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Study regarding the stability and the risk of landslides of the marginal slopes of Lake UNEX (Petrila, Romania)

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Abstract. Often, in areas where open pits were developed, after the cessation of productive activities, lakes, with different characteristics (morphological, geometric and related to the quality of the accumulated waters), were formed in the remaining voids. After the restitution of the lands occupied by these open pits to the former owners or local authorities, one of the options considered for their use is that of development for recreational purposes. In this sense, one of the investigations of utmost importance, regardless of the recreational infrastructures intended to be built on the site, is the one that takes into account the stability of the marginal slopes and the assessment of the risk of landslides. In this context, in the content of this paper, the geotechnical investigations carried out for Lake UNEX, located on the administrative territory of the city of Petrila (Romania), are briefly presented, as well as a series of constructive measures intended to increase the stability reserve and ensure the protection of future recreational objectives located in the risk area.

1 Introduction

The extraction in quarries and open pits of various useful mineral substances often leaves behind residual voids, which, in turn, naturally or through human interventions, are transformed into the so-called open pit lakes.

Depending on a series of factors that influence the flooding process of the residual void [1], these lakes may or may not subsequently take on various functions.

In some situations, especially in the case of former ore quarries, due to the rocks with which the water comes into contact, quarry lakes may become acidic or contain large quantities of harmful elements (such as heavy metals, phenols, etc.), either in dissolved form or concentrated in sediments. In these situations, quarry lakes are more likely to be seen as accumulations of wastewater, and their functionalization would require massive investments for pH neutralization or decontamination.

In the case of most former coal mines (lignite, brown coal or hard coal), the lakes formed after closure do not contain harmful elements and have a pH close to that of the natural lakes in the vicinity. These lakes can almost immediately take on some functions, such as the

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naturalistic one, which basically aims to restore the cadence of the landscape in the area, or, in rarer cases, these lakes become true floristic and faunal reservations.

When the aim is to obtain a functionality that also involves economic aspects (such as the use of water for land irrigation, energy storage, sport fishing and recreation, or a combination), the need for additional developments (different types of constructions and installations) arises and the issue of ensuring safety conditions in terms of the stability of the land on which they are to be located (represented in fact by the final slopes of the open pit and, often, of the internal dump) arises.

This issue of the stability of the land in the vicinity of lakes (banks) is all the more important when the aim is to develop recreational areas, which involve the presence of a relatively high number of people, whose safety or even life would be endangered in the event of a landslide.

There are numerous examples in the world of lakes that have been developed for recreational purposes, some recently such as Lake Most in the Czech Republic [2] or Lake Kubsow in Poland [3], that are true success stories.

A project of this type is also planned for the UNEX lake in Petrila, and before moving on to the design phase of future recreational developments, it was considered necessary to conduct a preliminary study to analyse the stability of the land and the risk of landslides on the marginal slopes. In fact, this is an indicative study, this character being given by the limitations that the research team faced, limitations described further in the paper.

2 General data

The land where lake UNEX is located is part of Hunedoara County, Petrila city (area 98,376 sq m). The investigated area is located in the eastern part of the Petroșani Depression. The administrative territory of Petrila city is bordered to the east by the Șureanu massif, to the north by Vârful lui Pătru, to the south by the Parâng massif, and to the west by the territory of Petroșani municipality (Figure 1).

Fig. 1. Location of the studied area [4].

Access is made from County Road 709 H trough a communal road.

From a morphological point of view, the investigated territory is located in the Petroșani Intramontane Depression, between the Sebeș, Parâng, Retezat and Vâlcan mountains

The geology of the area, described in a geotechnical study carried out at the end of 2022, establishes that the studied area, framed to the south by the Sălătruc syncline and to the north by the Petrila syncline, contains Oligocene deposits, as well as Miocene terms, and in the axis the Burdigalian deposits develop [5].

The documentation and field investigations carried out by the research team aimed to clarify aspects related to the topography of the land, geology (stratigraphy) as well as to validate some physical and mechanical characteristics of the rocks encountered in the marginal slopes.

The basic documents, available to the team, consisted of:
- Existing situation plan;
- Zoning Plan and inclusion in the Zonal Plan;
- Geotechnical study.

3 Initial observations, restrictive conditions and limitations

We must state from the outset that this study was influenced by a series of limitations and restrictive conditions:

a. During the first field visit carried out by the research team, it was found that the slope on the southern side was affected by a landslide that is not marked on the available situation plan, which is why a new field trip was carried out, the main purpose of which was to measure its topography.

b. During this last field trip, three material samples were also taken, one from the slipped area, one from the left lateral area of the slide (unaffected terrain) and one from the part above the slide. The purpose of taking these samples was to submit them to laboratory analyses and to compare the results obtained with those contained in the geotechnical study [5].

c. The geotechnical study [5] does not highlight the aforementioned landslide and is insufficient for carrying out complex stability analyses. This study was carried out for 3 boreholes (located in the vicinity of sections A – A (one) and C – C (two) in figure 2), and the maximum exploration depth was 2 m (practically the manually dug boreholes stopped when the formation considered to be bedrock and identified as sandstone was intersected).

d. In an attempt to establish a more detailed stratigraphy of the area (absolutely necessary for a complex stability study), the research team studied existing documentation at the University of Petroșani (UP). In this regard, data from exploration/prospecting boreholes carried out in the 1980s near the area of interest were identified, which highlighted a much more complex stratigraphy. These boreholes identified several different layers of clay, sandstones with different states of consolidation, but also layers of marl limestone [6].

The presence of marl limestones intercalated with sandstone layers is of particular importance, because, in fragmentation areas, which are actually also alteration areas, and in the presence of water infiltrated from precipitation, these easily change their state of consistency, passing from a solid state to a plastic one. The transition to the plastic state favors the occurrence of displacements of blocks or fragments of blocks along the path of the cracks in the form of translational or collapse movements, as the case may be. These displacements, in turn, are transmitted to the upper (covering) layers of sandstones and clays, the result being a complex landslide both in terms of triggering and transmission mechanism and in terms of rock types involved.

e. There are no data available on the possible crack systems affecting the sandstones and marl limestones that make up the slopes and which would allow for a more realistic modeling of them, absolutely necessary for a detailed stability study, but also for a classification of the massif from a qualitative point of view (RQD index - Rock Quality Designation). Such a classification would allow the adoption of coefficients for reducing the mechanical resistance characteristics of the rocks that make up the slopes, especially in the case of sandstones and marl limestones.

f. In the absence of these data, and given that the consulted geotechnical study [5] does not include determinations of the mechanical resistance characteristics for the rocks identified as sandstones, the research team took into account values of the physical and mechanical characteristics available in the UP documentation [6].

We would like to point out that, in our opinion, these values overestimate the mechanical strength characteristics of the rocks for two reasons:

- at the time of the drilling and laboratory analyses, the massif was intact, unaffected by subsequent drilling and blasting works (which led to the appearance of cracks and/or the development of the natural crack system), from the period of exploitation of the coal seams;
- the rock column analysed from the drillings was not subjected to alteration phenomena, such as the rocks exposed from the marginal slopes (exposure to precipitation, diurnal and seasonal temperature variations, freeze-thaw cycles).

g. Impossibility of modelling the flooded slopes (below the lake surface). The contact area of submerged slopes with those above the water level is of particular interest, given the significant influence that water can have on the stability reserve. In the absence of data on the geometry of the slopes before flooding, or data on the current geometry of the lake basin (bathymetric measurements), it was impossible for the research team to model these contact areas and perform adequate stability analyses.

4 Stability analyses

4.1 Initial considerations

The measured landslide was superimposed on the existing situation plan, and then 4 sections were drawn through the areas susceptible to landslides (Figure 2). After the field trip, during which it was found that there were changes compared to the initial plan, topographic surveys were carried out in the areas where landslides have occurred over time.

Thus, the four sections used in the stability analyses were established and named:

- Section A – A – through the central area of the landslide on the southern (SSE) slope (Figure 3);
- Section B – B - through the western steep area (earth path - pedestrian alley) (Figure 4);
- Section C – C - through the dump, northern area (Figure 5);
- Section D – D - through the north eastern steep area (quarry step and natural terrain) (Figure 6).

For section A – A (Figure 3), drawn through the central area of the landslide on the southern slope (SSE), the results of the stability analysis can be considered indicative, in the sense that from the observations made in the field, the stratigraphy is much more complex than that indicated by the geotechnical study [5]. Thus, starting from the upper part, in the area of the slope failure, a succession of clays is observed, followed by inclined layers of sandstones and possibly marl limestones, under which clays are encountered again. Also, in the landslide area, the presence of a layer, probably discontinuous, of coal was also observed.

Under these conditions, the model developed, which only takes into account the presence of a layer of topsoil (clay) followed by sandstones, is one that greatly simplifies the reality on the ground.

Moreover, even if the analyzed model obtains a stability reserve above unit (above the equilibrium limit), field observations largely contradict this result, with tension (traction) cracks present at the top of the failure zone, a clear indicator of instability and the high probability of the landslide extending towards the access road and possibly beyond it.

It should also be taken into account that the geotechnical investigations were carried out for a certain humidity of the constituent rocks, without carrying out tests at higher humidity, possibly close to the saturation limit, and that the possibility of a hydrostatic water level in the slopes was not taken into account (not having data on this aspect available, for this purpose it is necessary to carry out hydro-observation drilling), when, as is known, the values of the mechanical resistance characteristics decrease significantly, the behavior changes, while the volumetric weight (and implicitly the weight of the rocks in the slope, possible sliding mass) increases.

Cumulatively, these changes lead to a significant decrease in the stability reserve.

An even more unfavorable situation may occur if, in addition to the previously mentioned unfavorable factors, the region is also affected by seismic shocks (for example, the seismic episode at the beginning of 2023, felt quite strongly in the Jiu Valley region).

The western slope (section B – B, Figure 4) is represented by a generally steep slope (approx. 31º) from the contact with the water, with a height of approximately 21 m, followed by an area with a reduced inclination (15º) with a section width of approx. 4 m (on which there is an earth path), and at the top again a steep slope (approx. 38º), with a height of approximately 15 m.

The lower part of the slope is made up of a compact sandstone, but prone to fragmentation, and the upper part is made up of a sandy sandstone, prone to disintegration under the influence of natural factors. At the base, at the contact with the lake, at the middle part with a low slope and at the upper part, the land is covered with a superficial layer of topsoil. In the middle and upper areas there is arboreal vegetation, represented mainly by birch.

On the upper part of the slope, superficial landslides of topsoil are observed, in the form of patches of earth that move by translation towards the area with a low slope.

The eastern slope (section D – D, Figure 6) is represented at the lower part (the contact area with the lake) by a slope with a low inclination (11 - 12º) over a section width of approximately 45 m, followed by a steep slope (46º) with a height of 10 m, and at the upper part again by a low inclination (9 - 10º).

The first part of the slope and the last are covered by a layer of topsoil with a thickness of approximately 0.5 m, under which the base layer, considered to be sandstone, was intercepted.

The middle portion, the most inclined, is made up of sandy sandstones prone to disaggregation under the influence of natural factors.

In the case of these two sections, although the materialization of cylindrical-circular sliding surfaces is able to provide us with some information regarding the stability reserve, this type of surface is not characteristic of all types of rocks in the composition of the slopes.

In the case of slopes made up of cohesive rocks, such as sandstones and sandy sandstones, landslides occur through other mechanisms:

- Translational landslides, in the case of intensely fragmented rocks, which move on slopes with a low inclination;
- Rolling and roto-translations, of blocks or fragments of blocks, in the case of movement on slopes with a medium inclination;
- Collapses, in the case of movement on slopes with a medium to high and high inclination;
- Landslides that follow a concave contour, materialized at the intersection of the crack systems or between fault planes.

As we have previously stated, there is no qualitative data of the slopes in question nor data relating to any crack systems affecting the slopes, which makes it impossible to more rigorously model the analysis sections and use appropriate stability analysis programs.

Section C – C (Figure 5) is traversed through the waste dump, consisting of a heterogeneous mixture (both in rock types and grain size) of overburden and waste intercalations. In the context of stability analyses, this is the area where cylindrical slip surfaces are most likely to materialize.

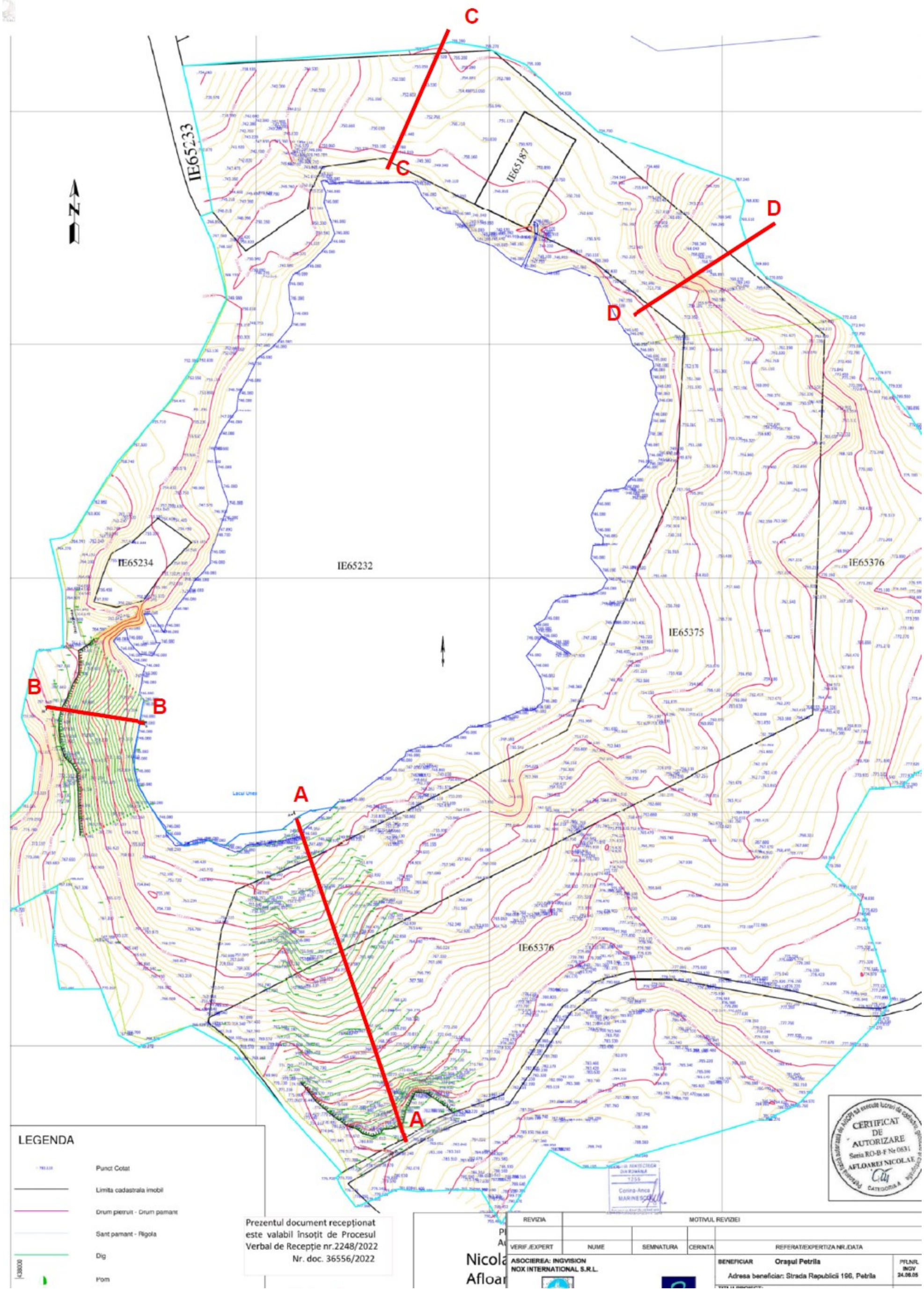

Fig. 2. Situation plan [5], with the superimposed sliding and the 4 analysis sections.

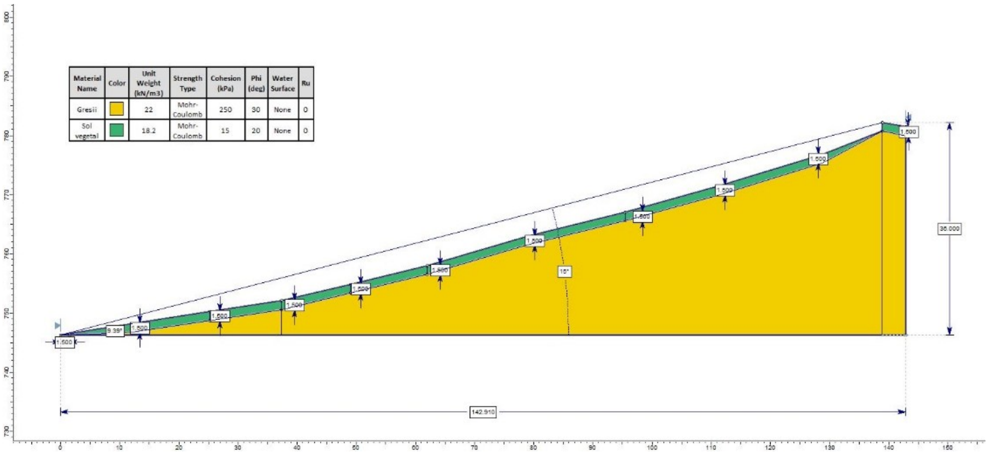

Fig. 3. Section A – A (trough the landslide).

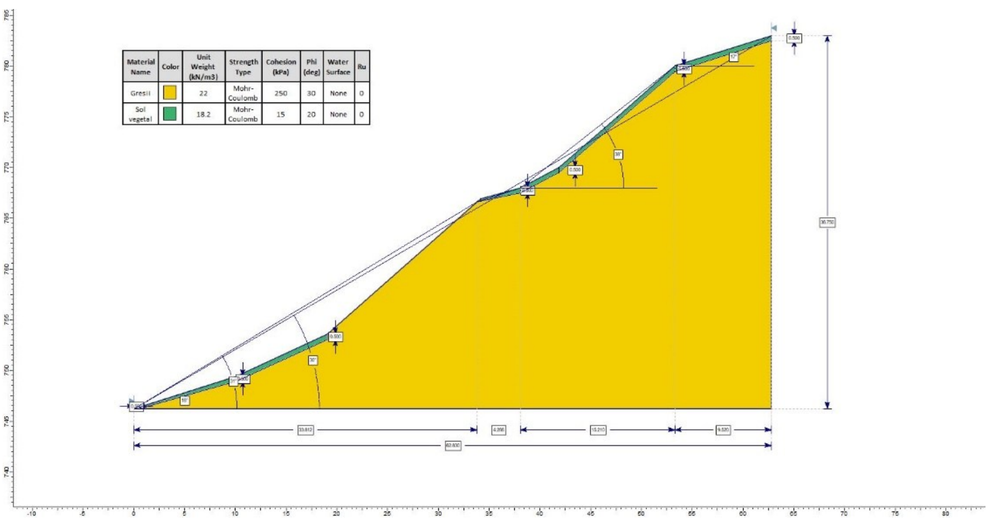

Fig. 4. Section B – B.

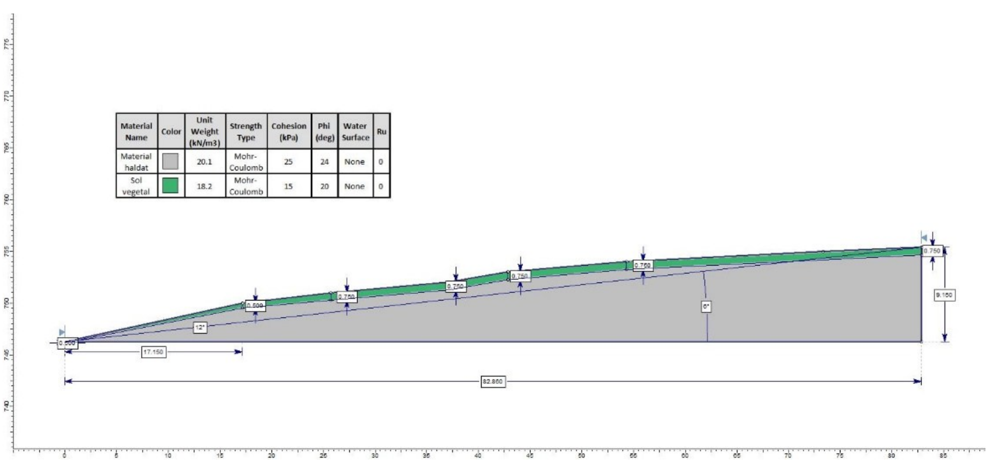

Fig. 5. Section C – C (trough the dump).

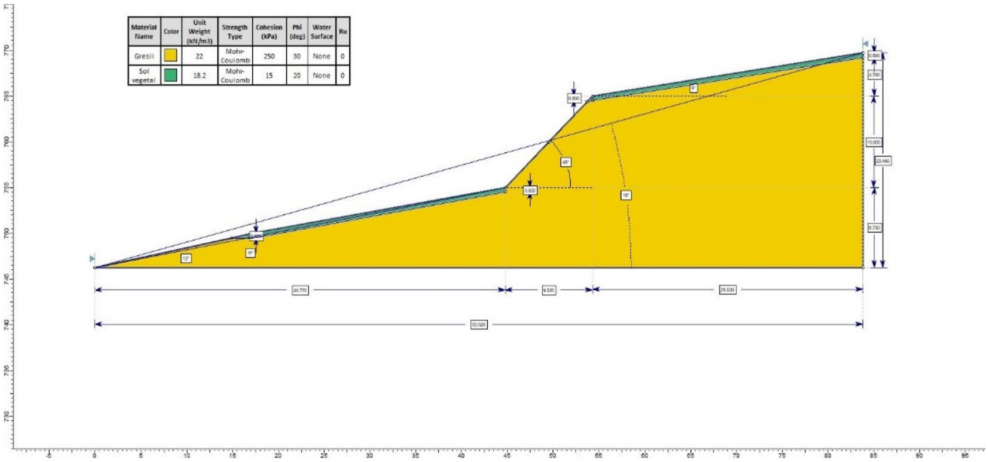

Fig. 6. Section D – D.

4.2 Results of stability analyses

To perform the stability analyses, the initial documents, a series of data and observations obtained from field trips and laboratory tests, as well as information and determinations from previous research in the area of interest, existing at the University of Petroșani, were used.

In order to investigate the stability reserves, the SLOPE software, developed by the GEOSTRU company, was used, dedicated to the stability of slopes in loose or rocky terrain, using traditional geotechnical methods (Limit Equilibrium), and the Discrete Element method with which the slope displacement can be calculated and the progressive failure can be examined. Analyses can be performed in seismic conditions, both in static or dynamic regime [7].

Assumptions taken into account:

- The physical and mechanical characteristics of the rocks in the slopes/slopes were processed from public sources [5], specialized literature [6] and values obtained through tests (carried out in the university laboratories);
- For all situations, the seismic potential of the area was taken into account, respectively ag = 0.1g;
- Simulations were performed for both drained and undrained rock conditions;
- The analysis methods used (simplified Janbu, Bishop and Fellenius) are based on the limit equilibrium theory, being recommended by the specialized literature [8-10];
- Stability analyses were performed according to the Guide on Geotechnical Design - indicative GP 129-2014 [11].

The values of the physical-mechanical characteristics of the rocks are presented in Table 1, and the results of the stability analyses are summarized in Table 2, and in Figures 7 – 10 (the most unfavorable situations for each analysis section).

Table 1. Physical-mechanical characteristics of the rocks.

Rock type	Volumetric weight γ (kg/m^3)	Saturated volumetric weight γ_{sat} (kg/m^3)	Cohesion c (kg/cm^2)	Internal friction angle φ (grade)
Top soil	1820	2100	0.15	20
Sandstone	2200	2350	2.50	30
Waste rocks	2010	2300	0.25	24

Table 2. Physical-mechanical characteristics of the rocks.

Method / Section	Fellenius		Bishop		Janbu	
	Drained	Undrained	Drained	Undrained	Drained	Undrained
A-A	2.17	1.01	1.94	0.94	1.92	0.94
B-B	1.83	1.19	1.63	1.10	1.61	1.09
C-C	3.15	1.09	2.92	1.04	2.81	1.03
D-D	1.93	1.38	1.72	1.26	1.70	1.20

Blue - sufficient stability reserve
Green - insufficient stability reserve
Yellow - equilibrium limit
Red – unstable slopes

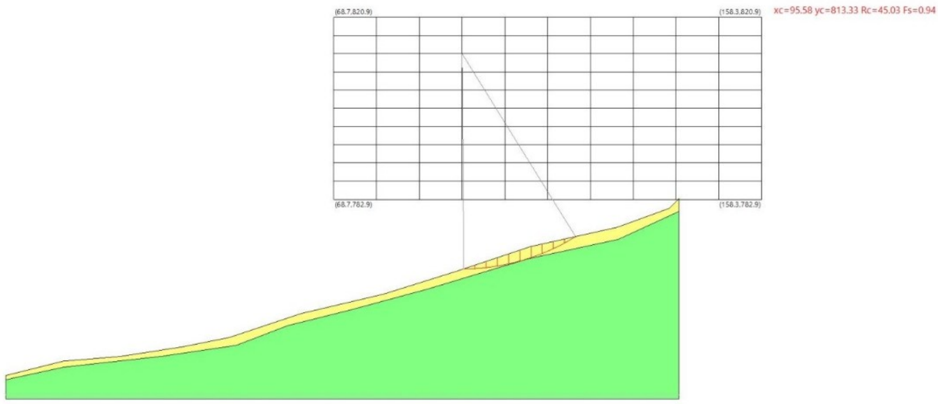

Fig. 7. Undrained state (influence of pore water pressure) – section A – A.

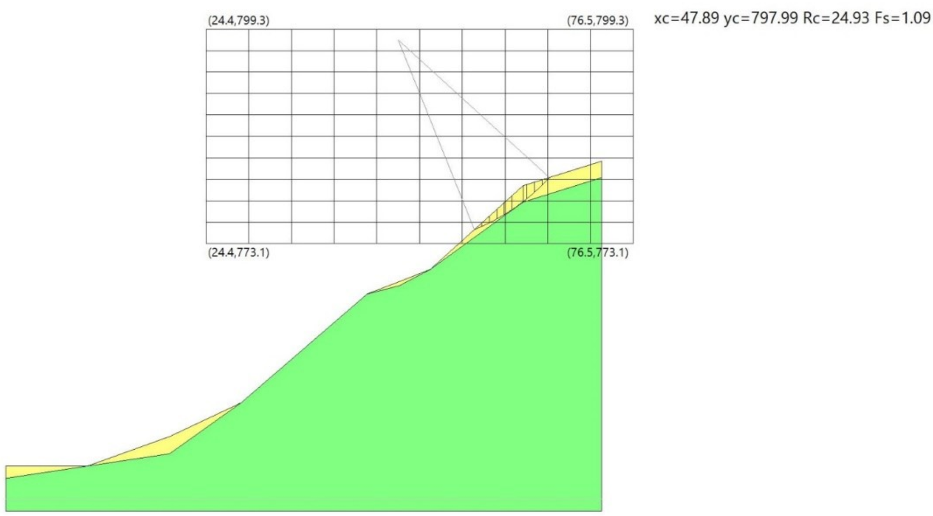

Fig. 8. Undrained state (influence of pore water pressure) – section B – B.

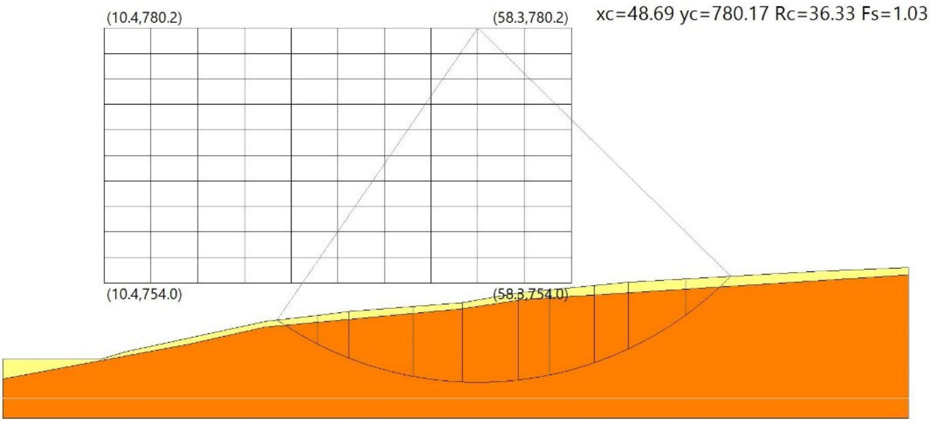

Fig. 9. Undrained state (influence of pore water pressure) – section C – C.

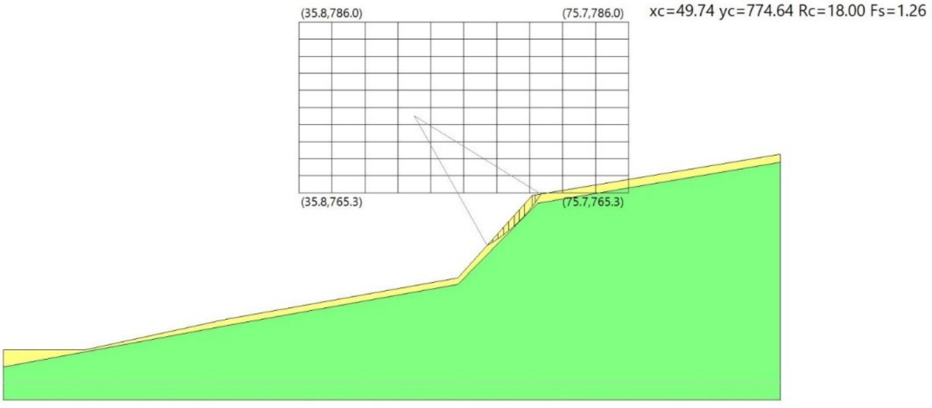

Fig. 10. Undrained state (influence of pore water pressure) – section D – D.

After carrying out the stability analyses, the following conclusions can be drawn:

- The sliding occurs in the topsoil state in the areas corresponding to sections A - A, B - B and D – D, explainable as a result of the large differences in mechanical resistance of the two types of rocks (top soil, respectively sandstone);

- The stability of the sandstone substrate seems to be sufficient, however, as we presented in paragraph 4.1, it was not possible to carry out adequate stability analyses as a result of the lack of knowledge of its structural conditions (crack systems, degree of alteration, microtectonic elements, etc.)

- The sliding surface has the same position both in the case of rocks in a drained or undrained state, entraining in both cases the same volume of material;

- The sliding surface is formed, in the case of the three sections, in the upper part of the slope;
- Such landslides may have a regressive development, that is, the material above the fracture zone will become unstable in turn (basically the material involved in the initial landslide serves as support for the one located above on the respective slopes);
- In the case of section C - C (the old dump over which a layer of topsoil was formed/deposited), the landslide surface is positioned at the bottom of the slope in the case of drained rocks and in its middle area in the case of undrained rocks. In both cases, the landslide will also affect the body of the dump. The most dangerous situation is recorded in the case of undrained rocks, when the slid material from the middle area can entrain large volumes of material from the bottom of the dump, which could reach the lake, giving rise to large waves, which can lead to the triggering of new landslides on the other slopes.

5 Risk analysis

To assess the risk of landslides in the various hypotheses considered in this study, we used a methodology developed by some of the members of the research team [12], verified in the framework of master's and doctoral theses, as well as in other contracts and specialized articles.

Thus, within the methodology [12], in a first stage a classification of rock massifs/deposits was developed depending on the nature of the objectives in the area of influence and the characteristics of the environment in order to establish their vulnerability in relation to the technical condition of the in situ and waste dump's slopes (Table 3).

Table 3. Vulnerability of the objectives in the area of influence depending on technical state of the slopes [12].

Stability degree / - Nature of objectives in the influence area - Environmental characteristics	1. Massive/rock deposits with significant volume and active displacements	2. Massive/rock deposits which can enter into dangerous movements due to some factors	3. Massive/rock deposits with movements that can be limited by arrangements/ exploitation technology	4. Massive/rock deposits stabilized, landslides are not probable
1. – Households, social constructions - Forests, water courses/lakes, high value terrains	**V = 5** Very high vulnerability	**V = 5** Very high vulnerability	**V = 4** High vulnerability	**V = 3** Average vulnerability
2. – Industrial constructions and installations, high traffic routes, - Arable land, forests, water courses, productive land	**V =5** Very high vulnerability	**V = 4** High vulnerability	**V = 3** Average vulnerability	**V = 2** Reduced vulnerability
3. - Low traffic routes, reduced pedestrian access - Wooded pastures with varying degrees of consistency, limited water resources, low value land	**V = 4** High vulnerability	**V = 3** Average vulnerability	**V = 2** Reduced vulnerability	**V = 1** Very reduced vulnerability
4. - Areas without buildings, with sporadic access by people - Brownfield, unproductive lands, bushy pastures	**V = 3** Average vulnerability	**V = 2** Reduced vulnerability	**V = 1** Very reduced vulnerability	**V =1** Very reduced vulnerability

According to this procedure, five vulnerability classes were established.

The next step involves identifying the objectives in the areas of influence, adjacent to the marginal slopes of Lake UNEX, thus making it possible to classify the slopes bordering lake into hazard groups, respectively into vulnerability categories (Table 4).

For this classification, we used the satellite image, presented in Figure 11, those found during field visits and the details on the situation plan. Thus, within the methodology [12], in a first stage a classification of rock massifs/deposits was developed depending on the nature of the objectives in the area of influence and the characteristics of the environment.

Fig. 11. UNEX Lake and lands in the area of influence [4].

Table 4. The nature of the objectives in the areas of influence

Section	Objectives and environmental aspects	
	Natural objectives	Anthropic objectives
A – A	Land affected by mining activity, undergoing ecological restoration (naturally), arable land in the potential landslide extension area	Acces road, household outbuildings
B – B	Arable land, forest patches	Residential houses, household outbuildings, tree plantations
C – C	Pastures	Waste dump undergoing ecological restoration (naturally)
D – D*	Land affected by mining activity, undergoing ecological restoration (naturally), natural slopes	-

*In the absence of anthropogenic objectives in the area of influence, the value established for the natural objectives will be considered as the average vulnerability value

Further, based on complex statistical processing, the probability of slope landslides was determined as a function of the stability factor (Figure 12).

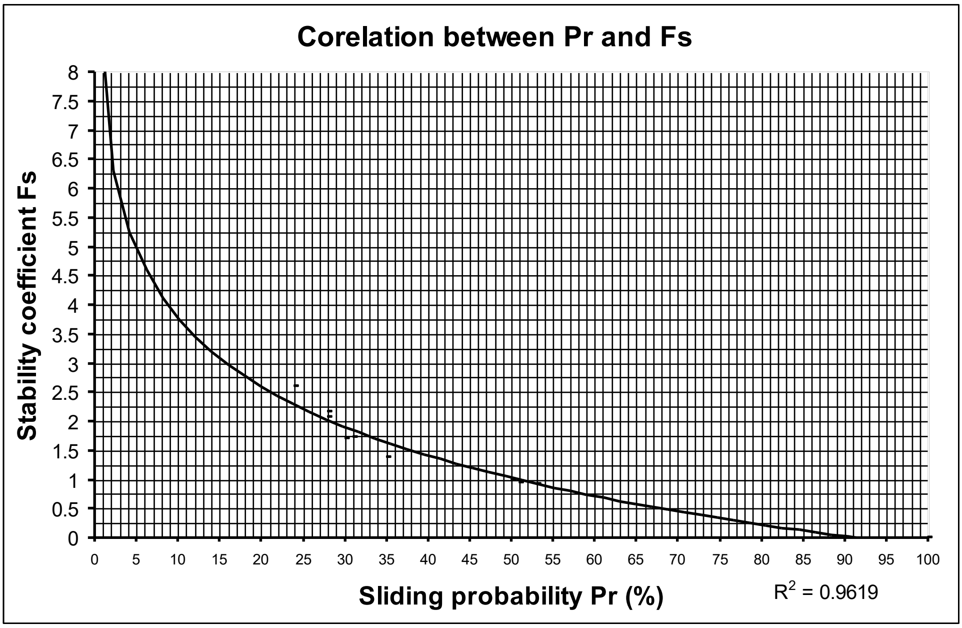

Fig. 12. Dependence between sliding probability (Pr) and stability factor (Fs) [12].

In the present study, the graph in figure 12 was used to determine the probability of landslide, the stability factor being known for the situations analyzed in the previous chapter.

According to models existing in the specialized literature, the following scale was established for defining the probability of landslide [12-14]:

Pr = 1 for Pral = 0 ÷ 15 % → very low; almost certain that the slope will not slide;

Pr = 2 for Pral = 16 ÷ 35 % → low; it is unlikely that the slope will slide;

Pr = 3 for Pral = 36 ÷ 65 % → medium; the loss or not of the slope's equilibrium are equally likely;

Pr = 4 for Pral = 66 ÷ 85 % → high; it is very likely that the slope will slide;

Pr = 5 for Pral > 85 % → very high; almost certain that the slope will slide.

Respecting the scale for defining the probability of landslide for each analysis section, the corresponding score was given. Using the relationship R = Pr x Vm (the risk is equal to the product of the probability of landslide and the average vulnerability of the objectives in the area of influence) the landslide risk for the marginal slopes of Lake UNEX is determined.

Considering the 5 vulnerability classes, respectively 5 probability classes, the following scale [12] was established for the assessment of the landslide risk:

- R = 1 → very low risk of landslide;
- R = 2 ÷ 4 → low risk of landslide;
- R = 5 ÷ 9 → medium risk of landslide;
- R = 10 ÷ 15 → high risk of landslide;
- R = 16 ÷ 24 → very high risk of landslide;
- R = 25 → extreme risk of landslide.

According to tables 3 and 4, we classified the UNEX Lake area into hazard groups, respectively into vulnerability categories (Table 5). Based on the values obtained from the classification into vulnerability categories depending on the nature of the objectives in the area of influence, an average vulnerability value was determined.

Table 5. Establishing the average vulnerability of the terrain in the UNEX Lake area.

Section	Natural objectives (V1)	Anthropic objectives (V2)	Average vulnerability: Vm = (V1+V2)/2
A – A	3	3	3
B – B	4	3	3.5
C – C	3	2	2.5
D – D*	3	-	3

*Under the conditions mentioned in the footnote of table 4

In the last stage, based on those presented in Table 6, and taking into account the probability of landslide of the final slopes (determined following the stability analyses presented in the previous chapter and using the graph in Figure 12) the landslide risk was calculated (using the calculation relationship R = Pr x Vm). These are presented in Table 6.

Table 6. Determining the landslide risk of the slopes surrounding UNEX Lake.

Section	Average vulnerability (Vm)	Probability				Risk R = Vm x Pr	
		Drained slope		Undrained slope			
		P_{ral} [%]	Pr	P_{ral} [%]	Pr	Drained slope	Undrained slope
A – A	3	29	2	54	3	6	9
B – B	3.5	37	3	47	3	10.5	10.5
C – C	2.5	18	2	50	3	5	7,5
D – D	3	34.5	2	44	3	6	9

By framing the slopes into risk classes and returning to the results of the stability analyses, the following were found:

- for the slopes analyzed in three of the sections (A – A, C – C and D -D) for drained rocks, the calculated risk has values between 5 and 7, which corresponds to an average risk in the event of a landslide;
- for the slopes analysed in three of the sections (A – A, C – C and D -D) for undrained rocks, the calculated risk has values between 7.5 and 9, which corresponds to an average risk in the event of a landslide (the value 9 being at the limit of high risk);
- this increase in risk is caused by the decrease in the value of the stability factor, which automatically leads to an increase in the probability of a landslide, moving to a higher category (from 2 to 3);
- for the slope in the analysis section B - B, for both drained and undrained rocks, the calculated risk has the value 10.5 (although the real probability (Pral) of a landslide occurring increases, the range, according to the presented methodology, assign the same value for Pr, namely 3), which corresponds to a high risk in case of a landslide.

6 Solutions to increase the stability reserve and recommendations

Considering the findings from the stability analyses and risk analysis for the marginal slopes of Lake UNEX, the research team comes up with the following solutions and recommendations:

a. For the slope in the southern part of the investigated area, starting from the central area of the existing landslide (see Figure 2), it is proposed to carry out some earthworks, the geometry of which is presented in Figure 13 (slope angles of 18 - 19º, respectively berms of 5 m width).

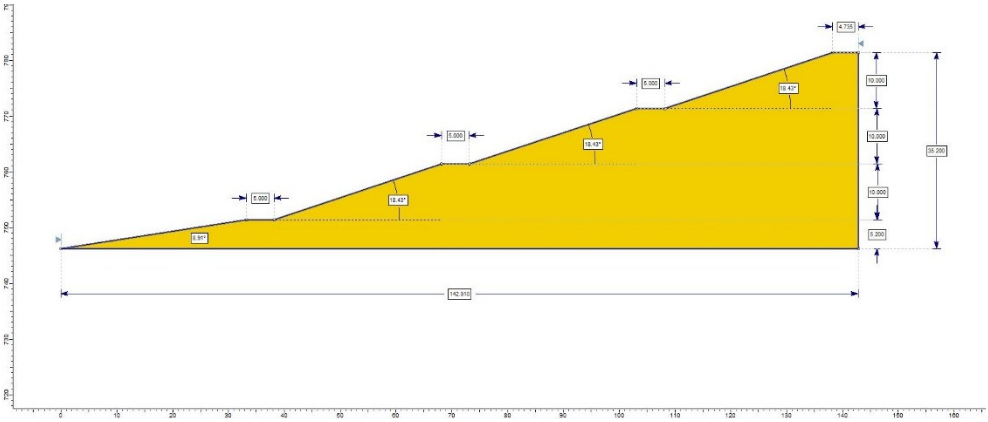

Fig. 13. Proposed geometry (execution of a terrace system) for the southern slope.

b. For the area of influence of section C – C, although, as shown in the stability study and in the risk analysis, in undrained conditions, there is a significant possibility of a landslide, we consider that by carrying out minimum development works (which involve a reduction in slope angle and height, carrying out a general leveling of the area, completed with related compaction works) the stability reserve will be substantially increased, reducing the risk of landslide to an acceptable level. Additionally, we propose the creation of an appropriate system for collecting and directing rainwater, so that the amount of water that infiltrates into what constitutes the base land (respectively the dumped material) is reduced as much as possible;

c. For sections B - B and D - D, because as we have specified, there is also a risk of landslides in the form of blocks or fragments of blocks collapses, made up of the sandstones in the structure of the slopes, we propose, as a solution to contain them, the placement of flexible metal barriers at the base of the slopes. This barrier can be of the flexible type - Geobrugg. It is worth mentioning that at the same energy capacity to absorb the impact due to falling rock blocks, the flexible barrier is much narrower than the semi-rigid ones (made of gabions) - a barrier of 1000 - 2000 kJ is recommended [15].

d. On the newly created terraces in the southern part of the study area, it is recommended to plant seedlings specific to the area (possibly pine or spruce) to accelerate the ecological recovery and further increase the stability reserve through the reinforcement effect of the tree roots;

e. The newly created terraces on the southern slope can be additionally reinforced with rockfill benches, which would occupy the berms (see Figure 13) over a section width of 2.5 – 3 m.

7 Conclusions

This study was conducted with the aim of having an overview of the stability of the slopes surrounding the UNEX lake in Petrila and to determine the risk associated with the occurrence of a landslide(s) in the context in which the Petrila City Hall intends to carry out a project to transform this abandoned mining area into one intended for recreation.

Based on these considerations, the research team followed a series of logical steps, starting from field visits, sample collection, topographic measurements, laboratory analyses, topographic and geotechnical modelling, stability analyses, risk analyses, finally presenting a series of solutions and recommendations to bring the land in question to a state that would allow such an approach.

Regarding the stability of the slopes, in principle, in the case of drained rocks, the slopes have sufficient stability reserves for structures with a long time to remain in place (FoS ≥ 1.5), but this situation is an ideal one.

Infiltrated water from precipitation and the lake can lead in certain circumstances to rock saturation, in which case most of the analyzed slopes reach the stability limit or even become unstable (especially in section A - A, where a significant landslide has already been observed).

The general conclusion that emerges from the risk assessment in the event of landslides is that, in the absence of measures to increase stability, this risk is medium to high.

Based on this general conclusion, in the opinion of the research team, the land in question requires the implementation of a set of measures that take into account, in particular, the increase of the stability reserve, but also the execution of additional works, before planning the construction of any recreational facilities.

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