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Analyzing stability of protective structures as the elements of geotechnical tailing pond safety

Vasyl Tymoshchuk[1*], Leonid Rudakov[2], Dmytro Pikarenia[3], Olha Orlinska[3], Hennadii Hapich[2]

[1] *Dnipro University of Technology, Dnipro, Ukraine*
[2] *Dnipro State Agrarian and Economic University, Dnipro, Ukraine*
[3] *Technical University "Metinvest Polytechnic" LLC*
**Corresponding author: e-mail vasyl.tymoshchuk@gmail.com*

Abstract

Purpose is the assessment of soil retaining wall stability to ensure geotechnical safety during the radioactive waste tailing pond closure and further recultivation (or rehabilitation) in Kamianske town (Ukraine).

Methods. Geomechanical stability of the protective structure has been assessed relying upon the analysis of geological-hydrogeological, engineering-geological, and geotechnical conditions of the certain tailing pond area using a deformation elastic-plastic model of a medium implemented on the basis of finite-element method. For the purpose, the dam slopes have been detalized taking into consideration their geometry as well as changes in vertical section of rock material characteristics in accordance with the earlier geophysical studies; exploration drilling; and engineering-geological surveys.

Findings. Stability coefficients of protective tailing pond dam have been identified within the typical areas of a hydraulic structure; it provides high reliability and representativeness of the whole structure health in time as well as under various conditions of the industrial waste water saturation. It has been defined that the stability coefficients varies from k_s = 1.372 to 4.758. Comparison of the indicators between 2022 and 2016 demonstrates a tendency of the slope stability coefficient decrease due to water saturation and groundwater level rise. Nevertheless, design characteristics of the structure make it possible to ensure satisfactory a stability coefficient along the whole dam length being 1.13 times higher than the standard one (i.e. k_s = 1.250).

Originality. The dependence of the tailing pond protective dam stability upon a water supply degree at the forecasted groundwater level rise at the expense of atmospheric and melt water ingress to the tailing pond has been defined. The danger of complete radioactive waste water saturation is a significant reduction in the stability coefficient of the protective structure, which can be supported by predictive modelling data. If strength parameters of a dam material decline for the most critical area then the strength coefficient decreases starting from 1.532 in terms of the current groundwater level down to 1.372 as for the forecasted dam water supply. The figure is more than 10% of its initial stability.

Practical implications. The obtained results substantiate the necessity; moreover, they are of practical value while improving hydrological, hydrogeological, and geotechnical monitoring of the analyzed tailing pond to ensure its radiation safety under different conditions of further behaviour during closure, recultivation, or rehabilitation.

Keywords: *tailing pond, environmental safety, radiation safety, protective dam, slope stability*

1. Introduction

Tailing ponds are an integral part of technological chains for mineral raw material mining, processing, and using; raw materials with the increased radioactivity are also involved. Protective dams are among the basic elements of waste accumulation since they block considerable the amount of dangerous radioactive waste (RAW) globally [1]. Tailing ponds are of a latent high potential environmental hazard in case of accidents or breakthrough of hydraulic structures (HSs). They result in the significant material damage and affect durably the ecosystem and human health [2].

International organizations together with the experts from radiation safety field note the increased frequency of emergencies within the objects. Climatic influence and anthropogenic factors are the key destruction agents of soil protective dams of tailing ponds. The world practices concerning operation of the last-mentioned shows that in the majority of cases, emergencies result from the impact by filtration processes both in a dam body and in its base influencing its integrity and stability [3].

Maintenance of the industrial waste and its safe storage depend heavily upon the reliable condition as well as stable performance of the protective structures. Large tailing ponds, put into operation in the 1950^s-1980^s, are the most vulnerable and unsafe. During the Cold War and maintaining nuclear parity between the USSR and the USA, such tailing ponds were constructed according to the current at that time standards. The level they considered environmental risks and safety rules could not be acceptable by the strict modern standards [4]. As a result, Ukraine inherited numerous radioactive objects, which the USSR used to take care [5], [6]. Today they need considerable attention and reliable rehabilitation level to ensure radiation safety.

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Kamianske town (former Dniprodzerzhynsk) is among those Ukrainian terrains where RAW accumulators are concentrated. Ten tailing ponds together with the industrial site of former Prydniprovsk Chemical Plant (PCP) are essential threat of radioactive state of the territory worsening. The tailing ponds within Kamianske and outside the town limits contain almost 40 million tons of solid radioactive waste, remnants of industrial buildings and ruined (or partially dismantled) structures of a technological cycle for uranium ore recovery [7], [8].

Tailing pond Dniprovske (“D”), located in the floodplain of the Dnipro River, plays a significant role since Dniprovske and Kakhovka (destroyed and devastated in June 2023) water reservoirs are downstream as well as such regional centres as Dnipro, Zaporizhzhia, and Kherson. Hence, in theory, the object is dangerous as for pollution of water area and adjacent zones with waste having high content of natural radionuclides (NRCs).

Taking into consideration a long service life of the majority of the tailing ponds (more than 70 years) as well as not always successful practices of disaster recovery within such objects in different world countries, and having regard to the principle that “it is easier to prevent extraordinary event than liquidate its after-effects” (especially it concerns martial law and restricted financial potential of a state), the problem to ensure both reliable and environmentally safe operation of the industrial waste storage protective dams is extremely topical.

Review of modern studies shows that stability of the tailing pond dam slopes can be calculated using different procedures. Generally, the modelling techniques are based upon physicomechanical characteristics of a dam body and its base. Currently, following methods and models are popular worldwide.

To identify minimal safety and prevent from sliding movements after formation of filtration fields, a model of water penetration at the expense of pressure gradient is applied. Analysis of the tailing pond dam stability by means of a finite-element method (FEM) and a traditional maximum equilibrium approach [9] has shown that the water level rise influences both the hydraulic depression state and the dam stability.

While defining stability indicators of rock-fill tailing pond [10], the stability coefficient value is proposed to calculate taking into consideration circular distraction surfaces. Results of various approaches for boundary balance, tested through a method of strength decrease which also involved fast Lagrangian analysis within continuum and based upon finite differences in the bivariate analysis have shown good agreement between the reliability and safety coefficient values calculated using different procedures.

Authors of paper [11] have performed probabilistic analysis of rapid lowering movement of depression curve of rock-fill dam with a puddle core, and represented its results. Two different lowering velocities have been simulated; in terms of each, two probabilistic calculation procedures for strength dispersion and failure probability have been applied: a first-order second-moment method (FOSM) and a point estimation method (PEM). Both methods gave very similar results.

Research [12] has identified the relation between geotechnical stability of flocculated and dehydrated fine tailings, and a flocculant type. In this context, authors analyzed geotechnical stability through a direct shear test and a case study using GEOSLOPE. The experiments demonstrated the flocculant type influence on the geotechnical stability. It has been understood that dehydration characteristics (i.e. dehydration velocity and shear strength) of fine tailings depend upon a flocculant type as well as upon its dosing. Hence, it is required to take into consideration moisture and physicomechanical characteristics of soil making up the dam and its base.

Waste penetration coefficient in tailing ponds, which may influence both separation and migration of heavy metals, also may have an effect of dam stability; moreover, it results in changes of saturation line height [13]. A computer simulation technique has been proposed to construct 3D model of a tailing pond. In terms of numerical analysis [14] and with the use of ANSYS software, a hydraulic development process for tailing pond has been simulated in three specific working points; moreover, dam body stability of the tailing pond has been assessed. It has been identified that during the tailing pond recovery, safety coefficient decreases within the three heights. Nevertheless, the total stability of the dam does not undergo significant changes but its strength reduces.

The review of methods, estimating stability of tailing pond dams, denotes sufficient amount procedures and task-oriented software. Analysis of the scientific data also supports high convergence of the research results obtained with the help of various approaches and models. The abovementioned makes it possible to apply affordable and reliable FEM to assess security of protective soil dams within Dniprovske tailing pond. The method is based upon a deformation elastic-plastic model of the medium which couples two theories being the foundation of rock mechanics, i.e. elasticity theory and boundary state theory. Having been implemented together with a finite-element method, a technique to reduce strength parameters while evaluating rock mass stability provides the possibility of simultaneous identification of a slide surface as well as stability coefficient if there are no restrictions as for the failure mechanism geometry. FEM advantage is its unification with other capabilities of numerical modelling which helps consider the immersed part of slopes while calculating stability on loose (compressible) soil involving processes of a base consolidation and its hardening. In addition, it helps calculate stability taking into consideration excessive pore pressure, which forms resistance in the central share of the slopes, and favours their stability decrease.

The research purpose is evaluation of soil protective dam stability to ensure both radiological and environmental protection during closure and further recultivation (or rehabilitation) of RAW tailing pond.

To achieve the purpose, following problems should be solved:

– assessing the stress-strain state of a protective dam of Dniprovske tailing pond using deformation elastic-plastic model of the medium implemented on the basis of a FEM;

– evaluating a geomechanical state of the protective dam areas through a method of strength parameter decrease implemented together with the FEM;

– predicting stability of the protective dam of Dniprovske tailing pond depending upon different conditions of its further operation during closure and recultivation.

2. Methods

Geomechanical stability of the protective structure was evaluated based upon analysis of geological and hydrogeological, engineering and geological, and geotechnical conditions of Dniprovske tailing pond site (Kamianske town, Ukraine). A deformation elastic-plastic model of the medium, implemented on the basis of FEM, has been applied.

For the purpose, the dam slopes were detalized taking into consideration their geometry as well as changes in vertical section of rock material characteristics in accordance with the earlier geophysical studies, exploration drilling, and engineering-geological surveys.

Boundary state consideration of the simulated rock mass and plastic flow implementation in the area of extreme deformations as a part of model calculations of the numerical model rely upon the initial stress method. Strain soil characteristics for the analyzed intervals were defined under compression; strength was determined under quick unconsolidated-drained cut.The characteristics of physicomechanical soil properties, defined resulting from the analysis and generalization of the laboratory data, have been assumed as the normative ones while substantiating analytical parameters of the numerical model and evaluating stability of protective dam for depth intervals above and below the water-saturated radioactive waste. According to open data [15], [16], filing pond area is 0.73 km^2 (Fig. 1). It contains almost 12 million tons (5.8 million square meters) of radioactive tailings.

The tailing pond is on the bank of the Konoplianka River which valley is 200-1000-m width here. Its northwest part neighbours waste dumps of Dniprovskyi metallurgical complex (Kametstal PJSC now). Coal and metallurgical slags and sludges are the waste. To the south, on the right bank of the Konoplianka River, industrial objects and infrastructure of the former PCP are arranged where radioactive waste is also placed.

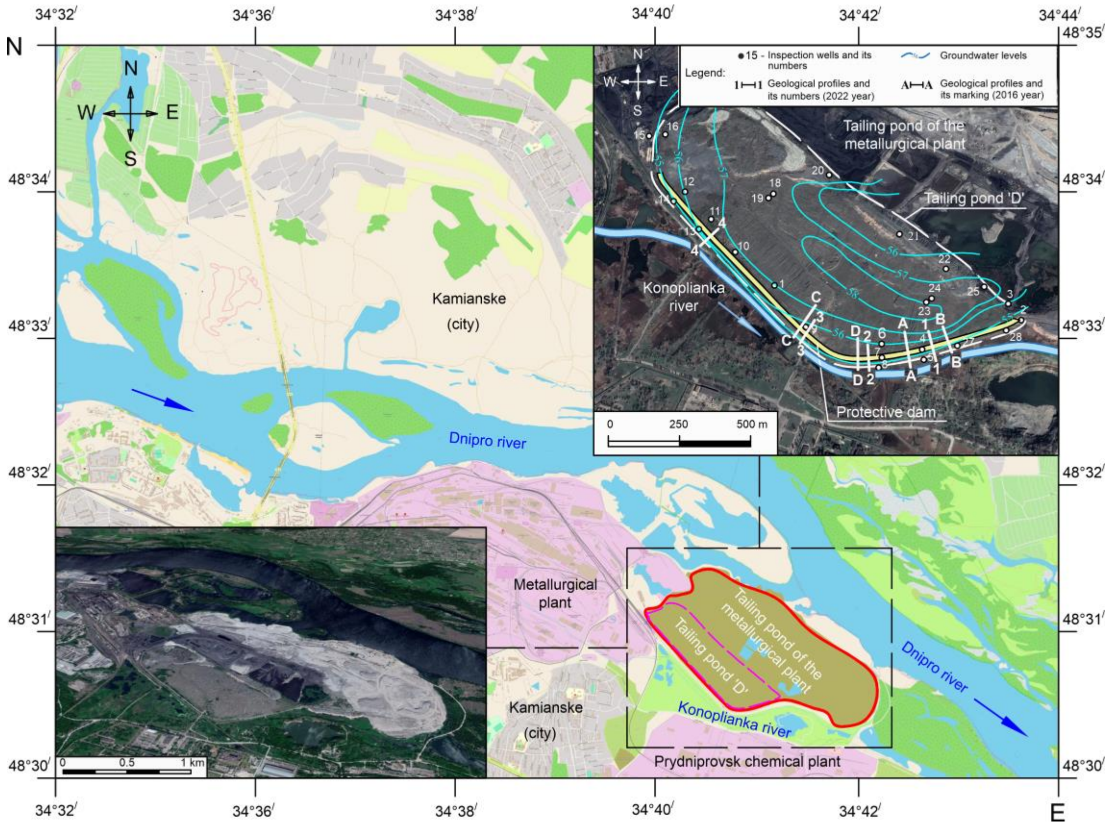


Figure 1. Areal scheme of the Dniprovske tailing pond location performed using such open services as OSM and Google Earth Pro

Within location of analytical profiles 1 and 2 (A, B, and D, respectively; Figure 1), a downstream slope of the dam neighbours the Konoplianka River bed. Profiles 3 and 4 (C, respectively) are within the area the dam borders on the additional body for railway and motor transport. Actually, it is the hydraulic structure (HS) body extension by several up to dozens meters. It influences positively the slope stability owing to the increased width of the structure.

In 1976-1980, the tailing pond was covered by a 1-5-m layer of phosphogypsum near dams, and up to 19-m layer in the central and eastern shares of the pot. It prevents from the radioactive substance getting into the ambient air if wind blows dust. Currently, the tailing pond surface is a drainless catch basin of atmospheric precipitation seeping through phosphogypsum and watering RAW. The polluted water is discharged by means of filtration through the protective dam body and base in surface and underground water [17], [18].

A class of consequences (responsibility) of the structure corresponds to CC3 level. The aforementioned stipulates the necessity to carry out numerous procedural studies at the object; the studies should be both systematic monitoring and the targeted in-depth ones [19], [20].

A protective dam of a tailing pond includes different elements of control and measuring equipment (CME); piezometers and inspection wells to control groundwater level (GWL) are among them. The tools help monitor technical state of the structure. However, preferential provision of the information concerning the structure condition only within their location points is a significant disadvantage of such point CME data.

Taking into consideration the class of structure consequences, system monitoring is followed by the targeted scientific and practical studies. In different years, S.H. Izmailov, D.P. Khrushchov, O.V. Voitsekhovych, H.V. Lyssenko, and O.S. Skalsky headed performance of numerous activities reflected in the scientific and technical reports. The materials are still archived by SE “Barrier”.

Similarly with [21], [22], geophysical surveys using natural pulse electromagnetic field of the Earth and vertical electric sounding were carried out in 2016 and 2022. Results of the activities, which took part in 2016, have helped identify the ways of RAW filtration migration through the HS body and base as well as define the areas where soil of the protective dam differs in stress, suffusion zones, water saturation sites etc. The repeated activities in 2022 showed that location of earlier identified filtration zones did not change; however, new filtration zones emerged within other dam sites near the Konoplianka River. Manifestations of such negative geotechnical phenomena as widening of suffusion conical depressions and moisture-loving vegetation development in a linear and island-like shape expanded visually. Moreover, CME-based geological survey data became the foundations to organize sample boring with further laboratory definition of physicomechanical properties as well as moisture degree of the HS body and base soil. Set of the aforementioned operations has helped substantiate the areas to select profiles required for assessment of geomechanical stability of the tailing pond protective dam.

Four profiles (Fig. 1) have been assumed for calculation and predictive simulation. The profiles pass through the dam areas, within which the development of filtration deformations as well as geotechnical processes is potentially possible.

According to the analytical profiles, geometry of the models has been identified from the condition of their periphery influence on the stress-strain state of the rock mass being simulated covering sites with 80-m length in terms of more than 9-m thickness of the soil near bottom slope of the protective dam up to 21 m within the tailing pond pot (Fig. 2). To provide spatial certainty of the simulated area, zero displacements have been prescribed within the lateral limits of the model as well as along its lower boundary. Force interaction between the model elements is defined through the gravity (volume) forces within the soil mass.

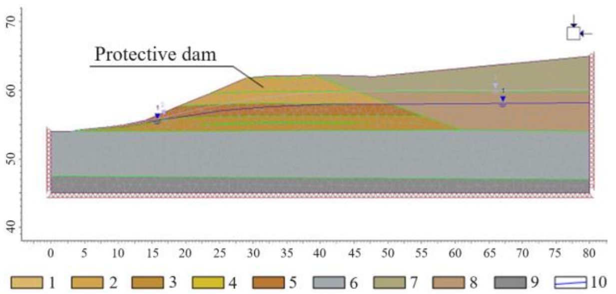


***Figure 2.** Analytical planning of the protective dam area of Dniprovske tailing pond (profile example is 2-2): 1 – light loam; 2 – sandy clay; 3 – sandy clay; 4 – mild clay; 5 – mild clay; 6 – sand; 7 – phosphogypsum; 8 – sandy clay (radioactive waste); 9 – granite; and 10 – groundwater level*

In general terms, the numerical model, implemented in the software environment Phase2, is represented within the areas, being assessed, through the finite elements of nine types in accordance with the geological and lithological structure of soil mass within the tailing pond base. They compose the mass up to the tailing pond of RAW and phosphogypsum as well as the soil material within the protective dam body.

Selection of the required density of the finite elements depends upon the geometry and simulated soil mass heterogeneity. Relying upon high accuracy of the calculation, a uniform network of triangular six-node finite elements was accepted for consideration, which met the possibility to obtain dependable credible computation procedure under the conditions of satisfactory convergence of iteration process.

Deformation soil characteristics for the analyzed intervals were identified in the context of compressive compression; strength was identified in the context of quick unconsolidated-drained cut. The obtained laboratory-based results have been applied to substantiate calculation parameters of a numerical model (Table 1) and assess the protective dam stability of depth interval above groundwater level and under it.

Implementation of inequation shear for the most dangerous prism has become the criterion to provide stability of the waste heap slopes [23], [24]:

$$\gamma_{fc} F \le \frac{1}{\gamma_n}\left(R \frac{\gamma_c}{\gamma_{m(g)}} \right), \qquad (1)$$

where:

γ_{fc} – is coefficient depending upon combination of loads;

F – generalized analytical value of active forces (or their moments) relative to the slide surface centreж

γ_n – reliability coefficient in terms of responsibility;

R – generalized analytical value of forces (or their moments) of boundary shear resistance along the considered surface;

γ_c – service factor;

$\gamma_{m(g)}$ – reliability coefficient in terms of materials or soil.

While defining the dangerous shear surface, the dependence for stability coefficient has been used [23], [24]:

$$k_s = \frac{R}{F}, \qquad (2)$$

from which, Condition (2) can be expressed as:

$$k_s \ge \left[k_s \right], \qquad (3)$$

where:

$k_s \ge [k_s]$ – admissible (standard) value of the stability coefficient:

$$\left[k_s \right] = \frac{\gamma_n \cdot \gamma_{fc} \cdot \gamma_{m(g)}}{\gamma_c}. \qquad (4)$$

According to the class of consequences (responsibility) CC3, under the basic combination between the structure loads and its components, the standard reliability coefficient is $[k_s] = 1.250$ [23], [24].

3. Results and discussion

The performed calculations, concerning geomechanical stability of the protective dam of Dniprovske tailing pond, have shown that its stress-strain state within the analyzed areas is identified through the dam geometry; stowing of its bottom slopes; state of the groundwater surface level; and distribution of the material deformation characteristics in the protective dam section (Table 2). In terms of 2-2 section, the shear surface locations have been represented within the protective dam if watering is not available as well as in the context of the current groundwater level (Fig. 3).

The stability coefficient k_s values, obtained as a result of the simulation, are higher than the normative one for the class structure being $[k_s] = 1.250$. Hence, there is significant strength reserve of bottom slopes of the protective dam within the areas under consideration.

Significant reserve of the stability coefficient as well as the factor invariability under various calculation conditions for 3-3 and 4-4 profiles should be mentioned separately.

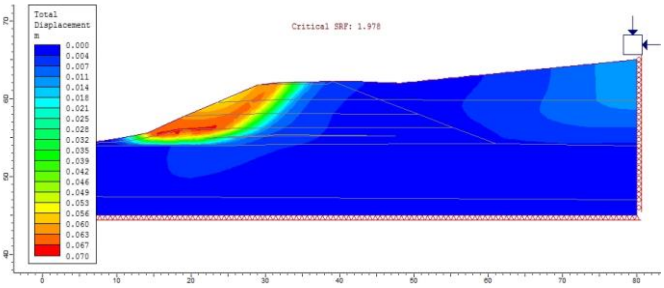
Table 1. Analytical values of physicomechanical characteristics of the base soil, tailings, and the protective dam material

Element type	Description	Specific weight, γ, kN/m^3	Stress-strain modulus, E, MPa	Poisson ratio, ν, fract. un.	Specific cohesion, C, MPa	Internal angle friction, φ, °
1	Light loam (dam)	19.23	53.19	0.30	0.0220	20.9
2	Sandy clay Sr < 0.8 (dam)	18.93	40.40	0.30	0.0110	24.7
3	Sandy clay Sr >0.8 (dam)	17.87	30.57	0.35	0.0070	18.3
4	Mild clay Sr < 0.8 (dam)	19.23	54.46	0.30	0.0267	22.0
5	Mild clay Sr >0.8 (dam)	19.03	33.48	0.35	0.0260	20.0
6	Phosphogypsum	15.00	15.00	0.30	0.0187	27.8
7	Sandy clay (RAW)	18.00	16.00	0.30	0.0087	20.9
8	Sand	17.00	40.00	0.30	0.0013	34.5
9	Granite	25.50	45000.00	0.12	110.00	32.0

Table 2. Analytical values of the stability coefficient of the protective dam bottom slope (the year of 2022)

Solution	Stability coefficient, k_s			
	Analytical profiles (Fig. 1)			
	1-1	2-2	3-3	4-4
Unwatered dam state	1.744	1.978	4.758	2.613
Dam at the current state of groundwater level	1.580	1.695	4.758	2.613

(a)



(b)

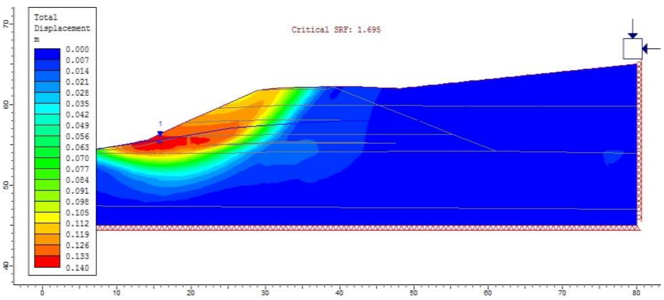


Figure 3. Shear deformation of bottom slope of the protective dam on the simulation data obtained in the software environment Phase2 (calculation profile 2-2): (a) unwatered state (k_s = 1.978); (b) in terms of current GWL state (k_s = 1.695)

The abovementioned depends upon considerable HS width; state of the analytical slide surface and shear prism relative to the watered mass within the soil dam where water level is lower than the share surface. Thus, the dam watering within the share cannot influence its stability.

Stability coefficients within the areas of 1-1 and 2-2 profiles are lower to compare with 3-3 and 4-4 profiles (see Table 2); in this connection, predictive modelling of stability changes depending upon RAW availability in the tailing pond has been performed. Moisture content was close to its complete water saturation (Table 3).

According to the data, a minimal value of the stability reserve coefficient k_s = 1.372 is typical for the dam site located within 1-1 section. It is connected with the influence of water-saturated RAW tailings which thickness is up to 3.8 m. The tailings, located above the groundwater level, impact decisively on the protective dam state.

Table 3. Predicted value of the stability coefficient for a bottom slope of the tailing pond protective dam

State of the protective dam	Stability coefficient, k_s	
	Analytical profiles (Fig. 1)	
	1-1	2-2
Current state of the underground water level; strength parameters are lowered higher than the water level	1.532	1.667
Analytical state of the underground water level; strength parameters are lowered within the watered zone	1.372	1.591

In general, the stability coefficient values, obtained for the analyzed areas, exceed the defined allowable standard value [k_s] = 1.250. Consequently, a stability state of the bottom slope of the dam is maintained even if water level rises analytically.

The results have been applied by operating organization as the targeted studies of health of the radioactively dangerous facility. The paper is an element of monitoring observations of geomechanical stability of the protective dam of Dniprovske tailing pond. Table 4 demonstrates comparison of the analytical values of the dam stability coefficient obtained in 2016 [25] and in 2022.

Table 4. Comparative calculations of the stable reserve of a bottom slope of the protective dam for several years

Solutions	Year	Stability coefficient, k_s				
Analytical profiles for several years (Fig. 1)	2016	A-A	B-B	C-C	D-D	–
	2022	1-1		3-3	2-2	4-4
Unwatered dam	2016	2.93	3.09	3.32	1.83	–
	2022	1.744		4.758	1.978	2.613
Dam at the current GWL state	2016	2.71	2.77	3.02	1.78	–
	2022	1.580		4.758	1.695	2.613
Analytical GWL state; decreased strength parameters in the watered zone	2016	2.29	2.48	2.75	1.57	–
	2022	1.372		–	1.591	–

Comparison of the monitoring results for several years denotes reduction in the stability reserve coefficient during previous six years in the context of the available groundwater level.

RAW water saturation as well as GWL rise within the dam body increases filtration RAW migration through the HS body and the tailing pond base up to surface and ground water level; it may result in water deterioration [26], [27] and its contamination by radionuclides [28].

To control health of protective dam of the tailing pond, monitoring system organization is expedient. The system should involve:

1) location of additional observational hydrogeological wells within the central areas of rock slopes of the protective dam as well as within the landside between the dam and the Konoplianka River bank;

2) establishment of the geodetic observation point to control both vertical and horizontal deformations of the external slopes of the protective dam within the areas of the most probable shear process development as well as within the areas where shears have already been recorded;

3) visual surveys of the refuse dump with recording of slope deformations of the protective dam and possible progress of unfavourable filtration processes (i.e. deformations);

4) water level measurements in the available and new hydrogeological wells at least once a month and water sampling for chemical analysis ones per quarter which will help specify ground water level in addition to filtration velocity, taking into consideration seasonal variations;

5) deformation stability of the tailing pond dam should involve the possibility to form a drainage gravel layer preventing from filtration removal of rock material of the dam under the conditions of its nonuniform vertical watering;

6) solving several organizational and technical problems to reduce atmospheric and melt water ingress to the tailing pond and organize its accumulation and withdrawal.

4. Conclusions

The calculations of geomechanical stability of a protective dam of Dniprovske tailing pond have shown that its stress-strain state within the analyzed areas is identified through the dam geometry; stowing of its bottom slopes; state of surface level of ground water; and distribution of the material deformation characteristics in the HS section. Under the current operation, stability coefficients vary from 1.580 to 4.758; it corresponds to regulatory standards where minimal value is 1.250, and ensures the required strength of the structure.

Predictive simulation of the potential future watering of RAW tailings as well as ground water rise influences the HS stability and reflects in changes of the stability coefficients. In this context, possible decrease in soil strength parameters may be 1.372-1.591; nevertheless, the condition of the slope stability provision is met. Comparison of the monitoring observation results and analytical values of stability coefficients denotes their tendency towards decrease under the current and prognostic GWL state. It is absolutely natural phenomenon being typical for all soil damps operating for a long period. If constant control of a HS state takes place and adequate steps are taken to prevent from geodetic process development, it cannot result in the occurrence of emergency situations.

The obtained results are of scientific and practical importance while improving hydrological, hydrogeological, and geotechnical monitoring of the analyzed tailing pond to ensure its radiological safety under different conditions arising during its closure, recultivation, or rehabilitation.

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Дослідження стійкості огороджувальних споруд як елементів екологічної безпеки хвостосховищ

В. Тимощук, Л. Рудаков, Д. Пікареня, О. Орлінська, Г. Гапіч

Мета. Оцінка стійкості ґрунтової огороджувальної дамби для забезпечення радіаційної та екологічної безпеки під час закриття і подальшої рекультивації (або реабілітації) хвостосховища радіоактивних відходів (м. Кам'янське, Україна).

Методика. Оцінка геомеханічної стійкості огороджувальної споруди виконана на онові аналізу геолого-гідрогеологічних, інженерно-геологічних та геотехнічних умов ділянки хвостосховища з використанням деформаційної пружно-пластичної моделі середовища, реалізованої на базі методу скінченних елементів. Для цього виконана деталізація укосів дамби з урахуванням їх геометричних розмірів та змін в вертикальному перерізі властивостей породного матеріалу згідно з даними попередньо виконаних геофізичних досліджень, розвідувального буріння та інженерно-геологічних вишукувань.

Результати. На характерних ділянках гідротехнічної споруди встановлені коефіцієнти стійкості укосів огороджувальної дамби хвостосховища. Це забезпечує високу достовірність і репрезентативність результатів для прогнозування зміни технічного стану всієї споруди у часі та за різних умов водонасичення промислових відходів. Визначено, що коефіцієнти стійкості змінюються в межах від k_s = 1.372 до 4.758. Порівняння цих показників у 2022 році з параметрами, визначеними у 2016 році, засвідчують тенденцію зниження коефіцієнтів стійкості укосів внаслідок водонасичення та підвищення рівня ґрунтових вод. Проте, конструктивні характеристики споруди надають змогу забезпечити відповідний коефіцієнт стійкості по всій довжині дамби в межах, що перевищує нормативний (k_s = 1.250) в 1.1-3.0 рази.

Наукова новизна. Встановлена залежність стійкості огороджувальної дамби хвостосховища від ступеня обводнення дамби при прогнозованому піднятті рівня ґрунтових вод за рахунок надходження до хвостосховища атмосферних і талих вод. Небезпека повного водонасичення радіоактивними відходами полягає у суттєвому зниженні коефіцієнту запасу стійкості огороджувальної споруди, що підтверджується даними прогнозного моделювання: при зниженні параметрів міцності матеріалу дамби для найбільш критичної ділянки значення коефіцієнту запасу стійкості зменшується від 1.532 при існуючому положенні рівня ґрунтових вод до 1.372 при прогнозованому обводненні дамби, тобто більш ніж на 10% від її початкової стійкості.

Практична значимість. Отримані результати обґрунтовують необхідність та мають практичне значення при вдосконаленні гідрологічного, гідрогеологічного та геотехнічного моніторингу досліджуваного хвостосховища для забезпечення його радіаційної безпеки за різних умов подальшого поводження під час закриття, рекультивації або реабілітації.

Ключові слова: *хвостосховище, екологічна безпека, радіаційна безпека, огороджувальна дамба, стійкість укосу*