay deposits can be divided into three groups (Figure 1):

1. Monitoring the dam crest level and changes in the SSB of foundation soils;
2. Accounting for transformations in hydrogeological conditions within the tailings storage facility body, its base, and adjacent areas;
3. Assessing contamination of groundwater and soils by both organic and inorganic compounds of abiotic and biotic origins.

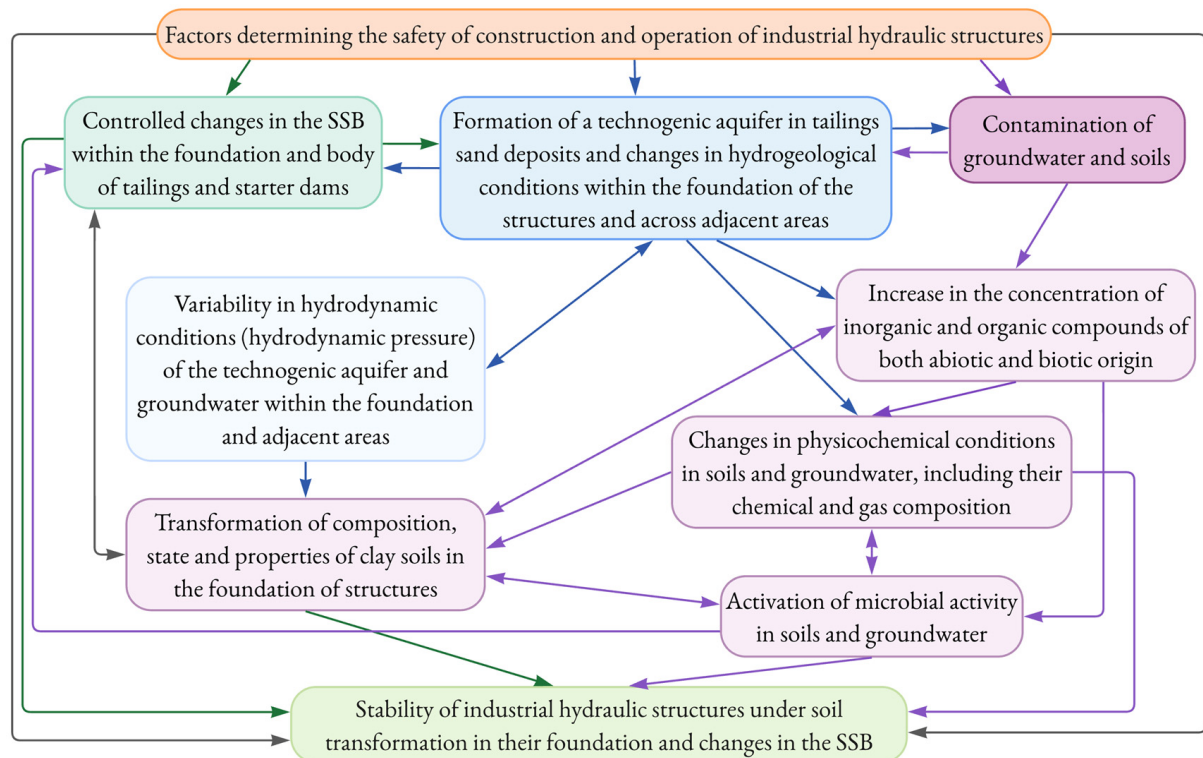


Figure 1. Key factors for the long-term stability of industrial hydraulic structures on clay soils using an interdisciplinary approach [according to the authors' data].

The block diagram (Figure 1) demonstrates the negative impacts of factor groups on changes in physicochemical conditions, activation of microbial processes, and—most critically—the transformation of composition, state, and properties of foundation soils.

3. Application of an Interdisciplinary Approach to Assess the Stability and Operational Safety of a Specific Facility (Tailings Storage Facility) in the Leningrad Region

Extensive experience with tailings storage facilities at processing plants in northwestern Russia, where relatively weak clay deposits form foundation soils, demonstrates the validity and necessity of such an interdisciplinary approach to ensuring the stability and operational safety of such facilities.

The analysed tailings storage facilities are plain type and are located in the watershed area of a river within the Baltic Sea basin. The minimum distance between the drainage ditches and the riverbank is 80 m. The regional climate is humid. The processing plant waste is delivered to the tailings storage facilities in the form of pulp with a specific ratio of solid and liquid phases. The solid phase primarily consists of sandy fractions of varying particle

sizes (resulting from sandstone crushing); whereas, the liquid phase is contaminated with the following reagents used for flotation beneficiation: tall oils, petroleum products (diesel oils), sodium silicate, sulfuric acid, and calcium chloride as well as natural compounds—phosphates and fluorides—present in the beneficiated ore. It should be noted that the area surrounding these structures had no anthropogenic influence on the environment prior to their construction.

The river territory and its watershed area are located within a buried valley in Cambrian Blue clays filled with Quaternary deposits. The moraine deposited during the Last Glaciation, with a thickness of 2–4 m, overlies the Cambrian Blue clays and outcrops in the southern and southeastern parts of the study area. The moraine is almost entirely overlain by glaciolacustrine deposits with a thickness of 6–8 m, which serve as the bearing layer for most of the tailings storage facility area (Figure 2). These formations gradually thin and pinch out in the southern direction. Notably, the construction site area is waterlogged; during tailings deposition, the swamp deposits were not removed.

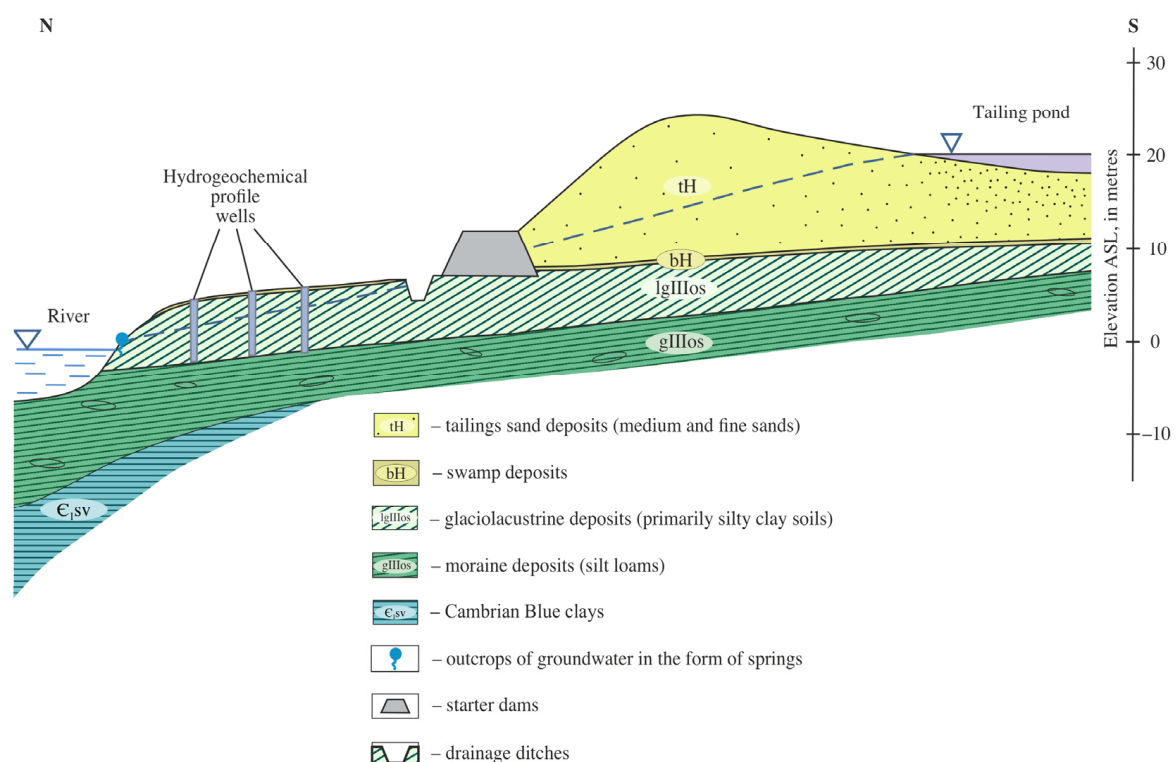


Figure 2. Schematic geological-lithological cross-section of the foundation soils of tailings storage facilities and sandy tailings deposits [according to the authors' data].

Glaciolacustrine clay deposits vary in their structural and textural features—from indistinctly laminated in the upper part to varved clays in the middle and lower sections. This variability results in anisotropic filtration properties and mechanical ones.

The glaciolacustrine deposits contain a relatively uniform aquifer, where sandy layers and lenses act as the water-bearing zones. As is known, the waterlogging of an area affects the chemical composition of groundwater as well as its physicochemical and biochemical parameters [19]. Prior to the operation of the tailings storage facilities, the chemical composition of the groundwater was characterised as sodium–calcium bicarbonate type, with total dissolved solids (TDS) of 0.3–0.6 g/dm³ (Table 1).

Table 1. Variation in the initial chemical composition of the glaciolacustrine deposit aquifer [according to the authors' data].

Concentration, mg/dm ³								COD ¹ , mgO ₂ /dm ³	pH	TDS, g/dm ³
Na ⁺ + K ⁺	Ca ²⁺	Mg ²⁺	HCO ₃ [−]	SO ₄ ^{2−}	Cl [−]	F [−]	HPO ₄ ^{2−}			
$\frac{30-60}{45/6}$	$\frac{30-50}{40/6}$	$\frac{10-30}{20/6}$	$\frac{200-400}{300/6}$	$\frac{5-20}{13/6}$	$\frac{10-40}{25/6}$	$\frac{0.1-0.8}{0.5/6}$	$\frac{0.1-0.5}{0.3/6}$	$\frac{2-18}{10/6}$	$\frac{6.9-7.3}{7.1/6}$	$\frac{0.3-0.6}{0.5/6}$

¹ COD—chemical oxygen demand. Note: The numerator shows the minimum and maximum values; whereas, the denominator indicates the average/number of measurements.

Due to the presence of swamps, these waters contain organic matter, including both readily oxidisable and slowly degradable compounds, while the redox potential Eh (mV) is close to zero or has negative values. It is essential to highlight a key component of swamp waters—the presence of various microbial taxa. Swamp microbial communities are characterised by the following groups: aerobic—nitrifying (microorganism concentration: 10⁴ CFU/g, hereafter); thionic (10⁴–10⁵); facultative—denitrifying (10⁶); anaerobic—ammonifying (10⁶–10⁷); sulphate-reducing (10⁶); cellulolytic (10³–10⁴); and methanogenic (10²–10⁴). The migration of microorganisms enriches underlying groundwater and soils with corresponding taxa of swamp microbiota. This influence extends to depths of 30 m or more [20].

Owing to the tailings pond zone, whose water composition is similar to that of flotation process water, a technogenic aquifer forms in tailings sand deposits, characterised by variable hydrodynamic conditions. Such an aquifer should be considered a local source of contamination for groundwater and sandy clay deposits of the foundation soils and adjacent areas of the tailings storage facilities. This contamination includes inorganic and organic compounds of both abiotic and biotic origins, which is of fundamental importance when analysing the transformation of sandy clay soils and groundwater [21]. The composition of the pond water, presented in Table 2, determines the chemical characteristics of the technogenic aquifer and the specific nature of groundwater contamination.

Table 2. Variation in the chemical composition of pond water (based on studies conducted over 14 years) [according to the authors' data].

Concentration, mg/dm ³								COD ¹ , mgO ₂ /dm ³	pH	TDS, g/dm ³
Na ⁺ + K ⁺	Mg ²⁺	Ca ²⁺	HCO ₃ [−]	SO ₄ ^{2−}	Cl [−]	F [−]	HPO ₄ ^{2−}			
$\frac{664-926}{785/6}$	$\frac{4-17}{11/6}$	$\frac{15-31}{24/6}$	$\frac{488-2008}{1377/6}$	$\frac{5-200}{89/6}$	$\frac{60-337}{203/6}$	$\frac{2.1-6.4}{3.9/6}$	$\frac{2.1-37.5}{24/6}$	$\frac{129-814}{215/6}$	$\frac{8.4-9.4}{8.8/6}$	$\frac{1.7-5.0}{3.2/6}$
The average concentration of organic flotation reagents (mg/dm ³): tall oils—168.0, petroleum products—16.9.										

¹ COD—chemical oxygen demand. Note: The numerator shows the minimum and maximum values; whereas, the denominator indicates the average/number of measurements.

Organic compounds, specifically petroleum products (diesel oil) play a key role in determining the formation of physicochemical conditions in the technogenic aquifer and groundwater. Field study results show that even relatively low concentrations of petroleum products reduce the Eh (mV) value to negative values, creating conditions for the reduction in iron hydroxide Fe(OH)₃ · n(H₂O), which cements the glaciolacustrine deposits in the upper zone. This significantly reduces their strength and increases the potential for plastic deformation. The breakdown of relatively rigid structural bonds is of fundamental importance when predicting the stability of starter and tailings sand dams under conditions where a reducing environment forms in groundwater.

Previously, among contaminants, organic matter of biotic origin has been highlighted. In the practice of studying and analysing the factors that determine the stability of foundation soils and the bodies of dams at tailings storage facilities, the role of subsurface microorganisms has been entirely overlooked. Field and laboratory studies have identified

the main sources of microorganisms in the subsurface environment. These sources can be divided into two groups: natural and technogenic.

Natural sources include swamps, gley soils, the underlying sandy clay strata, and groundwater enriched with swamp microbiota [22,23]. In engineering geology, hydrogeology, and geotechnics, the role of swamps and gley soils as natural formations is overlooked. These formations contain an active component, microbial communities, which primarily consist of anaerobic physiological groups of microorganisms that migrate into the underlying soils. In the presence of nutrient and energy substrates, their activity is significantly enhanced.

Technogenic sources of microbiota include petroleum products (diesel oil) used in the flotation process. Notably, anaerobic microorganisms are present in crude oil and its distillation products, serving as both a source of microbial communities and an energy substrate. Diesel oil is readily assimilated and decomposed by microorganisms of swamps and gley soils, as its structure, with a carbon chain length of C_{17} – C_{22} , is similar to that of swamp vegetation [24,25]. Notably, tailings pond, technogenic aquifer, and groundwater contain all the necessary nutrient substrates for the active development of microbiota, including elements such as potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), nitrogen, phosphorus, and sulfur compounds, as well as the organic compounds such as petroleum products and tall oils.

To assess the diversity of physiological groups of microorganisms and their abundance, specialised studies were conducted using microbial cultures on nutrient media [26,27]. The actual abundance of microbial communities was determined via a correction factor obtained through fluorescence microscopy. When microorganisms are quantified during the transition from oxidative to reducing conditions, the correction factor K is 10^5 ; whereas, for anaerobic environments it is 10^6 (Table 3).

Table 3. The number of microbial cells accounting for correction factors under various physicochemical conditions [according to the authors' data].

Microbial Taxa	The Number of Microorganisms in		Physicochemical Conditions for Bacterial Activity
	Glaciolacustrine Soils, CFU/g	Tailings Pond Water, CFU/g	
Hydrocarbonoclastic	10^8 – 10^9	10^{10}	Transitional conditions from aerobic to anaerobic
Denitrifying	10^8 – 10^9	–	
Sulfate-Reducing	10^6	10^{11}	Anaerobic conditions
Hydrogen-Producing	10^8 – 10^{12}	10^8	
Methanogens	10^8	10^8	

Among anaerobic microorganisms, gas-generating bacteria deserve special attention, as their metabolism is aimed at the complete utilisation of organic compounds, producing biochemical gases [28–30]. Sparingly soluble gases include methane (CH_4), molecular nitrogen (N_2), and hydrogen (H_2) [31]. Gas flow involves the transport of microorganisms, leading to secondary enrichment of the underlying and overlying soils with microbiota. The accumulation of sparingly soluble gases creates conditions for the decompaction of sandy clay soils, changes the SSB of the water- and water-gas-saturated deposits, and consequently reduces their strength [32–34].

To improve the reliability of predicting changes in foundation soils, two-year field studies were conducted on the negative transformation of the strength of glaciolacustrine deposits during groundwater contamination with diesel oil, with concentrations corresponding to actual observed values (see Table 2). Throughout the profile of the glaciolacustrine deposits, not only were changes in strength assessed via a vane shear test, but the

protein content (PC) was also quantified via the biochemical Bradford protein assay [35]. The total microbial PC can be represented by Equation (1):

$$PC = PC_{AC} + PC_{DC} + PC_{MP}, \quad (1)$$

where PC_{AC} , PC_{DC} , and PC_{MP} represent the protein contents of active cells, dead cells, and their metabolic products, respectively.

The size of microbial cells is similar to that of clay particles, which leads to an increase in the content of clay fractions (M_c) in soils. Moreover, all bacteria have adaptive functions, meaning that, along with their metabolic products, they adsorb to the solid surfaces of mineral particles, forming multilayered biofilms that reduce internal friction between particles to negligible levels [36]. Water-saturated clay soils transform into quasiplastic, whereas silts and sands turn into quicksand [37].

On the basis of the results of special field investigations, two depth zones were identified, depending on the nature of the strength decrease in the clay layer prior to groundwater contamination by petroleum products. The study depth ranged from 5 to 7 m, corresponding to the depth of the slip surface. Notably, initially in the upper part of the profile, in situ iron enrichment of the glaciolacustrine clay soils was observed, with a strength exceeding 0.1 MPa (according to vane shear tests). Three months after the introduction of diesel oil, a reduction in $Fe(OH)_3 \cdot n(H_2O)$ compounds was noted, accompanied by a change in the colour of the soil from ochre to grey and a decrease in strength to 0.04 MPa. This change in strength (up to 70%) is associated with the transformation of physicochemical conditions: the transition from oxidative to reducing conditions and, consequently, the breakdown of rigid structural bonds, as mentioned earlier, as well as the increase in microbial populations due to the influx of an energy substrate—diesel oil—that was reflected in the increase in total PC (to 150 $\mu\text{g/g}$ on average).

In the second depth zone, under persistent anaerobic conditions, an increase in microbial populations was observed, which was also confirmed by an increase in total microbial PC values (from 30 to 250 $\mu\text{g/g}$ on average). Consequently, field tests reveal a 35% reduction in the strength of glaciolacustrine deposits (from 0.04 MPa to 0.025 MPa).

4. Analysis of the Factors Influencing the Long-Term Stability of the Foundation Soils of Starter and Tailings Dams at Tailings Storage Facilities on the Basis of a Revision of the Theory of Filtration Consolidation

In Russia, the design of hydraulic structures is carried out according to the first group of limit states—bearing capacity—to ensure the stability of starter and tailings dams and, consequently, to correctly rate the slope angles of hydraulic structure embankments under conditions that prevent clay soil extrusion in the foundation zone and the formation of a unified slip surface [38,39].

According to soil mechanic principles, the small thickness of water-saturated clay deposits in the foundation soil zone of the structure, $h = 8$ m, relative to the large width of the loaded fill area, $b = 2000$ m, necessitates solving a one-dimensional consolidation problem ($h/b = 0.003 < 0.25$), i.e., the filtration consolidation of weak clay soils over time.

As is known, the theory of filtration consolidation was first proposed by K. Terzaghi in 1925 and is based on the following principles: (1) water in clay soils has bulk properties; (2) structural bonds between soil particles are absent; (3) the movement of pore water in soils follows Darcy's linear law; and (4) at any time t , other than zero, the external pressure $p = p_2 - p_1$ is distributed between the pore water p_w (pore water pressure) and the soil skeleton p_s (effective stress) [40]. The development and refinement of the filtration consolidation theory have been carried out by geotechnical engineers from many countries [41–43]. However, no

study has conducted experimental research aimed at investigating changes in the structure of pore water in clay soils [44].

A revision of the filtration consolidation of water-saturated clay soils can be achieved by analysing pore water as a ‘liquid crystal’ and its structural changes under the influence of various active centres in soil particles, primarily clay minerals, ions in the diffuse layer, microorganisms, and their metabolic products [45]. Furthermore, when improving the consolidation theory, it is necessary to consider the nature of the strength of clay soils and the formation of structural bonds.

It is necessary to address the question of how active centres of solid particles affect the structure of pore water in clay soils and how the radius of their influence increases, as determined by the crystallochemical features of the lattice structure of clay minerals. Research on energetically heterogeneous active centres associated with point defects on the solid surfaces of various materials (metallic and nonmetallic) was conducted by G.I. Distler [46]. The active centres are divided into two groups: (1) epitaxial, increasing water density, and (2) polarising—long-range, stopping the translational motion of water molecules at a distance of 1 μm , creating an ‘ice-like’ structure.

Currently, nuclear magnetic resonance (NMR) is an effective method for determining the structure of liquid and solid media. It detects transitions between magnetic energy levels of atomic nuclei induced by radio frequency pulses [47,48]. The hypothesis that bulk water is absent in clay soils of various compositions and states was first proposed and confirmed by R.E. Dashko’s work using an ECHO-4 NMR relaxometer (^1H frequency of 20 MHz) to study changes in the structural features of pore water in clay soils [49]. Experiments were conducted on water-saturated clay soils with varying granulometric and mineral compositions as well as varying physical states.

During studies using the ECHO-4 relaxometer, the influence of the following factors on the structure of pore water was investigated: the content of the clay fraction M_c in water-saturated clay soils, their physical state in terms of moisture content (w), changes in the mineral composition of the clay fraction, as well as TDC levels and the contents of various chemical elements in the pore water (Figures 3 and 4).

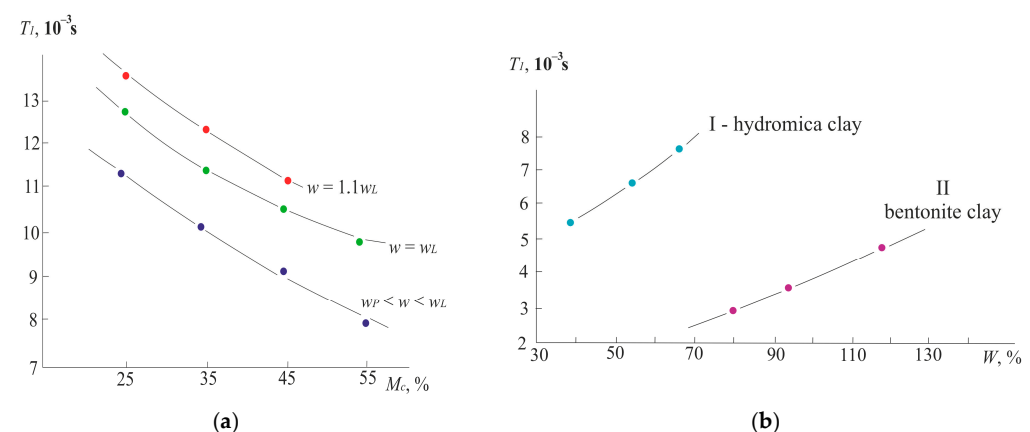


Figure 3. Changes in the spin-lattice relaxation time T_1 of pore water depending on (a) the content of the clay fraction in the soil (M_c) and the moisture state of the soil (w_L and w_P are the moisture contents at the liquid limit and plastic limit, respectively) and (b) the mineral composition of clay soils [49].

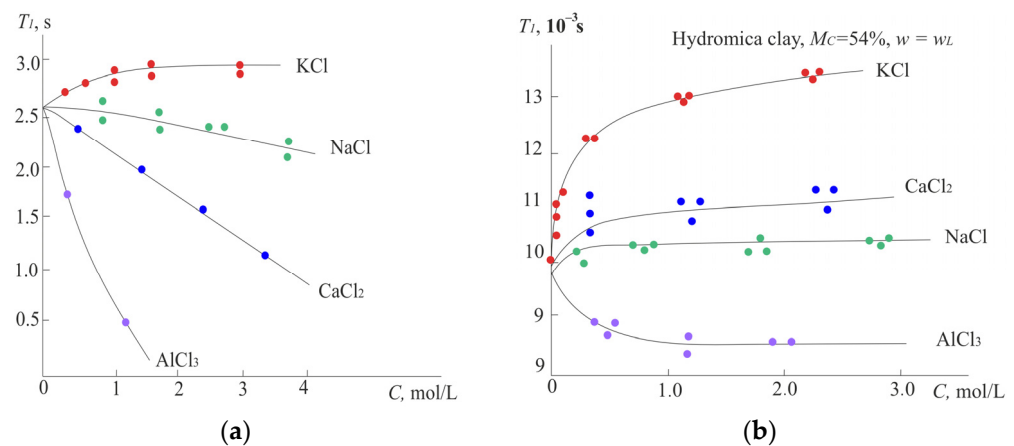


Figure 4. Changes in the spin-lattice relaxation time T_1 of water protons (a) in solutions depending on their concentration C and (b) in pore solutions of clay soils depending on concentration C [49].

The conducted studies established that bulk water is entirely absent under such variations in the composition and state of clay soils, as the average T_1 parameter is $n \cdot 10^{-3}$ s compared to bulk water ($T_1 = 2.5$ s). Moreover, the greatest reduction in T_1 is observed at the lowest moisture contents (with a constant mineral composition). In the presence of more active clay minerals from the montmorillonite group (bentonite), low T_1 values are typical at very high soil moisture levels— $w > 70\%$.

Analysis of the influence of the TDS level and ionic composition of pore solutions on the water structure confirmed that the primary impact comes from the active centres of clay particles. This is supported by the T_1 values measured in the presence of negatively (K^+) and positively hydrating ions (Na^+ , Mg^{2+} , Ca^{2+} , Al^{3+}), with T_1 remaining within the range of $n \cdot 10^{-3}$ s [50].

Studies on the structure of pore water in water-saturated clay soils were continued using NMR equipment (ECHO-12 relaxometer, Saint Petersburg State University, Saint Petersburg, Russia, ^1H frequency of 20 MHz). Spin-lattice relaxation times were measured via a standard inversion recovery pulse sequence. The results of these experimental studies made it possible to assess changes in the structure of pore water in water-saturated clay soils layer by layer as the distance from the active centres of solid particles increased (Table 4).

Table 4. Values of the spin-lattice relaxation time T_1 for clay soils of the liquid state with varying clay fraction contents [according to the authors' data].

Sample No.	Soil Type	Clay (<0.002 mm) Fraction Content, %	$w = w_L$, %	Spin-Lattice Relaxation Times T_1 , ms	
				T_{1S}^1 , ms	T_{1C}^2 , ms
1	Silt loam	16	26.7	0.4	17.6
2	Silt loam	28	34.2	0.7	11.9
3	Silty clay	40	45.0	0.9	10.8

Spin-lattice relaxation time: $^1 T_{1S}$ characterises the structure of the pore water at the solid surface of the particles; $^2 T_{1C}$ —in the central part of the pore.

The general trend in T_1 changes is a decrease in the maximum T_1 values as the clay fraction increases. The clay fraction content determines the highest number of active centres in the soil sample. This is undoubtedly linked to the reduction in pore size and, consequently, the greater influence of the active centres of the clay particles on the structure of the pore water. The main conclusion, on the basis of the results of previous studies, is the

absence of bulk water in the pores of water-saturated clay soils, even in their most unstable liquid state.

Importantly, clay soils have a high number of active centres due not only to the crystallochemical features of various aluminosilicates and silicates but also to the presence of microorganisms and their metabolites (proteins, lipids, acids, etc.). In this context, experiments using ^1H NMR were continued to establish patterns of pore water structuring in water-saturated clay soils in the presence of living components and water-soluble proteins.

The studies were conducted on clay soils ($M_c = 40\%$) primarily composed of hydromica, with moisture content equal to the liquid limit ($w = w_L = 45\%$) [51]. The protein component consisted of a solution of bovine albumin with a known concentration, which made it possible to determine the total microbial protein content (PC) in the studied solutions and during their subsequent transfer into the soils. The total PC concentrations in the solutions and clay soils were $300 \mu\text{g/g}$, $480 \mu\text{g/g}$, $720 \mu\text{g/g}$, $1020 \mu\text{g/g}$, and $1380 \mu\text{g/g}$. These values were chosen as possible when studying the microbial contamination of clay soils under various physicochemical conditions.

For solutions added to the same clay soils, the following taxa of soil bacteria were used: *Bacillus simplex*, *Bacillus subtilis*, and *Bacillus thuringiensis*, with a concentration of 10^8 CFU/mL.

The T_1 values for soils containing different microbial taxa and proteins are shown in Tables 5 and 6.

Table 5. Values of the spin-lattice relaxation time T_1 for clay soils in the liquid state ($w = 45\%$) with the clay fraction content ($M_c = 40\%$) and varying protein contamination levels [according to the authors' data].

Sample No.	Protein Content (PC) in Clay Soil Samples, $\mu\text{g/g}$	Spin-Lattice Relaxation Times T_1 , ms	
		T_{1S}^1 , ms	T_{1C}^2 , ms
1	300	0.018	12.2
2	480		11.6
3	720		11.6
4	1020		12.5
5	1320		12.6

Spin-lattice relaxation time: $^1 T_{1S}$ characterises the structure of the pore water at the solid surface of the particles; $^2 T_{1C}$ —in the central part of the pore.

Table 6. Values of the spin-lattice relaxation time T_1 for clay soils in the liquid state ($w = 45\%$) with the clay fraction content ($M_c = 40\%$) containing different bacteria [according to the authors' data].

Sample No.	Bacterial Taxa Added to Clay Soil Samples	Spin-Lattice Relaxation Times T_1 , ms	
		T_{1S}^1 , ms	T_{1C}^2 , ms
1	<i>Bacillus simplex</i>	1.15	24.7
2	<i>Bacillus subtilis</i>	1.13	11.3
5	<i>Bacillus thuringiensis</i>	1.06	7.6

Spin-lattice relaxation time: $^1 T_{1S}$ characterises the structure of the pore water at the solid surface of the particles; $^2 T_{1C}$ —in the central part of the pore.

The T_{1S} values were only detectable at the lowest PC of $300 \mu\text{g/g}$; at higher protein concentrations, the liquid-like properties of pore moisture in thin layers of clay soils were not observed. Notably, the T_{1S} value of 0.018 ms is an order of magnitude lower than that observed in the 'clay soil–distilled water' system. The comparability and relative consistency of the T_{1C} parameter arise from the dominant influence of clay mineral active centres on the pore water structure.

It is noteworthy that the presence of a biotic component induces greater structural organisation in pore water than in clay soils at equal moisture contents.

Research on the pore water structure in water-saturated clay soils as a multiphase system has demonstrated that the water properties central to the filtration consolidation theory are not supported by experimental investigations employing modern methodologies.

5. Transformation of the Strength and Load-Bearing Capacity of Clay Soils Under Changing Physicochemical and Biochemical Conditions

The conducted studies on changes in the physical state and physical and mechanical properties of clays as the foundation soils of tailings storage facilities have enabled an assessment of the general transformation trend in clay deposits under the influence of pressure exerted by tailings sands, contaminant influx, and enhanced microbial activity (Figure 5).

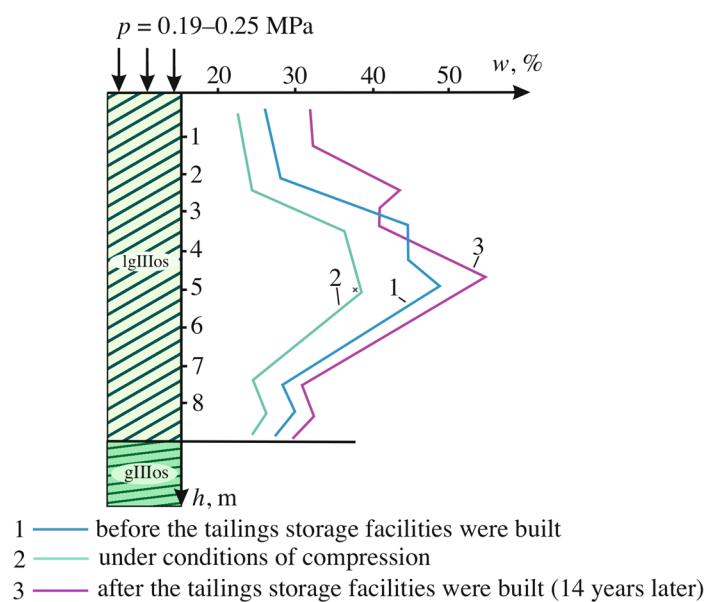


Figure 5. Cross-sectional depth h profiles of moisture content w in the foundation soils of tailings storage facilities [49].

These results reveal a consistent pattern in moisture content w variation with depth h , characterised by a central maximum due to the increased clay fraction content M_c in the soils. The analysis of Figure 6 indicates that there is no evidence of the filtration consolidation process. After 14 years of operation of industrial hydraulic structures, a slight increase in moisture content w is observed in the foundation soils due to the formation of anaerobic conditions, a reduction in iron compounds Fe^{3+} , and a sharp decline in clay soil aggregation, which enhance hydrophilicity through dispersion. Accordingly, a slight increase in w is also expected in the absence of a filtration consolidation process.

As previously noted, changes in physicochemical conditions, coupled with increased microbial populations and their metabolic products, lead to a reduction in the strength of clay soils, as described by Expression (2):

$$\tau(t) = \tau_0 - \Delta\tau_{sb} - \Delta\tau_{PC} - \Delta\tau_g \quad (2)$$

where τ_0 represents the initial strength of clay soils; the strength of clay soils is reduced because of the following: $\Delta\tau_{sb}$ represents the transformation of structural bonds under reducing conditions caused by groundwater contamination with petroleum products and the reduction in Fe^{3+} compounds; $\Delta\tau_{PC}$ represents the formation of biofilms on solid particles by microbial cells and their metabolic products; and $\Delta\tau_g$ represents the decompaction of clay soils due to

the generation of sparingly soluble gases during the activity of anaerobic microorganisms and their utilisation of organic compounds of both natural and technogenic origins.

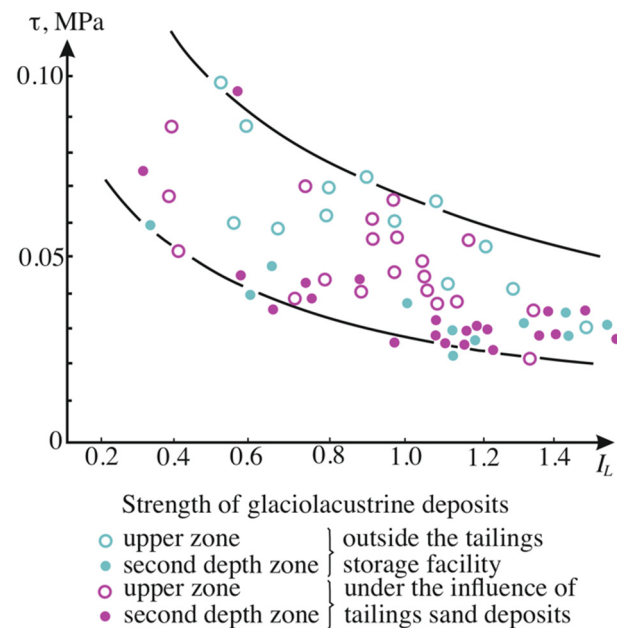


Figure 6. The dependence of the strength variation τ of glaciolacustrine clay deposits as the foundation soils of tailings storage facilities on their liquidity index I_L [49].

The general trend of strength reduction in glaciolacustrine deposits, both outside the tailings storage facility and under the influence of tailings sands in the upper and lower sections of the cross-section, is illustrated in Figure 6.

Notably, the comparative analysis of strength changes, based on field-test results, is presented as a function of the soil state according to the liquidity index I_L . The results of these studies imply that the greatest impact on the reduction in soil strength in the foundation soils is exerted by the transformation of physicochemical conditions and, consequently, the degradation of structural bonds: cementation interactions between particles are replaced by molecular interactions.

During the initial stage of tailings storage facility operation, as per design specifications, the need to ensure stability was justified on the basis of the principles of filtration consolidation. Stability analysis for starter and tailings dams was performed using shear strength parameters—the angle of internal friction (ϕ) and cohesion (c)—derived from consolidated drained (CD) tests, a method widely used in geotechnical engineering practices across many countries. The use of CD values for ϕ and c led to the development of landslide displacements, affecting both starter and tailings dams, accompanied by the extrusion of weak clay foundation soils and the formation of an extended ridge. The design was conducted without considering the weak layer, employing $\phi = 18^\circ$, $c = 0.028$ MPa for the upper zone of the engineering–geological cross-section and $\phi = 15^\circ$, $c = 0.022$ MPa for the second zone. The subsidence of the dam crest caused the failure of the tailings pond, resulting in an emergency discharge of contaminated water into the Baltic Sea river system. Following the accident, scientific and engineering investigations were initiated by the Department of Hydrogeology and Engineering Geology at Empress Catherine II Saint Petersburg Mining University under the supervision of Prof. R.E. Dashko.

The operation of industrial hydraulic structures was managed through an interdisciplinary approach to assess stability and ensure operational safety. This methodology enabled the construction of a second-level tailings storage facility, accompanied by a reduction in the overall slope angle of starter and tailings dikes. Stability analysis for tailings

and starter dams on weak clay foundations employed reduced shear strength parameters (according to unconsolidated undrained test scheme) for glaciolacustrine deposits, considering the formation of anaerobic conditions, increased microbial populations, and soil transformation into quasiplastic states (Table 7 and Figure 7). The calculations were performed under conditions where the slip surface passed through a weak layer, as identified through drilling data.

Table 7. Shear strength parameters of glaciolacustrine deposits within the tailings storage facility area [according to the authors' data].

Depth Zone	Cohesion c , MPa	Angle of Internal Friction ϕ , °
Upper zone	0.035	8
Second depth zone	0.032	5
Weak layer	0.018	3

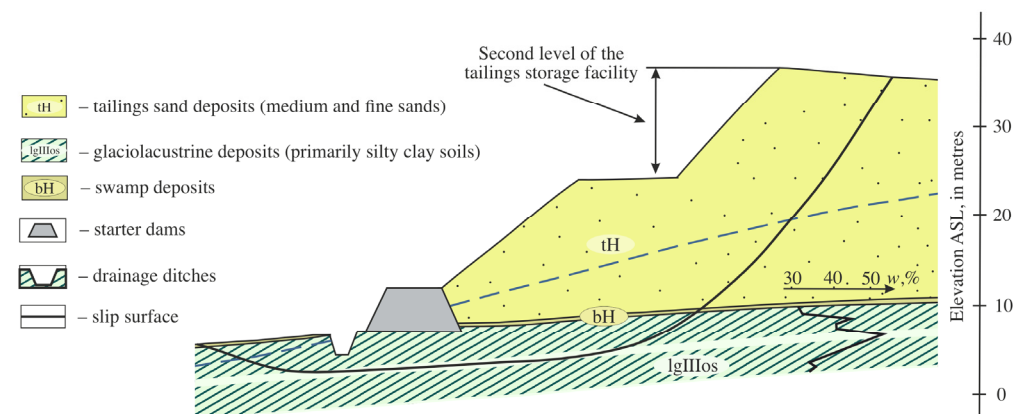


Figure 7. Scheme for stability analysis of tailings storage facilities on weak foundation soils during the construction of a second level [according to the authors' data].

The extension of tailings storage facility operation through the construction of a second tier was accompanied by comprehensive monitoring. This monitoring provided data on the state of foundation soils, slope deformation, and self-purification of groundwater through physicochemical and biochemical processes during discharge into the Baltic Sea river system [52].

Self-purification from inorganic compounds is associated with active sorption processes on clay particles. Self-purification from organic hydrocarbons, i.e., diesel oil, occurs through complete biochemical degradation and their utilisation to gas generation. Strains of microorganisms involved in the degradation of diesel oil were identified, and their activity was tested under conditions of water contamination by petroleum hydrocarbons [53–55]. These experiments fully confirmed the effects of biochemical self-purification observed in groundwater in the presence of diverse microbial communities. Field measurements of petroleum product concentrations in drainage ditches, hydrogeochemical wells, and groundwater discharge zones (see Figure 2) confirmed the effectiveness of their self-purification. A decrease in the diesel oil concentration from 6–10 mg/dm³ in drainage ditch waters to nearly complete disappearance was observed in the groundwater seepage zone, where springs discharge into the river system. Notably, the disruption of cementation bonds under anaerobic conditions, and the resulting dispersion of clay soils, leads to a reduction in their strength and increases their specific surface area. This enhancement facilitates improved sorption capacity and the potential for soil self-purification. Safe operation of the tailings storage facility under such conditions prevents contamination of

Baltic Sea riverine waters due to intensive biochemical processes in the aquifer and the sorption capacity of clay particles.

6. Conclusions

1. An interdisciplinary approach is proposed to enhance operational safety by integrating stress–strain behaviour monitoring of foundation soils, changes in hydrogeological conditions, and contamination assessment of groundwater and soils. A stability assessment block diagram was developed from this analysis.
2. The formation of anaerobic conditions during the oxidation of organic compounds activates subsurface microbial activity. The primary sources of these microorganisms are the waterlogged areas and gley soils underlying the tailings storage facility as well as direct hydrocarbon inputs. These compounds also serve as energy substrates for anaerobic microbial taxa.
3. The field experiments conducted (vane shear tests) demonstrated a reduction in the strength of clay soils due to changes in physicochemical conditions, leading to the formation of an anaerobic environment induced by diesel oil contamination.
4. Experimental studies of pore water structure in various clay soils were conducted using nuclear magnetic resonance. These investigations accounted for both abiotic and biotic components, including microorganisms. The results established a high degree of pore water structural organisation under the influence of active centres of different phases in water-saturated clay soils.
5. The physical nature of deformation processes in clay foundation soils of tailings storage facilities in the absence of filtration consolidation has been examined and experimentally confirmed, which is of fundamental importance for justifying the design parameters of foundation soil shear strength in stability analysis for starter and tailings dams.
6. The study identified biochemical processes and sorption mechanisms on clay particles responsible for groundwater self-purification from organic and inorganic compounds of various genesis.
7. The interdisciplinary approach was implemented during construction of a second-tier tailings storage facility. The effectiveness of this approach was demonstrated in enhancing operational safety of the starter and tailings dams over an extended period.

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