

ASSESSING THE SUFFOSION RISK FOR THE FINAL IN-SITU SLOPES OF THE NORTH PEȘTEANA OPEN-PIT

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Abstract: *With the occasion of complex and detailed studies, conducted especially from the geotechnical point of view (between 2016 and 2019), on the North Peșteana mining perimeter (more precisely on the lignite open-pit with the same name) numerous areas affected by suffosion were highlighted, mainly located on the lower steps (steps III and IV). Starting from these observations, the present paper analysis the risk of suffosion phenomenon to occur in the case of the final slopes of North Peșteana open-pit. In general, as observed, these areas have small and medium sizes, and do not affect significantly the stability of the steps, being immediately remedied with the advancement of the work front. Also, it was observed that, with the advancement of the excavation fronts, the groundwater currents constantly entrain the fine particles from the aquifer formations, and therefore new such suffosion areas occur. Taking into account the fact that the exploitation of lignite in this perimeter is ending soon, it was considered as necessary to assess the risk of suffosion at the final slopes (long term slopes) in order to be able to identify appropriate measures to prevent future potential catastrophic events.*

1. Introduction

Suffosion is a type of internal erosion, which consists of entrainment (hydrodynamic suffosion) or dissolution (hydrochemical suffosion) and transport of fine granules and mineral salts from a porous environment under the action of aquifer currents. Suffosion phenomenon often occurs in the case of open-pit mining works, when aquifer formations are intersected, thus taking place the natural drainage of groundwater and when the speed of groundwater flow exceeds the critical speed. In non-cohesive materials (sands) suffosion leads to areas of high permeability (and water transmission), potential outbreaks of increased seepage, increased erosive forces and potential collapse of the skeletal soil structure [1].

The fine particles are replaced by gaps of different sizes, while the coarse granules tend to settle, thus, over the aquifer stream, suffosion cones can occur. Suffosion cones appear on the ground surface in the form of circular depressions or on slopes.

In more severe cases the suffosion cones can be united forming suffosion channels or even small irregular depressions, thus putting in danger different natural or anthropic objectives located in the influence area.

The underground gaps that are created, depending on their size and depth, can lead to the loss of the natural balance of the rocks situated on top and, sometimes, the occurrence of landslides (if they are located on slopes) [2]. Even if the areas affected by the suffosion phenomena do not always involve landslides, they can cause damages or total destruction of various installations, households, infrastructures, utility corridors, and, in extreme conditions the loss of human lives [3-4].

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This phenomenon is usually characteristic to tailings ponds, but can sometimes manifest itself in the case of waste dumps. In the case of in-situ slopes, suffusion can lead to undermining, followed by collapses and landslides. In the latter case, it is an even more dangerous phenomenon when it occurs at the base of the slope.

The suffusion phenomenon is manifested under the action of groundwater by:

- hydrodynamic suffusion, a process by which water entrains fine particles of sandy rocks under the action of hydrodynamic pressure, when the filtration speed exceeds the critical speed. Under these conditions, the so-called “underground torrent” is formed (Figure 1) [5 - 7];

- hydrochemical suffusion, a process by which water dissolves and entrains the soluble substances that bind the rock particles in the massif [8].

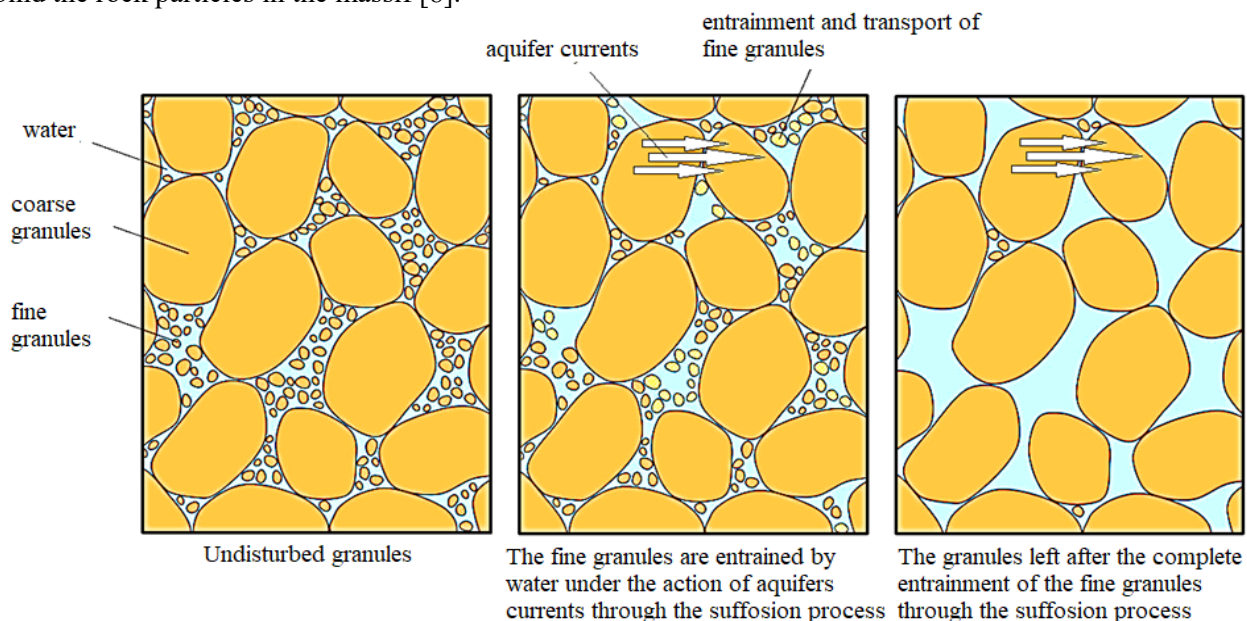


Figure 1. Manifestation of hydrodynamic suffusion in sandy rocks [9]

In the paper, this phenomenon is analyzed in the case of the North Pesteana open-pit, where more suffusion areas occurred on some slopes. Considering the lithological structure in the North Pesteana perimeter and the fact that several suffusion areas were observed (Figure 2) resulting from the natural drainage of water through the open-pit slopes, it was found that it is necessary to assess the risk of hydrodynamic suffusion in order to prevent unwanted events that may affect different objectives located in the influence area.



Figure 2. Suffusion zone observed on in-situ slopes

According to the visual analysis performed during the exploitation period, in the North Pesteana mining perimeter, several suffusion areas were observed on the slopes of IIIrd and IVth steps of the open-pit. The causes that led to the manifestation of the suffusion phenomena are represented by the natural drainage of the underground waters through these two in-situ steps, which include in their structure sandy rocks.

The North Pesteana mining perimeter belongs to the Rovinari mining basin, which is part of the well-known Oltenia Coal Basin, the largest and most important coal basin in Romania (Figure 3). It develops in the meadow area of the Jiu River. The access to North Pesteana mining perimeter can be made on the national road DN 66 Craiova - Filași - Tg. Jiu or on the county road DJ 674 Turceni - Roșia de Jiu - Rovinari.

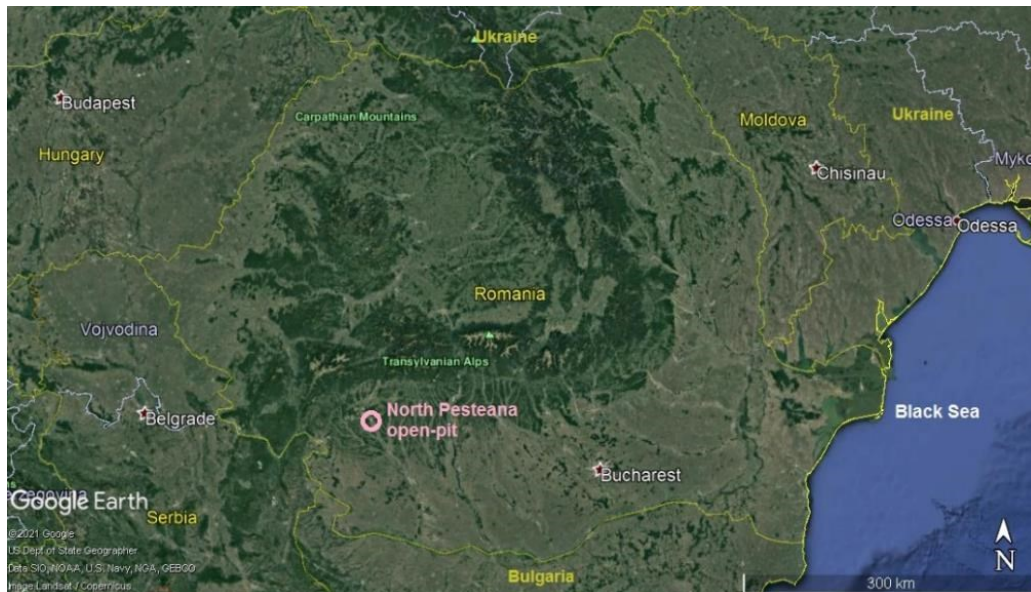


Figure 3. Location of North Pesteana open-pit

It must be stated, from the beginning, that North Pesteana open-pit is surrounded by agricultural lands, pastures and county roads (in the areas situated on the directions that may be affected in the future by suffosion phenomena; these areas are called “areas of influence” and extend as far as the current areas of influence of the dewatering systems extend).

2. Materials and methods

Although the risk associated with geotechnical phenomena is usually (in quantitative evaluations) expressed in monetary units, material/numerical losses or human casualties recorded as a result of the catastrophes caused by their occurrence, the present paper has as primary objective the assessment of the risk on a priority scale developed by the authors, following a simple but effective methodology.

The suffosion risk (R) is defined as the product between the suffosion probability (Pr) and the vulnerability of the objectives located in the influence area, according to the technical state of the in-situ steps (V) (1):

$$R = Pr \cdot V \quad (1)$$

Methods for assessing the probability of occurrence of suffosion phenomena in rock massifs/deposits include historical records and observations of phenomena occurring in previous periods and the study of maps of areas with potential for suffosion.

The vulnerability of the objectives located in the influence area can be established by taking into account their nature in relation to the type of aquifer formations present in the area, thus estimating the severity of the suffosion phenomena that may occur.

Studying the dependence between the hydraulic gradient and the nonuniformity coefficient of the sandy rocks, two domains were separated [10]: the domain of critical gradients that produce suffosion processes and the domain of permissible harmless gradients (Figure 4).

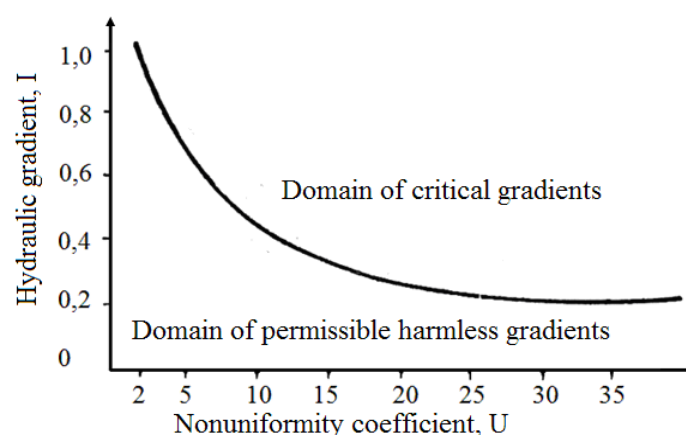


Figure 4. Dependence between the hydraulic gradient and the nonuniformity coefficient [10]

According to the specialized literature [10], the suffosion finds development conditions in the case of sands with nonuniform granulation and less in the conditions of sands with uniform granulation. Working on this hypothesis and accepting a critical hydraulic gradient, the potential for suffosion in sandy rocks was analyzed according to the nonuniformity coefficient (Table 1).

Table 1. Suffosion potential according to the nonuniformity coefficient of the rocks under the conditions of a critical hydraulic gradient

Nonuniformity coefficient, U	Hydraulic gradient, I	Suffosion potential
U < 5 - uniform	$I_{critical}$	low
U = 5 - 15 - medium uniformity		medium
U > 15 - nonuniform		high

Analyzing Figure 3, a sharp decrease of the hydraulic gradient is observed with the increase of the nonuniformity coefficient. Therefore, according to the graph, for sands with low values of the coefficient of nonuniformity, so for sands with uniform granulation, the phenomenon of suffosion can occur only in the case of very high values of hydraulic gradients [11-13].

These areas often appear at the working steps of the North Pesteana open-pit, but they are eliminated with the advancement of the work fronts and have never endangered the overall stability of the steps. However, it is possible that when the dewatering systems from the North Pesteana mining perimeter will be shutdown, the influx of groundwater that will supply and contribute to the restoration of aquifer resources and the flooding of the remaining gap may favor the manifestation of larger-scale suffosion phenomenon [14].

Fourteen rock samples were collected from the North Pesteana open-pit and further subjected to granulometric analysis. Eleven of these samples are composed of sandy rocks or contain significant fractions of sandy rocks (Table 2) [3]. In the study, in addition to the data obtained from the analysis of these samples, other data existing in the literature were taken into account, respectively the data obtained from the reports made available by the Oltenia Energy Complex [15].

Table 2. Granulometric composition and nonuniformity coefficient of rocks [3]

Sample no.	Granulometric composition, %				Nonuniformity coefficient, U	
	Clay	Dust	Sand	Gravel	Value	Description
1	-	-	100	-	2.17	uniform
2	-	-	100	-	2.28	uniform
3	7.5	27.5	65	-	8	medium uniformity
4	33	17	50	-	66.67	nonuniform
5	24	28	42	6	33.33	nonuniform
6	-	38.5	61.5	-	3.78	uniform
7	-	-	91	9	5.71	medium uniformity
8	20	43	27	10	14.62	medium uniformity
9	10	55	33.5	1.5	8.6	medium uniformity
10	-	-	99.5	0.5	1.97	uniform
11	-	-	73	27	5.21	medium uniformity
12	-	-	78	22	5.62	medium uniformity
12	41	52	7	-	44	nonuniform
14	-	-	89.5	10.5	3.16	uniform

Based on the specialized literature [14, 16-18], it is estimated that if by the time of the complete flooding of the remaining gap of the North Pesteana open-pit, no suffosion phenomena will occur, the possibility of their manifestation in the future is reduced due to the hydrostatic pressure which acts on the final slopes of the remaining gap, positively influences their stability reserve and prevents the process of entrainment of mineral granules from the rock mass. Therefore, geotechnical problems may occur especially during the flooding of the remaining gap.

3. Results and discussions

In order to solve the problem of the suffosion risk, a characterization of the aquifers from geological and hydrogeological point of view was performed (based on data existing in specialty papers [19]), depending on the thickness and inclination of the aquifer layers in relation to the remaining gap, the filtering coefficient and

the water inflow coefficient. Thus, 3 classes were established according to the type of aquifers (Table 3):

- 1st class - aquifers characterized by easy drainage conditions, with low potential for suffosion;
- 2nd class - aquifers characterized by average drainage conditions, with medium potential for suffosion;
- 3rd class - aquifers characterized by heavy and very heavy drainage conditions, with high potential for suffosion.

Table 3. Types of aquifers depending on the potential for suffosion [after 19]

Type of aquifer	1 st class - easy drainage conditions, with low potential for suffosion	2 nd class - average drainage conditions, with medium potential for suffosion	3 rd class - heavy and very heavy drainage conditions, with high potential for suffosion
Characteristics			
Inclination of the aquifer layers	layers that does not incline towards the remaining gap	horizontal layers	layers that incline towards the remaining gap
Thickness of aquifer layers (or horizons), M [m]	0 - 10 (< 20)	10 - 20 (20 - 40)	> 20 (> 40)
Filtering coefficient, k_f [m/day]	< 1	1 - 10	> 10
Water influx coefficient*, k_a [m ³ /t]	< 3	3 - 5	> 5

* The water influx coefficient represents the volume of water discharged per tonne of useful material extracted. High permeable and uniform rocks in the conditions of a high water influx are a premise for the occurrence of suffosion phenomena. It is important to control the water influx until the moment when the risk area become submerged to prevent the occurrence of suffosion phenomena [17, 20].

Depending on the type of aquifer and nature of the objectives located in the influence area, a classification was made on hazard groups of in-situ slopes and three categories of vulnerability were established (Table 4).

Table 4 Vulnerability classes established according to the type of aquifers and the nature of objectives located in the influence area

Potential of suffosion	Households, industrial objectives, highways, national roads, railways, important surface bodies of water, utility corridors, ecosystems of high value	Annex buildings, agricultural lands, pastures, county or tertiary roads, small lakes and stream, utilities ramifications, ecosystems of low value	No buildings, brownfields, abandoned pastures, no infrastructure, no surface waters, no utilities, degraded and highly degraded ecosystems
Type of aquifer			
3 rd class – aquifer layers that inclines to the remaining gap, with great thickness, high permeability and high water inflow coefficient	3	2	1
2 nd class – horizontal layer, with average thickness, average permeability and an average water inflow coefficient	2	2	1
1 st class – aquifer layer that does not incline to the remaining gap, with reduced thickness, reduced permeability and low water inflow coefficient	1	1	1

where: $V = 1$ – low vulnerability; $V = 2$ – medium vulnerability; $V = 3$ – high vulnerability

The main area of interest, from the potential of suffosion point of view, coincides with the main aquifer horizon in the basin (Figure 5; the one between the layers VI and VIII of lignite).

Major problems were observed in the twinning zones of the IIIrd and IVth in-situ steps, because the manifestation of the phenomena of suffosion at the base of the slope may involve the displacement of the above mass of rocks.

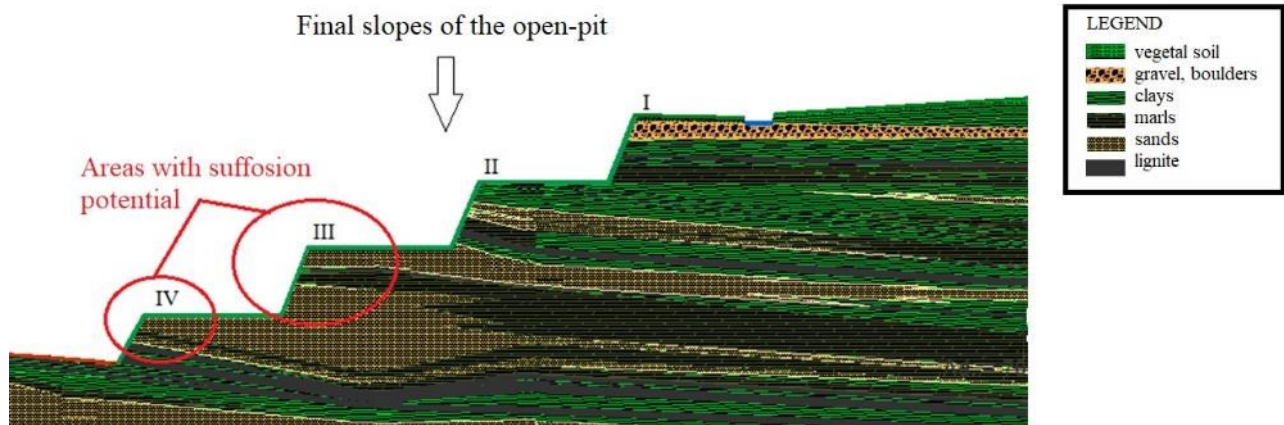


Figure 5. Highlighting areas of suffosion potential

Between the VIIth and VIIIth lignite layers there are 2 aquifer layers, separated by a layer of marl and a thin layer of lignite. The lower aquifer layer is 15 to 34 m thick and does not incline towards the remaining gap, while the upper aquifer layer is up to 6 - 7 m thick, is horizontal, then tilts slightly from the remaining gap to the south. The aquifer horizon between the VIIth and VIIIth lignite layers has a maximum thickness of approx. 40 m. The water inflow coefficient in the North Pesteană perimeter is 12.87 m³/t, and the filtration coefficient varies between 0.62 - 1.71 m/day.

According to Tables 3 and 4 and the scale chosen for the representation of vulnerability, the IIIrd and IVth steps of the open-pit were classified in the hazard groups, respectively in the vulnerability categories taking into account the characteristics of the aquifer. From the point of view of the inclination of the layers and of the permeability, the aquifer horizon falls in the second class, and from the point of view of the other characteristics, it also falls in the second class. Based on the values obtained from the classification of vulnerability categories, depending on the technical condition of IIIrd and IVth steps of the open-pit, and to ensure a high degree of security, it was established that the objectives in the area of influence present a medium vulnerability ($V = 2$).

In order to evaluate the probability of manifestation of suffosion phenomena, over the graph proposed by Istomina [10], presented in Figure 4, a network comprising of 10 x 10 cells was superimposed (each cell marking the probability of manifestation of suffosion phenomena) (Figure 6). Thus, three areas have been delimited that describe the probability of occurrence of suffosion phenomena, depending on the occupied position of one or more points (described by the hydraulic gradient and the nonuniformity coefficient of the aquifer at a certain moment) relative to the curve that delimits the critical hydraulic gradients from the admissible ones.

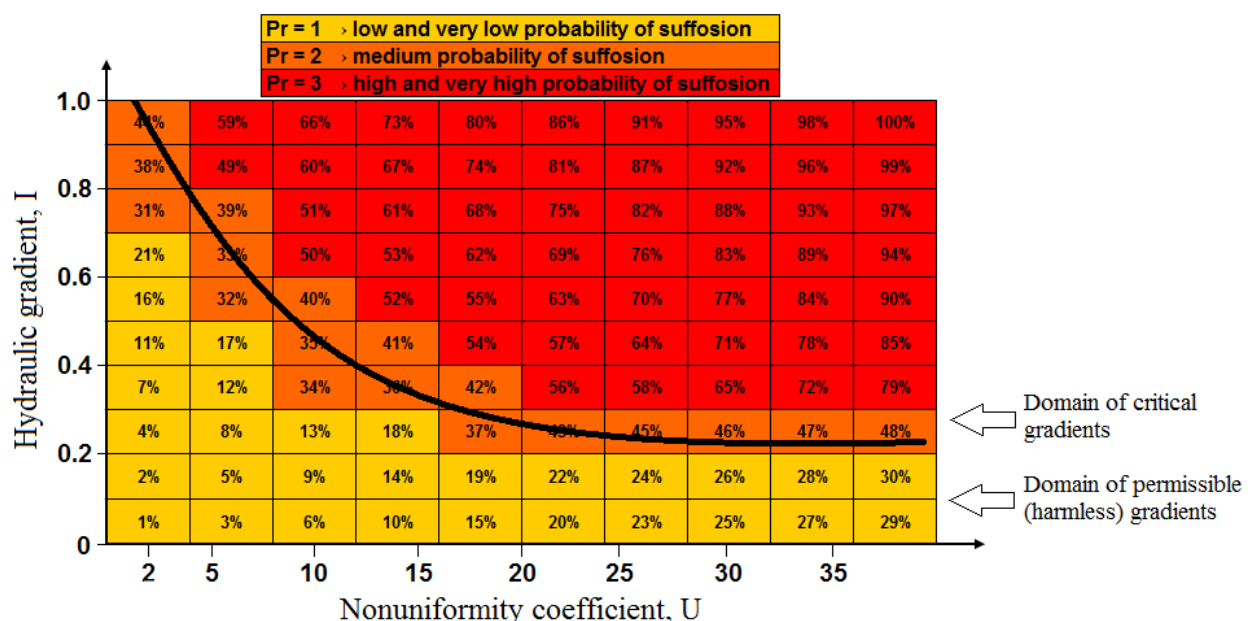


Figure 6. Probability of suffosion according to the hydraulic gradient and the nonuniformity coefficient

In the case of North Pesteana open-pit, from the point of view of the risk of suffusion, the inflow of water coming from the SSE and SSW towards the remaining gap (when the dewatering systems will be shutdown) is of particular interest. This may lead to the entrainment and transport of the finer particles from sandy rocks layers with nonuniform granulometry. In order to analyze the situation in the North Pesteana perimeter from this point of view, it was necessary to determine, analyze and interpret the values of the hydraulic gradients.

The hydraulic gradients were calculated taking into account the last available data regarding the aquifer formations within the Motru complex [15] (from the existing boreholes: Figures 7 and 8 and Table 5).



Figure 7. Location of dewatering boreholes of phreatic aquifers and the Motru complex aquifers

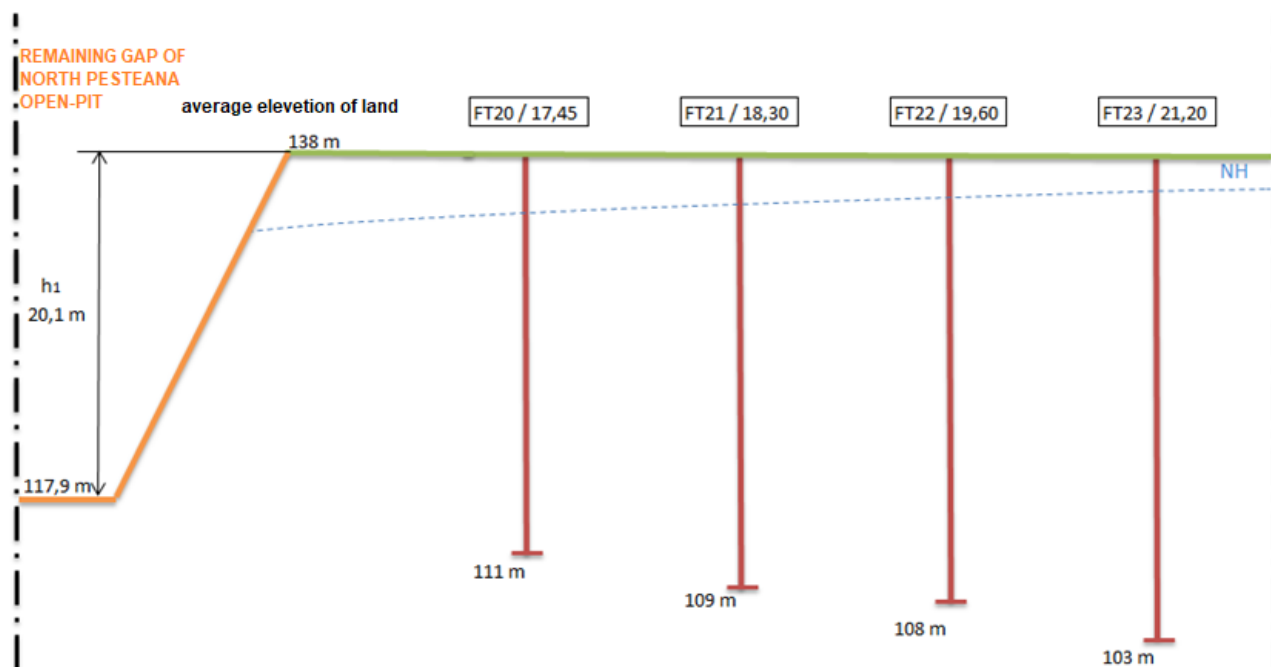


Figure 8. Groundwater aquifer - Hydrostatic level (according to FT20-FT23 boreholes on the eastern slope)

Table 5. Calculated hydraulic gradients*

Aquifer		Borehole	Distance between the boreholes [m]	Level difference [m]	Hydraulic gradient	
					I	I _{med}
Phreatic aquifer		FT21-FT20	150	0.85	0.005667	0.007619
		FT22-FT21	150	1.30	0.008667	
		FT23-FT22	150	1.60	0.010667	
		PC6-PC2	356	1.60	0.004494	
		PC8-PC4	291	0.73	0.002509	
		PA6-PC6	178	1.90	0.010674	
		PA6-PC2	424	3.50	0.008255	
		PA6-PC3	457	4.13	0.009037	
		PA6-PC4	649	5.60	0.008629	
The Motru aquifer complex	Between layers VII-VIII of lignite	PC8-PC4	291	8.58	0.029485	0.019982
		PA6-PC4	649	6.8	0.010478	
	Between layers IV-V of lignite	PC8-PC4	291	13.35	0,045876	0.031890
		PA6-PC4	649	11.62	0,017904	
Artesian from the bad of the IV th layer of lignite		RA1-RA3	280	0.41	0,001464	0.001464

* The primary data, namely the distance between the boreholes and the level difference, on which the calculations of the hydraulic gradient were based, were taken from the technical documentation of the Oltenia Energy Complex [15].

Analyzing the results, we can observe the low values of the hydraulic gradients ($I < 0.05$), which denotes a reduced probability ($P = 1$) for the occurrence of suffosion phenomena at these two steps, even in case of nonuniform sands.

Considering the 3 vulnerability classes, respectively 3 probability classes, the following scale was established to assess the suffosion risk:

- For $R = 1 \rightarrow$ very low risk of suffosion;
- For $R = 2 \rightarrow$ low risk of suffosion;
- For $R = 3 \div 4 \rightarrow$ medium risk of suffosion;
- For $R = 6 \rightarrow$ high risk of suffosion;
- For $R = 9 \rightarrow$ extremely high risk of suffosion.

Therefore, due to the fact that the probability is equal to 1 (low depending on the hydraulic gradient and the nonuniformity coefficient), the risk of occurrence of suffosion phenomena is determined to be also a low one ($R = 2$), as highlighted in the risk assessment matrix (Table 6).

Table 6. Risk assessment matrix for North Pesteana open-pit

Probability \ Vulnerability	Pr = 1	Pr = 2	Pr = 3
V = 1	1	2	3
V = 2	2	4	6
V = 3	3	6	9

In order to eliminate the suffosion risk and prevent other more serious geotechnical phenomena that may occur in the conditions of flooding of former open-pits, some simple measures can be taken. Studying the specialized literature and taking into account the results of the assessment of the suffosion risk, it is recommended to control the inflow of water that contributes to the flooding of former open-pits by maintaining in operation some of the existing dewatering systems and by the development of water supply systems from other sources. The control of the water inflow and the supply from external sources is applied to reduce the risk of suffosion and the acceleration of the flooding process (that has positive effects for all types of geotechnical risks) [16]. The water pressure on the slope leads to increased resistance forces, opposed to sliding, and the water mass in the lake behaves like a support prism. So it is advisable to accelerate the process of flooding the remaining gap of North Pesteana open-pits, a solution which can be materialized by the construction of a water supply system from the nearby Jiu River, the only permanent surface water source. The amount of water that can be taken over can only be determined by the Romanian Waters Administration.

4. Conclusions

In conclusion, according to the study, there is a low risk for the occurrence of suffosion phenomena at the IIIrd and IVth steps of the North Pesteana open-pit in the conditions of flooding its remaining gap mainly as a result of lithological structure of the perimeter in which layers of sandy rocks with variable nonuniformity coefficients are highlighted, that may affect the objectives located in the influence area.

The suffosion phenomena recorded in the perimeter over time were manifested at the top of the IVth step and at the bottom of the IIIrd step and did not jeopardize the stability of the individual steps or the system of steps. The results obtained confirm that the risk of suffosion exists, but the occurrence of a large-scale suffosion phenomenon is not question. In order to eliminate the suffosion risk during the flooding of former open-pits, it is recommended to apply a controlled method of flooding and to maintain the speed of aquifer currents lower than the critical speed.

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