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MATHEMATICAL MODELLING OF TAILINGS DAM STABILITY BASED ON GEOMECHANICAL ANALYSIS WITH VARYING KEY PARAMETERS

Abstract. The aim of this study is to analyze the influence of the key parameters of dams on the stability safety factor in terms of a developed numerical model of one of the control sections of the 'Kryvi Luky' tailings storage facility of PJSC 'Ordzhonikidze Mining and Processing Plant' (Ordzhonikidze GZK). The study considers both geomechanical parameters and variability of the influencing factors, with the subsequent scaling of the obtained results to different types of dams under similar mining-geological and hydrogeological conditions.

A geomechanical state of the research object was modelled, and a numerical calculation involving a finite element method was performed. The obtained data were compared with the results of monitoring observations. Convergence of the results from the test calculation and field studies confirmed the correctness and reliability of both the computational scheme and the obtained results.

A series of stability factor calculations was performed according to changes in following key parameters: unit weight, internal friction angle, cohesion and deformation modulus of the dam materials etc. Overall, a variation analysis confirmed that the stability factor increases along with the decreasing slope angles and increasing base width. In this regard, an immediate height of the structure and the filling levels of the sections were among the significant parameters. However, excessive increases in dam height led to the stability loss of the entire system.

It was also confirmed that friction and cohesion, although dependent on unit weight, are not the dominant factors compared to the shear forces, which increase along with the growing integral value of the material's unit weight within the dam body.

Based on the research results, a hypothesis was proposed regarding the expediency to develop a set of measures that would allow for adjusting the balance of the main influencing parameters. In particular, artificial enhancement of the dam material characteristics (either mechanically or chemically), while controlling a moisture content of the dam body, is quite promising, especially considering the dual effect of the material's weight within the dam structure. At the same time, the available moisture within the dam body is a critical factor affecting the overall safety level of the facility.

Keywords: dam, tailings storage facility, analytical studies, geomechanical stability, monitoring, stability safety factor.

1. Introduction

A great share of any process of mining and processing of mineral resources is accompanied by the accumulation of significant volumes of industrial waste, which, depending on the adopted technology, may be in various aggregate states. Fine and dust-like wastes from the processing stage are usually transported hydraulically to tailings storage facilities [1–3].

Like all other hydraulic structures, tailings storage facilities are subjected to substantial loads from numerous external factors [3, 4], including water pressure, temperature fluctuations, precipitation, erosion etc. Accordingly, the stability of such structures depends considerably on their ability to withstand these loads without failure or critical, beyond-design deformations [5, 6].

Thus, ensuring the stability of the tailings dam foundations, i.e. by implementing effective geomonitoring systems, which includes both field observations and geotechnical modelling with forecasting of possible development scenarios, is a relevant scientific and practical task. The goal of this task is to provide predictable

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control over the technical condition and operational suitability of the entire complex of hydrotechnical structures included into a specific tailings storage facility.

A direct analysis of the geomechanical stability of a tailings storage facility allows for a highly reliable assessment of its load-bearing capacity and the timely identification of potential hazards. This makes it possible to implement preventive measures promptly, reduce accident risks, and ensure the overall safety of the structures and the adjacent areas [3, 7].

Thus, the aim of this study is to evaluate the effect of the key dam parameters on the stability safety factor in terms of a developed numerical model of one of the control sections of the ‘Kryvi Luky’ tailings storage facility of PJSC ‘Ordzhonikidze Mining and Processing Plant’, taking into account geomechanical parameters and variability of the influencing factors, with the subsequent scaling of the obtained results to different types of dams (external, internal, constructed in a single stage or through gradual raising, with or without a cutoff wall etc.) under similar mining-geological and hydrogeological conditions.

According to open sources, currently there are about 465 tailings storage facilities in Ukraine, with a significant number located in the Dnipropetrovsk Oblast.

The dams of the ‘Kryvi Luky’ tailings storage facility of PJSC ‘Ordzhonikidze Mining and Processing Plant’ were selected as the research object.

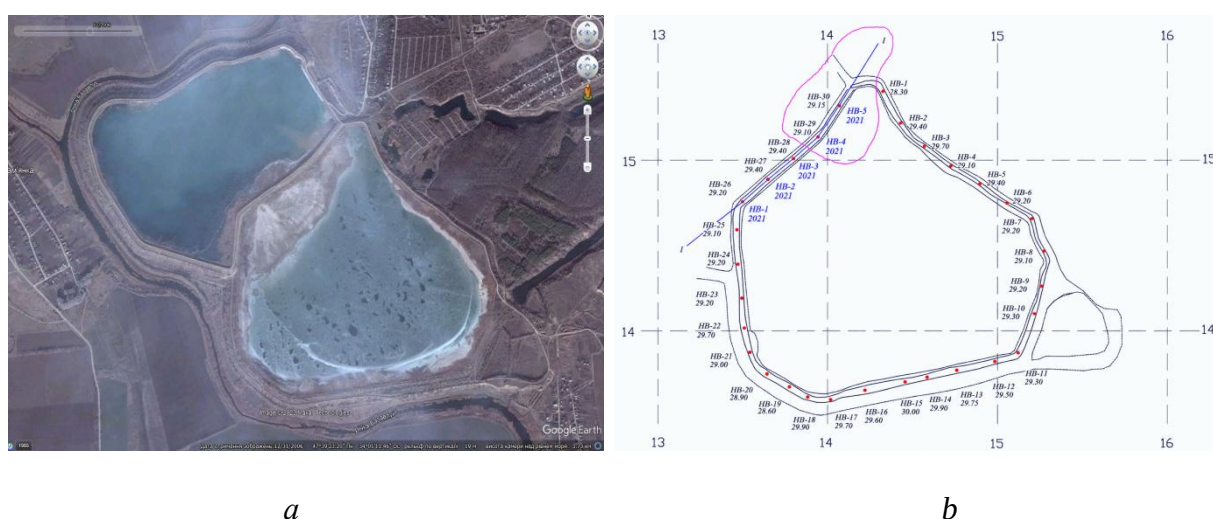


Figure 1 – Image of the site from Google Maps (a) and extraction from the borehole layout scheme of the 2021 engineering survey works (b), where the purple line indicates the area of increased thickness of the plastic-consistency soil lens compared to 2017

The previous research stages [8] comprised the update for a topogeodetic framework including the establishment of a base of reference stations; restoration of the control and observation network within the structure; and implementation of a geomonitoring system through the systematic execution of comprehensive engineering-geological and hydrogeological surveys (Fig. 1). At this stage, a corresponding basis was established to implement a system to monitor technical conditions of the tailings storage facility. It involved obtaining the baseline data for subsequent analytical studies and substantiation of a set of technical solutions to

ensure the long-term stability of the facility and its future reconstruction. Specifically, detailed plans and cross-sections of the structure were developed; a geological and lithological composition of the soil mass was determined; the engineering-geological and hydrogeological conditions were assessed; and the physical and mechanical properties of the soils were defined [8].

2. Methods

The available global and national experience shows that substantiation of the rational approaches to ensuring the stability of such specialized construction facilities as tailings storage facilities, when each of them is situated within its own unique mining-geological and hydrogeological conditions, is possible while using modern methods of geomechanical process modelling [9–14].

A geomechanical modelling of the facility conditions is based on determining the components of the stress-strain state (SSS) of the artificially created environment, treated as a deformable continuous solid body, which includes the components of stress tensor, relative strains, and displacements. The entire system stability is then assessed in terms of a certain criterion derived from the adopted theory of strength.

In this study, a finite element method (FEM), which has proven highly reliable, is applied to determine SSS of the tailings storage facility. Regarding problems in structural mechanics, FEM allows for consideration of the structural characteristics of the rock mass comprising both the immediate tailings facility and its foundation, taking into account heterogeneity, fracturing, stratification, and other features.

Furthermore, in problems of geomechanics where a study object is represented by soil or rock mass, the actual deformation magnitudes can only be obtained if a deformation model allows for irreversible (plastic) deformations. It is the failure of the dam materials and its foundation as well as their deformation beyond strength limits, that is responsible for the vast majority of all emergencies. Therefore, the structure stability must be assessed within the framework of an elastoplastic material model that allows for a nonlinear relationship between stresses and strains as well as material strength based on a corresponding criterion.

In the practice of geotechnical calculations, Mohr-Coulomb strength criterion is the most widely validated one [7, 8, 10, 11].

It should be noted that not all software products capable of implementing FEM are suitable for studying geomechanical processes. Only those are applicable, that can solve elastoplastic problems, based on strength conditions appropriate for describing failure of brittle rocks under dilatancy. To meet the requirements, a well-established software product ‘Phase 2’ by Rocscience was selected as the primary working environment [15].

The analytical studies were carried out by analyzing the results obtained using the Strength Reduction Method (SRM), which makes it possible to determine the critical stability factor, expressed as the strength reduction factor (SRF).

SRM is applied to linear failure criteria, such as Mohr-Coulomb criterion. When the Mohr-Coulomb criterion is used with the strength reduction method, cohesion, internal friction angle, and dilation angle are reduced simultaneously until mechanical

equilibrium is lost. The reduction of material parameters results in decreasing shear strength of the soil, which eventually becomes unstable. This phenomenon leads to a slope failure under a certain combination of loads, material properties, and boundary conditions. The ratio between the initial cohesion and cohesion at failure defines a stability safety factor.

The essence of the method is in a gradual reduction of the material strength parameters (e.g. internal friction angle and cohesion) in the model until it reaches a state where calculation no longer converges. The point at which convergence is lost is considered the critical state; the maximum strength reduction factor at which it occurs is used to determine the stability safety factor.

Thus, a strength reduction method, combined with the finite element method, is a tool for determining the stability safety factor in geomechanics. It is rather informative to analyse the stability of slopes and earth embankments.

3. Results and discussion

Being residual objects of the mining industry, tailings storage facilities are a significant potential hazard to the environment and population. Any accident at these sites can lead to severe environmental and human consequences [5–7].

As mentioned above, a significant number of tailings storage facilities are concentrated in the Dnipropetrovsk Oblast, five of them are located within the Nikopol manganese ore basin. These structures were selected for comparative analysis at the earlier stages of the research. These are following tailings facilities: Morozov gully, Baburin gully, Berehove gully, the one in the Marievskiy quarry of PJSC ‘Marhanets Mining and Processing Plant’, and the tailings storage facility in the ‘Kryvi Luky’ area of PJSC ‘Ordzhonikidze Mining and Processing Plant’.

The listed tailings storage facilities were constructed mostly in gullies by building of dams and containment embankments. During their construction, there were no technological processes for foundation preparation or cutoff walls, and much of the design and as-built documentation has now been lost. As a result, today we have tailings storage facilities built largely in gullies by means of dams and containment embankments, sometimes within the worked-out space of a quarry. Even a visual assessment of the dam conditions shows signs of scour beneath them, exposed seams, reed overgrowth on the dams, and the condition of water intake and spillway structures, slopes, berms, and dam crests all require reinforcement or restoration measures [8].

The ‘Kryvi Luky’ tailings dam of PJSC ‘Ordzhonikidze Mining and Processing Plant’ is the most illustrative among these facilities; it was selected as the primary object for the subsequent studies.

The results of the previous comprehensive monitoring of the technical state of the ‘Kryvi Luky’ tailings dam [8] made it possible to identify the main causes of deformation processes and develop corresponding recommendations to ensure its geomechanical stability. They also helped determine main directions for further research and compilation of a complete set of necessary baseline data for further

development and verification of a digital model of the facility, including the following:

- the monitoring made it possible to identify and localize potentially hazardous areas and determine the causes of dam stability loss;
- a series of drainage, anti-filtration, and reinforcement measures were recommended to reduce the emergency risks; and
- the need for an in-depth geotechnical analysis for further operation of such structures was substantiated.

The main objectives of the study were to model stability of a dam and determine the critical parameters affecting its stability and resilience.

As the baseline option for the calculation scheme, a cross-section along the 30th group of boreholes in the eastern section of the tailings storage facility was selected (see Fig. 1). As an example, Fig. 2 shows geological cross-section of the surveyed area, while the main characteristics of the engineering-geological elements (EGE) and their physical and mechanical properties are represented in Table 1.

Table 1 – Geomorphology of the dam and main physical and mechanical characteristics of the engineering-geological element (EGE) within control section No. 30

No. (EGE)	EGE	Specific soil weight ρ , kN/m ³ (MN/m ³)	Modulus of elasticity E , MPa	Poisson's ratio μ	Internal friction angle φ , deg	Specific cohesion c , MPa
1	Soil-vegetation layer – loam, dark brown, humified	17.9 (0.0179)	18	0.35	20	0.03
2	Fill soil – heavy, silty loam with layers and inclusions of light clay, of firm and semi- firm consistency	18.9 (0.0189)	9.5	0.35	12	0.02
3	Fill soil – light, silty loam with streaks of sandy loam, brown, of low-plastic consistency	19.5 (0.0195)	7.3	0.35	13	0.03
4	Fill soil – light, silty clay, brown and light brown, of firm and semi-firm consistency	20.1 (0.0201)	14.5	0.30	19	0.081
5	Fill soil – silty sand with sand inclusions, brown to dark yellow, of plastic consistency	19.9 (0.0199)	11.6	0,30	26	0.015

A schematic layout of the computational model (2D cross-section of the dam within the control section), made in the Phase2 software environment, is shown in Fig. 3.

For clarity, Figs. 4–8 show graphical results of the modelling for the ‘baseline’ scenario, along with the corresponding charts.

As the graphs demonstrate, the stability factor for the baseline scenario (current state of the control cross-section) is Critical SFR = 2.18 > 1, meaning that the mass (the dam body within the section) is in a stable state. It corresponds to the results of field observations and, together with the convergence of the test calculation results, confirms the correctness and reliability of both the calculation scheme and the obtained results.

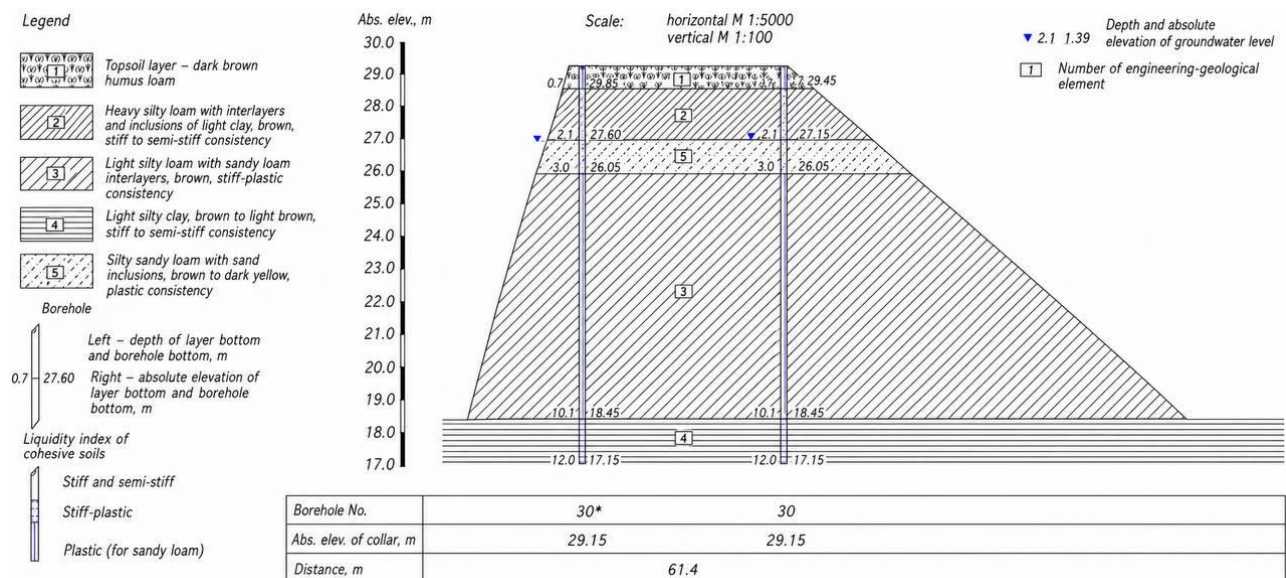


Figure 2 – Extraction from the geological cross-section along the 30th group of boreholes within the eastern section of the ‘Kryvi Luky’ tailings storage facility

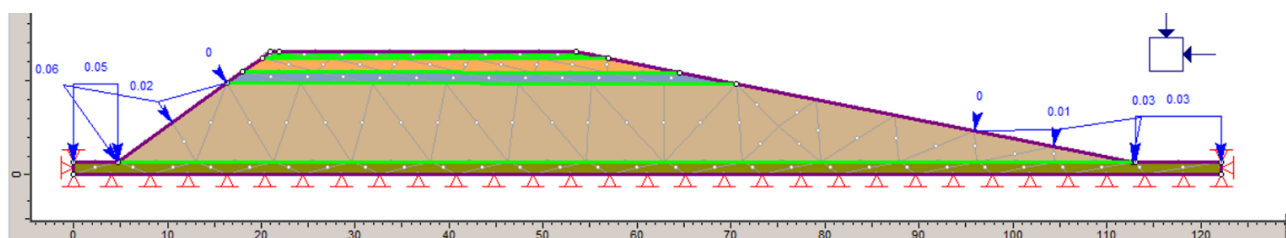


Figure 3 – Schematic view of the baseline computational model (2D cross-section of the dam within the control section)

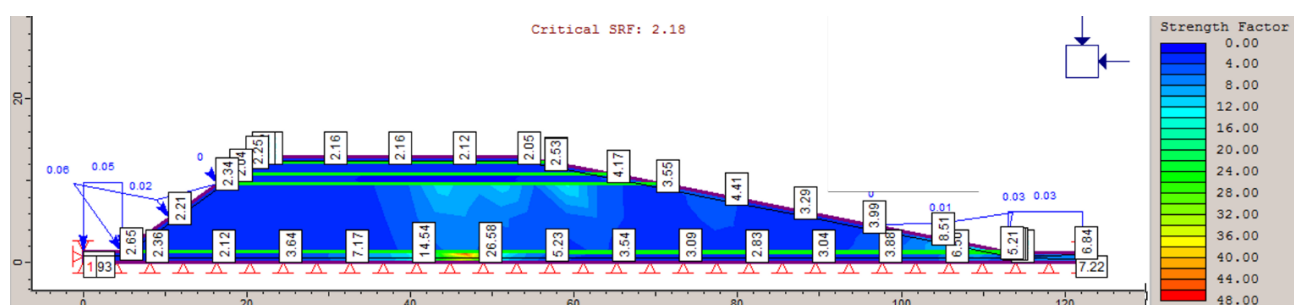


Figure 4 – Distribution of the stability factor along the mass contour for the baseline scenario

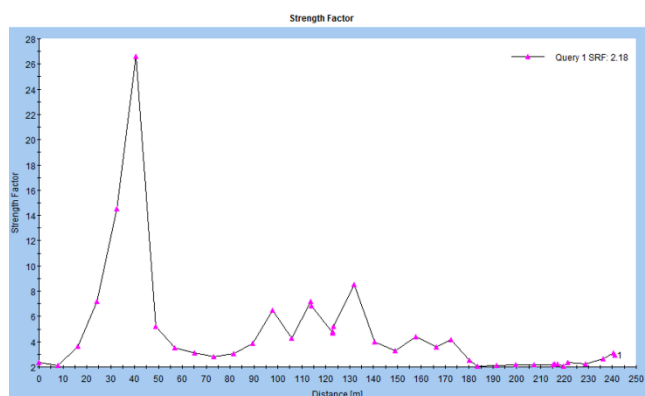


Figure 5 – Summary plot of the stability factor values along the mass contour for the baseline scenario

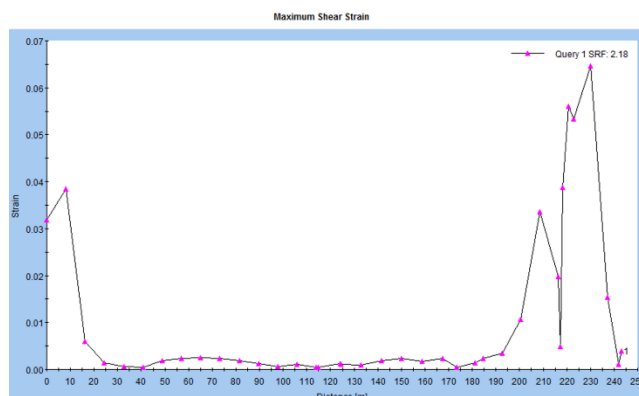


Figure 6 – Summary plot of the maximum shear deformations (m) along the mass contour (at 0.1 m inward from the contour) for the baseline scenario

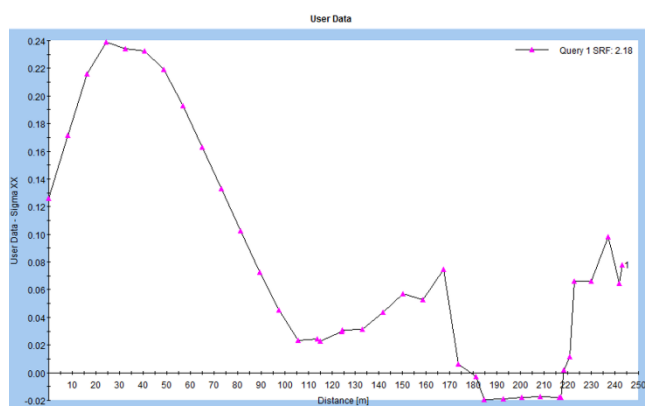


Figure 7 – Summary plot of stress values σ_{xx} (m) along the mass contour (at 0.1 m inward from the contour)

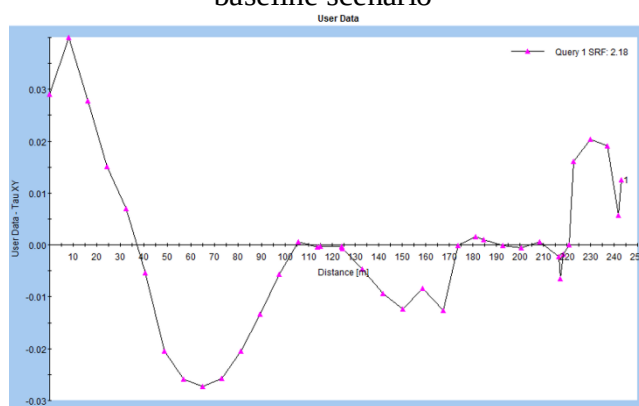


Figure 8 – Summary plot of stress values σ_{xx} (m) within the dam body

The next stage involved performing a variation analysis by changing the key parameters of the computational model and identifying the most influential ones for the subsequent substantiation of rational solutions to ensure dam stability and for scaling the obtained results to similar mining-geological and hydrogeological conditions. Table 2 shows the adopted range of variable parameters relative to the baseline scenario.

The calculation results made it possible to define that the dam's technological parameters are the ones having the greatest influence on the stability safety factor (Table 3).

The analysis of the calculation results given in Table 3 confirms generally that the stability safety factor increases along with the decreasing slope angles and increasing base width. At the same time, the optimal approach is to maintain the natural slope angle for the corresponding dam material (which can sometimes be difficult to achieve due to technological specifics of the facility and anisotropy of the embankment material). Another significant parameter is the immediate height of the structure and filling levels of the sections. As the results show, excessive increase in slope height leads to a loss of stability of the entire system.

Table 2 – Adopted range of variable parameters relative to the baseline scenario

Parameters	Description	Value	Min	Max	Increment
α , deg	slope angle	36	15	60	5
A, m	berm width	32.536	5	50	5
B, m	base width	108.016	50	140	10
H, m	slope height	11.633	10	46	4
γ_1 , kN/m ³	unit weight (layer 1)	17.9	15	22	0.7777
γ_2	unit weight (layer 2)	18.9	15	20	0.5555
γ_3	unit weight (layer 3)	19.5	17	22	0.5555
γ_4	unit weight (layer 4)	20.1	13	21.5	0.9444
γ_5	unit weight (layer 5)	19.9	15	21	0.6666
γ_{mid}	–	19.26	15	21.3	0.7
φ_1 , deg	internal friction angle	20	15	40	2.7777
φ_2	–	12	12	23	1.2222
φ_3	–	13	10	25	1.6666
φ_4	–	19	6	22	1.7777
φ_5	–	26	14	28	1.5555
φ_{mid}	–	18	11.4	27.6	1.8
c_1 , kPa	cohesion	30	5	35	3.3333
c_2	–	20	5	40	3.8888
c_3	–	30	10	60	5.5555
c_4	–	81	5	100	10.5555
c_5	–	15	2	21	2.1111
c_{mid}	–	35.2	5.4	51.2	5.0888
E_1 , kPa	deformation modulus (Young's modulus)	15000	2000	20000	2000
E_2	–	9500	12000	24000	1333.333
E_3	–	7300	9000	27000	2000
E_4	–	14500	9000	19000	1111.111
E_5	–	11600	7000	37000	3333.333
E_{mid}	–	11580	7800	25400	1955.556

Table 3 – Summary table of the results of a series of calculations of the dam slope stability factor in terms of parameter variation (Nv is variant number; Kust_L is stability safety factor of the left slope; and Kust_R is stability safety factor of the right slope)

Nv	Slope angle α , deg			Base width B, m			Berm width A, m			Slope height H, m		
	α	Kust_L	Kust_R	B, m	Kust_L	Kust_R	A, m	Kust_L	Kust_R	H, m	Kust_L	Kust_R
1	15	3.25	2.24	50	1.7	0.76	5	2.14	5.41	10	2.24	3.89
2	20	2.56	2.6	60	1.69	1.36	10	2.12	5.09	14	1.57	2.49
3	25	2.25	2.7	70	1.85	1.78	15	2.15	4.63	18	1.25	1.41
4	30	2.07	3.28	80	1.89	1.92	20	2.11	4.05	22	1.11	1.12
5	35	1.91	3.36	90	1.91	2.17	25	2.14	3.78	26	0.97	0.98
6	40	1.76	3.41	100	1.9	2.64	30	2.11	3.5	30	0.81	0.79
7	45	1.62	3.71	110	1.9	3.14	35	2.12	3.4	34	0.67	0.63
8	50	1.5	4.39	120	1.91	3.61	40	2.11	3.23	38	0.61	0.54
9	55	1.41	4.74	130	1.91	4.31	45	2.12	3.04	42	0.6	0.43
10	60	1.41	5.73	140	1.93	4.9	50	2.11	2.72	46	0.58	0.36

Tables 4–7 represents the results of a series of stability factor calculations corresponding to the variations in: unit weight of the dam materials γ , kN/m³; internal friction angle of the dam materials ϕ , degrees; cohesion of the dam materials c , kPa; and deformation modulus of the dam materials E , kPa.

As Table 4 shows, while friction and cohesion depend on the unit weight, they are not dominant compared to the shear forces, which increase as the integral value of the unit weight of the dam body material rises. In this scenario, a unit weight increase is almost directly proportional to a decrease in the overall stability.

Table 4 – Results of a series of calculations of the dam slope stability factor in terms of parameter variation – unit weight of dam materials γ , kN/m³

Nv	γ_1 , kN/m ³	γ_2	γ_3	γ_4	γ_5	γ_{mid}	Kust_L
1	15	15	17	13	15	15	2.48
2	15.7777	15.5555	17.5555	13.9444	15.6666	15.6999	2.4
3	16.5555	16.1111	18.1111	14.8888	16.3332	16.3999	2.34
4	17.3333	16.6665	18.6665	15.8332	16.9998	17.0999	2.27
5	18.1111	17.222	19.222	16.7776	17.6664	17.7998	2.21
6	18.8889	17.7775	19.7775	17.722	18.333	18.4998	2.15
7	19.6667	18.333	20.333	18.6664	18.9996	19.1997	2.1
8	20.4445	18.8885	20.8885	19.6108	19.6662	19.8997	2.05
9	21.2223	19.444	21.444	20.5552	20.3328	20.5997	2.01
10	22.0001	19.9995	21.9995	21.4996	20.9994	21.2996	1.96

Table 5 – Results of a series of calculations of the dam slope stability factor in terms of parameter variation – internal friction angle of dam materials ϕ , deg

Nv	ϕ_1 , deg	ϕ_2	ϕ_3	ϕ_2	ϕ_2	ϕ_{mid}	Kust_L
1	15	12	10	6	14	11.4	1.92
2	17.7777	13.2222	11.6666	7.7777	15.5555	13.1999	2.02
3	20.5554	14.4444	13.3332	9.5554	17.111	14.9999	2.12
4	23.3331	15.6666	14.9998	11.3331	18.6665	16.7998	2.22
5	26.1108	16.8888	16.6664	13.1108	20.222	18.5998	2.32
6	28.8885	18.111	18.333	14.8885	21.7775	20.3997	2.43
7	31.6662	19.3332	19.9996	16.6662	23.333	22.1996	2.55
8	34.4439	20.5554	21.6662	18.4439	24.8885	23.9996	2.68
9	37.2216	21.7776	23.3328	20.2216	26.444	25.7995	2.77
10	39.9993	22.9998	24.9994	21.9993	27.9995	27.5995	2.9

Table 5 shows that unlike the negative effect of the unit weight of the dam body material on the overall stability of the facility (the material's self-weight results in almost direct increase in shear forces), an increase in the internal friction angle of the dam materials has a distinct positive impact on its stability.

The analysis of a series of calculations of the dam slope stability factor in terms of varying deformation modulus of the dam materials confirms that soil with a high modulus of elasticity (deformation) deforms less under loads, making it more resistant to shear and failure. Nevertheless, in this particular case, its influence on the overall stability is not critical, although it will necessarily be considered when

substantiating the selection of appropriate reinforcement methods during the design phase.

As Table 6 demonstrates, a similar positive effect on the dam stability is observed along with the increasing cohesion of the dam body materials.

Table 6 – Results of a series of calculations of the dam slope stability factor in terms of parameter variation – cohesion of dam materials c , kPa

Nv	c_1 , kPa	c_2	c_3	c_4	c_5	c_{mid}	Kust_L
1	5	5	10	5	2	5.4	1.21
2	8.3333	8.8888	15.5555	15.5555	4.1111	10.4888	1.47
3	11.6666	12.7776	21.111	26.1111	6.2222	15.5777	1.72
4	14.9999	16.6664	26.6665	36.6667	8.3333	20.6666	1.97
5	18.3332	20.5552	32.222	47.2223	10.4444	25.7554	2.23
6	21.6665	24.444	37.7775	57.7779	12.5555	30.8443	2.46
7	24.9998	28.3328	43.333	68.3335	14.6666	35.9331	2.71
8	28.3331	32.2216	48.8885	78.8891	16.7777	41.022	2.95
9	31.6664	36.1104	54.444	89.4447	18.8888	46.1109	3.21
10	34.9997	39.9992	59.9995	100.0003	20.9999	51.1997	3.46

Table 7 – Results of a series of calculations of the dam slope stability factor in terms of parameter variation – deformation modulus of dam materials E , kPa

Nv	E_1 , kPa	E_2	E_3	E_4	E_5	E_{mid}	Kust
1	2000	12000	9000	9000	7000	7800	2.13
2	4000	13333.33	11000	10111.11	10333.33	9755.56	2.13
3	6000	14666.67	13000	11222.22	13666.67	11711.11	2.13
4	8000	16000	15000	12333.33	17000	13666.67	2.13
5	10000	17333.33	17000	13444.44	20333.33	15622.22	2.15
6	12000	18666.67	19000	14555.56	23666.67	17577.78	2.13
7	14000	20000	21000	15666.67	27000	19533.33	2.15
8	16000	21333.33	23000	16777.78	30333.33	21488.89	2.14
9	18000	22666.66	25000	17888.89	33666.66	23444.44	2.14
10	20000	24000	27000	19000	37000	25400	2.15

It should be noted that a first-level baseline model is too complex and resource-intensive for the operational facility monitoring. Therefore, at the second stage, it is planned to develop an interpretative mathematical model that will be a translator between the calculation data and field measurement results. The second-level model will perform several tasks:

- development of diagnostic indicators – based on a series of first-level calculations, analytical relationships of varying degrees of detail (statistical, regression or neural network-based) are derived, linking operational factors (water level, temperature, tailings particle size distribution etc.) with control parameters (deflections, filtration rates, pollutant content etc.);

- calibration and verification – comparison of theoretical values from a geomechanical model with actual sensor readings to refine the facility parameters; and

- forecasting – the second-level model allows for assessing whether the current state of a hydraulic engineering facility falls within design, technological, and environmental standards.

The analysis of the research results also makes it possible to hypothesize that it is advisable to develop a set of measures that can adjust the balance of the key influencing parameters. Although the primary retaining forces (friction and cohesion) do not prevail directly over the shear forces (the most significant being the material's unit weight, physical height, and slope angles), artificial enhancement of the material properties through mechanical or chemical means appears quite promising. It is particularly relevant considering the dual effect of the dam body's material weight: on the one hand, a higher unit weight increases pressure on the slope; on the other hand, in a dry state with proper compaction, it enhances shearing resistance by increasing frictional forces. In this context, the available moisture within the dam body becomes a critical safety factor, as confirmed not only by analytical studies but also by practical experience, including field investigations within this area. Key considerations include economic feasibility, technical possibility of implementing the relevant design solutions, and timing. Relying on the results of specific survey stages, it was recommended to implement a series of drainage, anti-filtration, and reinforcement interventions as the initial measures to reduce the emergency risks at the facility.

4. Conclusions

One of the most effective mechanisms to control the operating conditions of tailings dams is to monitor their technical state. Among other things, this approach makes it possible to accumulate essential technical data and collect and analyse current statistics both for a specific facility and for the groups of facilities. Immediate monitoring conducted at various stages of this study, i.e. of the 'Kryvi Luky' tailings dam of PJSC 'Ordzhonikidze Mining and Processing Plant', helped identify and localize potentially hazardous areas and determine the dam stability loss causes.

Analysis of the geomechanical stability of the tailings storage facility enables both a highly reliable assessment of its load-bearing capacity and timely identification of potential hazards. This, in turn, allows for the prompt implementation of preventive measures to avoid accidents and ensures the overall safety of the structures and the surrounding areas.

The result of this research stage was identification of the influencing factors on the geomechanical dam stability, being the basis for developing a fundamental mathematical model of tailings dam stability. The basic mathematical model represents the initial stage of a two-level (or multi-level) modelling process, where stage one involves development of a geomechanical model of the hydrotechnical structure, and stage two forms a mathematical model to interpret calculation results using the model developed during stage one. As the modelling result, the objective of developing a baseline model to obtain a 'theoretical response' of the structure (stress-strain state) under various loading scenarios was achieved.

A stability factor for the baseline scenario (current state of the control cross-section) is Critical SRF=2.18 >1, indicating that the mass (the dam body at the control section) is in a stable condition. It corresponds with the field observation results and, together with the convergence of the test calculation results, confirms the correctness and reliability of both the calculation scheme and the obtained results.

The results of a series of stability factor calculations were also obtained and analyzed with respect to variations in the following dam material parameters: unit weight; internal friction angle; cohesion; and deformation modulus.

In general, the variation analysis of the baseline computational model by adjusting its main parameters confirms that the stability factor increases along with the decreasing slope angles and increasing base width. Another significant parameter is the immediate structure height and filling levels of the sections. As the results show, excessive increases in slope height leads to a loss of stability of the entire system.

It should be noted that, although friction and cohesion depend on the unit weight, they are not dominant relative to the shear forces, which increase along with the growing integral value of the unit weight of the dam body material. In this scenario, an increasing unit weight is almost in direct proportion to a decrease in the overall stability.

In contrast to the negative effect of a unit weight of the dam body material on the entire structure stability (the self-weight of the material leads to an almost direct increase in shear forces), an increase in the internal friction angle of the dam materials has a clear positive effect on the stability. Similarly, an increase in the cohesion of the dam body materials also influences positively the dam stability.

The next stage of the research will involve risk assessment and scaling the obtained results to similar mining-geological and hydrogeological conditions.

Conflict of interest

Authors state no conflict of interest.

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МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ СТІЙКОСТІ ДАМБИ ХВОСТОСХОВИЩА НА ОСНОВІ ГЕОМЕХАНІЧНОГО АНАЛІЗУ З ВАРІАЦІЄЮ ОСНОВНИХ ВПЛИВОВИХ ПАРАМЕТРІВ

Говоруха О.В., Рябко А.І., Халимендик О.В.

Анотація. Метою роботи є дослідження впливу основних параметрів дамб через коефіцієнт запасу стійкості на прикладі розробленої чисельної моделі однієї з контрольних ділянок хвостосховища «Криві Луки» ПАТ «Орджонікідзевський гірничо-збагачувальний комбінат» із врахуванням геомеханічних параметрів і варіативності впливових чинників з наступним масштабуванням отриманих результатів стосовно різних типів дамб для аналогічних гірничо-геологічних та гідрологічних умов в майбутньому.

Виконано моделювання геомеханічного стану об'єкта досліджень та чисельний розрахунок за допомогою методу скінчених елементів та співставлення отриманих даних з результатами моніторингових спостережень. Збіжність результатів розрахунку тестової задачі та натурних досліджень підтвердило коректність та достовірність самої розрахункової схеми та отриманих результатів.

Виконано серію розрахунків коефіцієнту стійкості відповідно до зміни наступних впливових параметрів: питома вага, кут внутрішнього тертя, зчеплення та модуль пружності матеріалів дамби тощо. Варіаційний аналіз дозволив в цілому підтвердити зростання коефіцієнту стійкості при зменшенні кутів укосів і збільшенні ширини її основи. Одним із суттєвих параметрів при цьому також стала безпосередня висота об'єкту та рівні заповнення секцій, при цьому надмірне збільшення висоти дамби призвело до втрати стійкості всієї системи.

Також підтверджено, що основні стримуючі сили, а саме тертя та зчеплення, хоч і залежать від питомої ваги, але не є переважними до зсувних зусиль, які тим більше чим вищий інтегральний показник питомої ваги матеріалу тіла дамби.

За результатами роботи висунуто припущення щодо доцільності розробки комплексу заходів, які дозволять змінювати баланс основних параметрів впливу – так, штучне підвищення характеристик механічним або хімічним способом із контролем вологості масиву дамби є досить перспективним, особливо з врахуванням подвійної дії ваги матеріалу тіла дамб. При цьому критичним фактором який впливає на загальний рівень безпеки об'єкту є наявність води в самому тілі дамби.

Ключові слова: дамба, хвостосховище, аналітичні дослідження, геомеханічна стійкість, моніторинг, коефіцієнт запасу стійкості.