STABILITY ASSESSMENT OF THE FINAL SLOPES OF THE NORTH PESTEANA QUARRY IN THE CONTEXT OF LONG TERM SAFETY OF OBJECTIVES IN THE INFLUENCE AREAS

Izabela-Maria, APOSTU[1], F. FAUR[1]
[1]University of Petrosani, Faculty of Mining
E-mail: izabelamaria.nyari@yahoo.com

Abstract:*The problem of slope's instability has always been a concern for scientists. The superficial or deep landslides are manifested in the conditions of an imbalance occurring at the level of the rock masses or the engineering constructions due to the influence of many internal or external factors, which causes the worsening of the quality of the geotechnical characteristics of the rocks. The disastrous effects of landslides have highlighted the importance of deepening the studies in order to understand the way of manifestation and the causes of the loss of stability, respectively the implementation of rational measures to increase stability. The causes of landslides include: the presence of overloads, precipitation, groundwater and surface water, alteration of rocks, vibrations, seismic shocks, etc. In most cases, the occurrence of negative geotechnical phenomena occurs as a result of the influence of a cumulus of factors whose action is manifested over time. This paper aims at assessing the stability of the final slopes of the North Pesteana quarry. Knowing the hydrogeological structures characteristic of the site and the history of the sewatering works, the problem of the stability of the final slopes is raised after the mining activity ceases, which also means the stopping of the dewatering systems. The inflow of water which, according to current studies, will contribute to the restoration of the aquifer resources and to the flooding of the gap, will have a major negative influence because it involves the increasing of the humidity of the rocks, thus causing the worsening of their strength characteristics and the significant reduction of the stability reserve, the action of water being one of the most influential causes of landslides. A major problem is that the objectives in the area are at relatively small distances from the mining perimeter. Under these circumstances, it is important to assess the stability of the definitive slopes, to apply the measures to increase the stability reserve, also taking into account a safety margin, in order to minimize the risk of sliding is, given the long service life of the final slopes (for decades) and the influence of external or internal factors.*

Key words: *quarry, remaining gap, final slope, stability, safety*

INTRODUCTION

The problem of slope stability analysis is particularly complex due to the large number of factors involved in the sliding processes and the impossibility of quantifying their influence on the stability degree. For this reason, the results of the stability calculations have relative values, and it is recommended that safety coating coefficients (factors) be adopted when designing slopes (FODOR, 1980; LAZAR, 2001; ROTUNJANU, 2005).

Description of the North Pesteana mining perimeter

The mining perimeter of North Pesteana quarry is part of the Rovinari Mining Basin and belongs, from an administrative point of view, to Gorj County (***, APMG, 2016). The opening of North Pesteana quarry began in 1980 but, after decades of operation, the exploitation works are approaching the end. According to the report drawn up by the Ministry of Energy, in 2016, North Pesteana quarry stops its activity starting from 2023 (*** ME, 2016).

Among the objectives in the adjacent areas of the North Pesteana quarry are individual farms and agricultural lands belonging to the villages: Valea cu Apă, Pesteana de Jos, Hotăroasa, Urdari, Pesteana Jiu, Cocoreni and Balteni, natural landscapes with pastures or forests, the Jiu River, the road network and others (Figure 1).

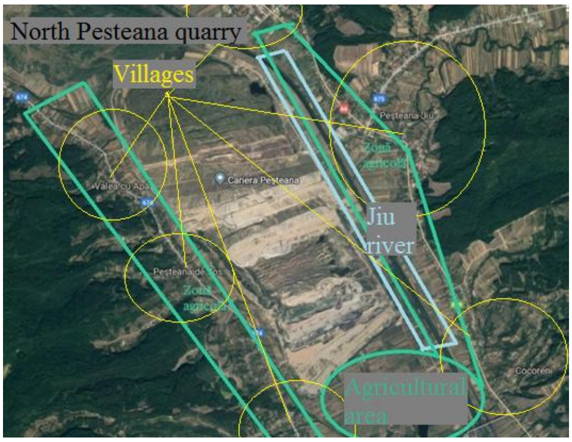

Figure 1. Uses of land adjacent to the mining perimeter

The North Pesteana mining perimeter is about 50 - 100 m up to 1 km distances from the surrounding villages. Considering the fact that some individual households are at very small distances from the mining perimeter and possibly even in the zones of influence, in the event of negative geotechnical phenomena, the risks are significant. Therefore, after the closure of the mining perimeter, it is necessary to assess the stability of the slopes, but also to evaluate and mitigate the risks that may occur over time.

MATERIAL AND METHODS

The works from the North Pesteana mining perimeter are carried out in 4 steps of excavation and 4 steps of dumping. Figure 2 shows the final configuration of the remaining gap of the North Pesteana quarry in longitudinal section. Considering the location and development of the North Pesteana quarry in the Jiu River meadow, it is noticed that the remaining gap is below the level of the surrounding terrain and has impressive dimensions.

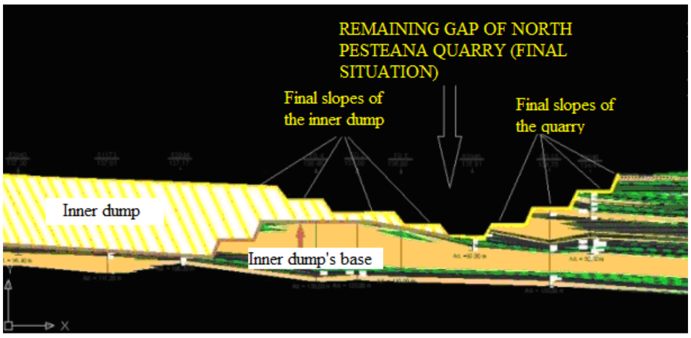

Figure 2. Longitudinal section - the remaining gap of North Pesteana quarry (APOSTU, 2018)

The geometrical characteristics of the final slopes

Based on the documentation and situation plans provided by the Oltenia Energy Complex and the Institute of Scientific Research, Technological Engineering and LigniteMine Designing, Craiova, the projected values and the existing ones at the end of the activity of the geometrical characteristics of the final slopes of the North Pesteana quarry, are centralized in the Tables no. 1 and 2 (*** C.E.O., 2018; *** I.C.S.I.T.P.M.L., 2018).

Table 1

The geometrical characteristics of the final slopes of the quarry

Values		Height of working steps, h [m]	Slope angle for the working steps, α [°]	Berms width [m]	Total height of the quarry (maximum) [m]	Overall slope angle of the quarry, α_{gen} [°]
Projected		20	45	60 - 80	80	14
Existing	Interval of values	14.2 - 20.1	36 - 46	97.4 - 107.7	74.1	10
	I[st] step	14.2	36	102.4		
	II[nd] step	20.1	40	107.7		
	III[rd] step	19.7	36	97.4		
	IV[th] step	20.1	46	80*		

* in the model of the quarry's steps, a length of 80 m was considered at the top of step IV

Table 2

The geometrical characteristics of the final slopes of the inner dump

Values		Height of inner dump's steps, h [m]	Slope angle for the innner dump's steps, α [°]	Berms width [m]	Total height of the inner dump (maximum) [m]	Overall slope angle of the inner dump, α_{gen} [°]
Projected		10 - 15	18 - 27	minimum 100 m	105	9
Existing	Interval of values	10.2 - 15.1	25 - 27	> 100	39.5*	6
	I[st] step	10.2*	25*	100.4		
	II[nd] step	15.1	26	174.6		
	III[rd] step	14.8	27	102.5		
	IV[th] step	14.9	26	181**		

* measured from the base of the inner dump
** in the model of inner dump steps was considered a length of 181 m at the top of step IV

The inner dump extends from north to south with the advancing of the work fronts and covers the quarry base, so the foundation of the quarry is represented by the base of the quarry. The foundation line presents major variations due to the local conditions and the exploitation plan.

Analyzing the longitudinal section, the configuration of the quarry base and of the inner dump and the rock formations from the base of the dump, it was established that only a small portion of the dump presents the probability of occurence of sliding phenomena. The geometric features of this portion of the base of the dump are shown in Figure 3.

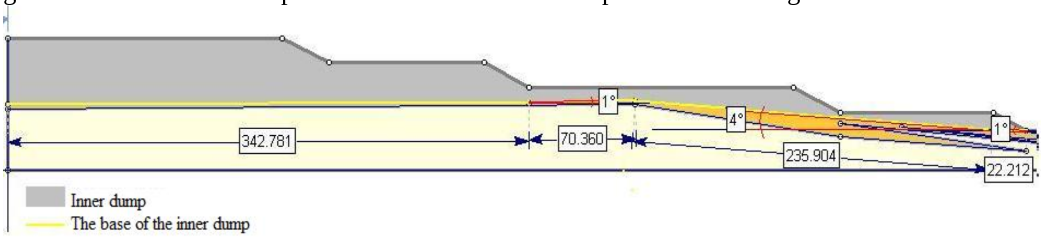

Figure 3. The base of the inner dump - geometrical characteristics (APOSTU, 2018)

It is essential to know the optimal values of the geometric characteristics after which the quarries and dumps are built. These values are set in geotechnical studies. Failure to comply with design values may favor the occurence of negative geotechnical phenomena (FODOR AND LAZĂR, 2006; LAZĂR ET AL., 2008).

Methods of stability analysis of the slopes

For the stability analysis of the final slopes of the remaining gap of the North Pesteana quarry, the Slide geotechnics software was used (ROCSCIENCE, 2010). The Slide Software is the most comprehensive software for stability analysis of slopes. Slide analyzes the stability of natural and artificial slopes irrespective of their geometry. It can perform analyzes both in static and dynamic conditions as well as in the case of water pressure in rocks or in the case of submerged slopes. For the calculation of stability factors, the software uses different methods and offers the choice of the desired method.

In the present study, 3 methods were used to perform stability analyzes: Fellenius, Janbu and Bishop. The three methods offered close values of the stability coefficients, so only the minimum values, generally resulting from the Janbu method, were taken into account.

Stability analyzes will be based on 2 assumptions. According to the geotechnical field surveys, the previous studies, but also the geometrical characteristics of the final steps, which revealed that the base of the dump, on a part on which the 1st and 2nd steps of the dump are built, slightly inclines towards the steps of the quarry, it results that the surfaces more likely to slide are cylindrical-circular and polygonal.

Fellenius's method

The Fellenius method, known in the literature as the vertical strip method or the Swedish method, is used to estimate the stability of slopes. Although it was developed for unclear clayey and homogeneous rocks, this method is currently used by some scientists and for lithological stratified and heterogeneous rock formations (STĂNCIUCU, 2018).

The sliding mass, determined by the sliding surface, is divided into several strips (Figure 4). As a rule, the width of a strip is bi = 0,1R. If the sliding surface passes through the base of the slope, the sliding mass consists of an active prism and a passive prism, separated from the vertical passing through the center O of the sliding surface. In the active prism predominates the sliding forces, while in the passive prism predominates the resistance forces, which oppose sliding (ROTUNJANU, 2005; LAZAR, 2010).

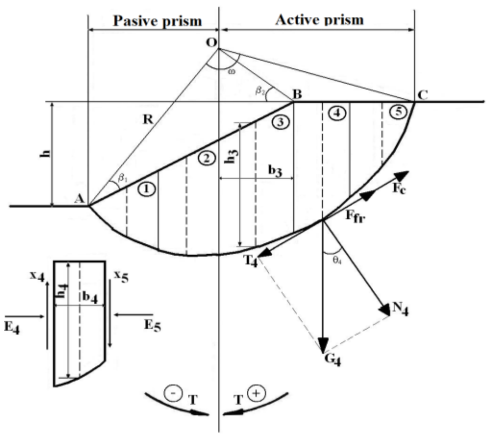

Figure 4. Calculation principle of the stability coefficient using the Fellenius method (ROTUNJANU, 2005; LAZĂR ET FAUR, 2015)

Janbu's method

Janbu's method is known in the literature as the non-dimensional parameter method and is used for situations where the slope consists of several layers with different geotechnical properties and is based on the shear stress calculation. Mathematical solutions and work charts are deduced from the work system used by Nilmar Janbu, known as Janbu's charts (STĂNCIUCU, 2018).

Janbu's method analyzes:

- slope stability in pure cohesive rock formations ($c \neq 0$, $\varphi = 0$),
- the stability of the slopes in rock formations with cohesion and internal friction ($c = 0$, $\varphi = 0$).

In the case of simple slopes, unaffected by the influence of other factors, based on Janbu's graphs, the elements necessary for calculating the stability factor and the coordinates of the center of the critical arc are determined.

Also Janbu's method allows the calculation of the value of the stability factor under the conditions of the influence of other factors, and a series of relations of calculation of the stability factor are given in the literature (ROTUNJANU, 2005).

Bishop's method

Bishop's method differs from the Fellenius's method by deducting the expression of the actual normal forces on the slide surface. Thus, the expression of normal forces in the Bishop's method is deduced from the vertical equilibrium condition of the forces. The implicit character of Bishop's relationship requires the use of iterative computation. For a rapid convergence of stability factor values, it is recommended that the starting value of the stability factor be that calculated by the Fellenius's method. By successive iterations the corresponding Fs value is determined for two interactive cycles for which the difference between the adopted value and the obtained value is very small (less than 0.001 in the case of electronic calculation) (ROTUNJANU, 2005; STĂNCIUCU, 2018).

Slopes on polygonal surfaces generally occur in the case of tectonized masses, depending in particular on the layering, the contact between the strata, the cracks or the fissures, as well as the strength characteristics of the rocks on these surfaces. When the sliding surface consists of a succession of planes with different slopes (Figure 5), the calculation of the stability factor is quite difficult because the tangential components that cause the slide change with the change of inclination of the respective sliding surface, so the stability factor varies from one sector to another (ROTUNJANU, 2005; LAZĂR ET FAUR, 2015).

A similar situation is also found in sterile dumps built on slopes with variable inclination.

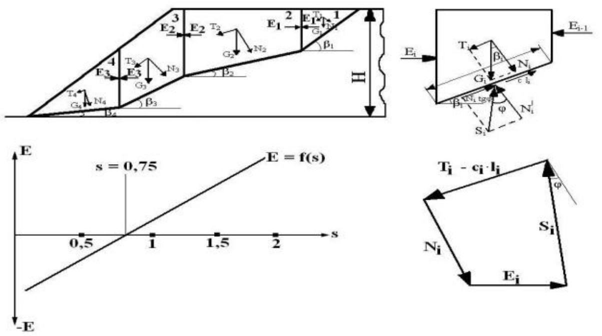

Figure 5. Stability analysis for polygonal surfaces (ROTUNJANU, 2005; LAZĂR ET FAUR, 2015)

It is determined the stability factor for each sector "i" taking into account the forces acting on it. Depending on the stability of individual sectors, there may be two situations: when a sector is unstable, it can exert tasks on the neighboring sector, reducing its stability reserve, and when a sector is stable, it can play the role of a support prism, increasing its stability reserve.

Analysis of the stability of the final slopes of North Pesteana quarry

The stability of the slopes is jeopardized by the destruction of the local or overall balance between the stress forces and the inner strength of the rocks under the direct action or only under the partial influence of the various external or internal factors, natural or artificial (FODOR, 1980).

The expression of the stability coefficient is given by the ratio between the sum of the moments of the forces opposing the slide and the sum of the moments of the forces that tend to move the rock masses (ROTUNJANU, 2005). For the slope to be stable, the calculated safety factor must be higher than 1.

The geotechnical characteristics of the rocks

The values of the geotechnical characteristics taken into account for the assessment of the stability of the individual steps and of the ensemble of steps of the quarry and of the inner dump are those resulting from the calculation of the average values and of the geostatistical processing (Table 3), thus:

- for in-situ rocks, stability analyzes were performed on the basis of characteristic average values, depending on the nature of the rocks; the geotechnical characteristics of the vegetal soil were taken from the literature (ROTUNJANU, 2005);
- in the case of steril rocks, three hypotheses were established and the stability analyzes were made on the basis of 3 sets of values characteristic of these assumptions: average - σ, average and average + σ, since the dumped material is a mixture of rocks (marly, clayey, sandy, gravel and boulders, but also charcoal rocks for which selective extraction is inefficient), thus it is almost impossible to model the steps of the dump depending on the content.

The minimum and maximum values were not taken into account as they give the extremes, generally rare, and the situations in which these values characterize the entire wasteland are unlikely (APOSTU, 2018).

Table 3

Average values of geotechnical characteristics of in-situ and steril rocks

Nature of the rock		Values	Volumetric weight γ_V [kN/m^3]	Cohesion c [KN/m^2]	Angle of internal friction φ [˚]
In-situ rocks	vegetal soil	Average values	14.70	24.00	20.00
	marly		19.22	38.50	17.50
	clayey		19.49	34.99	18.98
	sandy		19.28	6.35	23.73
	boulders, gravel		21.13	0.00	34.25
	coal rocks		12.72	114.22	30.57
Sterile rocks	mixture of rocks: marl, clays, sands, gravel, boulders, coal rocks	Average values - σ	16.76	3.47	17.53
		Average values	18.72	22.89	23.74
		Average values + σ	20.68	42.32	29.95

The values of the geotechnical characteristics of the rocks at the base of the dump are assimilated to those of the rocks in the in situ slopes.

Quarry steps, characteristic rock layers, inner dump's foundation, and inner dump's steps have been modeled and defined using the Slide software.

RESULTS AND DISCUSSION

After the introduction of the geotechnical characteristics values for the definition of in-situ rock layers and the rock mix in the dump, the network of centers or the sliding surface (curved or polygonal) for which the software automatically calculates the stability factors is established.

Stability calculations were performed for normal humidity conditions, without taking into account pore water pressure, since the geometry of the quarry steps, the inner dump geometry, the nature and granulometry of the materials facilitate the drainage of groundwater.

The results of the stability analyzes, both for the final steps of the quarry and for the inner dump. are shown in Tables 4 and 5.

Table 4

The value of the stability coefficients for the individual steps and for the ensemble of steps of the final slopes of the quarry (APOSTU, 2018)

Step/System of steps	Sliding surface	Stability coefficient value		
		Bishop	Janbu	Fellenius
I	1	1.485	1.414	1.433
	2	2.381	2.009	2.238
II	1	1.134	1.052	1.078
	2	1.193	1.087	1.116
III	1	1.409	1.292	1.323
	2	1.576	1.502	1.545
IV	1	1.144	1.056	1.073
	2	1.141	1.076	1.091
I-II	2	4.347	4.137	4.232
II-III	2	3.458	3.281	3.330
III-IV	2	2.776	2.630	2.678
I-IV	2	3.381	3.317	3.327

** 1 curved surface of minimal resistance; 2 curved surface defined through the foot of the slope*

Table 5

The value of the stability coefficients for the individual steps and for the ensemble of steps of the final slopes of the inner dump (APOSTU, 2018)

Step/ System of steps	Sliding surface	Stability coefficient value								
		Average - σ			Average			Average + σ		
		B	J	F	B	J	F	B	J	F
I	1	0.972	0.925	0.934	2.407	2.211	2.264	2.557	2.306	2.289
	2	1.755	1.714	1.720	2.438	2.357	2.381	3.351	3.213	3.256
II	1	1.045	0.960	0.963	1.929	1.718	1.760	2.390	2.149	2.156
	2	1.114	1.087	1.088	2.011	1.908	1.927	3.334	3.212	3.238
III	1	1.342	1.167	1.175	2.288	2.010	2.035	3.129	2.683	2.592
	2	1.271	1.215	1.218	2.355	2.210	2.235	3.205	3.086	3.112
IV	1	1.034	0.919	0.931	1.932	1.736	1.782	2.754	2.490	2.561
	2	1.374	1.321	1.324	2.482	2.273	2.308	3.601	3.443	3.477
I-II	2	4.507	4.395	4.443	5.170	5.038	5.087	5.585	5.506	5.524
II-III	2	6.334	6.155	6.232	6.429	6.279	6.318	7.217	7.165	7.171
III-IV	2	2.924	2.806	2.832	4.553	4.399	4.440	5.731	5.444	5.499
I-IV	2	5.168	5.107	5.125	5.574	5.552	5.555	5.892	5.868	5.867
I-IV	3	4.168	4.136	4.176	7.129	7.071	7.198	10.077	10.006	9.994

** 1 curved surface of minimal resistance; 2 curved surface defined through the foot of the slope; 3 polygonal surface defined on the inner dump - base contact surface; B – Bishop; J – Janbu; F - Fellenius*

To be able to say that the slope has a certain stability reserve, the value of the safety factor must be higher than 1. In order to have good protection against sliding, the value of the safety factor must be as large as possible, but its high value leads to the design and execution of non-economic slopes. Therefore, it was considered that the optimal value of the safety factor should be in the range Fs = 1.25 ÷ 1.5, and the choice of the optimum value should be made taking into account the economic and social importance of the objective, as well as its service time. For buildings of low social and economic importance, the stability factor values may be lower (Fs = 1.2 - 1.3), and for important constructions, the stability factor values should be higher (Fs = 1.5 - 3) (***, MLSP, 1997; ROTUNJANU, 2005).

The determination of the defined contours of the final slopes shall also take into account the period of stagnation. For approximate calculations the following stability coefficients are recommended:

- for short service time (< 1 year), Fs = 1.1 - 1.2;
- for average service time (1 - 20 years), Fs = 1.2 - 1.5;
- for long service time (> 20 years), Fs = 1.5 - 2.0;
- for very long service time (centuries), Fs ≥ 3 (FODOR, 1980; ROTUNJANU, 2005).

In the case of the system of steps, the departmental rules for the construction, maintenance and supervision of the sterile dumps impose a value of the stability coefficient above 3 (Fs > 3) (LAZĂR ET FAUR, 2015).

Based on recommendations in the literature on the value of the stability factor (FODOR, 1980; ROTUNJANU, 2005; LAZĂR ET FAUR, 2015) and taking into account the interval containing the optimal stability factor Fs = 1.25 ÷ 1.5 for the individual slopes, respectively Fs > 3 for the system of steps, as a result of the stability analyzes performed on the definitive slopes of the North Pesteana quarry, the following were found:

- according to the stability analyzes and the stability factors obtained on the critical sliding surfaces, the 1st and 3rd steps of the quarry are stable, while the 2nd and 4th steps are at the stability limit (Figure 6), the value of the stability factor approaching the unit value;

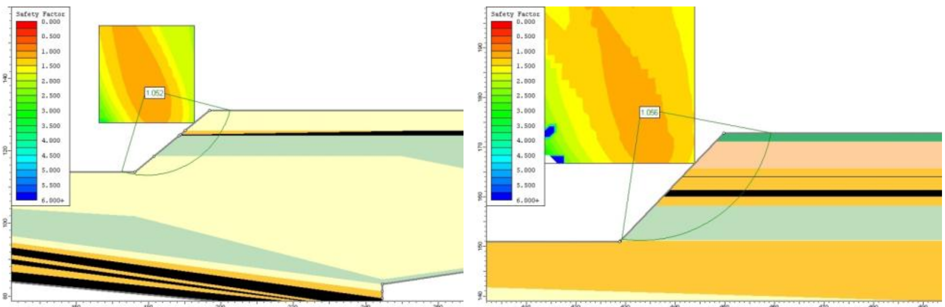

Figure 6. 2nd step of the quarry (left); 4th step of the quarry (right) - the critical sliding surface

- in the case of system of steps (of the quarry) and of ensemble of steps, the value of the stability factor exceeds the recommended limit, with the exception of the III-IV system (Figure 7 left) whose stability factor is slightly below the recommended value;
- both the individual steps and in the case of the system of steps and the inner dump ensemble of steps, the values of the stability factors are above those recommended for the assumptions in which the geotechnical characteristics have average and average + σ values;

- it has been found that the values of the stability factors defining the minimal resistance surfaces are lower than 1 or slightly higher than 1 for the individual steps, which characterizes unstable slopes or slopes at the limit of stability; in the case of system of steps and the ensemble of steps of the inner dump, the stability factor values exceed the recommended value indicating a high stability reserve, except for the III-IV system of steps (Figure 7 right) where the stability factor value is slightly lower than the recommended value;

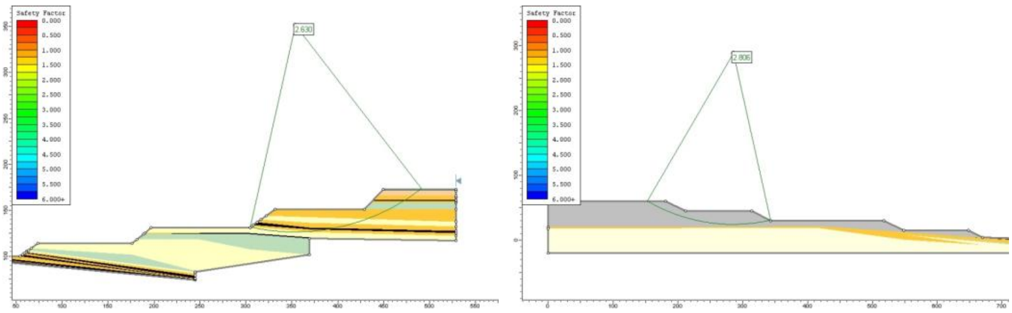

Figure 7. System of steps of the quarry III-IV (left); System of steps of the inner dump III-IV (right) - the sliding surface through the foot of the slope

- for all three assumptions, it has been established that slidings following the surface at the contact between the base terrain and the inner dump are unlikely (Figure 8);

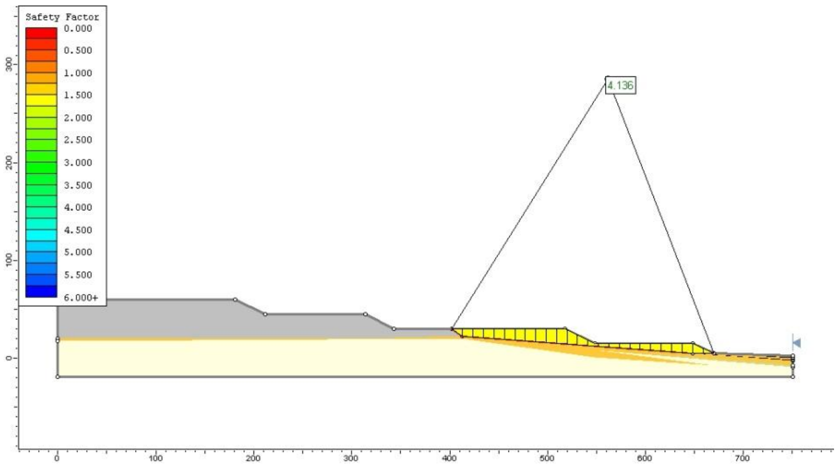

Figure 8. System of steps I-II of the inner dump - the polygonal sliding surface defined at the contact between the base terrain and the inner dump (at average - σ values of the geotechnical characteristics of the sterile rocks)

According to the results of the stability analyzes, it is more likely that the sliding of the final slopes of the remaining gap will occur after a curved surface and especially at the individual slopes. It has been found that the sliding surface can pass through the slopes, through the foot of the slope or under the step's slope.

CONCLUSIONS

The results of the stability analyzes revealed that under the (geometric and geotechnical) conditions existing at the end of the exploitation activity in the North Pesteana perimeter there is the risk of occuring of negative geotechnical phenomena at individual steps or system of steps.

According to the stability analyzes and the stability factors, it was found that the 2nd and 4th steps of the quarry are right at the stability limit (Fs ≈ 1), and for the III-IV system of steps of the quarry, the stability factor value is slightly below the recommended limit.

In the case of the inner dump, for the assumption that the sets of average - σ values have been taken into account, all individual steps present risk of slinding, being at the stability limit or below it (Fs ≈ 1 / Fs < 1). Also, for the III-IV system of steps of the inner dump, the stability factor value is slightly below the recommended limit.

Taking into account the exploitation activity of the North Pesteana quarry, which is approaching the end and the long service time of the final slopes, for the safety of the objectives in the zones of influence, it is necessary to adopt covering factors, which can be done by dimensioning the geometrical elements of the definitive slopes taking into account, as far as possible, all external or internal factors that will act upon them in future periods. Thus, the recovery and reproduction works in the economic or ecological circuit of the degraded mining land can only start after measures have been taken to prevent landslide phenomena.

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