Assessment of the Stability State and the Risk of Landslides within Berbești Mining Basin (Romania) Post Closure

Florin FAUR1), Maria LAZĂR2), Izabela-Maria APOSTU3), Constantin RADA4), Daniel MOISUC-HOJDA5)

1) Lecturer Dr. Eng.; University of Petroșani, Faculty of Mining, Department of Environmental Engineering and Geology; email: florinfaur@upet.ro

2) Prof. Dr. Eng.; University of Petroșani, Faculty of Mining, Department of Environmental Engineering and Geology; email: marialazar@upet.ro

3) Assist. Dr. Eng.; University of Petroșani, Faculty of Mining, Department of Environmental Engineering and Geology; email: izabelaapostu@upet.ro

4) PhD Stud. Eng.; University of Petroșani, Faculty of Mining, Department of Environmental Engineering and Geology; email: constantin.rada1965@gmail.com

5) Lecturer Dr. Eng.; University of Petroșani, Faculty of Mining, Department of Mining Engineering, Surveying and Constructions; email: daniel.hojda@gmail.com

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Abstract

Berbești mining basin, located in the area of the Getic Subcarpathians, is part of the Central Heating Power Plant (CHPP) Govora, in fact representing the mining division, and has four open pits: Alunu, Olteț, Panga, and West Berbești.

Given that, at least in Europe, there is the issue of giving up energy production based on the burning of fossil fuels, especially coal, the four open pits will be in operation for a relatively short period of time, and one of the major problems related to the exploitation of lignite deposits is that of the post-closure stability of the lands in the influence area.

The research was conducted in such a way as to take into account in the stability analysis the factors and natural causes that predispose the lands in the Getic Subcarpathians to landslides, factors and anthropogenic causes (lignite mining) and the effect of their concomitant action.

These stability analyzes took into account different hypotheses related to the geometry of the final slopes and the influence of external factors. Also, a predictive analysis of the long-term stability of the lands (especially the final slopes of the open pits – as they were designed) was carried out, taking into account the behavior over time of the disturbed rocks. Based on the results obtained, after a series of statistical processing, a risk analysis was performed, using a methodology developed by a part of the research team.

It should be noted from the outset that the research focused on the West Berbești and Panga mining perimeters, as the lignite mining activity will be completed by the end of 2022 (at most).

However, taking into account the similar conditions (geology, morphology, tectonics, seismic zoning, weather and climatic conditions, applied exploitation methods), the research team considers that a significant part of the conclusions and recommendations contained in this study can be considered valid and for the rest of the active perimeters (Alunu and Olteț open pits).

In this context, the study ends with a series of conclusions on the stability of land in the Berbești mining basin (West Berbești and Panga perimeters) at the time of cessation of productive activities and recommendations that once put into practice will ensure long-term land stability.

Keywords: *Berbești mining basin, CHPP Govora, lignite, open pit, sliding risk, stability*

1. Introduction (short presentation of Berbești mining basin)

Berbești mining basin is geographically located in the Getic Plateau, along the parallel of 45º north latitude, at the confluence of Gorj and Vâlcea counties, being bounded on the west by the Gilort river, and on the east by the Bistrița river (Dican, 2011).

Berbești mining basin has a length of over 45 km and an inclined development of 2.5–5 km. The lignite deposit was divided into four mining perimeters: Gilort-Amaradia, Amaradia-Tărâia, Tărâia-Cernișoara, and Cernișoara-Bistrița. Within each mining perimeter, several mining fields have been outlined, these being the object of exploitation of some underground mines (closed at present) and open pits. Access to the mining perimeters can be done both by car and by rail (Fodor and Dican, 2013).

The geological formations present in the Berbești mining basin are made up of rocks belonging to the Pliocene and Quaternary, the Pliocene having the greatest development, being represented by: Pontian, Dacian, and Romanian (fig. 1).

The coal (productive) horizon is located in the Upper Dacian (Parscovian) and has a thickness that decreases, from south to north, from 150 to 60 m. Lithologically, it consists of a complex of sands, clays and marls, in which six layers of lignite numbered from I to VI are interspersed (fig. 1), found both in the drillings and in the outcrops from the northern part of the exploitation perimeters (Dican, 2014; Chiriță, 2019).

The transition from the Upper Dacian to the Romanian is delimited by the presence of a lumachelle level with a thick-

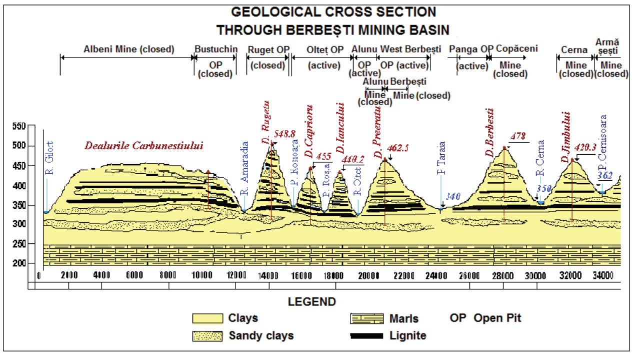


Fig. 1. Longitudinal geological section through the Berbeşti mining basin (Dican, 2014)

Rys. 1. Podłużny przekrój geologiczny przez zagłębie górnicze Berbeşti (Dican, 2014)

Tab. 1. Open pits and waste dumps within Berbeşti mining basin (Chiriţă, 2019)

Tab. 1. Odkrywki i hałdy odpadów w obrębie zagłębia górniczego Berbeşti (Chiriţă, 2019)

Open pit	Waste dump	Occupied surface [ha]		Stored volume [mil. m³]		Status
		2018	Designed	2018	Designed	
Alunu perimeter (2 open pits: Alunu and Olteţ)	Interior	198	490.5	47.5	210	Active
West Berbeşti	Interior	129	188	21.1	76.8	Active
Panga	Interior	99.5	171	53.5	95.5	Active

Tab. 2. Physico-mechanical properties of slope rocks

Tab. 2. Właściwości fizyko-mechaniczne skał zboczowych

Rock type	Volumetric weight, γ_v [daN/m³]	Cohesion, c [daN/cm²]	Internal friction angle, φ [°]
Yellow-brown clay	1843	0.31	10
Sandy marl	1933	0.45	21
Lignite	1187	1.10	26.5

ness of 1.5–2 m. The Romanian is represented by an alternation of gray, gray-green, or yellowish clayey sands, sometimes with reddish areas, of varied granulation, with torrential sedimentation and gray, green, or blackish clays, between which are interspersed 2–3 thin layers of lignite numbered VII, VIII, and IX (fig. 1) (Fodor and Dican, 2013).

After cessation of mining activity and the closure of the open pits, they become remaining gaps, thus changing the morphology of the region, and by the accumulation of rain and/or groundwater forms puddles, swamps, or open pit lakes that can increase the risk associated with land instability.

The waste dumps, generally positive forms of anthropogenic relief, are made up of heterogeneous rocks devoid of trophic substances necessary for plant growth and development and therefore cannot be considered soils. Due to their heterogeneity and relatively high degree of loosening are often prone to landslides.

Table 1 shows the centralized situation of the active open pits and waste dumps belonging to the Berbeşti mining basin.

Next, the open pits in which mining economic activities are currently carried out in the Berbeşti mining basin, respectively: Alunu, Olteţ, West Berbeşti and Panga, as well as the active waste dumps, are briefly presented.

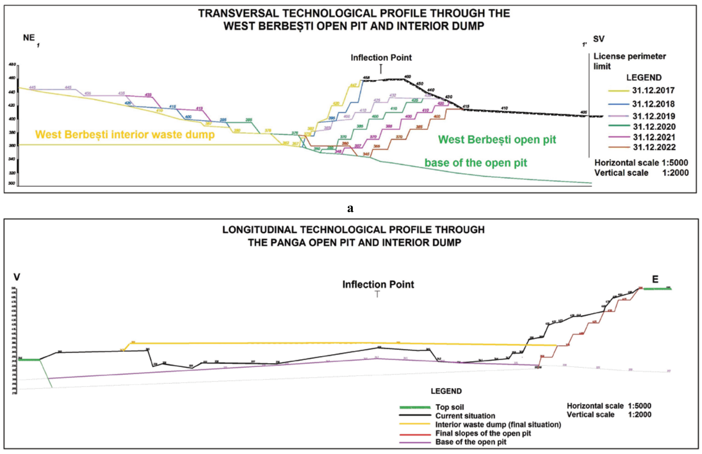
1.1 Open pits

The Alunu, Olteţ, West Berbeşti, and Panga open pits are located in the western part of Vâlcea County. The currently mined lignite seams are no. I (with a maximum thickness of over 5 m), no. II and sporadically no. III (in Panga open pit). The operating method is "the method of transporting the overburden to the internal dump and partial transhipment", and the technology used is "the technology of excavation, transport and dumping in continuous flux" (***, 2021).

1.2 Interior waste dumps

They are located in the excavated area of the open pits, having the shape and dimensions of the foundation corresponding to the base of the open pit.

- Alunu interior waste dump – has the foundation in the form of a monocline with E-W direction and N-S inclination, between 3–5°, being made up of marly-clayey rocks with coal intercalations, the clayey rocks being represented by a gray to blackish greasy clay, plastic, with low compressibility (***, 2021);
- West Berbeşti interior waste dump - has a stable foundation consisting of gray marls with coal inclusions, with a general slope of 4–5° from north to south. Most of the first step of the dump was built by direct deposition of the waste rocks from the overburden (***, 2021);
- Panga interior waste dump - has a stable foundation consisting of gray marls with coal inclusions, with a general slope of 4–5° from east to west on half of the extension and an identical slope, of 4–5°, but inclined from west to east, on the other half. Most of the first step of the dump was built by direct deposition (transhipment) (***, 2021).



a

b

Fig. 2. Longitudinal sections through the open pits: a – Berbeşti West; b – Panga (***, 2021)
Rys. 2. Przekroje podłużne przez odkrywki: a – Berbeşti West; b – Panga (***, 2021)

2. Stability analysis of the designed slopes

2.1 Conditions for performing stability analyzes

As we have mentioned since the introduction, the stability analyzes for the designed situation at the end of the activity (end of 2022), refers to 2 open pits out of the four active in the Berbeşti mining basin (West Berbeşti and Panga). For the Alunu and Olteţ open pits, it is expected that the lignite mining activity will continue until 2025 (at least).

In order to perform stability studies and determine the geometry of the steps that ensure the long-term stability of the slopes (post-closure), the following were completed:

- Study of documentation (***, 2019; ***, 2021) (description of the deposit, geotechnical drillings, situation plans, longitudinal and cross sections, stratigraphic columns);
- Sampling campaigns of overburden rocks and lignite from open pits slopes and dumps. Following the field trips some findings were made: geometric non-uniformity of the excavation fronts caused by the morphology of the terrain; phenomena of fragmentation and detachment of rocks from slopes in conditions of low humidity and tendencies of plastic flow of clay from the top of the step in conditions of saturation; local slides affecting the stability of the whole step, with variable magnitude depending on the structure of the massif and the hydrometeorological conditions; given the current geometry (December 2021) of the excavation fronts, the risk of massive landslides, involving large volumes of rocks and affecting the safety of equipment and personnel is relatively low; the difficulties in ensuring a relatively uniform geometry of the excavation fronts will be accentuated as they advance (taking into account the morphology of the terrain); it will be necessary to design appropriate operating technologies so that the geometry of the slopes will ensure their stability;
- Discussions with the representatives of CHPP Govora, regarding the working technologies, the projected works for the year 2022, problems of stability of the working slopes and of the lateral slopes encountered so far;
- The slopes of the open pits in the Berbeşti mining basin are essentially made up of clayey, marly, and sandy rocks and different combinations of them. Based on the sections from the documentation (***, 2021), and completed with field observations, the lithological sequence is as follows: a layer of yellow-brown clay, with a thickness between 5–15 m; a layer of sandy marl with a thickness between 3–4 m; layer no. II of lignite with a thickness between 2.6–5 m; an intercalation of sandy marl between the layers of lignite, with a thickness between 0.3–1.5 m; the no. I layer of lignite with a thickness between 2.3–3.2 m (maximum 5 m in Panga open pit, respectively 5.4 m in West Berbeşti open pit); a layer of sandy marl that represents the bed of the first layer of lignite;
- Carrying out laboratory tests on samples taken from the field and determining the physical and mechanical characteristics of the rocks;
- Collaboration with another specialized laboratory to confirm the results and expand the database for statistical processing;
- Analysis, comparison and statistical processing of data obtained in laboratories and those obtained from technical documentation.

Stability analyzes were performed using the Slide geotechnical software, in which the calculation sections were modeled.

2.2 Stability analysis results for the designed final slopes

Table 2 shows the physical-mechanical characteristics of the rocks in the structure of the analyzed steps (resulted from statistical processing) used in stability calculations.

The situation of the final slopes of the two open pits (West Berbeşti and Panga) and of the Berbeşti interior dump, as it was designed at the end of 2022, is presented in figure 2.

As can be seen from the two longitudinal sections, the final slopes designed for the two open pits have a uniform geometry (steps with a height of 10 or 15 m and slope angles of 63° and 41° for West Berbeşti open pit and steps with 25 m high and 54° slope angles for Panga open pit).

Interior waste dumps:

- In the case of the West Berbeşti dump – its steps, 6 in number, were designed with heights between 10 and

Tab. 3. Results of the stability analysis for the final slopes (designed)

Tab. 3. Wyniki analizy stateczności zboczy końcowych (projektowych)

Slope	**Geometry**		**Rock type**	**F_{S1} (Fellenius)**	**F_{S2} (Bishop)**	**F_{S3} (Janbu)**	**F_{S4} (M-P)**
	H (m)	**α (°)**					
T1 West Berbeşti	10	63	Yellow-brown clays	1.101	1.114	1.149	1.151
			Strata (6 m clay/4 m marl)	1.540	1.547	1.548	1.548
T2 West Berbeşti	15	41	Yellow-brown clays	1.073	1.103	1.081	1.100
			Strata (11 m clay/4 m marl)	1.351	1.377	1.356	1.375
T3 Panga	25	54	Yellow-brown clays	0.658	0.664	0.666	0.667
			Strata (21 m clay/4 m marl)	0.930	0.933	0.938	0.946

20 m, some of them having a maximum horizontal inclination of 5° towards the base of the open pit. It should be noted that, under the designed conditions, a remaining gap will result, located between the final steps of the interior dump and those of the open pit, with a variable depth, and which will most likely be filled with water;

- In the case of Panga interior dump, the designed situation at the end of the activity shows that it will be twinned with the final steps of the open pit. This will be done by pushing the dumped material with bulldozers, after withdrawing the mining equipment from the work fronts, towards the final steps of the open pit. In this way, the formation of a remnant gap is avoided and any problems related to its filling with water are prevented.

2.2.1. Stability analyzes for the final steps of the open pits

Given the designed situations at the end of the activity and those presented in the previous paragraph (related to the degree of knowledge of stratigraphy and the stratigraphic structure adopted in the stability analysis of working slopes), for the final slopes of the two open pits stability analyzes were performed for the following situations:

- slopes made entirely of yellow-brown clays;
- slopes composed partly of sandy marls (4 m) and partly of yellow-brown clays.

The heights considered for the final steps are 10, 15, and 25 m, according to the sections made on the designed situation plans, and the values of the physical-mechanical characteristics are those presented in table 2.

The results of these analyzes, performed by means of four procedures (Fellenius, Bishop simplified, Janbu simplified, and Morgenstern-Price) recommended by the literature (Hoek and Bray, 1981; Marinescu, 1988; Rotunjanu, 2005; Lazăr and Faur, 2015), are presented in table 3 and figure 3.

In the case of final slopes made exclusively of yellow-brown clays, even in conditions of lower slope angles, the minimum values determined for the stability factor (by Fellenius' procedure) indicate that the stability reserve is of 10% for slopes with a height of 10 m, respectively 7.3% for slopes with a height of 15 m and a sub-unit one for slopes with a height of 25 m (slopes below the equilibrium limit). In other words, we are dealing with either unstable slopes or close to the equilibrium limit, which is why, in order to ensure long-term stability, a resizing is required. This resizing is presented in Chapter 3.

For the steps excavated in both the clay and the marl layers, for the slopes with heights of 10 and 15 m, the values of the stability factor indicate stability reserves of 35 and 54%. These stability reserves can be considered as covering, but, as will be presented in the rest of the paper, when we talk about long-term stability, even these values cannot be considered sufficient.

In the case of slopes with a height of 25 m, the minimum value determined (by the Fellenius procedure) is subunit, ie the slopes are below the equilibrium limit (landslides can occur).

Another aspect is related to the position of the sliding surfaces in the case of slopes made of yellow-brown clays and sandy marls, with heights of 15 and 25 m. Thus in these situations, as can be seen in figure 3.d, the surfaces of minimum resistance materialize only through the layer of yellow-brown clay. This observation leads us to keep in mind that, depending on the angle of the slope, the height of the steps excavated in clays can not exceed 9-12 m, or if the designed height of the steps is maintained, it will be necessary to reduce the final slope angles.

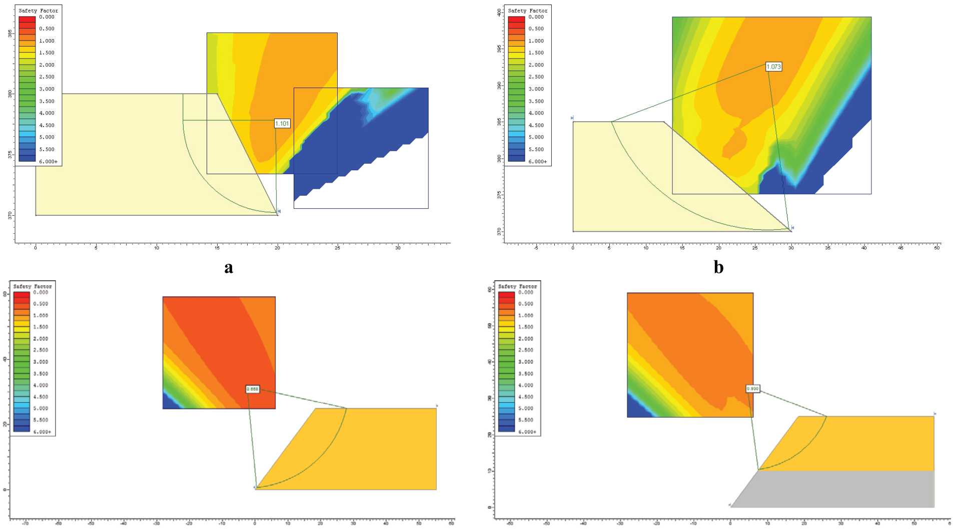
2.2.2. Stability analyzes for the final steps of Berbeşti West interior dump

The stability analyzes were performed for each of the 6 steps designed in conditions of natural humidity of the stored rocks, and because it is very probable that a water accumulation will form in the remaining gap, this hypothesis was also taken into account. Basically, in this case, the first step of the dump becomes submerged and the material saturated.

The physical-mechanical characteristics of the dumped material were taken from a geotechnical study made available to the research team by the representatives of CHPP Govora (***, 2021) (table 4). This study aimed to determine the load-bearing capacity of the rocks in the base of the open pits, in the conditions of the expansion of the dump areas. In order to determine the effective pressure exerted by dumps, geotechnical drilling was performed through the dump's body and the average characteristics of the deposited heterogeneous mixture were determined.

In the case of the steps of the West Berbeşti interior dump, following the stability analyzes, it can be concluded that they have a sufficient stability reserve. Therefore, given the medium-term stability, all the steps analyzed can be considered stable, and in the case of the need to ensure long-term stability, ie Fs > 2, four of them (Tr1, Tr2, Tr3, and Tr5) require a resizing (Chapter 3).

In the conditions in which the first step is submerged, and in the body of the dump the pore pressure is manifested, a stability factor of 2,448 is obtained, superior to the one obtained under normal conditions (with the material at natural humidity and without the presence of water accumulation in the remaining gap).



a b c d

Fig. 3. Stability analyzes for slopes of: a – 10 m made of clays; b – 15 m made of clays; c – 25 m made of clays; d – 25 m made up of clays and sandy marls
Rys. 3. Analizy stateczności skarp: a – 10 m wykonanych z iłów; b – 15 m z gliny; c – 25 m z gliny; d – 25 m zbudowane z iłów i piaszczystych margli

This result is in accordance with the theory that, under the conditions of submerged slopes, the water exerts a hydrostatic pressure on the slope behaving like a supporting prism (Rotunjanu, 2005; Lazăr and Faur, 2015) and is sustained by the results of previous studies published by the research team in specialized journals (Lazăr et al., 2019; Apostu et al., 2021).

However, as previous studies (Lazăr et al., 2019; Apostu et al., 2021) have shown, during the filling of the remaining gap with water, especially if the flooding occurs exclusively by natural means, due to the relatively long time required to raise the water level, the rocks initially unsaturated in the dump are in contact with water for a longer period. These conditions allow the rapid saturation of the rocks and the increase of the hydrostatic level in the body of the dump (due to the capillary pores that allow the water to rise in the body of the dump), without being counteracted by the hydrostatic pressure exerted on the slopes by the water in the lake. Such a situation leads to an initial decrease in the stability factor, increasing the risk of negative geomechanical phenomena, such as landslides or liquefaction of the deposited material.

The period in which this decrease in the stability factor is observed is limited in time, and can be counteracted by accelerating the rate of filling the remaining gap with water. This acceleration can be achieved through adductions (Lazăr et al., 2019). The flooding process itself and the behavior of the dump during this period must be monitored, at least through observations, so that it can be intervened if there are signs of loss of stability (superficial landslides, plastic flows, abnormal settlements, tension cracks, etc.).

3. Determining the stable geometry of the slopes

The recommended value of the stability factor depends on the designed operating life of the slopes. In this regard, the following values are recommended (Rotunjanu, 2005):

- Fs = 1.1-1.2 - for short periods of existence, up to 1 year;
- Fs = 1.2-1.5 - for average periods of existence, up to 20 years;
- Fs = 1.5-2 - for long periods of existence, over 20 years;
- Fs = 3 - for very long periods of existence, of the order of centuries.

An important role in the formation and development of landslides is played by the rheological behavior of the rocks, materialized under two essential aspects: the slow flow (creep) of the lands in time, respectively their long-term resistance, which is reduced in time in close relation with deformation (Marinescu, 1988).

Slope slides can be defined as three-phase rheological processes (Todorescu, 1986):

- slow flow, characterized by successive local failures and the formation of the sliding surface, which can last as long as there is no movement in the slope;
- the actual slide, respectively a very large displacement in a very short time;
- stabilized slide, which is characterized by small displacements and local landslides.

In general, it is found that under the condition that only structural cohesion is considered to be maintained over time, taking into account Maslov's second criterion (Maslov, 1977; 1984) and the thixotropic behavior of clay rocks, the stability coefficient is reduced by about 25%.

Because the waste dumps are made up of loose rocks (at least immediately after cessation of mining activity) and store large volumes of waste rocks and their slides endanger all objectives in their influence area, to ensure long-term stability, we took into account a stability coefficient, also recommended by the literature (Rotunjanu, 2005), of 2. This is a covering value even in the conditions of the deterioration in time of the resistance characteristics.

For the final slopes of the open pits, where the rocks are close to the natural state of the massif, we considered that a value of 1.8 of the stability coefficient is sufficient.

In these conditions, to determine the stable geometry we used the grapho-analytical procedure of E. Hoek (Hoek and Bray, 1981) which proved its viability in many cases of stability analysis and design of the geometric elements of slopes.

Tab. 4. Physico-mechanical properties of rocks

Tab. 4. Fizyko-mechaniczne właściwości skał

Rock type	Volumetric weight, γ_v [daN/m^3]	Cohesion, c [daN/cm^2]	Internal friction angle, φ [°]
Mixture of dumped rocks	1827	0.21	21.6
Foundation (sandy marls)	1933	0.45	21

Tab. 5. Stability analyzes of dump steps

Tab. 5. Analizy stateczności stopni zrzutowych

Slope	Geometry		Rock type	F_{S1} (Fellenius)	F_{S2} (Bishop)	F_{S3} (Janbu)	F_{S4} (M-P)
	H (m)	α (°)					
Tr1	13.50	27	Mixture of dumped rocks	1.623	1.719	1.656	1.715
Tr2	15.00	45		1.294	1.375	1.311	1.373
Tr3	16.50	29		1.884	2.142	1.895	2.142
Tr4	16.00	28		2.413	2.772	2.413	2.772
Tr5	16.33	31		1.953	2.214	1.971	2.215
Tr6	10,00	18		2.311	2.588	2.385	2.586
Tr1 submerged	13.50	27		2.448	2.600	2.516	2.598

The hypothesis on which this procedure is based is that the landslide of the dump slopes occurs after a circular surface.

Starting from the factors influencing the stability of the slopes, Hoek graphically shows the correlations that exist between the functions “X” (of the slope angle, α) and “Y” (of the slope height, H), in correlation with the geotechnical characteristics of the rocks (γv, c, φ) and the slope safety or stability factor. The functions X and Y have the expressions (Hoek and Bray, 1981): $X = \alpha - 1{,}2 \cdot \varphi$; $Y = \gamma v \cdot H / c$.

To obtain a required value for the stability coefficient Fs = 2 for the steps of the interior dump and Fs = 1.8 for the final slopes of the open pits, the resizing procedure can follow either the determination of the angle of the slope for given heights or the determination of the maximum height of the slope for given slope angles.

In this regard, the geometric elements were determined to ensure a stability reserve appropriate to the situation in which the designed heights is maintained (achieved), with the help of the graph and calculation relations being determined the allowable slope angles.

For different heights H - of the slope and the geotechnical characteristics of the deposited rocks, the function Y is calculated, and from the points of intersection of its value with the curve of the stability coefficient Fs = 1.8, respectively 2, the value of the function X of the slope angle α is obtained on the abscissa axis, from which its size is determined.

The values of the physical and geotechnical characteristics considered in the calculations are those in tables 2 and 4, and for the slopes formed by the combination of clay + sandy marl, the weighted average values were calculated. The results obtained are shown in table 6.

Based on these data, it results that in the conditions of the designed heights of the final slopes of West Berbeşti Vest and Panga open pits, respectively of West Berbeşti interior dump, in order to ensure the imposed stability reserve, it is recommended in all cases to reduce the existing (initially designed) slope angles.

It can be seen that the lowest values of the calculated slope angle (necessary to ensure long-term stability), while maintaining the designed height of the steps, are those for the final steps of the open pits, excavated exclusively in clay, with h = 25 m (designed for Panga open pit) and with h = 15 m (part of the steps designed for West Berbeşti open pit).

A reduced value of the permissible slope angle (12.11°) under the imposed conditions is also obtained for slopes partially excavated in clay and sandy marl, also for slopes with a height of 25 m (designed for the Panga open pit).

In these conditions, it is recommended to adopt the solution with the division of the final steps of the open pits (those of 15 and 25 m excavated exclusively in clays and those of 25 m excavated in clays and sandy marls) in substeps, in which those excavated in clays do not exceed 10 m in hight. Such an approach would make it possible to achieve slope angles with values between 21.5° and 24°. These slope angles can be obtained by using for the final modeling of some classic excavators (power shovel).

For the final steps with a height of 10 m (part of the steps designed for the West Berbeşti open pit) a reduction of the slope angle from 63° to 24° is required, for the slopes excavated exclusively in clays, and from 41° to 33.28°, for slopes excavated in clay and sandy marls. The final modeling can also be done with the help of classic excavators.

In the case of the steps of the interior dump, which require a resizing (Tr1-Tr3 and Tr5), the slope angles necessary to achieve long-term stability (while maintaining the designed heights) are between 20° and 23.42°. These angles can be achieved a little easier than in the case of the open pits steps, and bulldozers can be used for the final modeling. This backdrop operation with bulldozers is facilitated by the condition of the deposited material (loose condition), and can be performed in the most advantageous variant, ie by pushing the material from top to bottom.

It is mentioned that these slope angles are well below the value of the natural slope angle of the deposited rocks, α0 = 35° ÷ 37° (***, 2021).

4. Determination of the sliding risk for different assumptions

4.1 Working methodology

Sliding risk assessment analysis is required in particular in conditions of instability of the final slopes. The risk is defined as the product of the probability of landslides and the vulnerability of existing anthropogenic and natural objectives in the influence area of the landslide R = V x Pr (where: R – landslide risk; V – vulnerability – vulnerability of objec-

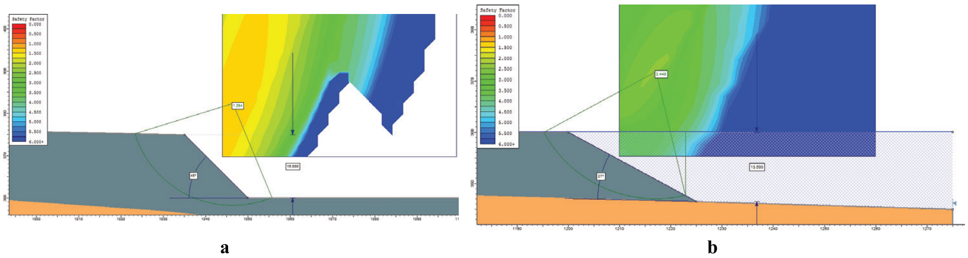


Fig. 4. Stability analyzes for the West Berbeşti interior dump: a – Tr2 (Fs1 = 1,294); b – Tr1 in the conditions of flooding of the remaining gap (submerged) (Fs1 = 2,448)

Rys. 4. Analizy stateczności składowiska wewnętrznego West Berbeşti: a – Tr2 (Fs1 = 1,294); b – Tr1 w warunkach zalania pozostałej luki (zanurzony) (Fs1 = 2448)

Tab. 6. Results of slope angle resizing calculations

Tab . 6. Wyniki obliczeń zmiany wielkości kąta nachylenia

Slope	**Height (designed), H, [m]**	**Slope angle (determined), α, [°]**
Final slopes of open pits excavated exclusively in clays (Fs=1.8)		
T1	10	24
T2	15	17
T3	25	9
Final slopes of open pits excavated part in clays and part in sandy-marls (Fs=1.8)		
T1	10	33.28
T2	15	21.56
T3	25	12.11
Final slopes of West Berbeşti interior dump (Fs=2)		
Tr1	13.50	23.42
Tr2	15.00	20.92
Tr3	16.50	20.42
Tr5	16.33	20.02

tives in the area depending on the technical condition of the slopes; Pr – sliding probability) (Lazăr et al., 2015; Apostu et al., 2021).

In order to evaluate the risk of landslides in the different hypotheses considered in this study, we used a methodology developed by part of the members of the research team (Lazăr et al., 2015), verified in the completion of master and doctoral thesis, as well as in other scientific articles (Apostu et al., 2021).

Thus, within the methodology, in a first stage, a classification of rock massifs/deposits was elaborated according to the nature of the objectives located in the area of influence and the characteristics of the environment. Based on this, the vulnerability classes of the objectives in the area were established according to the technical condition of the in situ and waste dumps slopes (table 7).

According to the 2015 study (Lazăr et al., 2015), based on complex statistical processing, the probability of landslides was determined, after which a graph was constructed showing the dependence between the stability coefficient determined after the analyzes and the sliding probability (fig. 5).

In the present study, this graph was used to determine the probability of sliding, the stability coefficient being known for the situations analyzed in the previous chapter.

Based on existing models in the literature (US ACE, 1997; Gibson, 2011), the following scale has been established for defining the sliding probability:

- Pr = 1 for the range 0 ÷ 15% → very low sliding probability; the slope will almost certainly not slide;
- Pr = 2 for the range 15 ÷ 35% → reduced sliding probability; the slope is unlikely to slide;
- Pr = 3 for the interval 35 ÷ 65% → average sliding probability; whether or not the balance is lost is equally likely;
- Pr = 4 for the interval 65 ÷ 85% → high sliding probability; it is very likely that the slope will slide;
- Pr = 5 for the range > 85% → very high probability of sliding; the slope will almost certainly slide.

Following the scale for defining the sliding probability, each step (of the open pits and interior waste dump) was given the appropriate score. With the help of the calculation relationship, the risk of sliding is determined for the final slopes (initially designed and after resizing the slope angle) of the West Berbeşti and Panga open pits, respectively of the West Berbeşti interior dump.

Considering the 5 classes of vulnerability, respectively 5 classes of probability, for the evaluation of the sliding risk the following scale was established (Lazăr et al., 2015): R = 1 → very low sliding risk; R = 2 ÷ 4 → low risk of sliding; R = 5 ÷ 9 → average risk of sliding; R = 10 ÷ 15 → high risk of sliding; R = 16 ÷ 24 → very high risk of sliding; R = 25 → extreme sliding risk.

4.2 Slide risk assessment

The first stage to be completed involves the inclusion of natural and anthropogenic objectives in the influence area of the two open pits and the interior dump in one of the 5 categories contained in table 7.

For this classification, we used the satellite images presented in figure 6, supplemented with those found during field visits and details of the situation plans.

According to table 7 and figure 6, we classified open pits, as well as the interior dump (post-closure) in the vulnerability categories (table 8).

For the open pits slopes, taking into account the stability analyzes and field observations, it was considered that we are dealing with "rock masses that can enter in dangerous move-

Tab. 7. Vulnerability of rock masses/deposits according to the nature of the objectives in the area of influence [modified after (Lazăr et al., 2015)]
Tab. 7. Wrażliwość mas skalnych/złóż w zależności od charakteru celów w obszarze oddziaływania zmodyfikowana za [Lazăr et al., 2015]

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

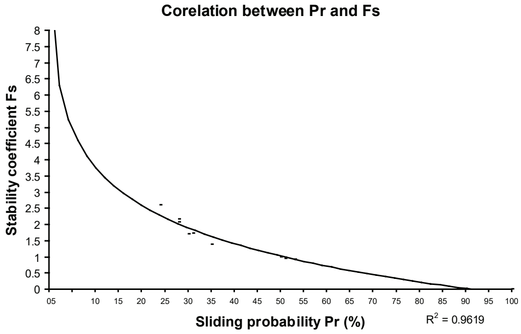


Fig. 5. Correlation between sliding probability (Pr) and stability coefficient (Fs) (Lazăr et al., 2015)
Rys. 5. Korelacja między prawdopodobieństwem poślizgu (Pr) a współczynnikiem stateczności (Fs) [Lazăr et al., 2015]

ments due to some factors", and for the interior dump with "moving rock deposits which can be limited by arrangements or by the technology of exploitation".

Based on the values obtained as a result of the inclusion in the vulnerability categories according to the nature of the objectives in the area of influence, an average value of the vulnerability was determined (table 8).

In the last step, based on those shown in Table 8, and taking into account the probability of sliding of the final slopes (determined from the stability analyzes presented in Chapter 2 and using the graph in figure 5), the risk of sliding was calculated, using the relation presented at the beginning of this chapter (table 9).

Framing the slopes in the risk classes and returning to the results of the stability analyzes, the following can be stated:

- for the final designed slopes of the two open pits, the calculated risk is 10.5, which corresponds to a high risk of sliding;
- for the slopes originally designed for the West Berbeşti interior dump:
- for the first two steps, the calculated risk is equal to 7.5, which corresponds to an average sliding risk;
- for the rest of the steps, the calculated risk is equal to 5, which also corresponds to an average risk of sliding.
- for the final slopes of the open pits, after the reduction of the slope angle, in the conditions of maintaining the designed heights and imposing a stability coefficient, the calculated risk decreases from 10.5 to 7. This reduction, passes the risk from high to average category;
- for steps Tr1 - Tr3 and Tr5, even after resizing the slope angle, under the conditions of a imposed stability coefficient of 2, the calculated value of the risk is 5, ie it implies an average risk of sliding;
- for the step Tr1 of the interior dump, in the conditions in which it is submerged and a possible landslide would produce a flood wave that would affect the downstream households, the calculated risk has a value of 8, ie an average risk.

Therefore, when we consider the displacement of a volume of water and its movement to the downstream areas where the individual households of the locals are located, although we fall into the same risk class (average), the calculated value increases to 8, compared to 5, provided if the slide would not have such an effect.

The general conclusion that emerges from the landslide risk assessment is that, even after the design of retrofit works (which aimed to reduce the slope angles, while maintaining the originally designed heights) the risk of landslide is medium. Only in the case of the final steps of the open pits was a lower risk class than the initial one, otherwise the classification in the category of the average risk of sliding is maintained.

a b

Fig. 6. The lands from the influence area of the open pits: a – West Berbești; b – Panga (***, 2022)

Rys. 6. Tereny z obszaru oddziaływania odkrywek: a – West Berbești; b – Panga (***, 2022)

Tab. 8. The nature of the objectives and the vulnerability of the land in the influence areas

Tab. 8. Charakter celów i wrażliwość gruntów na obszarach oddziaływania

Open pit/waste dump	**Objectives in the influence area and environmental components**				
	Natural objectives	**Natural objectives (V1)**	**Anthropic objectives**	**Anthropic objectives (V2)**	**Average vulnerability: Vm = (V1+V2)/2**
West Berbești open pit (post-closure)	Arable lands, forests, water curses, productive land	4	Roads with limited traffic or restricted movement of people	3	3.5
Panga open pit (post-closure)	Orchards, forests, water curses, productive land	4	Roads with limited traffic or restricted movement of people	3	3.5
West Berbești waste dump (at the end of 2022)	Brownfield, unproductive	1	Industrial constructions and installations, high traffic communication routes	4	2.5
* West Berbești waste dump (post-closure)	Arable lands, water curses, productive land	4	Households, social constructions	4	4

* We point out that, although the interior dump may slide into the remaining gap of the open pit (area of no value in terms of natural or anthropogenic objectives) and theoretically could not cause damage, the situation changes after the flood of the remaining gap. In this situation, a possible large landslide would dislodge an important volume of water that would move through the NE part of the perimeter, through the valley that separates the open pit from the West Berbești exterior dump. As individual households are located along this valley, the volume of water displaced would behave like a flood wave, being able to endanger not only goods but also the lives of the inhabitants of the area. For this reason, we considered the anthropic objectives in the area of influence as social housing and constructions, and the natural ones as arable, productive lands.

Tab. 9. Determining the risk of landslides

Tab. 9. Określanie zagrożenia osuwiskami

Slope		**Vulnerability V**	**Probability**		**Risk**
			Pr [%]	**Pr**	
Final slopes, West Berbești open pit (initially designed)					
T1 (10 m)	Clay	3.5	47.5	3	10.5
	Clay +Marl		37	3	10.5
T2 (15 m)	Clay		48	3	10.5
	Clay +Marl		41	3	10.5
Final slopes, Panga open pit (initially designed)					
T3 (25 m)	Clay	3.5	61.5	3	10.5
	Clay +Marl		52.5	3	10.5
Final slopes, West Berbești interior dump (initially designed)					
Tr1	Natural state	2.5	35	3	7.5
Tr2	Natural state		42.5	3	7.5
Tr3	Natural state		30	2	5
Tr4	Natural state		22	2	5
Tr5	Natural state		29	2	5
Tr6	Natural state		23.5	2	5
Tr1 submerged	Saturated		21.5	2	5
Final slopes, West Berbești open pit (after resizing the slope angle)					
T1 (10 m)	Clay or Clay	3.5	32*	2	7
T2 (15 m)	Substeps	3.5	32*	2	7
Final slopes, Panga open pit (after resizing the slope angle)					
T3 (25 m)	Substeps	3.5	32*	2	7
Final slopes, West Berbești interior dump (after resizing the slope angle)					
Tr1 – Tr3, Tr5**	Natural state	2.5	28***	2	5
Tr1 submerged	Saturated	4****	21.5	2	8

* Value corresponding to an imposed stability coefficient Fs = 1,8; ** For the Tr4 and Tr6 steps no resizing was required, the stability coefficient for the initially designed situation being Fs > 2; *** Value corresponding to an imposed stability coefficient Fs = 2; **** In the event of a landslide-induced flood wave.

5. Final conclusions and recommendations

☑ The stability analyzes performed for the designed situation at the end of the extractive activity in the two open pits (West Berbești and Panga) showed that the slopes excavated exclusively in clays are unstable or at equilibrium limit, while the slopes excavated in clays and marls have satisfactory reserves of stability for average period of existence (less than 20 years) for slopes of 10 and 15 m, and are unstable for slopes of 25 m.

☑ In order to ensure the conditions of long-term stability (over 20 years) it was necessary to perform some resizing calculations, in this sense being used the grapho-analytical procedure of Hoek.

☑ Through the resizing calculations for the final slopes of the open pits and the interior dump it was concluded that, in order to maintain the current designed heights and to ensure long-term stability, it is necessary to reduce the slope angles to values between 20 and 24° (except for an open pit slope, the 10 m slope made of clay and marl, where the slope angle can slightly exceed 33°).

☑ Under these conditions, it is necessary to restore the designed situation plans at the end of the activity, taking into account the elements of resizing the final slopes in order to ensure long-term stability.

☑ In the influence area of the open pits (post closure) arable lands, orchards, forested areas, and watercourses were identified. Only in the conditions in which we considered as possible a slide of the internal dump towards the remaining and flooded gap of the West Berbești Vest open pit, which in turn would generate a flood wave, were also identified individual households located in the extended area of influence.

☑ The lands in the influence area, taking into account the objectives in the area and the technical condition of the slopes, fall into vulnerability classes 1, 3 and 4 (or between 2.5 and 4 as an average value), and the sliding probability falls into classes 2 and 3.

☑ After performing the resizing calculations, the stability factor being imposed (1.8 for the final slopes of the open pits and minimum 2 for the final slopes of the interior dump), the probability of a landslide becomes 2 for all the analyzed slopes.

☑ After performing the resizing calculations, the final slopes of the open pits pass into a lower risk class, namely that of an average risks.

☑ For the final slopes of the interior dump the risk of sliding is average both for the situation initially designed and after the resizing of the slope angles.

☑ It is observed that in case of a landslide in the interior dump, capable of producing a flood wave, although the risk remains in the average category, the calculated value increases from 5 to 8.

☑ The fact that the calculated risks, both for the slopes of the two open pits and for the interior dump, after resizing do not fall into the low risk class (they remain in the average category), leads us to the conclusion that land stability depends to a large extent on the natural conditions (geology, hydrology, hydrogeology, tectonics, etc.) and natural factors (morpho-structural processes, seismicity, freeze-thaw cycles, etc.) characteristic of the region, the mining activity being able to start at an accelerated pace and aggravate the geomorphological processes specific to the investigated area.

☑ It is recommended the post-closure monitoring of the area, both by direct observations (in the field), by classical topographic measurements, but also by means of the latest technology such as: GPS, satellite observations, drone photogametry, LIDAR etc.

☑ Elaboration of intervention plans in case of signs preceding the triggering of landslides but also in case of occurrence of such phenomena.

☑ Regularly informing the inhabitants of the direct and extended influence areas about the situation regarding the stability/instability of the lands and the risks involved.

☑ Revegetation of the slopes as soon as possible, by grassing in a first phase, in order to reduce the amount of water coming from the precipitations that infiltrate in the final slopes (especially of the interior dump), in the conditions in which, as it was shown, this has an unfavorable influence on the physical-mechanical characteristics of the rocks and can favor the triggering of different types of landslides.

☑ Establishing the final destination of the lands released from technological tasks and carrying out the designed ecological rehabilitation works (afforestation, tree plantations, restoration of agricultural lands, etc.).

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Ocena stanu stabilności i ryzyka wystąpienia osuwisk w zagłębiu górniczym Berbeşti (Rumunia) po zamknięciu kopalni

Zagłębie Górnicze Berbeşti, położone na obszarze Podkarpacia Getyckiego, jest częścią Zagłębia Centralnego (EC) Govora, posiada cztery odkrywki: Alunu, Olteţ, Panga i West Berbeşti. Biorąc pod uwagę, że w Europie istnieje koncepcja rezygnacji z produkcji energii w oparciu o spalanie paliw kopalnych, zwłaszcza węgla, relatywnie krótko funkcjonować będą cztery odkrywki. Jednym z głównych problemów związanych z eksploatacją złóż węgla brunatnego jest stabilność gruntów na obszarze górniczym po zamknięciu eksploatacji. Badania przeprowadzono w taki sposób, aby uwzględnić w analizie stateczności czynniki i przyczyny naturalne, tenedencje terenów Podkarpacia Getyckiego do osuwisk, czynników i przyczyn antropogenicznych (wydobycie węgla brunatnego) oraz skutków oddziaływań towarzyszących. Analizy stateczności uwzględniały różne hipotezy związane z geometrią zboczy i wpływem czynników zewnętrznych. Przeprowadzono także analizę predykcyjną długoterminowej stabilności gruntów (zwłaszcza końcowych zboczy odkrywek) z uwzględnieniem zachowania się gruntów w czasie. Na podstawie uzyskanych wyników, po wykonaniu serii analiz statystycznych przeprowadzono analizę ryzyka, wykorzystując metodologię opracowaną przez część zespołu badawczego. Na wstępie należy zaznaczyć, że badania koncentrowały się na obszarach wydobywczych West Berbeşti i Panga, ponieważ wydobycie węgla brunatnego zostanie zakończone do końca 2022 roku. Biorąc jednak pod uwagę podobne warunki (geologia, morfologia, tektonika, strefy sejsmiczne, warunki pogodowe i klimatyczne, zastosowanych metod eksploatacji), zespół badawczy uważa, że znaczna część zawartych wniosków i rekomendacji w tym badaniu można uznać za ważne i dla pozostałych obszarów czynnych (odkrywki Alunu i Olteţ). W tym kontekście opracowanie kończy się szeregiem wniosków dotyczących stabilności gruntów w zagłębiu górniczym Berbeşti (zachodnie Berbeşti i obwód Panga) w momencie zaprzestania działalności produkcyjnej oraz zalecenia, które po wprowadzeniu w życie zapewnią długoterminową stabilność gruntów.

Słowa kluczowe: *zagłębie wydobywcze Berbeşti, elektrociepłownia Govora, węgiel brunatny, odkrywka, ryzyko, osuwiska, stateczność*