ENVIRONMENTAL DATA SCIENCE SESSION

STABILITY ANALYSIS OF FLOTATION TAILINGS POND „RTH“

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Abstract:

The stability of soil and rock slopes is important in the design and construction of cuts and embankments and construction on natural, previously stable slopes or conditionally stable slopes (landslides). The formation of landslides on natural slopes usually occurs due to earthquakes and changes in pore pressure. Landslides on artificially created slopes are the result of non-compliance of the construction of the slope with the solid material in which the slope is located, taking into account the expected seismic activity and changes in the groundwater level. Technogenic materials represent the product of certain exploitation processes that are treated as their by-product. Their disposal and sweetening is a problem from the technical and ecological point of view, while from the economic point of view, it causes high costs. During the numerous researches carried out in the top of the formation and study of the stability of man-made landfills, it has been found that the disposed material differs in many of its characteristics from the natural material. Determining the geomechanical properties of landfill materials also requires a certain analysis of the technological process from the moment of its excavation, processing, and treatment, to the disposal method itself. The work aims to analyze the slope stability of the tailings pond in the Slide v6.0 program of the company Rocscience, using the limit equilibrium method, on the formed geotechnical model of the RTH flotation tailings pond in Bor, that is, selected sections.

The results of the research and the conducted analysis, presented in this paper, served as the basis and guidelines for the accompanying mining projects of overhang, in terms of presenting the current geotechnical structure of the tailings, as a limiting factor for the planned overhang.

Keywords:
Technogenic Materials, Slope Stability, 3D Model Of Lithological Members, Landslide.

INTRODUCTION

For this work, engineering geological and hydrogeological investigations of the entire tailings pond and the surrounding area were used, which were carried out in the period February-April 2022, to obtain sufficiently reliable geotechnical and hydrogeological foundations necessary for the analysis of the stability of the tailings overhang. The flotation tailings pond in the area of the old surface mine of the ore body "H" has been in operation since 1985. It is located in the central part of eastern Serbia, on the territory of the municipality of Bor, near the city center, located about 500 m east of the flotation facilities in Bor (Figure 1.).

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Three types of bulk materials predominate mine tailings, smelter slag, and flotation tailings. In addition to them, various industrial wastes, construction debris, etc. were deposited in places, mostly on the surface of the field.

Field investigations were carried out at the location of the tailings in question. Engineering-geological mapping was carried out to get a better understanding of the actual situation on the subject field, a total of 20 geomechanical wells were carried out and the total drilling depth for all wells was 766 m. Detailed mapping and selection of the required number of samples for laboratory geomechanical tests was carried out. Standard penetration tests were performed to obtain data on penetration resistance and the degree of soil compaction, based on which the strength parameters of the tailings material were determined by depth, which were later used to calculate the slope stability of the tailings pit.

2. LITHOLOGICAL COMPOSITION OF TERRAIN WITH BASIC GEOTECHNICAL PROPERTIES

Based on the known data on the geological structure of the flotation tailings and immediate surroundings, as well as the mapping of the newly exploration drilling hole, a 3D model of the spatial position of lithological members was obtained (Figure 2).

Figure 1. Satellite image of the location of the flotation tailings “RTH”.

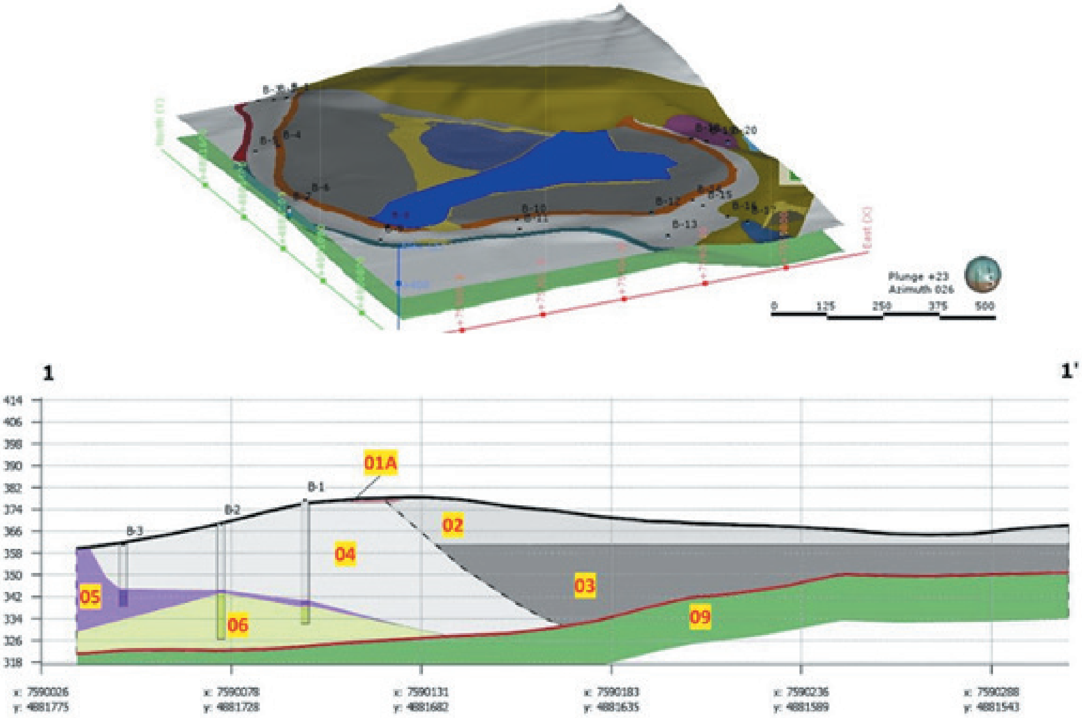


Figure 2. Lithological model of the RTH flotation tailings site.

The construction of the terrain is of heterogeneous lithological composition. The substrate of the landfill consists of solid rock masses (andesites, conglomerates, sandstones, pyroclastics), over which lie thinner alluvial deposits of the Bor river and deluvial-eluvial layers. The former terrain surfaces, including the surface mine of the "H" ore body, are covered with various filled materials.

Three types of mound material predominate: flotation tailings (silt and sand), mining tailings, smelting slag, and various mounded materials (embankments).

All geological environments and complexes established by research, are isolated and grouped according to their lithogenetic composition, physico-mechanical properties of environments, and structural characteristics, which are covered by exploration to the depth of exploration geomechanical drillholes. The adopted physico-mechanical parameters of quasi-homogeneous environments used in the analysis in Slide 6.0 are given in Table 1.

3. STABILITY CALCULATION METHODS

Stability analysis methods play a crucial role in ensuring the safety and reliability of these structures. By utilizing advanced techniques and software, engineers are able to assess factors such as the critical slip surface of slopes, plastic zone distribution, deformation characteristics of slopes, and factor of safety. There are conventional analytical approaches based on the limit equilibrium methods (LEM), with multiple techniques belonging to LEM: Swedish slip circle, ordinary method of slices, i.e., Bishop, Morgenstern–Price, Spencer, Janbu, Fredlund, etc., which usually establish very conservative and safe estimations of FOS due to their simplification assumptions. These methods have been used for several decades and proven to be effective in many practical engineering problems.

Since the embankment is usually built from chopped, incoherent wet material and the landfill "stores" and free water there are opportunities to partially or completely demolish the circumferential embankments and the landfill itself.

To prevent this, it is necessary to carry out constant checks and computational checks on the stability of the tailings. The analysis has been carried out in static and dynamic (earthquake, artificially induced vibration) conditions. The appearance of embankment instability can occur for four main reasons:

- the load on the substrate or slope of the embankment is too large in relation to the characteristics of the material: a large height of the embankment, too steep slopes
- when building embankments on soft fine-grained saturated soil, the temporary stability of the embankment is more critical than permanent stability. Critical is the relatively deep sliding surface and the moment of completion of the embankment
- increase in pressure, pressure, filtration water filtration. If the embankment substrate has low water permeability, the npv lowering increases the load on the soil by the embankment. Internal erosion when water leaks can cause the material to be carried out - suffosion.

Table 1. Adopted physical-mechanical characteristics of geotechnics units.

Material	**Label**	**Unit weight, kN/m^3**	**Cohesion, kN/m^2**	**Friction angle, °**	**Water permeability, m/s**
Flotation tailings,	1A	17.50	5	27	
Flotation tailings,	1B	18.50	17	19	$1.3 \times 10^{-6} – 4.9 \times 10^{-8}$
Sand	2	18	0	29	
Mine tailing	3	18.60	20	22	$1.1 \times 10^{-6} – 3.2 \times 10^{-7}$
Mine tailing - high planners	4	21	11	32	
New embankment	5	17.15	28	25	1.9×10^{-6}
Melting slag	6	30	0	37	
Embankment	7A	18.60	15	24	$8.5 \times 10^{-7} – 9.2 \times 10^{-7}$
	7B	17	39	0	
	7C	17.40	27	23	5.8×10^{-7}
Deluvial- eluvial sediments	8	18.90	17	16	$1.1 \times 10^{-7} – 6.4 \times 10^{-8}$
Autochthonous rock mass	9	24	240	38	
Colluvium	K	17.80	0	15	

- dynamic forces. Vibrations caused by an earthquake, blasting, or rebuttal of piles.

At each occurrence of instability, one of the above factors is decisive, but the instability of the tailings, as a rule, is the sum or product of the joint action of all factors.

The situation of landfills in terms of geotechnical stability can also be expressed precisely by the stability budget. All stability calculations of landfills in which unbound, finely chopped, and wet material is stored are based on the following assumptions:

- first, when disturbing stability, sliding surfaces are formed by having the mass of the upper sliding surface slide over the lower mass, and both sliding surfaces are rigid,
- Secondly, sliding occurs when the shear voltage (τ) exceeds the shear resistance value that has the material from which the circumferential embankment is built.

The investigation of the causes of the resulting slippage, or the conditions that must be met to occur, usually starts from the analysis of the load that acts on an already launched or potentially sliding body.

In doing so, the problem is almost always simplified, so the three-dimensional geometry of the landslide is replaced by a two-dimensional, vertical cross-section through the slope, in the direction of sliding.

3.1. LIMIT EQUILIBRIUM METHOD

The limit equilibrium method analyses the stability of an imaginary or actual sliding body that is in contact with the surrounding ground via a sliding plane. The sliding body is divided into a series of vertical slats. Such a system of slats is without introducing assumptions about their rigidity, statically indeterminate. By analyzing the conditions of the balance of forces acting on each of the slats and introducing assumptions to eliminate the static vagueness of the system, the size of tangential and normal stress on the sliding plane at the bottom of each lamella is determined.

The problem of earth masses stability analysis boils down to determining the relationship between the available shear strength and the average shear voltage or mobilized strength, which is required to keep the hypothetical sliding body in balance. For a measure of the degree of stability, the term Factor of Safety (F_s) is commonly introduced, which is defined as the ratio of shear (peak) strength and shear voltage required to maintain the balance of a sliding body, τ_m.

In geotechnical practice, the following definition of Factor of Safety proposed by Bishop (Equation 1) is most often used:

$$F_s = \frac{\tau_f}{\tau_m}$$

Equation 1. The Factor of Safety proposed by Bishop

Where is: τf - shear strength of the soil

τ_m - vailable resistance

The practical application of the limit equilibrium method consists in finding a sliding body with the smallest Factor of Safety. A sliding plane belonging to a sliding body with the smallest Factor of Safety is commonly referred to as a critical sliding plane.

In practice, the design value of the minimum Factor of Safety (at high parameter reliability) $F_s = 1.4$ was commonly applied.

4. STABILITY ANALYSIS AT OVERHANGING TAILINGS

The analysis was made by the Slide v6.0 program by Rocscience. Slide v6.0 is a 2D program for calculating slope stability and assessing the Factor of Safety of circular or complex sliding planes in the ground or rock. Slide v6.0 is very easy to use, yet complex models can be quickly created and easily analyzed. External load, groundwater, and other influences can be modeled in different ways. The calculation of stability was carried out in conditions of boundary equilibrium by the simplified method of Yanbu, which is applied in conditions of complex inhomogeneous soil composition, with a complex shape of the sliding plane.

Yanbu (1956) assumed in his simplified method that interlamelforces were horizontal (Figure 3).

So that the certainty Factor of Safety is determined from the equation (Equation 2),

$$F = \frac{f_0 \sum \left[c_i \cdot l_i + \left(P_i - u_i \cdot l_i \right) tg\varphi' \right] seca_i}{\sum W_i \cdot tga_a}$$

Equation 2. The Factor of Safety proposed by Janbu.

The factor of Safety is located on both sides of the equation, so its value is determined by successive approximations. Convergence is very fast. The calculation process can be done with or without an electronic computer. If it is done without a computer, it is most often carried out in a tabular manner.

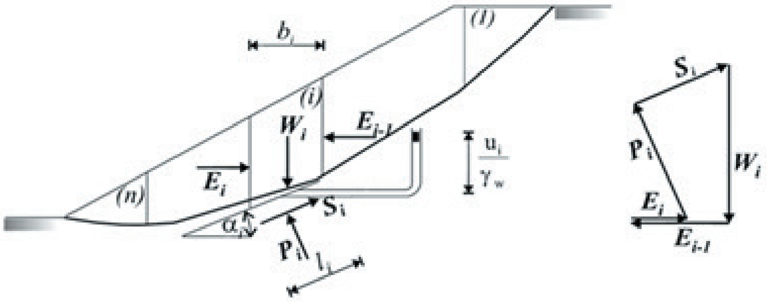


Figure 3. Janbu's simplified method - sliding body and forces acting on a typical lamella.

Janbu's simplified method gives conservative values of the Factor of Safety. In shallow, elongated sliding surfaces, errors are not large (below 10%), but become pronounced (up to 15%) in deep sliding bodies. An increase in accuracy can be achieved by applying Janbu's general method.

4.1. FAIRY THE RESULT TRANSPARENT

When analyzing stability, it is first necessary to construct a model that corresponds to the terrain, followed by the adoption of the parameters of the meter. The used computational parameters for stability calculation are shown in Table 1.

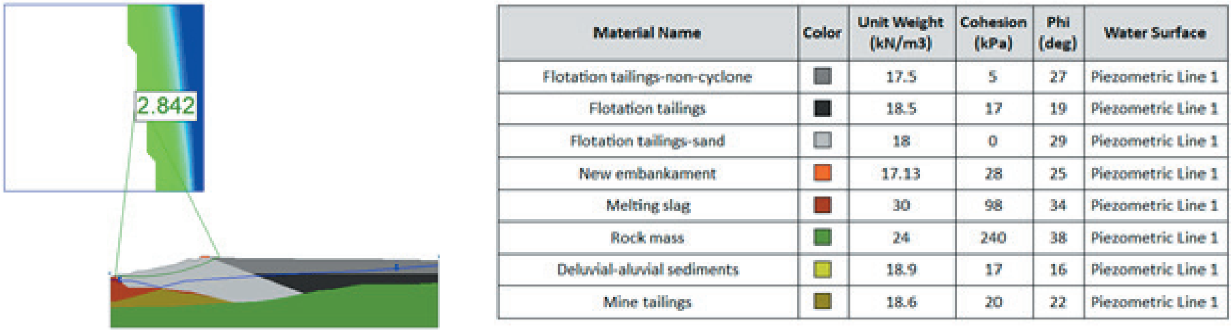
The effect of water on stability is modeled by a piezometer line. The piezometer line at the geotechnical sections before overhanging represents the water level obtained by hydrogeological analysis. The stability analysis after the overhang was carried out with the maximum water level.

The impact of the earthquake on stability is modeled by the coefficient of seismic, which for the area of Bor is KS = 0.08 for an earthquake of 8 ° ISS (T = 475 years).

The calculation of stability by analyzed profiles (1-1'; 2-2'; 3-3') for constant static loads, and dynamic loads for the occurrence of earthquakes, before overhanging and after overhanging, is shown in figures 4 to 7 on section profile 1-1'. On profiles, there are shown sliding planes with the smallest Factor of Safety. All other sliding planes on the corresponding profiles have a higher Factor of Safety than those shown. When analyzing stability, firstly it is necessary to construct a model that corresponds to the terrain, followed by the adoption of parameters. The used computational parameters for the analysis of stability are given in Table 2.

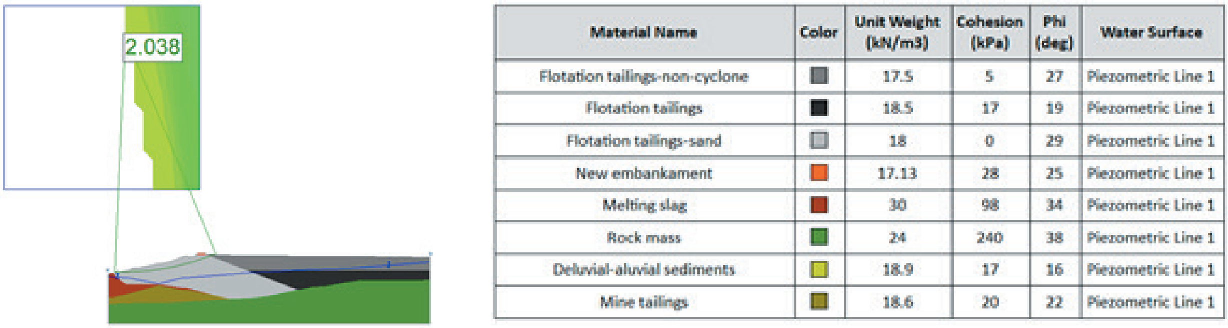
By comparing the Factor of Safety obtained from the flotation tailings dam (Table 2) with the permissible minimum factor, prescribed technical conditions for the design of dams and hydrotechnical embankments – SRPS U.C5.020, which, for dams with a height of more than 15 m is a minimum of Fs = 1.50 in the case of constant static load, or Fs = 1.00 in the case of occasional dynamic load for earthquakes, it can be concluded:

- The Factor of Safety of all profiles for static loads is higher than the minimum prescribed value, i.e. they are over 1.50, which indicates that the terrain before and after overhanging in static conditions is stable
- The Factor of Safety of all profiles for dynamic loads is higher than the minimum prescribed value, i.e. they are over 1.00



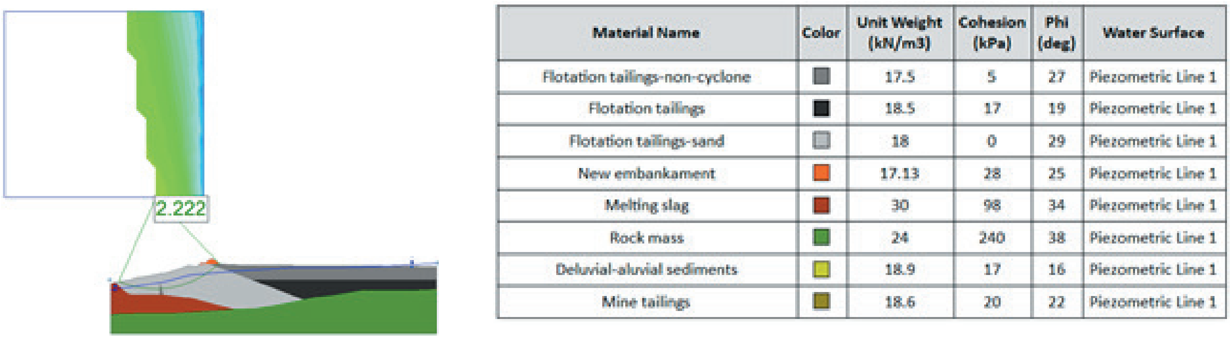
Material Name	Color	Unit Weight (kN/m3)	Cohesion (kPa)	Phi (deg)	Water Surface
Flotation tailings-non-cyclone	▩	17.5	5	27	Piezometric Line 1
Flotation tailings	⬛	18.5	17	19	Piezometric Line 1
Flotation tailings-sand	⬜	18	0	29	Piezometric Line 1
New embankament	🟧	17.13	28	25	Piezometric Line 1
Melting slag	🟥	30	98	34	Piezometric Line 1
Rock mass	🟩	24	240	38	Piezometric Line 1
Deluvial-aluvial sediments	🟨	18.9	17	16	Piezometric Line 1
Mine tailings	🟫	18.6	20	22	Piezometric Line 1

Figure 4. Static Factor of Safety c for profile 1 - 1' pre-overhang.



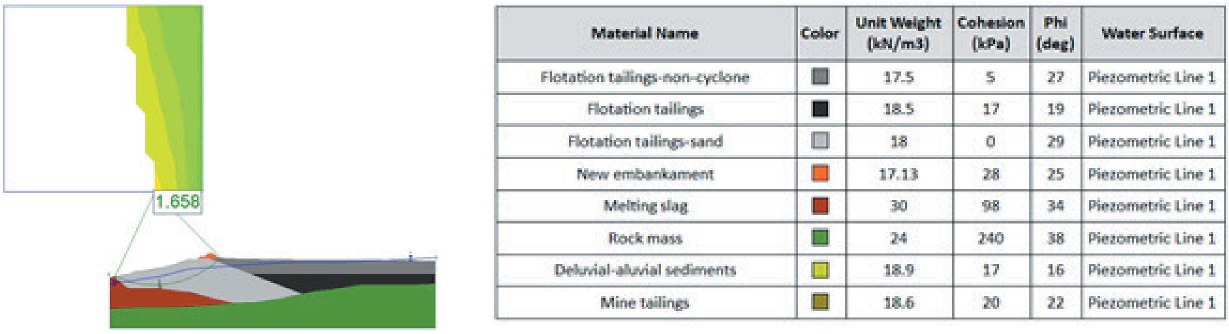
Material Name	Color	Unit Weight (kN/m3)	Cohesion (kPa)	Phi (deg)	Water Surface
Flotation tailings-non-cyclone	◼	17.5	5	27	Piezometric Line 1
Flotation tailings	⬛	18.5	17	19	Piezometric Line 1
Flotation tailings-sand	◻	18	0	29	Piezometric Line 1
New embankament	🟧	17.13	28	25	Piezometric Line 1
Melting slag	🟥	30	98	34	Piezometric Line 1
Rock mass	🟩	24	240	38	Piezometric Line 1
Deluvial-aluvial sediments	🟨	18.9	17	16	Piezometric Line 1
Mine tailings	🟫	18.6	20	22	Piezometric Line 1

Figure 5. Dynamic Factor of Safety c for profile 1 - 1' pre-overhang.



Material Name	Color	Unit Weight (kN/m3)	Cohesion (kPa)	Phi (deg)	Water Surface
Flotation tailings-non-cyclone	◼	17.5	5	27	Piezometric Line 1
Flotation tailings	⬛	18.5	17	19	Piezometric Line 1
Flotation tailings-sand	◻	18	0	29	Piezometric Line 1
New embankament	🟧	17.13	28	25	Piezometric Line 1
Melting slag	🟥	30	98	34	Piezometric Line 1
Rock mass	🟩	24	240	38	Piezometric Line 1
Deluvial-aluvial sediments	🟨	18.9	17	16	Piezometric Line 1
Mine tailings	🟫	18.6	20	22	Piezometric Line 1

Figure 6. Static Factor of Safety for profile 1 - 1' after overhang.



Material Name	Color	Unit Weight (kN/m3)	Cohesion (kPa)	Phi (deg)	Water Surface
Flotation tailings-non-cyclone	◼	17.5	5	27	Piezometric Line 1
Flotation tailings	⬛	18.5	17	19	Piezometric Line 1
Flotation tailings-sand	◻	18	0	29	Piezometric Line 1
New embankament	🟧	17.13	28	25	Piezometric Line 1
Melting slag	🟥	30	98	34	Piezometric Line 1
Rock mass	🟩	24	240	38	Piezometric Line 1
Deluvial-aluvial sediments	🟨	18.9	17	16	Piezometric Line 1
Mine tailings	🟫	18.6	20	22	Piezometric Line 1

Figure 7. Dynamic Factor of Safety for profile 1 - 1' after overhang.

Table 2. Sum Factor of Safety.

Profile	The factor of Safety before overhanging		*The factor of Safety after overhanging*	
	Static	Dynamic	Static	Dynamic
1-1’	2.842	2.038	2.222	1.658
4-4’	1.672	1.356	1.659	1.330
7-7’	1.849	1.319	1.521	1.245

5. CONCLUSION

An analysis of slope stability was carried out with Slide program, on three characteristic profiles, in case before and after overhanging tailings (with maximum groundwater level). The calculation was carried out using the Janbu method in static and dynamic conditions. The resulting safety factors of all profiles for static and dynamic load are higher than the minimum prescribed value, which indicates that the tailings will remain stable after overhanging.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] D. Knežević, S. Torbica, Z. Rajković, M. Nedić, "*Odlaganje industrijskog otpada*". RGF, Belgrade 2014.

[2] F. Dumitru Popescu, S. Mihai Radu. "*Stability assessment of the dam of a tailings pond using computer modeling*". Coroiesti, Romania 2023.

[3] Ć. Ćosić, “Geostatistički proračuni,”. RGF, Belgrade 2008.

[4] G. Hadži-Ninković, “*Primena računarskih programa, Geostatički proračuni 2.*“ RGF, Belgrade, Serbia 2022.

[5] S. Singh, T.G. Sitharam, A. Kumar, “*Stability investigation of embankments of a tailings pond with varying embankment raising rate,*” Mining, Metallurgy and Exploration, 2023, № 3, p. 851-869, New Delhi, India, November 2023.

[6] D. Jevremović, “Metode inženjerskogeoloških istraživanja,” Faculty of Mining and Geology, Belgrade, 2015.