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Slope Stability Assessment of Tailings Dam

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Abstract. The paper examines a complex methodology for calculating the slope stability of a tailing storage facility based on comparing the results obtained through deterministic and probabilistic approaches. The analysis is performed in GeoStudio software, based on the limit equilibrium method, and with a probabilistic approach that uses a Monte Carlo simulation to compute a probability distribution of the resulting factor of safety. A slope stability assessment of tailing dam was conducted on the example of Ferrexpo Poltava Mining, and a conclusion was reached about their reliability and safety. The results of the deterministic analysis showed that the calculated factor of safety is by those established in Ukrainian regulatory standards. It has been recognized that the factor of safety is not a consistent measure of risk for tailings dam. Considering the variability inherent in the soil materials of tailings dam is a way to achieve more accurate results. The importance of obtaining a failure probability and a reliability index due to tailing dam stability was highlighted by comparing deterministic and probabilistic approaches.

Introduction

Tailings storage facilities (TSF) are engineering structures of high environmental, economic and social significance. Their reliability and safety are of the utmost importance, as tailings dam failures can have a multifactorial impact on the natural environment and human activities. In Ukraine, such structures are considered potentially hazardous, and their reliability and safety must be ensured during construction, operation, conservation and closure.

Methods for assessing the operational reliability of hydraulic structures, statistical methods for analyzing their condition, and developing criteria for their reliability are considered in [1-5]. Slope stability failure is one of the leading causes of accidents at tailings dams [6-8].

During the construction and operation of the tailings dam, the focus is primarily on ensuring the reliability and safety of these facilities, as a failure of such structures can have catastrophic consequences. Tailings dam is usually constructed in stages as the TSF is filled. Assessment of the reliability of tailing dams is a complex task taking into account many factors that determine their condition, namely changes in technological parameters during TSF operations (dam height, slope, volume and type of stored material), significant variability of operating loads, impacts and soil properties of the tailings dam, which significantly complicates the choice of methods, calculating schemes and load combinations.

Currently, in Ukraine, there are regulatory design documents for tailings storage facilities, according to which the assessment of the reliability and safety of these structures is performed based on a deterministic approach using the limit state method [9,10]. According to this method, the variability of loads and effects, material and soil properties is taken into account based on a system of normative coefficients. This method does not allow for an objective assessment of the reliability of tailings dam. This is because the values of the normative coefficients are not always objective and are conditional. It is assumed that the strength properties of soils are accurately known, unchanged and homogeneous. At the same time, it is evident that the soil properties undergo significant changes during the construction and operation of tailings dam due to irregular deposition of tailings in the TSF, changes in piezometric line, seepage, consolidation dam and impact of vehicles.

A more objective assessment can be obtained using the probabilistic approach of reliability theory, which, based on probabilistic methods, allows for quantitative evaluations of the reliability and safety of tailing dams. The essence of the probability approach is to determine the probability distribution function of the factor of safety (FoS), depending on the probability distribution functions of soil strength properties. The resulting calculated values of the probability of failures should not exceed the critical values [10].

The research purpose is assessment of slope stability for the Ferrexpo Poltava Mining TSF using a deterministic and probabilistic approach. Slope stability analyses are conducted using three limit equilibrium methods (LEM), i.e. Bishop [11], Janbu [12,13] and Morgenstern-Price [14]. In the probabilistic analysis, the distribution of the safety factor is determined. Probability of failure and reliability index is calculated using the probability distribution of FoS.

Materials and Methods

Study area. The Ferrexpo Poltava Mining is located on the left bank of the Kamianske reservoir, 40 km from Kremenchuk, in Horishni Plavni, Poltava region, Ukraine. The TSF is an unlined paddock type facility, divided into two compartments, namely "Section 1-2" and "Section 3" (Fig. 1). TSF has been in operation since 1970. It currently measures approximately 45 m in height, 5.5 km in length, and 4 km in width, with a level surface footprint area equal to approximately 1,290 hectares.

Prior to 1984, the TSF comprised three compartments with a volume of 27.0, 29.0 and 60.6 Mm^3. The starter dam of all three compartments is constructed of alluvial sand with an elevation of 75 mRL. Since 1984, the TSF has been constructed in two compartments with outer embankments constructed from reclaimed dry tailings to a current elevation of 110.0 mRL. The final design height of the TSF is 117.5 mRL [15]. The tailings storage facility was constructed using the upstream method. The principal deposition method at the TSF is to deposit tailings into the cells. A drainage system is provided along the perimeter of compartments Section 1-2 and Section 3 to drain seepage water from the tailings storage facility.

The study area's geological structure involves Quaternary deposits (aIII) overlaying the bedrock of the Kharkiv Formation (P3hr). The thickness of the sedimentary formations covers the weathered crust of crystalline rocks, i.e., kaolin or sands of the Paleozoic-Mesozoic age (Pz-Mz).

The seepage face of the tailing dam and the slope stability assessment have been determined for the typical profile of Section 1-2 TSF during its construction up to an elevation of 117.5 mRL by GeoStudio 2012 software. Two software modules were used: SEEP/W (seepage analysis) and SLOPE/W (slope stability analysis). The GeoStudio suite enables all types of calculations within a single file, establishing the sequence of calculations in a hierarchical structure. Moreover, the output data from a previous calculation can serve as input data for the subsequent one.

Seepage Analysis. The assessment of slope stability analysis usually starts with the seepage modeling of the tailing dam using SEEP/W, which determines piezometric line, seepage flow through a dam embankment, maximum gradients of total hydraulic head and pore-water pressure of soil along the structure's cross-section. SEEP/W is based on the premise that the flow of water through soil, whether saturated or unsaturated, follows Darcy's Law [16]:

$$q = ki, \tag{1}$$

where q is the specific discharge, k is the permeability, and i is the gradient of the total hydraulic head.

The general governing differential equation for two-dimensional seepage under steady-state conditions can be expressed as:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right)+Q=0, \tag{2}$$

where H is the total head, k_x is permeability in x-direction, k_y is the permeability in y-direction and Q is the applied boundary flux.

The total hydraulic head, H, is defined as:

$$H=\frac{u_w}{\gamma_w}+y, \tag{3}$$

where u_w is the pore-water pressure, γ_w is the unit weight of water and y is the elevation.

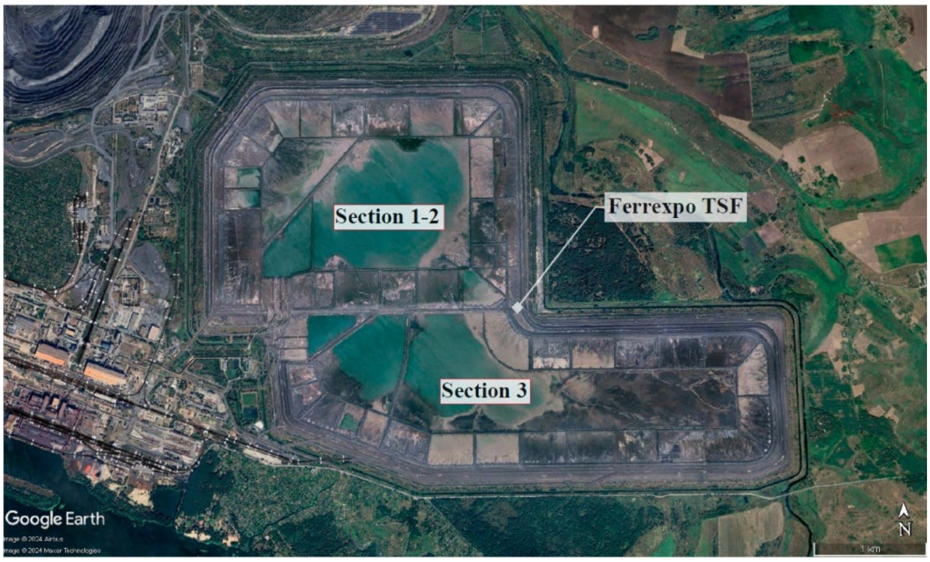

Fig. 1. Ferrexpo Poltava Mining TSF location performed using Google Earth Pro

The computational domain is approximated by triangular and quadrilateral finite elements. The Van Genuchten hydraulic conductivity function is employed for seepage analysis.

To expedite the creation of a model in GeoStudio, there's an option to import the geometric component from a pre-prepared DXF file, adhering to specific rules: measurement units, display scale and font sizes are set; finite element mesh parameters are determined, and boundary conditions are assigned. During the computational schematization, the geometry of the tailings dam and the geological features were considered. The resulting model is shown in Fig. 2. The permeability of materials used in the dam body [17] is shown in Table 1.

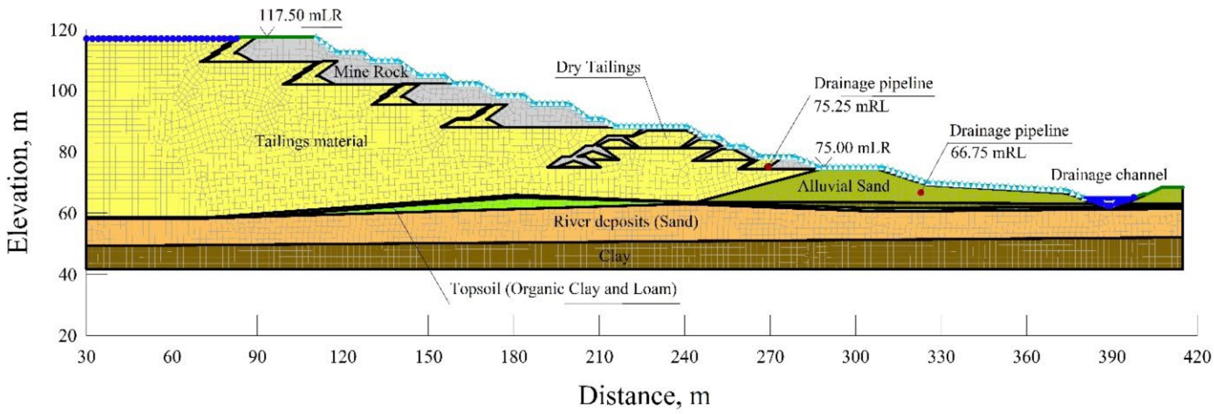

Fig. 2. Design model with a finite element mesh and boundary conditions

Deterministic slope stability analysis. Following the current design standards in Ukraine for hydraulic structures [10], slope stability analysis should be performed using the limit state method in compliance with the following conditions, which ensures the prevention of the occurrence of limit states:

$$\gamma_{1c} F \le \frac{R}{\gamma_n}, \tag{4}$$

where γ_{1c} is the load combination coefficient, F is the generalized calculated value of active forces or moments of these forces relative to the center of the slip surface, R is the generalized calculated value of the forces (or their moments) of the limit shear resistance to the surface under consideration, γ_n is the reliability factor.

The factor of safety is the ratio of resisting to driving forces. When searching for a critical slip surface, the following relationship for the FoS can be used:

$$k_s = \frac{R}{F}. \tag{5}$$

Then equation (4) can be written as:

$$k_s \ge [k_s], \tag{6}$$

where $[k_s]$ is minimum factor of safety:

$$[k_s] = \gamma_n \gamma_{1c}. \tag{7}$$

According to the class of consequences CC3, previously classified as Ferrexpo Poltava Mining TSF, the reliability factor value is $\gamma_n = 1.25$. The load combination coefficient in the calculations for the first group of limit states regarding serviceability for the basic load combinations $\gamma_{1c} = 1.0$ [10]. Then, the minimum factor of safety is $[k_s] = 1.25 \cdot 1.0 = 1.25$.

SLOPE/W was employed for the stability analysis [18]. This software uses limit equilibrium theory to determine a critical factor of safety for slope stability of a geomechanical model, which describes the overall geometry, material zones with different strength properties and pore water pressure conditions. Pore water pressure is calculated from SEEP/W. The reported methods of analysis used to calculate the FoS for potential slip services are Bishop's method (based on the equilibrium of moments), Janbu's method (based on an equilibrium of forces) and Morgenstern-Price method (based on the equilibrium of forces and moments).

The Morgenstern-Price method is the most rigorous of the chosen. Therefore, this paper considers the results obtained using the Morgenstern-Price method as the main results. Equation (8) shows the expression used to calculate FoS in the Morgenstern-Price method [14]:
force equilibrium FoS:

$$k_s = \frac{\sum N_i \operatorname{tg} \varphi_i \cos\alpha + \sum c_i \beta_i \cos\alpha}{\sum N_i \cos\alpha}, \tag{8}$$

moment equilibrium FoS:

$$k_s = \frac{\left(\sum N_i \mathrm{tg}\,\varphi_i + \sum c_i\,\beta_i\right)R}{\sum W_i x - \sum N_i f}, \tag{9}$$

where W is the total weight of slice, N is the total normal force on the base of the slice, c is the cohesion, φ is the friction angle, x is the horizontal distance from the centerline of each slice to the center of moments, f is the perpendicular offset of the normal force from the center of rotation or from the center of moments, β is the base length of each slice, α is the angle between the tangent to the center of the base of each slice and the horizontal.

Once the interslice normal force is known, the interslice shear force is computed as a percentage of the interslice normal force according to the following empirical equation:

$$X = E\lambda f(x), \tag{10}$$

where X is the vertical interslice shear forces, E is the horizontal interslice normal forces, λ is the percentage (in decimal form) of the function used, $f(x)$ is the type of functional relationship between X and E.

The Mohr-Coulomb model is used to model soil properties containing three main input parameters: cohesion, friction angle and unit weight. The values of the tailing dam's soil parameters are determined according to available in-situ measurements and laboratory tests [17] and are presented in Table 1.

Table 1. Material properties of Ferrexpo Poltava Mining TSF

Material type	**Properties**			
	Unit weight (kH/m^3)	Friction angle, (˚)	Cohesion (kPa)	Permeability (m/d)
Foundation soils				
Topsoil (Organic Clay and Loam)	18,7	15	25	0,5
Alluvial deposits (Loam)	19,7	18	30	0,03
Alluvial deposits (Clay)	19,2	11	47	0,01
River deposits (Sand)	19,6	24	0	2
Clay	18,6	16	67	0,0001
Outer Embankment materials				
Alluvial Sand (placed < 75 mRL)	19,2	26	0	3
Mine Rock	18,2	38	4	10
Dry Tailings (placed > 75 mRL)	19,0	25	0	1,5
Tailings material				
Tailings material	19,0	26	0	0,9

Probabilistic slope stability analysis. Probabilistic slope stability analysis allows for considering input parameter variability and quantifying slope failure probability. The most common and reliable method for probabilistic stability assessment is the Monte Carlo simulation. It is well-founded and meets all the requirements of mathematical statistics. Monte Carlo method uses a random number generator according to specified distribution laws to create a set of variables, which are used to calculate the values of the output function. These values are recorded and sorted into intervals, forming a histogram of the random function. After a sufficiently large number of random variable values have been generated, a step approximation of this function's experimental distribution curve is constructed based on the grouped intervals. The probability of failure (p_f) is obtained by direct integration of the probability density function of the FoS<1:

$$P_f = \int_0^1 f_{k_s}(k_s)\,dk \quad . \tag{11}$$

In the present study, a random field comprises random unit weight, cohesion and friction angle values. The distributions are defined by specifying a type, a mean, and a coefficient of variation (COV). Then, utilizing a search algorithm for the critical slip surface and limit equilibrium method (Morgenstern-Price method), the factor of safety for each Monte Carlo simulation is calculated.
The probability of failure using Monte Carlo simulation is possible to calculate using equitation (12):

$$P_f = \frac{N_{k_s<1}}{N}, \tag{12}$$

where $N_{k_s<1}$ is the number of iterations with FoS less than 1, N is the total number of Monte Carlo iterations.

Then, the risk of a dam failure is determined for the entire operational period and recalculated into an annual risk value.

Another approach to quantifying risk involves calculating a reliability index (β). After the mean and standard deviation of FoS are determined, the reliability index can be calculated by:

$$\beta = \frac{\mu_{k_s} - 1}{\sigma_{k_s}}, \tag{13}$$

where μ_{k_s} is mean of FoS, σ_{k_s} is standard deviation of the distribution function of FoS.

This parameter allows for assessing slope stability from the perspective of reliability theory. The slope with a higher reliability index value has more excellent stability and a lower probability of failure than the one with a lower value.

This study determined the probability of failure in 1,000, 10,000, 100,000, and 1,000,000 simulations.

Results and Discussion

Seepage analysis was performed for a steady-state regime under saturated and unsaturated soil flow conditions. The results of the seepage analysis allow us to obtain piezometric line, pressure isolines, pore-water pressure, gradients of total hydraulic head, velocity vectors in the nodes of the finite element mesh, and the trajectory of an elementary fluid particle passing through a given point of the computational domain, with the determination of the movement time, distance, and average speed. Fig. 3 shows a steady-state seepage study of the tailing dam.

Based on the results, the nature of seepage within the slope during the construction of the tailing dam up to the elevation of 117.5 mRL is determined by the presence of predominantly well-permeable deposits in its body, represented by sandy loam, fine and medium-sized sand. These deposits are underlain by the foundation's relatively poorly permeable loam and clay deposits. The drainage of the tailings dam is ensured by operating the drainage system elements, represented by horizontal pipeline drainage.

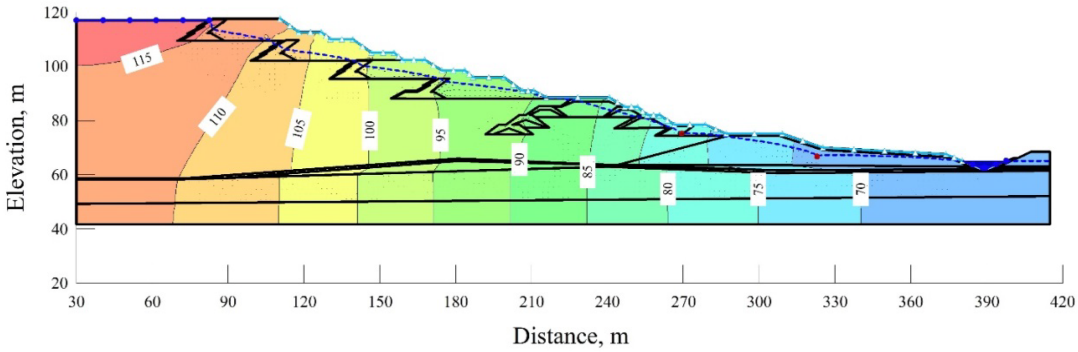

Fig. 3. Steady-state seepage study of the tailing dam

As a result, the values of seepage loads were obtained and then transferred in SLOPE/W. Slope stability analysis was performed by LEM. Table 2 shows the summary results of stability analysis using Bishop, Janbu and Morgenstern-Price methods. The critical slip surface corresponding to FoS using the Morgenstern-Price method is presented in Figure 4.

Table 2. Stability results

Factor of Safety	Bishop method	Janbu method	Morgenstern-Price method
k_S	1,342	1,256	1,272

The factor of safety obtained from the deterministic analysis indicates that Janbu's method gives the least FoS, and Bishop's method gives the highest one. The calculated values of the factor of safety do not exceed the normative ones. Thus, the results indicate that, according to the deterministic methodology, the stability of the tailings dam slope is ensured.

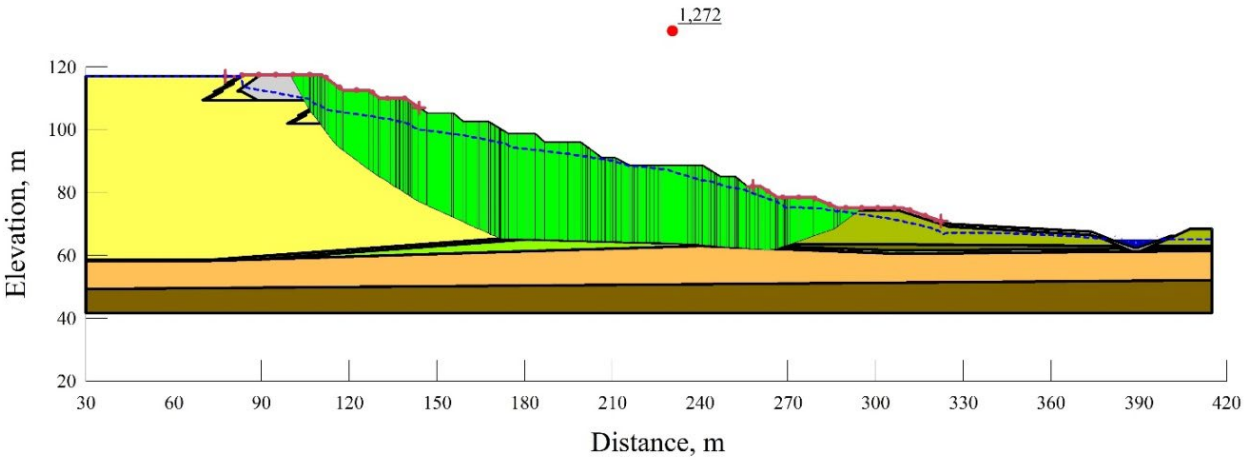

Fig. 4. Slope FoS obtained from LEM (Morgenstern-Price method)

The variability in the value of tailings dam soil properties plays a significant role in the uncertainty of slope stability. The probability distribution functions of soil physical and mechanical characteristics were determined in the first stage. The analysis of soil properties composing tailings dam has shown that the most significant influence on its stability is caused by the variability of property characteristics for topsoil (organic clay and loam), alluvial sand (placed < 75 mRL) and tailings material. Table 3 shows all these soil standard deviations. The mean of the parameters was those values already used in the deterministic analysis, shown in Table 3.

Table 3. The standard deviation of soil properties

Material type	**Properties**		
	Unit weight (kH/m^3)	Friction angle, (˚)	Cohesion (kPa)
Topsoil (Organic Clay and Loam)	±1.4	±5.8	±13.3
Alluvial Sand (placed < 75 mRL)	±0.9	±1.6	0
Tailings material	±1.7	±2.3	0

The values for the standard deviation were calculated taking in statistical analysis of soil data represented in [17]. Further, based on the distribution functions of soil properties, the probability distribution of FoS was calculated using the Monte Carlo simulation.

As mentioned earlier in this study, 1,000, 10,000, 100,000, and 1,000,000 simulations were conducted. Figure 5 presents the FoS's probability density function (PDF) as a normal distribution. Table 4 shows the results of the probabilistic stability analysis for different number simulations.

The annual probability of failure of the tailings dam can be found using the formula:

$$P_u = 1-(1-p_f)^{1/T}, \tag{14}$$

where p_f is the probability of failure, T is the designated service life of the structure, which according to [10] is assumed to be 100 years for the class of consequence CC3.

The obtained value of the annual probability of failure of tailing dam resulting from the 1,000,000 Monte Carlo simulation is $1{,}44\text{x}10^{-6}$ year^{-1}, which does not exceed the permissible value of the probability of $5\text{x}10^{-5}$ year^{-1} [10].

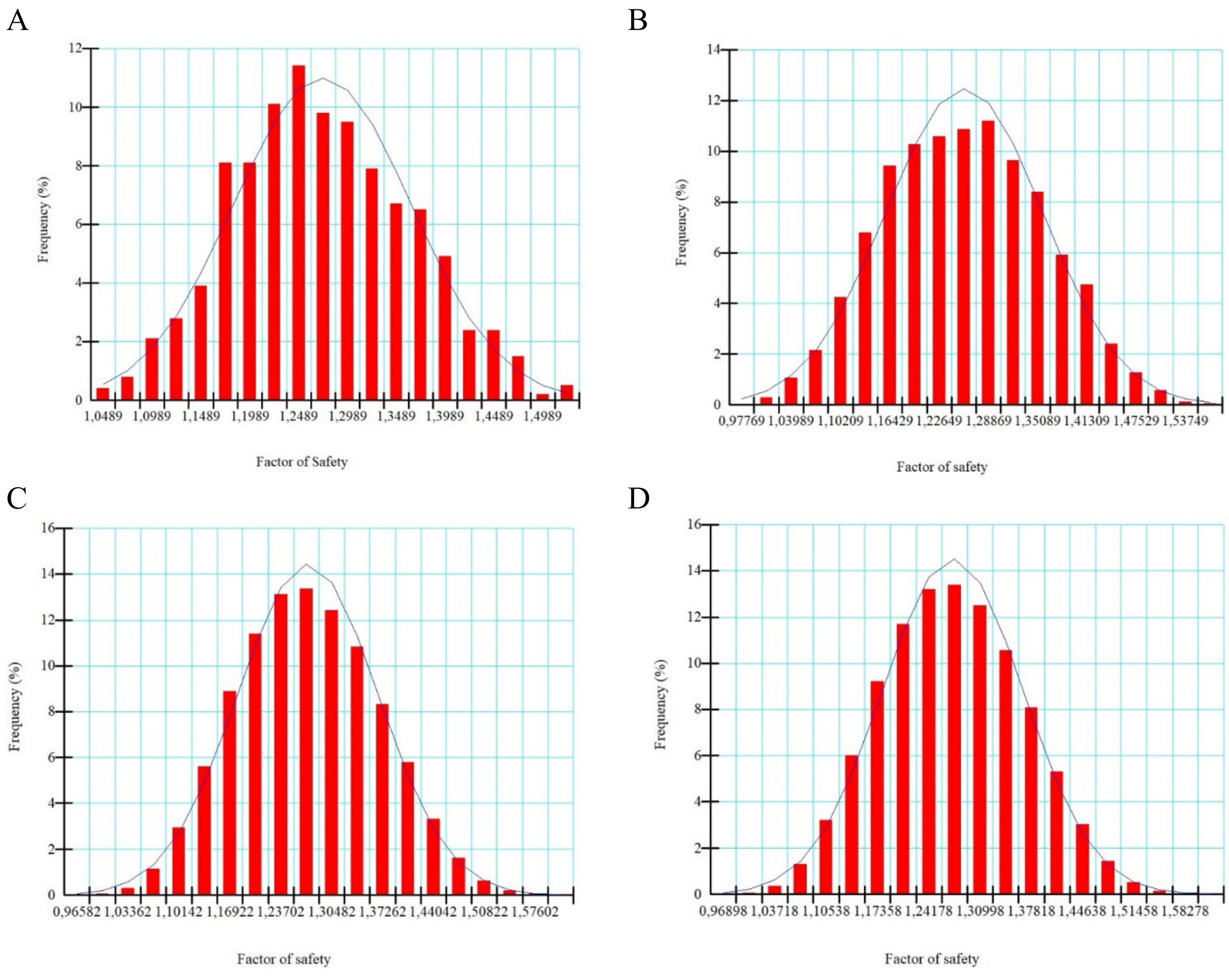

Fig. 5. Normal distribution PDF for FoS. A. 1,000 simulations. B. 10,000 simulations. C. 100,000 simulations. D. 1,000,000 simulations

Table 4. Results of probabilistic analysis

1,000 simulations		10,000 simulations		100,000 simulations		1,000,000 simulations	
Mean k_s	1,273	Mean k_s	1,273	Mean k_s	1,273	Mean k_s	1,273
Reliability index	2,995	Reliability index	2,906	Reliability index	2,912	Reliability index	2,920
k_s<1 (%)	0,0000	k_s<1 (%)	0,0100	k_s<1 (%)	0,0180	k_s<1 (%)	0,0144
Standard deviation	0,0912	Standard deviation	0,0939	Standard deviation	0,0937	Standard deviation	0,0937
Min k_s	1,036	Min k_s	0,958	Min k_s	0,949	Min k_s	0,952
Max k_s	1,535	Max k_s	1,612	Max k_s	1,626	Max k_s	1,633
Probability of failure	0	Probability of failure	10^{-4}	Probability of failure	$1,8x10^{-4}$	Probability of failure	$1,44x10^{-4}$

Fig. 5 and Fig. 6 show the variations of the reliability index and probability of failure depending on the number of Monte Carlo simulations. Increasing the number of simulations beyond 100,000 does not significantly change the reliability index and probability of failure.

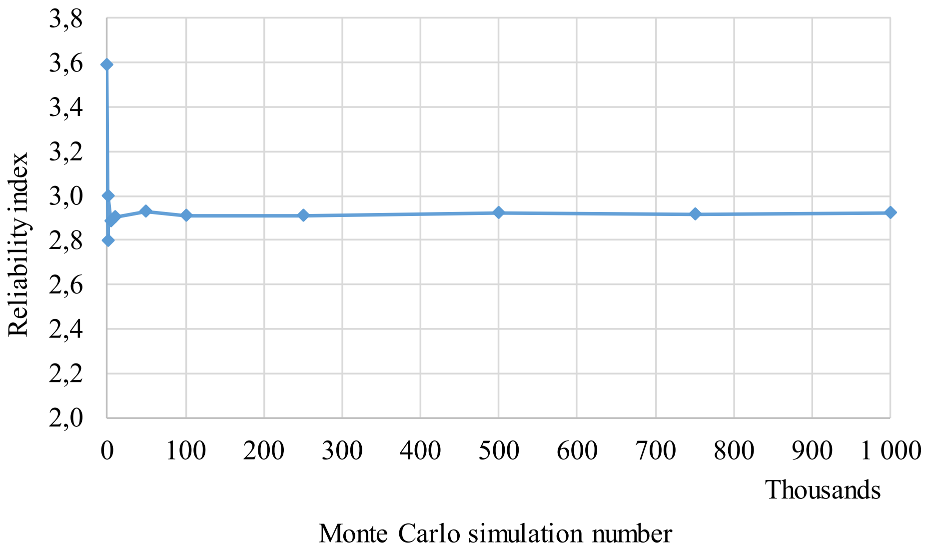

Fig. 5. Change of reliability index to number of Monte Carlo simulations

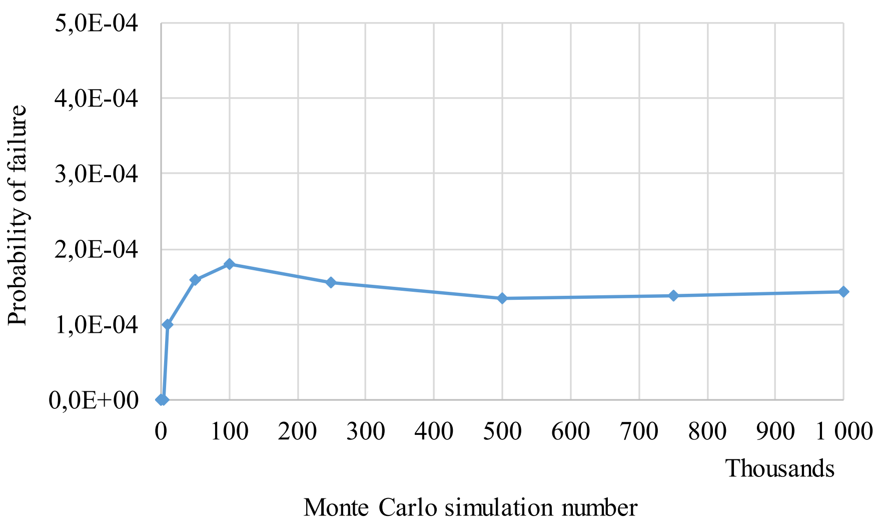

Fig. 6. Change of probability of failure to number of Monte Carlo simulations

Conclusion

The seepage analysis confirms the effectiveness of the drainage system and its elements, which were designed to prevent the rise of the piezometric line (specifically its elevation to the dam's surface) and the suffusion removal of fine tailing particles.

Factor of safety was calculated using SLOPE/W. It is maximum by Bishop's method and minimum by Janbu's method, 1.342 and 1.256, respectively. The calculated values of factor of safety do not exceed the normative ones.

The results of the probabilistic assessment of the reliability of Ferrexpo TSF indicate the following: the calculated value of the annual probability of occurrence of the limit state for the tailing dam is $1{,}44x10^{-6}$ $year^{-1}$, which does not exceed the permissible value of the probability of $5x10^{-5}$ $year^{-1}$ for structures of the classes of consequences CC3.

Slope stability assessment of tailings dams based on a deterministic method does not always reflect a reliable picture of the facility's safety. The FoS obtained through the deterministic method does not determine the actual level of danger, as it is impossible to establish a correlation between it and the probability of a dam failure. The transition to probabilistic methods of assessing the reliability of tailings dam allows us to show with arguments how a particular factor included in the probabilistic assessment of reliability affects the overall stability.

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