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Stability Conditions in Lignite Open Pits from Romania, Case Study: Olteţu Open Pit

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Abstract: The problem of the slope stability of open pit mines is one of constant interest and great importance, both during the period of operation, but also post-closure. The research focused on the Olteţu open pit (located in Berbesti Mining Basin, Romania) and was directed in such a way as to allow consideration in the stability analyses of natural (predisposing the investigated area to landslides) and anthropogenic (specific to open pit mining) factors and causes as well as their combined effect. The field investigations (observations on the technical condition of the slopes, discussions with the technical personnel from Olteţu open pit, and sampling) were completed with analyses and laboratory tests (physical–mechanical properties of rocks in the composition of the slopes). The stability analyses took into account different hypotheses related to the actual geometry of the working slopes, and a predictive analysis was also carried out for the forecasted evolution of the working fronts and lateral slopes. Following stability analyses, it was found that for most slopes, the stability reserve is insufficient to allow continuing lignite exploitation under safe conditions. The last part of the paper presents the solutions identified by the authors (adoption of new geometries of the working front and lateral slopes) in order to increase the stability reserve to a minimum acceptable level, which would allow the safe continuation of lignite extraction, and, in the end, some practical recommendations are briefly presented.

Keywords: lignite; open pit; slope stability; stability reserve

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1. Introduction

Signing the European Green Deal by Romania, doubled by the National Recovery and Resilience Plan, means the abandonment of coal-based energy production by 2025 (at the latest by 2032, according to the first document), a fact that attracts the closure of the current lignite exploitation perimeters. However, as long as the lignite open pits are in operation, it is necessary to ensure the stability conditions of the work fronts and thus ensure the safety and security of the workplace.

The exploitation of lignite in Romania began in a systematic way in the second half of the last century, coal production having over time a significant weight in the national energy mix. In the last 10 years, the lignite extracted in Oltenia Mining Basin has contributed 15–25% to the total electricity production of Romania [1–4].

The stability of slopes is one of the most important problems that must be solved throughout the life of the open pits. Landslides are phenomena with a high probability of occurrence, even more so in the case of lignite open pits, which operate in predominantly soft rocks (sedimentary rocks and soils), such as clays, sands and marls. The failure and sliding of slopes in an open pit can have more or less serious consequences. Among the consequences of landslides produced over time in lignite open pits are the total or partial damage of machinery (mostly bucket wheel excavators), the degradation or destruction of the nearby habitats involved in the sliding process, the blocking of water courses, the destruction of communication routes, or even the death of people operating the machines or who live in nearby area.

To support the research topic, we mention two large landslides which involved the displacement of important quantities of material by sliding and generated important material losses (destruction of machinery and equipment) and supplementary costs related to the elimination of the effects of these slides: the sliding of the working front of the Alunu open pit in 2019 [5,6] (total destruction of a large-capacity excavator, the loading trolley and the transport lines); and the sliding of the Alunu open pit steps system in 2020 (which led to the cessation of productive activities for more than 2 years). Additionally, several instability phenomena were recorded over time that involved the movement of material from the dumps, from the working slopes or from the natural slopes, damage to households and communication and utility networks, and geostructural changes, mainly as a result of the influence of a complex of factors (geological, hydrogeological, hydrometeorological, climatic and anthropological), among which we mention the following: the sliding occurred on the southern part of the Berbești–Alunu mining perimeter from 2010; about 20 landslides occurred in the Panga mining perimeter (on the northern, southern, or north-eastern parts of the open-pit, and also on the slopes of the external dump) between 2008 and 2016; and the sliding of the West Berbești external dump from 2017 [6,7].

In fact, landslides that affect either the working or final slopes of lignite open pits, or the steps of internal or external dumps, are quite common phenomena (their occurrence and manifestation being signaled all over Europe, for example, in Poland, Czech Republic, Greece, Serbia, Kosovo, Germany, and Spain, but also in other parts of the world), being described in specialized literature (in terms of favoring or triggering factors and causes, unfolding mechanisms, damage caused, and preventive measures for the future) [8–15].

Although the triggers of major landslide can often be technically detected, their prediction and mitigation remain a major challenge, both for practicians and scholars.

The slope angle and height of the slopes are the main geometric elements that can influence their stability/instability [16–25]. Therefore, the design and compliance with the geometry of the in situ and dump slopes are extremely important elements for maintaining their stability both in the exploitation process and in the closing and reclamation phases of the open pits. In addition, the identification and control of the factors that influence the technical condition of the slopes must represent a permanent concern throughout the life of the open pit. The stability of slopes is influenced by numerous factors, which can be grouped into several categories (geological, mechanical, meteorological, etc.) [16–27]. It is difficult to assess the extent to which these factors contribute to triggering a landslide, which is why they must be analyzed and controlled as carefully as possible for each particular situation [25,27–31].

In the conditions where unforeseen sliding phenomena occur, the causes must be analyzed, and proper measures to eliminate them must be taken [29,32–36]. In any situation, monitoring the stability conditions is absolutely necessary, early warning systems being the solution to avoid sliding phenomena that can result in material and human losses [37–43]. Sometimes, the evolution of major landslides can be subdivided into several sliding models, offering the possibility to analyze the evolution, in terms of space and time, of similar ones [44].

Slope stability in mining perimeters is important for the security of the production processes, mining equipment, and especially for workers. The purpose of the stability analyzes is to evaluate the safety factor or to check the stability reserve of a slope and, based on it, to reduce the geotechnical risks that may occur by identifying and implementing the appropriate stabilization measures [17,19,27,28,45].

The specialized literature has been enriched over time with numerous stability analysis methods developed by researchers in the field, among which we mention the following:

- The analysis methods based on the limit equilibrium concept (LEM) [17,18,21–28,34] considers the soil both a load and a resistance factor, being commonly used, as it gives accurate results on an acceptable level.
- The finite element method [21,25,46] is a modern, precise method that can be applied to complex structures. It allows the consideration of hydrological and hydrogeological

conditions, the elements of support and improvement of land, and drainage systems. It does not require the imposition of preliminary assumptions, and it provides indications regarding the evolution of the safety factor and deformations during the entire sliding process.

- Methods based on 3D analyses [47–50] are applied in the case of slopes with complex geometries, variable structure, and partial loading, with a very well-defined breaking mechanism, and assume the addition of the third dimension in the 2D procedures, which leads to an increase in the number of unknowns. Three-dimensional methods are used quite rarely due to the fact that they have limited applicability.
- Probabilistic methods [21,25,51–53] assume, in principle, the probabilistic analysis/processing of the physical and mechanical properties of the rocks and the probabilistic calculations by numerical or analytical methods.
- Different combinations of the above-mentioned methods.

Dynamic programming methods can be used to determine the critical sliding surface and the stability factor and allow the incorporation of aspects such as spatial variability and time decay of the mechanical parameters. The results obtained by this method may differ substantially from those obtained by static models [54,55].

In this paper, slope stability analysis was performed using the limit equilibrium methods (Fellenius, Bishop, Simplified Janbu and Morgenstern–Price), as they offer satisfactory and credible results.

2. Materials and Methods

2.1. Problem Statement

Berbeşti Mining Basin (Figure 1) is localized within the Amaradia-Tărâia interfluve, the basin also bearing this name in the specialized literature. Geographically, the basin is located in the hilly area between Gorj and Vâlcea counties. The high-capacity mining exploitations (open pits) operating in Berbeşti Mining Basin are Olteţu, Alunu, Panga, and West Berbeşti. These exploitations have produced, since the date of commissioning and up to now, a quantity of approximately 90 million tons of lignite, and approximately 550 million cubic meters of waste rocks resulted to obtain this production. The average lignite/overburden ratio, of approximately 1/6.2 t/m^3, is due to the location of these perimeters in a hilly area [56].

Figure 1. Berbeşti Mining Basin [57,58].

For the Olteţu open pit (located in the Alunu exploitation perimeter along with Alunu open pit), part of Govora Electric-Heating Plant (more precisely, the mining division), which is planned to be kept in operation at least until 2025, at the end of 2021, it was considered imperative to conduct a research on the stability of the actual working fronts and lateral slopes, as well as a predictive one, for the 2022 forecasted situation.

The major structural unit of which the lignite deposits in Northern Oltenia are a part is the premontane "Getic Depression", which took over the function of a sedimentation area, evolving as such in the Paleogene and Neogene [59].

The premontane depression, formed during the Laramic movements, subsequently endured a sedimentation process that began in the Paleogene and during which several discontinuities with non-general character were noted. The sedimentary rocks of the Getic Depression belong to the Paleogene–Quaternary interval, and they are kilometers thick [60,61].

The studies carried out between 1985 and 1992 by I. Andreescu, N. Ţicleanu et al. [62–64] led to the division of the Dacian–Romanian deposits into three lithostratigraphic formations (Figure 2). This division represents a local fragmentation of the aforementioned deposits, the Jiu-Motru Formation incorporating the other two, the Berbeşti Formation and the Cîndeşti Formation, with lithostratigraphic differences specific to each area. It can also be noted the comprehensive nature of the formation of Jiu-Motru, which includes both Dacian and Romanian.

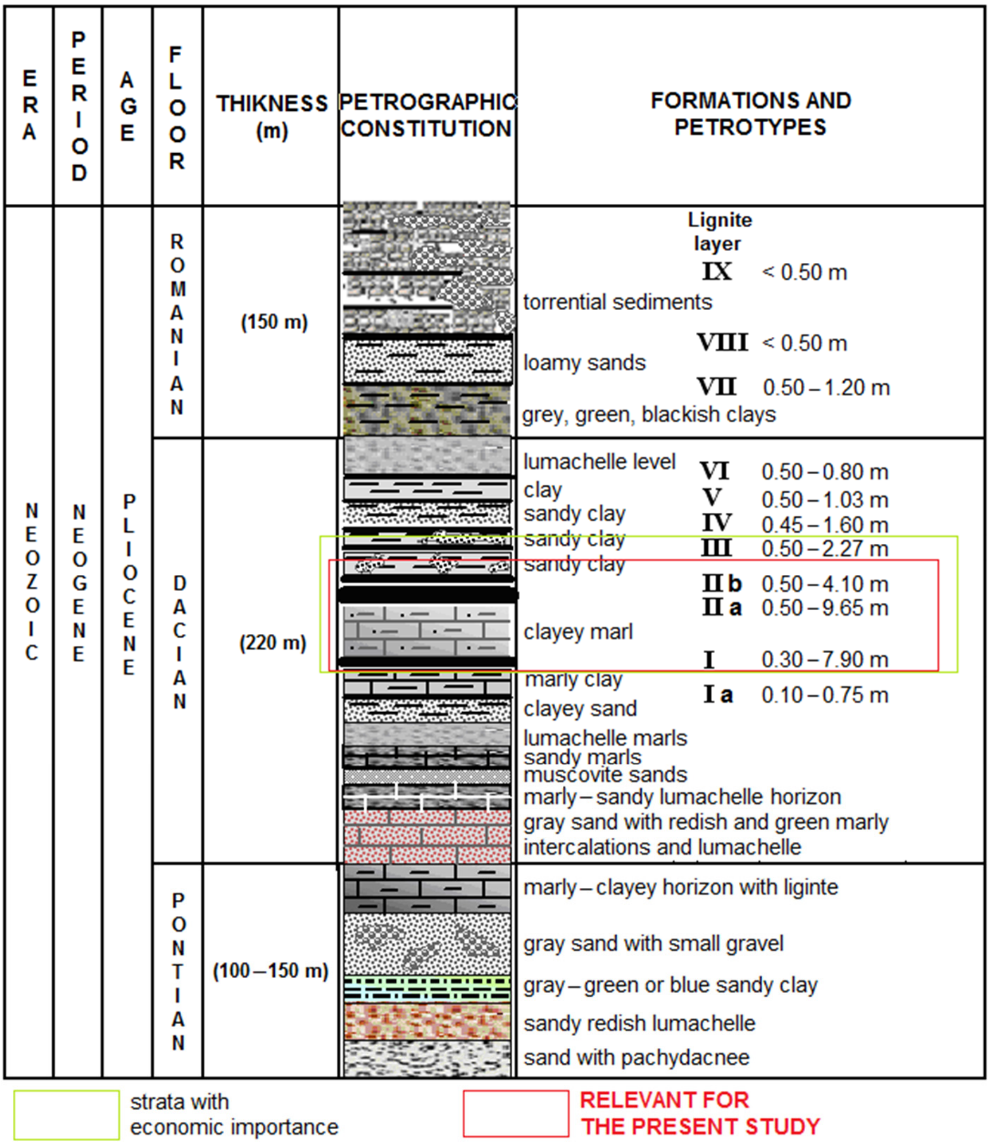


Figure 2. Lithostratigraphy of Berbeşti Mining Basin [61].

The exploitation of lignite in the Oltenia open pits includes a series of activities, such as excavation (mostly carried out in continuous flow with bucket wheel excavators, in working tiers with heights of 25–30 m); the transport of the excavated material (on belt conveyors); the deposition of waste rocks with dumping machines (into internal and external dumps); and the deposition of coal using storage machines.

In the particular case of the Oltețu open pit, at the upper part of the excavation slope, there is a layer of clay that is very unstable, sliding frequently and covering the excavation front (Figure 3).

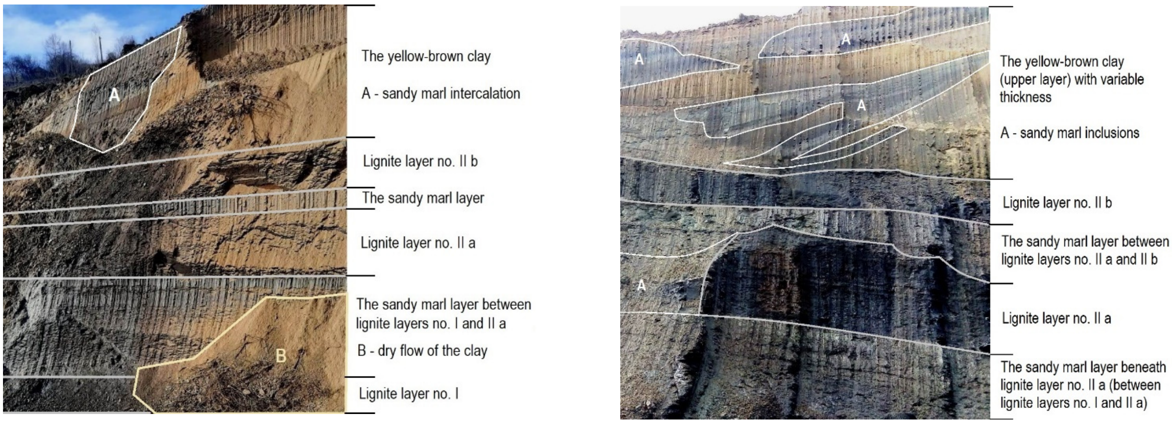
For this reason, there are losses of time and productivity of the machines, which is reflected in the economic efficiency of the mining activity. Moreover, the continuous sliding of the clay layer can cause the lower layers to move as well, triggering a large-scale slide that can put the excavator in danger.

Figure 3. Intense fragmentation and (dry) flows of the clay upper layer.

2.2. Field Observations and Laboratory Tests

The lithological sequence (see Figure 2) found in the structure of the working step in the Olteţu open pit is the one that appears in the Berbeşti mining basin and consists of yellow-brown clay, sandy marl, and lignite. The layers made up of these rocks alternate and have variable thicknesses within the analyzed perimeter (Figure 4).

The main rock types that participate in the structure of sterile intercalations and the overburden of the lignite deposit are found in various proportions: clay 65–72%; dust 13–21%; sand 5–14% [65].



(**a**) (**b**)

Figure 4. (**a**) The alternation of rock layers; (**b**) the discontinuity of rocks with variable thicknesses (the pictures were taken at different moments in time, in different weather conditions and from different distances and angles relative to the working front).

2.2.1. The Yellow-Brown Clay

The yellow-brown clay layer is the first encountered from the surface of the land, and its thickness varies widely, between 5 and 15 m. In the bedding of this horizon, a layer of sandy marl is found.

After performing the grain size analyses, the specific curves were graphically represented and it was found that they have a similar shape, with reduced inclinations, characteristic of very uneven rocks (the resulting non-uniformity coefficient, U, being variable and much higher than 15), with a large diversity of particle diameters. The compaction capacity is increased, as the small particles tend to fill the gaps between the larger ones and, in theory, under these conditions, the porosity should be reduced. However, cracking, disaggregation, and repeated contraction, swelling, and compaction phenomena that affected the rocks overtime led to a relatively high porosity (49–58%). The high porosity allows the accumulation of large volumes of water, which leads to a significant reduction in the cohesion [65].

The meteorological conditions influence the moisture of the yellow-brown clay, which varies widely, respectively its behavior. The determinations showed that the natural humidity of this clayey rock is about 40% in the conditions of a dry period. When the moisture increases, the amount of adsorbed water also increases. When the clayey rock particles are surrounded by water, and they are separated from each other, the flow phenomenon can occur. This situation defines a fluid state when the rock, due to high moisture, has weak cohesion and practically does not resist shear stress. The swelling potential of this clay was observed while determining the flowing limit when, prior to flowing, a sudden swelling of the material occurred. The increase in volume is caused by a change in the state of stress and in turn, produces displacements or landslides. The flow limit corresponds to a moisture value of approximately 69–73%, which confirms the property of clay to adsorb water in large quantities. Thus, the clay can pass from a solid state to a fluid state, leading to the production of large flow–slide phenomena.

With the decrease in moisture (relatively high moisture, but unsaturated state), this type of rock becomes plastic, and its cohesion increases significantly. The lower the moisture, the harder the rock becomes. In these conditions, the yellow-brown clay contracts and cracks, forming fissures of different lengths and depths and favoring rock disaggregation. These characteristics determine the occurrence of cracks and fissures (transverse cracks and fissures being typically observed), causing the detachment of rocks and the appearance of sliding phenomena named "dry flows" (also described as rotational landslides/dry landslides, rock falls or rolling). These types of landslides occur successively and do not involve large volumes of rocks. In this way, the massif is gradually unloaded, the situation being favorable for its stability.

Locally, on the lateral slopes, sandy intercalations were observed. These intercalations have an inclination that concurs with the inclination of the land or the open pit slope, thus representing detachment or sliding surfaces of clayey rocks. The cracks and fissures that appear in dry periods favors water infiltration during rainy periods. Therefore, there are conditions that favor the appearance of negative geotechnical phenomena, regardless of the situation.

Depending on the degree of moisture (saturation coefficient), the yellow-gray clay is classified as very wet to saturated.

According to current standards [66–68] and specialized literature [18,19,21], depending on the value of the plasticity and consistency indexes (Ip higher than 35% and Ic between 0.69 and 0.88), the yellow-brown clay is a clay with very high plasticity and belongs to the class of consistent plastic clayey rocks.

Relying on classifications in the specialized literature [18,19,21], such as the classifications based on grain size composition, the consistency and plasticity index, and the ternary diagram, the classification and description of the rock were made. Thus, it was determined that it is a fat clay (a cohesive soil with relatively low sand, dust, and gravel content, more than 60% clay with a diameter lower than 0.005 mm, with a plasticity index of over 35%). The sand and gravel validate the presence of a sedimentation area.

In conclusion, the analyzed yellow-brown clay presents, due to its characteristics, a risk of sliding in both dry and wet conditions. Slides can occur in various forms/types, from drops, and rolls to flows, depending on the moisture.

According to the studies and observations made over time, the following aspects were found regarding the yellow-brown clay:

- In the case of very low moisture, a gradual discharge of the massif takes place;
- In the case of high moisture, the risk of landslides in which significant volumes of rocks can be entrained increases;
- In the case of difficult conditions, such as a thick yellow-brown clay layer and the unfavorable geometrical elements of the slopes (high slope and large slope angle), the risk of sliding becomes greater, regardless of the moisture of the rocks.

2.2.2. The sandy Marls

In the area of the working fronts, there are three layers of sandy marls located, as follows: in the bed of the first lignite layer (open pit base), in the roof of the first lignite layer (respectively in the bed of the second lignite layer) with variable thickness between 0.3 and 1.5 m, and in the roof of the second lignite layer with a thickness between 3 and 4 m.

After carrying out the grain size analysis, it was found that the sandy marl is composed mostly of sand, dust, some elements of gravel, and clay (5–10%), having an average uniformity.

The natural moisture of the sandy marl varies from 16.93% to 56%, and it influences the behavior and the resistance characteristics in the sense of increasing the shearing resistance with the decreasing of the moisture. In case of high moisture, due to the content of sand and dust, the rock is easily breakable, and in cases of low and very low moisture, the rock is hard, compact, and it has a high cohesion (between 1.38 and 1.72 daN/cm^2) [65].

2.2.3. The Lignite

The first and second lignite layers (I, II a and II b, see Figure 2) represent the main (with economic importance) lignite layers in the Oltețu perimeter by quantity. They are thick and extend over almost the entire mining field.

Within the Oltețu mining perimeter, the first layer varies between 2.3 and 3.2 m thick. Qualitatively and qualitatively, it represents the main layer of lignite [56].

The second lignite layer is complex from a lithological point of view. It consists of two coal banks (layers II a and b) separated by a thin intercalation of sandy marl rocks. The second layer varies from 2.6 to 5 m in thickness [56].

The two lignite layers are separated in the roof and in the bed by sandy marl layers with varying thicknesses.

Generally, the physical–mechanical properties of lignite are favorable in terms of slope stability, but their values also vary as a result of the partially woody structure and clay inclusions.

Field research also led to the following findings:

- The geometric non-uniformity of the excavation fronts is caused by the morphology of the land, as the excavation process is completed in one step. This way of excavation leads to variations of the geometric elements, both on the width and on the depth (expansion) of the working front.
- Phenomena of fragmentation and detachment of the rocks from the slopes in conditions of low moisture and plastic flow tendencies of the clay from the upper part of the step under conditions of its saturation.
- Local manifestation of instability, affecting the entire height of the step, with variable extent depending on the structure of the massif and the hydro-meteorological conditions.
- Under the conditions of the initial geometry (December 2021) of the excavation fronts, the risk of massive landslides, which would involve large volumes of rocks and affect the safety of machinery and personnel, is relatively low.
- Taking into account the terrain morphology, the difficulties of ensuring a relatively uniform geometry of the excavation fronts will be accentuated with their advance.
- In the areas with increased amplitudes (the western part of the perimeter), taking into account the functional technological parameters of the E-02 excavator (ERC 1400-30/7 type) and possible instability phenomena, the design of appropriate exploitation technologies must be imposed so that the geometry of the slopes ensures their stability.

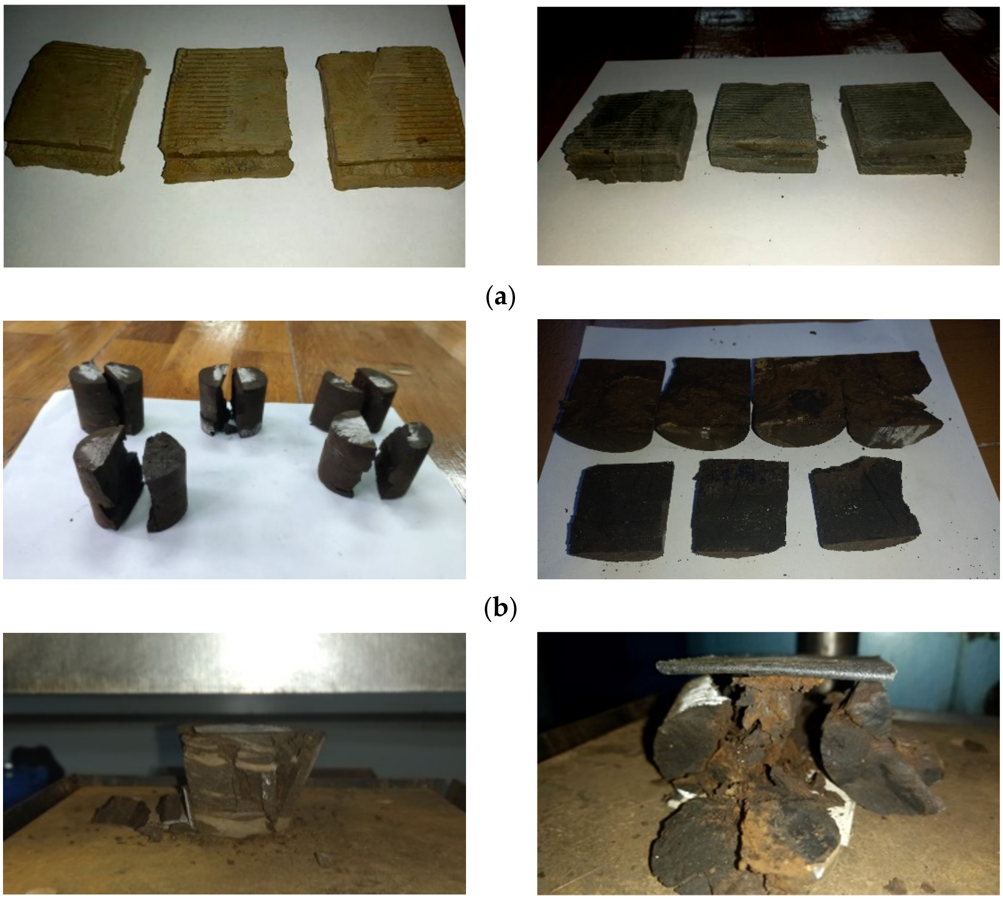
In order to carry out the stability analyses, three sampling campaigns were carried out (22 October; 12 November, and 2 December 2021) from all the rock layers encountered, and the samples were analyzed within the Soil Mechanics Laboratory (LMP) of the University of Petroşani (Figure 5). To verify the results, some tests were demanded from the Călan GeoLogic laboratory, especially for the first layer from the surface, consisting of yellow-brown clay (Table 1).

Following the analyses, it was clear that the yellow-brown clay was the least resistant rock. It has the highest affinity for water, and therefore, the deterioration of these characteristics is likely under unfavorable hydro-meteorological conditions. In this situation, the state of tension in the massif changes, and structural deformations occur. This conclusion is also confirmed by field observations. Stability analyses were performed, taking into account these aspects.

Table 1. Physical–mechanical properties of the rocks.

Type of Rock	Layer Thickness [m]	Values Determined in the Laboratory LMP / GeoLogic Lab. [69]				Values Determined from Documentations [56]		Statistically Determined Values	
		w [%]	$\gamma_{nat}/\gamma_{sat}$ [daN/m^3]	c [daN/cm^2]	φ [°]	c [daN/cm^2]	φ [°]	c [daN/cm^2]	φ [°]
Yellow-brown clay	5–15	46.15 39.66	1845/1920 1782/1825	0.23–0.63 0.33	0–10 11.18	0.22	15	0.31	10
Sandy marl	3–4	22.35 16.13	1850/1970 1911/2000	0.43 1.72	32 22.82	0.32	20.5	0.45	21
Lignite (IInd layer)	2.6–5.0	36.25	1180/1300	0.7 */1.6 **	18 */34 **	0.3/1/1.2	30/19/38	1.1	26.5
Sandy marl	0.3–1.5	22.35 16.13	1850/1970 1911/2000	0.43 1.72	32 22.82	0.32	20.5	0.45	21
Lignit (Ist layer)	2.3–3.2	36.25	1187	0.7 */1.6 **	18 */34 **	0.3	30	1.1	26.5
Sandy marl	-	22.35 16.13	1850/1970 1911/2000	0.43 1.72	32 22.82	0.32	20.5	0.45	21

w—natural moisture; $\gamma_{nat}/\gamma_{sat}$—natural/saturated volumetric weight; c—cohesion; φ—internal friction angle.
* Determined by shearing strength. ** Determined based on tensile and compressive strengths.



(**a**)

(**b**)

(**c**)

Figure 5. Laboratory tests: (**a**) direct shearing tests on yellow-brown clay and sandy marl; (**b**) shearing tests on lignite (mandatory planes); (**c**) uniaxial compression and traction (Brazilian method) on lignite [65].

3. Results and Discussion

As shown in the introduction, there are a number of factors that influence the stability of slopes. For the case study analyzed in the paper, the main factors that can be considered are the hydrostatic pressure generated by the water from rock pores, seismic shocks (the analyzed area being characterized by a seismic intensity of 8/MSK scale, the average return period being about half a century [70]) and the vibrations generated by machines.

Following the in situ documentation, it was found that the vibrations transmitted mainly by the E-02 excavator to the slope, under the conditions where the yellow-brown clay layer was at natural moisture (approximately 40%, after a period without of significant precipitations) favored its fragmentation and the appearance of "dry flow" type slides (rolling, falling of "lumps" of clay) characterized as rotational and successive slides. These types of slides involve small volumes of rocks, gradually unloading the massif, so the mining activity can continue under relatively safe and satisfactory conditions.

It is difficult to appreciate the influence of the vibrations on slope stability in conditions of high moisture of the rocks (mainly clayey rocks) when such simulations cannot be carried out in the laboratory [65].

The authors considered that the vibrations produced by the heavy tonnage machines (excavators) are much lower in intensity and amplitude compared to those originating from natural earthquakes such that they cannot trigger liquefaction-type slides or slides caused by the thixotropic behavior of the material.

The maximum value for the seismic acceleration in the studied area is a = 0.2 g, the return period of the earthquake is over 2 centuries (about 225 years according to [70]), and the exceeding probability is low. Knowing these and the fact that the vibrations contribute to a small degree to triggering a major landslide, in the performed stability analyses, the seismic acceleration was considered to be a = 0.1 g.

3.1. Analysis of the Stability of In Situ Slopes

The stability analyses were carried out in seven sections, including two longitudinal (L1 and L2) and five cross (P0, P1, P2, P4 and P5), and in each section, the position of the working fronts was taken into account at the level of December 2021 and quarters I-IV of 2022, which led to the analysis of 13 geotechnical profiles, drawn on the situation plan with the projection of the open-pit evolution (Figure 6). The stability analyses for the lateral slopes were performed only in the case of the slopes located on the southwest side, as slopes on the north-eastern side have heights that do not exceed 15 m, so they do not raise stability problems.

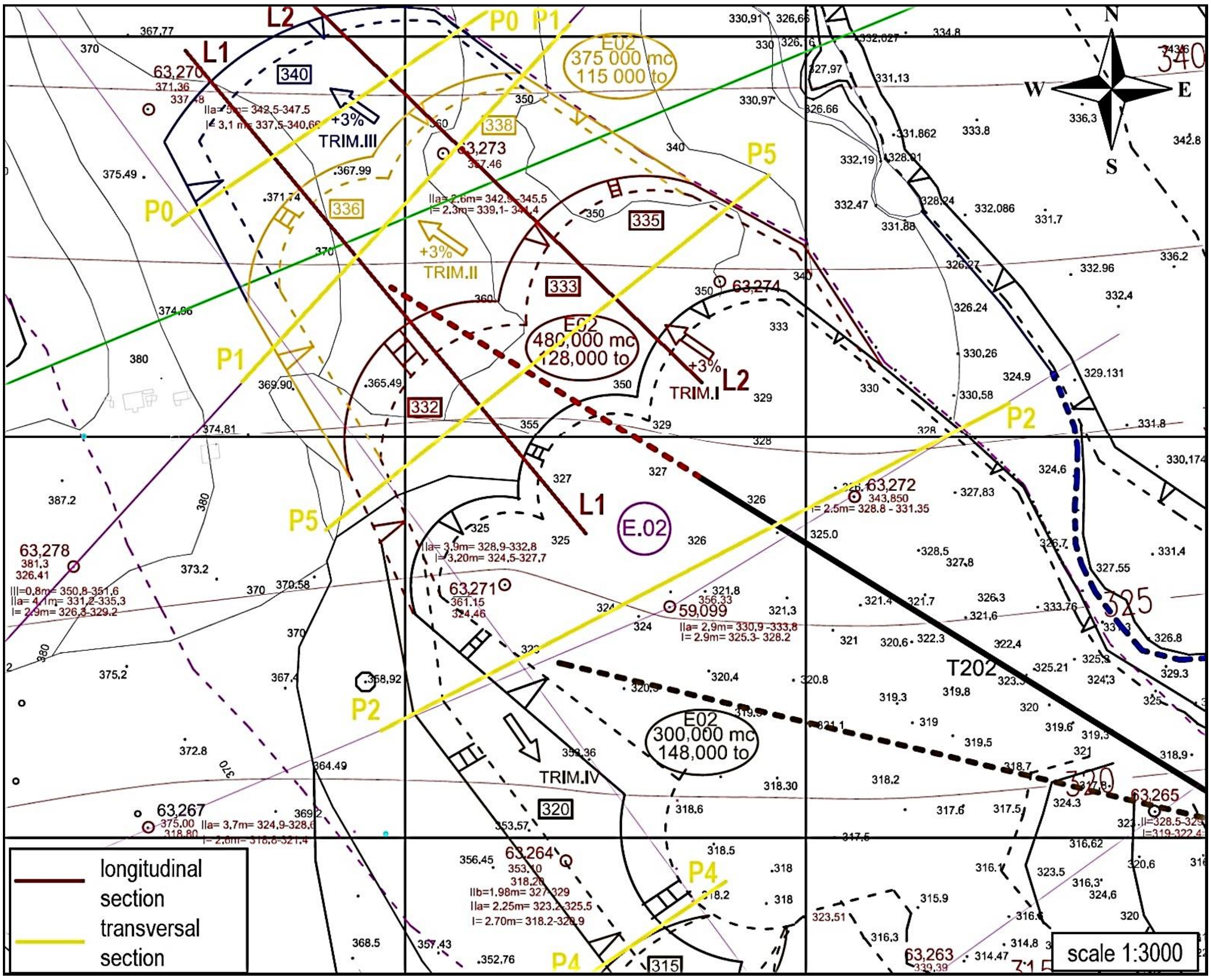


Figure 6. Evolution of Olteţu open pit and the longitudinal and cross sections [56].

The cases of lateral slopes in sections P0, P1, and P5 were analyzed from the perspective of ascending slopes, considering that their height increases and substantial changes in the geometry of the steps are required. We mention that, at the request of the research team, the mining operator made available eight sections L1, L2, P0–P5, essential for the development of the stability study. Of the provided sections, the P3 cross section was not used, being outside the interest area.

The stability calculations were carried out in three variants, respectively:

- Drained slopes, unaffected by external factors (F_{s1});
- Undrained slopes, where pore water pressure can induce landslides (F_{s2});
- Undrained slopes and under the influence of seismic shocks, caused by the vibrations generated by the excavator and conveyor belts and/or the occurrence of an earthquake (F_{s3}).

The results of the stability analyses are presented in Table 2 for the working front slopes in sections L1 and L2, and for lateral sections P2 and P4 (it is planned that in the IV quarter of 2022, the E02 excavator will be withdrawn in the approximately same position as December 2021, and the excavation will be carried out in the lateral slope, corresponding to cross sections P2 and P4, thus becoming the working front) taking into account the advance of the open pit, in Table **??**, for the lateral slopes, P0, P1, and P5 (in accordance with the semester in which they materialize) and in Figures 7–10.

Table 2. Results of stability analyses for working fronts (sections L1, L2, P2, and P4).

Section	Stage	Height h [m]	Slope Angle α [°]	Thickness of the Yellow-Brown Clay Layer [m]	Stability Factor			Observations on the Transmission Mode of the Potential Slide Surface
					F_{s1}	F_{s2}	F_{s3}	
L1	December 2021	23	65	10	1.01	0.81	0.71	Sliding through layers of clay and very little sandy marl
	I quarter	28.5	56	13	0.98	0.79	0.67	Sliding through layer of clay
	II quarter	31.3	70	14	0.74	0.59	0.53	Sliding through layers of clay and sandy marl
	III quarter	28	61	9.5	1.05	0.84	0.73	Sliding through layers of clay and sandy marl
L2	December 2021	26	47	7	1.22	0.98	0.81	The potential sliding surface is transmitted over the entire height of the step exits in front of the foot of the slope
	I quarter	21	64	11	0.91	0.73	0.71	Sliding through layers of clay and sandy marl
	II quarter	20	64	10	1.12	0.90	0.79	Sliding through layers of clay and sandy marl
	III quarter	18	46	10	1.54	1.23	1.08	The potential sliding surface is transmitted over the entire height of the step and exits in front of the foot of the slope
P2	IV quarter	27	69	13.5	0.80	0.64	0.56	Sliding through the clay layer and very little through the sandy marl
P4	IV quarter	22	57	10	1.01	0.81	0.70	Sliding through the clay layer, very little through the sandy marl, tangent to the layer no. II of lignite
Section	Stage	Height h [m]	Slope Angle α [°]	Thickness of the Yellow-Brown Clay Layer [m]	Stability Factor			Observations on the Transmission Mode of the Potential Slide Surface
					F_{s1}	F_{s2}	F_{s3}	
P5	I quarter	40	61	18	0.65	0.52	0.45	Sliding through layers of clay and sandy marl
P1	II quarter	41	63	28	0.52	0.42	0.36	Sliding through the clay layer and very little through the sandy marl
P0	III quarter	38	48	25.5	0.67	0.53	0.44	Sliding through layer of clay

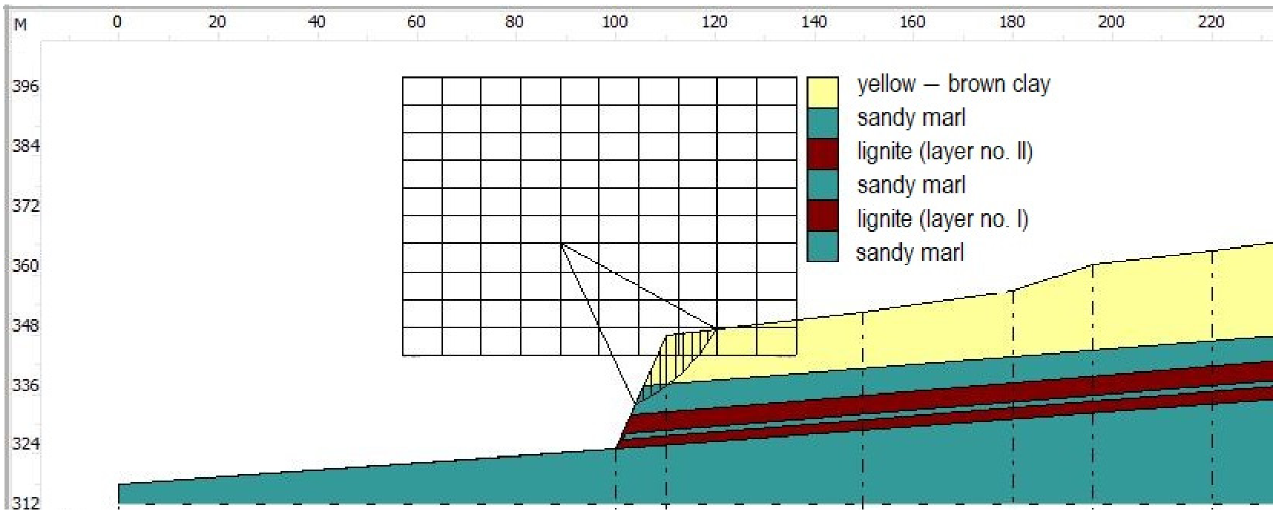


Figure 7. Section L1, F_{s1} = 1.01 (December 2021).

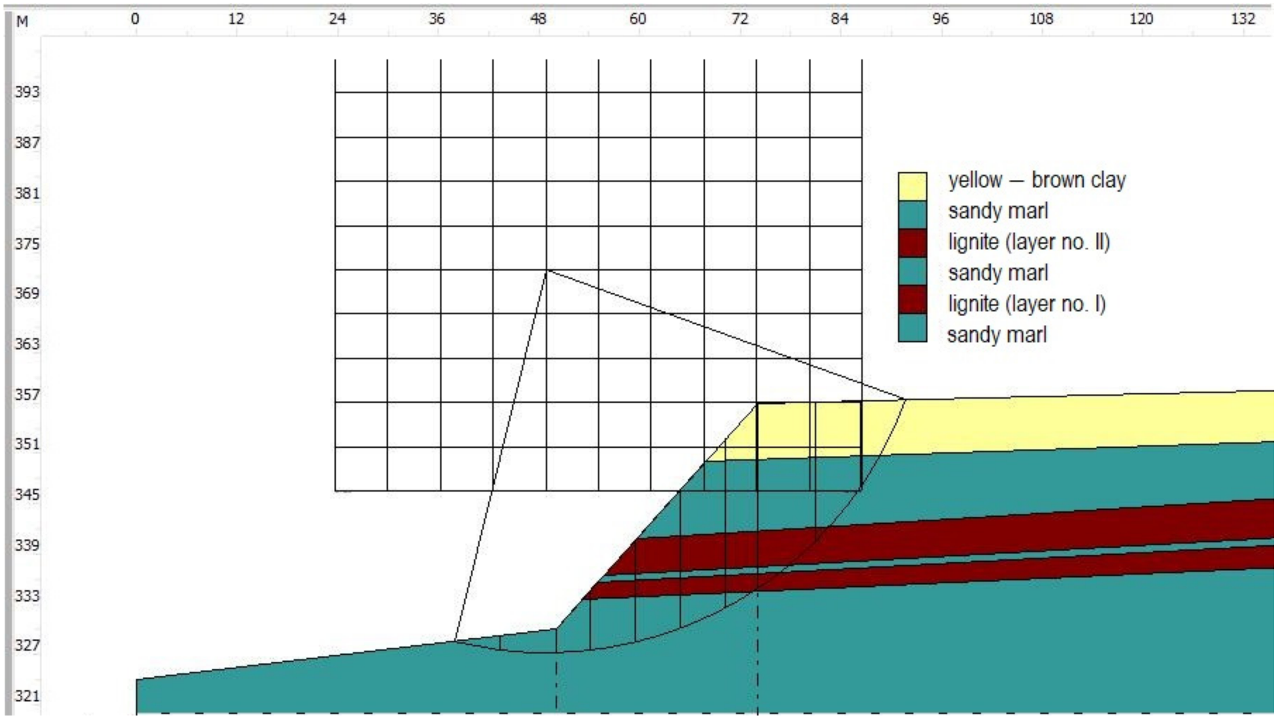


Figure 8. Section L2, F_{s1} = 1.22 (December 2021).

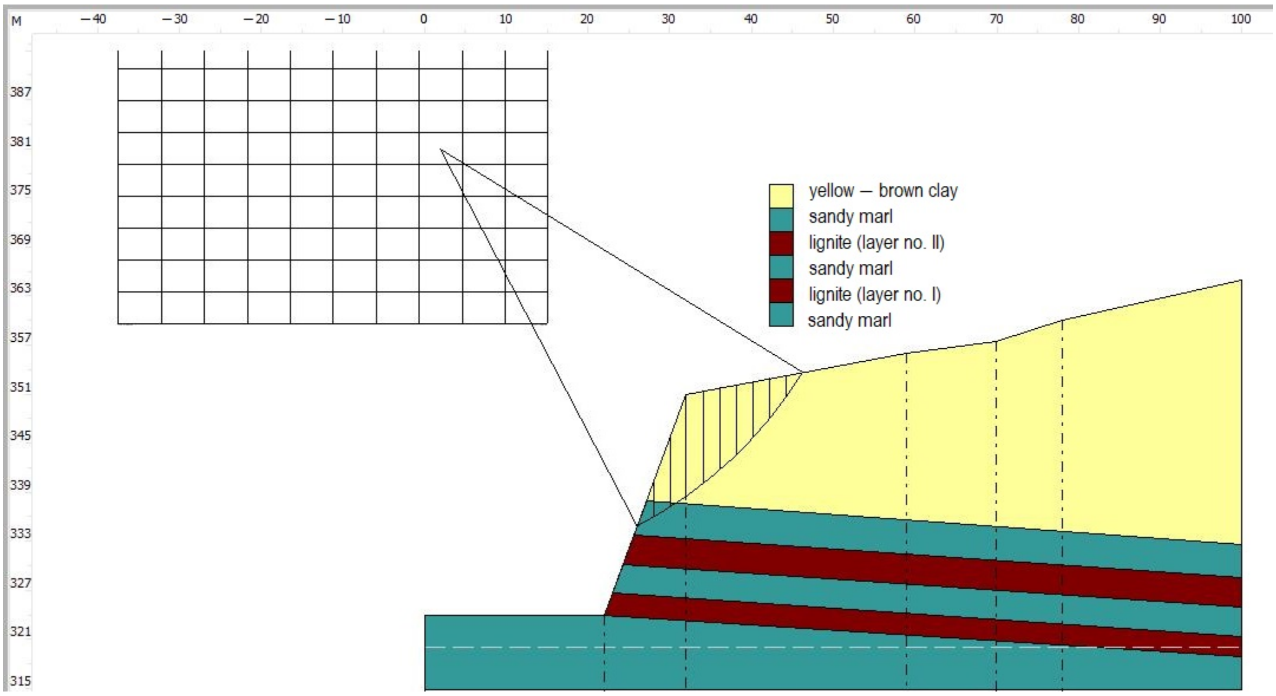


Figure 9. Section P2, IV quarter, F_{s1} = 0.80.

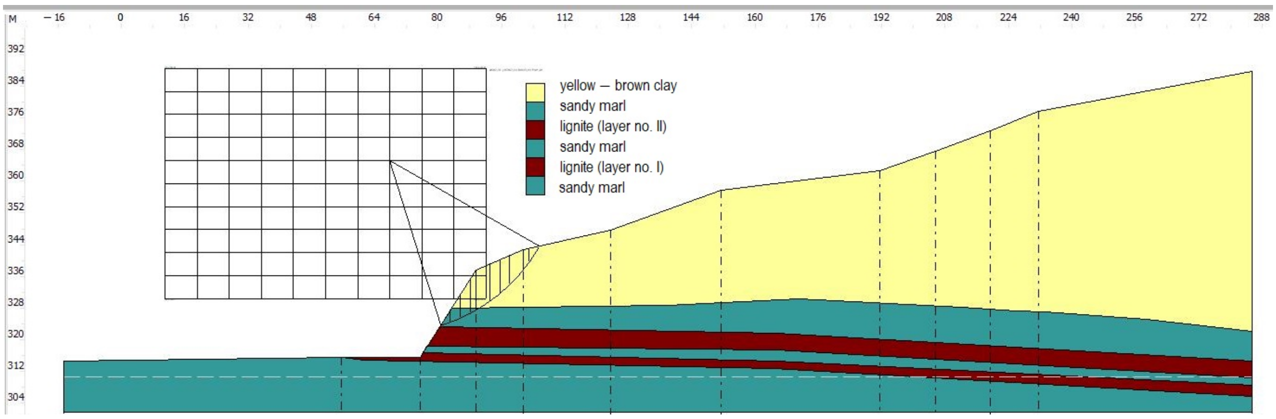


Figure 10. Section P4, IV quarter, F_{s1} = 1.01.

The stability analyses were performed using the SLOPE software, a software specialized in geotechnical problems, considering that a possible landslide can occur along a curved sliding surface.

This software performs stability analyses based on limit equilibrium theory (LEM), the safety factor, or the stability coefficient being given by the ratio between the sum of the moments of the resistance forces and the sum of the moments of the forces generating the slide. For this purpose, based on the recommendations of the literature [17,18,21,34], the methods of Fellenius, Bishop, Simplified Janbu and Morgenstern–Price were used. The values presented in Table 2 and **??** are the lower ones as determined for each section and quarter.

As a result of carrying out the stability analyses, the following conclusions can be drawn:

- The stability analyses were performed for the initial conditions of the slopes only in the L1 (December 2021) and L2 (December 2021) sections, using the stratigraphic columns provided by the mining operator, and confirm the situation observed during the field investigations. Thus, in the area of L1 section, for the configuration of the slope from

December 2021, instability phenomena of the clay and marl layers were manifested. The stability analysis carried out led to a value of 1.01 for the stability factor under conditions of no external stress on the slope (limit equilibrium state) and to sub-unit values for the case where pore water pressure and/or the effect of vibrations were manifested. The slope in L2 section was stable in December 2021, and the analyses performed indicate a stability reserve of 22% under no external stress, equilibrium limit under the conditions of the manifestation of pore water pressure, and instability under the conditions of the simultaneous effect of water and vibrations (shocks).

- The other sections, namely cross sections P0–P2, P4 and P5, present the hypothetical position of the lateral slopes at the end of the four quarters of 2022 (as they materialize).
- The stability factor depends on the height, inclination, and structure of the slope, a significant influence on the physical state (static and dynamic) coming from the weight of the clay layer in the structure of the slope. As for the sliding surface, in conditions where the thickness of the clay layer on the upper part exceeds 9–10 m, it is transmitted only through this layer and, as a rule, the stability coefficient is sub-unitary, indicating clay instability phenomena. Under the conditions of a clay layer of less thickness, the sliding surface is transmitted either through the layers of clay and sandy marl or through the entire step.
- Stability is ensured for slopes between 18 and 26 m high, and slope angles of up to 60°, in conditions of no external stress. For all other cases, namely the presence of water and seismic shocks (except for the slope in section L2, III quarter), the stability factor is sub-unitary or approaches the equilibrium limit.

Considering the advancement of work fronts in areas with an ascending slope, in most cases, it is necessary to build a system of steps, which can ensure, on the one hand, the technical possibility of excavation (considering the fact that the theoretical excavation height of the ERC 1400-30/7 bucket wheel excavator is of maximum 30 m), and on the other hand, maintaining stability conditions. Such situations are recorded in the case of cross-sections P5, P1 and P0, corresponding to the stage of the excavation works in the I, II, and III quarters of 2022, where the distance between the bed of the first lignite layer (open-pit base) and the surface of the land is 40, 41, and, respectively, 38 m. For these cases, the stability of the designed (forecasted) slopes (with the geometry resulting from the provided sections) was analyzed, and the general conclusion is that such slopes would be unstable in all the three calculation hypotheses of the stability factor.

3.2. Determination of the Stable Geometry of the Working Front and Lateral Slopes

To ensure the stability conditions of the slopes, several geometries of the working steps and the lateral slopes were analyzed, determining their height and inclination for an imposed value of the stability factor.

In order not to affect in an unjustified manner the excavator's efficiency indicators, the dimensioning took into account the fact that the working slopes have a short lifetime, so a stability reserve of 5–10% can be considered sufficient, and in the case of side slopes, which remain in place from a few months up to a year, a stability reserve of 20–25% was considered sufficient.

3.2.1. Stable Geometry of Working Slopes

For this case, section L1 was taken into account (Figure 11), and the following values of geometrical elements were established in order to ensure a stability reserve of 5%:

- H = 25 m;
- $\alpha = 52°$;
- Yellow-brown clay layer thickness: 9 m;
- $F_{s1} = 1.05$.

The thickness of the yellow-brown clay layer is lower than 10 m (the maximum allowed height), so it is not necessary to create sub-steps in this case.

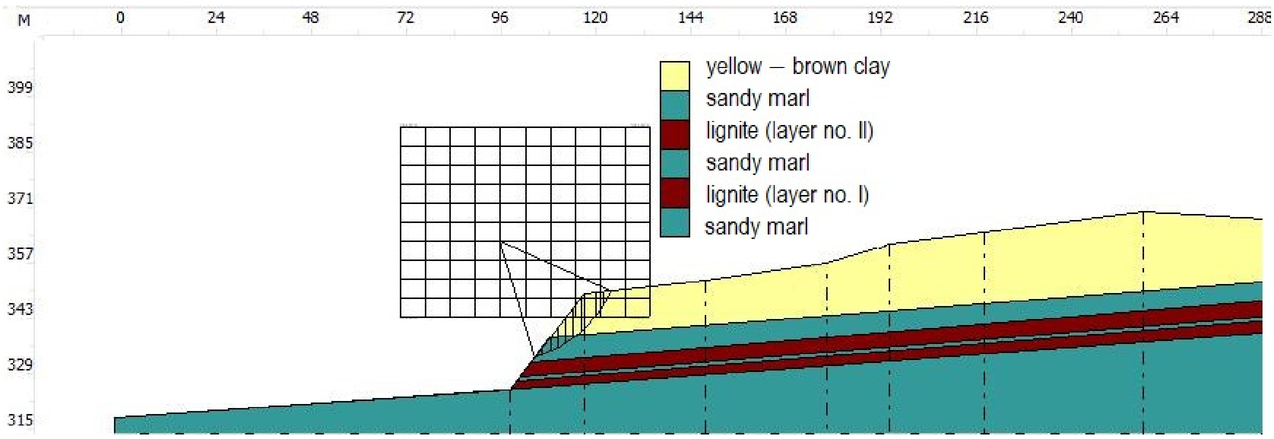


Figure 11. Section L1–Stability analysis for the proposed design.

3.2.2. Stable Geometry of Lateral Slopes

For this case, section P1 was taken into account, where the thickness of the rock package between the lignite layer no. I bed (elevations +345 to +334 m above sea level) and the land surface (elevations +350 to 380 m above sea level) records maximum values, respectively, 41–46 m at a distance of 70–90 m from the outcrop area of the lignite layers.

In these conditions, it is necessary to adopt a technology of excavation in steps and sub-steps to ensure stability conditions.

The first step (from the base of the open pit) up to +370 m surface level should be of maximum 26 m (crossing the lignite layers, the sandy marl between and above the lignite layers and the yellow-brown clay at the top on maximum thickness of 7.6 m).

The second step, up to +380 m surface level, will be excavated exclusively in the yellow-brown clay layer, and will have a maximum height of 10 m.

When the yellow-brown clay layer exceeds 10 m thickness (above the elevation of +380 m surface level), it is necessary to divide the second (upper) step into sub-steps so as not to exceed the maximum allowed height of 10 m. The upper sub-step will have a variable thickness, between 3 and 10 m, as the excavation advances toward the planned configuration (in the final stage, the slope will be divided in two steps, one of 26 m (the lower one) in height and one of 20 m (the upper one) divided in two sub steps of 10 m in height each).

a. Lower step with lignite layers (Figure 12):

- H = 26 m;
- $\alpha = 55°$;
- Yellow-brown clay layer thickness: 7.6 m;
- $F_{s1} = 1.25$.

b. Upper step and sub-steps in yellow-brown clay (Figure 13):

- Height of sub-steps H = 10 m;
- The height of the sub-step system (upper step) $H_{gen} = 20$ m;
- The width of the intermediate berm B = 60 m;
- The width of the safety berm b = 30 m;
- Inclination of sub-steps slopes $\alpha_{ind} = 45°$;
- General inclination of slope $\alpha_{gen} = 25°$;
- The stability factor for sub-steps $F_{s1ind} = 1.15$;
- The stability factor for general slope (sub-step system) $F_{s1gen} = 1.26$.

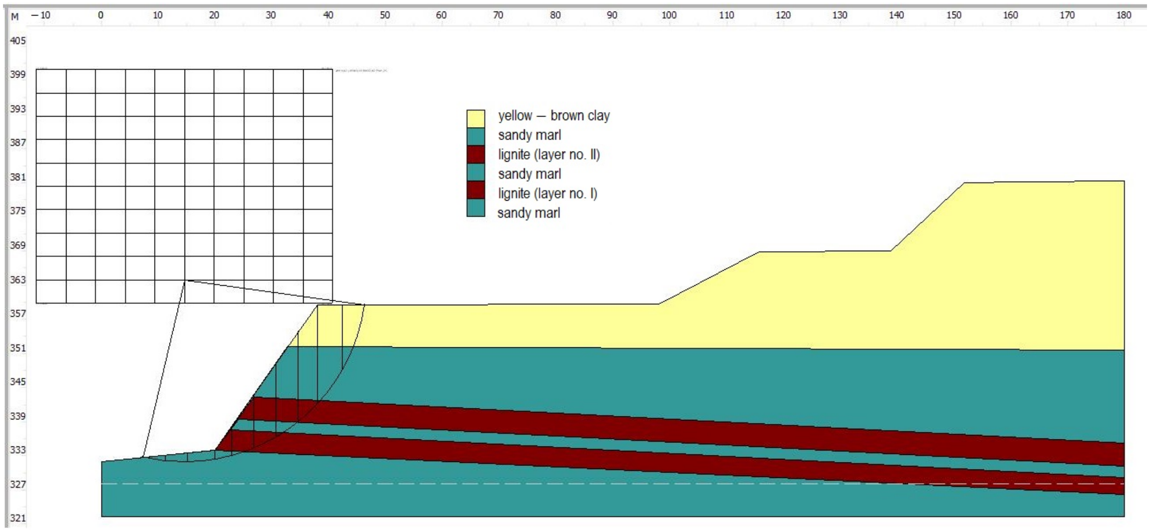


Figure 12. Section P1—Stability analysis of the lower excavation step.

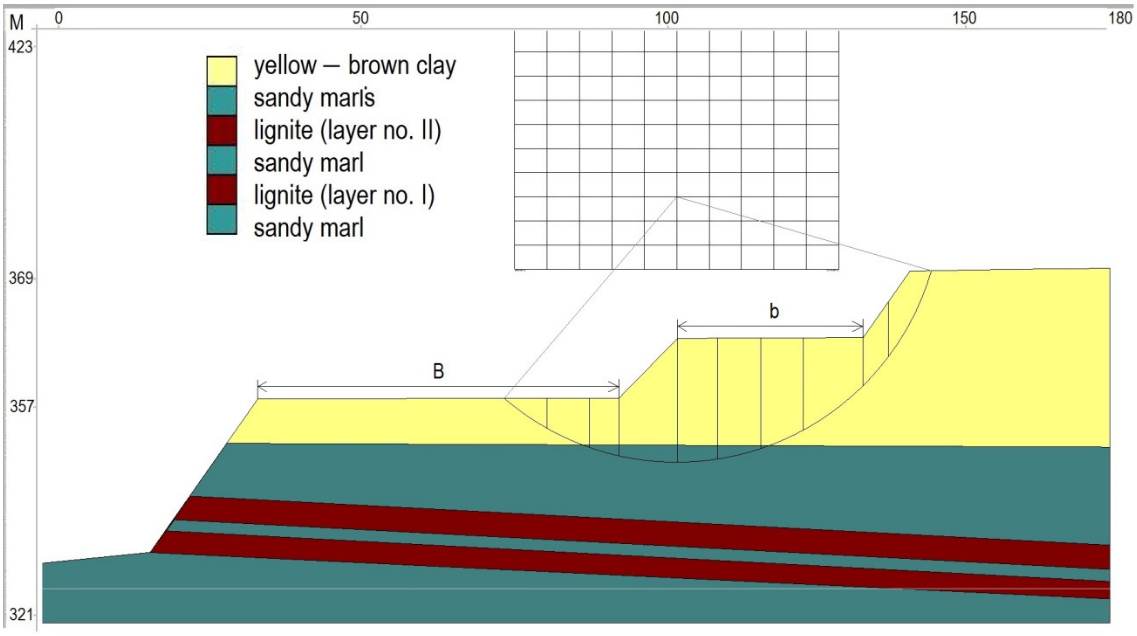


Figure 13. Section P1—Stability analysis of the sub-steps system (excavated in yellow-brown clay).

3.3. Recommendations for Ensuring the Stability Reserve

1. Framing the excavation fronts in the geometric parameters that ensure the necessary stability reserve, depending on the type and lifetime of the slopes, according to the elements resulting from the determination of the stable geometry.
2. Preliminary uncovering (stripping) of areas with pronounced non-uniformity of the land morphology, thus ensuring the geometry of the slopes in conditions of stability.
3. Taking into account the tendency of the yellow-brown clay layer to disaggregate and the possibility of plastic failure, manifested by phenomena of "flow" on the slope both in a dry state as well as in the wet state, the maximum thickness in the structure of the excavation steps must be of maximum 10 m.
4. A permanent monitoring of the deformation phenomena of the front and lateral slopes (cracks and fissures, subsidence or swelling areas, and other signs that reflect changes in the state of tension in the massif).
5. Detailing the geological structure from the advance of the open pit, either by recovering the data of the initial exploration drillings or by executing new drillings that

provide more precise information regarding the stratigraphy, tectonics, and hydrogeology of the area.

4. Conclusions

As a result of this research, the following observations were made regarding the characteristics and behavior of rocks:

- The lignite layers in the perimeter of the Oltețu quarry are buried in sedimentary formations, being intercalated by clayey and marly rock layers;
- According to the grain size analyses, these rocks contain variable amounts of sand (generally fine sand), dust, and gravel;
- The geometry of the working fronts is uneven, being conditioned by the geomorphology of the region;
- The variation of the physical and mechanical properties of rocks is accentuated and highly influenced by the water content (moisture);
- The mechanical characteristics (cohesion and internal friction angle) decrease with increasing moisture, being dependent on hydro-meteorological conditions;
- The great variety of physical–mechanical characteristics required statistical processing and the selection of values considered representative for the stability analyzes;
- Considering the reduced resistance characteristics and the plastic behavior of the yellow-brown clay, the first layer from the land surface, it can be stated that it determines the occurrence of instability phenomena, such as sliding, disaggregation, dry flow, and plastic failure, regardless of the rock moisture;
- The stratigraphy is variable and not known precisely until the time of excavation (relatively small number of prospecting drillings on the advancement direction).

The stability analyses were carried out for the areas of interest of the mining operator, respectively, for the forecasted slopes in 2022 according to the preliminary production plan. The results of the analyses show that the most unfavorable stability conditions occur in the case of front structures where the clay layer at the top of the slopes exceeds 10 m in thickness. In the presence of other disturbing factors (precipitation, vibrations, and seismic shocks), in most cases, large-scale instability phenomena can be triggered.

It is recommended to provide slope angles of maximum 52° and step heights of 25–26 m for front slopes. In the case of the lateral slopes, in order to ensure the reserve of stability of the step configured in the clay layer, it is necessary to divide it into sub-steps of 10 m each, and to reduce the slope angle to the value of 45°, resulting in a general slope angle of 25°.

By studying the behavior of the rocks that appear in the geometry of the working and final slopes depending on the thickness of the layers, their location in the lithological structure, and the existing meteorological conditions allowed the authors to draw some general conclusions regarding the necessary measures that must be taken in order to safely continue the lignite extraction activity in Oltețu open pit.

However, as the general geology (in particular the lithological structure), as well as other natural and anthropogenic factors, is similar throughout the entire Berbești Mining Basin, these results can provide valuable information to mining developers and engineers operating the other three open pits on how to deal with the top layer of clay so as to avoid unwanted events (large landslides capable of producing significant economic or even human losses).

The present paper has the merit of addressing a geotechnical phenomenon in the mining perimeters of Oltenia that was not particularly taken into account in the stage of designing the geometry of the open-pit slopes, namely the dry or wet flow of the yellow clay from the upper part of the open pit. Such flows generate changes in the state of stresses and strains and can lead to the triggering of slope failure along the entire height. Thus, detailed laboratory studies were carried out and, following stability analyses, the main failure mechanisms were defined. Based on the results obtained, it was proposed to modify the geometry of the working steps and implicitly the excavation technology, so that the lignite exploitation can be carried out in safe conditions, even if the lithological structure of the slope is less known. The results obtained are valuable both for mining specialists (the risk of slope failure will be greatly reduced), but also for students who are preparing in the field of mining and geotechnics (by including these results in the academic training process).

An interesting, and at the same time challenging, direction of continuing this research is represented by the introduction within the existing models of structural weakening coefficients of the massifs, when we are dealing with rocks with a behavior similar to that of the yellow-brown clay described in this paper, or even introducing this type of behavior into dynamic simulations.

Therefore, the paper makes a definite contribution to mining practice (especially the extraction by surface mining techniques of coal deposits, confined in sedimentary formations, weakly cohesive and prone to alteration and modification of resistance characteristics under the influence of external factors, mainly hydro-meteorological), but it also serves as a useful study material and starting point for improving existing software and stability models.

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