QUALITATIVE ANALYSIS OF SLOPE STABILITY

Izabela-Maria APOSTU, Maria LAZĂR**, Florin FAUR****

Abstract: *Assessing land stability is a difficult process. Over time, evaluation methods have been developed providing a high degree of reliability. Stability studies are complex activities that involve interdisciplinary research, time, material resources, and financial resources. In addition, many uncertainties and errors could affect the stability studies. Also, simplified procedures for assessing land stability were developed. The fuzzy method is applied in many fields when a qualitative evaluation is required starting from uncertain data. The applicability of the method is presented in this paper, the fuzzy method being used to estimate the stability of the slopes of North Pesteana open-pit. The analysis was performed on 8 different slopes in terms of geometric, structural elements and geotechnical characteristics, both during operation, in conditions of natural water drainage and post-operation, taking into account an unfavorable situation, namely the restoration of aquifer resources.*

Key words: *qualitative analysis, fuzzy method, stability, open-pit slope, dump slope*

1. Introduction

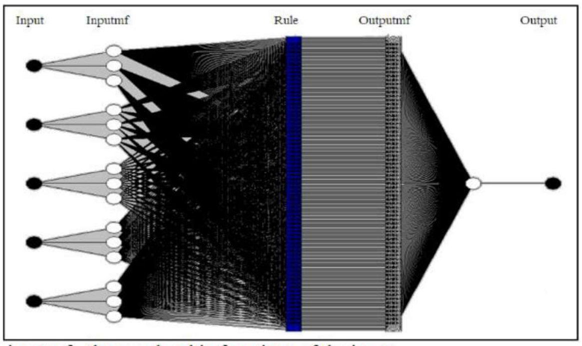
Qualitative analysis is a preliminary stage to quantitative analysis and provides a subjective assessment of the proposed issue.

The tools of fuzzy logic have been used in various circumstances and fields since the early part of the XXth century. Assessing the degree of stability of a slope is one of the many possible applications of this method. Kacewicz (1987), Dodagoudar and Venkatachalam (2000) and others, describe the uncertain parameters by fuzzy sets that they use in slope stability analyses. Ruigeng (1998), Yuanyou and Ruigeng (2000), as well as others, presented intelligent systems and applications of fuzzy sets. These are based on decisions for control plans on slope instability assessments. Other researchers, such as Khakestar et al. (2016) applied multicriteria decision methods for assessing slope stability. In a recent research, conducted by Mohamed et al. (2019), input and output parameters were used as membership functions to build a fuzzy interference system for estimating the stability of the slopes (fig. 1) and the results showed that this method allows the determination of the stability coefficient with a satisfactory degree of accuracy.

The advantages of applying the fuzzy method consists in its ability to provide a fast and quite accurately (Azarafza et al., 2020), qualitative indications on the degree of slope stability using a simplified but rigorous procedure and guidance on possible consolidation works.

In the present paper, the fuzzy method and N. Janbu's method (a deterministic method), are applied to estimate the degree of stability of the slopes of a lignite open-pit (North Pesteana open-pit).

* *Assist.eng. Ph.D, University of Petroșani*
** *Prof.eng. Ph.D, University of Petroșani*
*** *Lect.eng. Ph.D, University of Petroșani*



inputmf - the membership functions of the input
outputmf - the membership functions of the output

Fig. 1. *Fuzzy interference system for slope stability prediction (Mohamed et al., 2019)*

2. N. Janbu's method

N. Janbu's method is known in the stability literature as the method of dimensionless parameters. It is based on the calculation of shear stress. Janbu's method is used for slopes consisting of several layers with different geotechnical properties (Janbu, 1954), but it is increasingly used in the case of waste rocks, providing results similar to those obtained by other methods such as the method of Fellenius, Bishop and so on.

Janbu's method analysis:

- the slope stability for purely cohesive rock formations ($c \neq 0$, $\varphi = 0$);

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

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

The stability coefficient (Fs) can be calculated taking into account the stability number for simple slopes (N; the stability number for simple slopes in the case of purely cohesive rocks is noted N_o and the stability number for rocks with cohesion and internal friction angle is noted $N_{c\varphi}$) deduced from the graph of Janbu, cohesion (c), volumetric weight of rocks in the natural state (γ_a) and slope height (H), with the following relationship (Relation 1):

$$F_s = N \cdot \frac{c}{\gamma_a \cdot H} \quad (1)$$

Also, Janbu's method allows the calculation of the stability coefficient in the conditions of the influence of other factors, in the specialized literature being presented a series of relations of calculation for stability coefficient (Janbu, 1954).

Slope stability analyses for the North Pesteana open-pit were made using the Slide software specialized in geotechnics (Rocscience, 2010), which analyses the stability of natural and artificial slopes regardless of their geometry. It can perform analyses in both static and dynamic conditions, as well as in the case of the manifestation of pore water pressure or in the case of submerged slopes.

Stages in slope stability analysis:

I. *Introduction of geometric and geotehnical characteristics of slope.*

The soft allows the manual or automatic definition of sliding surfaces.

II. *Calculation of stability coefficients.*

The program automatically calculates the stability coefficients, using different methods for this purpose and offering the possibility to choose the evaluation method/methods. In the present study, the method described above, namely Janbu's method, was chosen for performing stability analyses.

III. *Determination of the critical sliding surface.*

The critical sliding surface area corresponding to the minimum value of the stability coefficient shall be determined.

3. Fuzzy method

The tools of fuzzy logic allow the rigorous treatment of the problems, when a qualitative evaluation is required starting from a series of data with a high degree of approximation (Zadeh, 1965).

Calculation stages:

I. *Defining the membership functions of the characteristic parameters.*

The membership function is the basic tool of fuzzy logic and indicates the degree of belonging of a data series to a certain set. Those values of the parameters considered that belong to the mass / deposit considered will have a degree of membership equal to 1. The values of the parameters that do not belong to the mass/deposit have a degree of membership equal to 0. The intermediate values have intermediate degrees of membership.

II. *Generating the membership function of the stability coefficient.*

By combining the available value sets and using a deterministic calculation method, the corresponding values of the stability coefficient are obtained (one for each set of values). The possible sliding surface can be determined by a preliminary check with a set of average values of the chosen parameters. With the determined values of Fs, the function of membership of the stability coefficient is constructed.

III. *Qualitative assessment of slope stability.*

The equilibrium condition is Fs = 1. Based on the function of membership to the stability coefficient Fs = 1 it is possible to obtain a qualitative indication of the degree of stability of the analyzed slope, using the scheme proposed by Sakurai and Shimizu (1987) (Fig. 2).

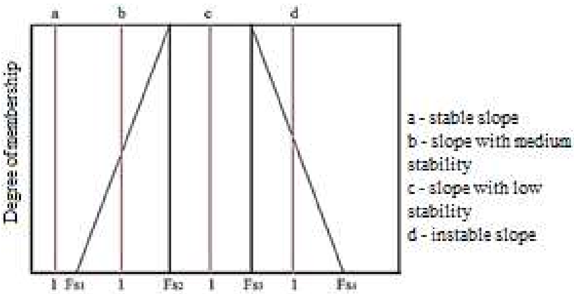


Fig. 2 *Scheme for estimating the degree of stability*

In the present paper, the input parameters are the slope height, slope angle, volumetric weight, cohesion and internal friction angle, and the output parameters are the stability coefficients based on which the degree of stability is estimated.

4. Qualitative analysis of slope stability of North Pesteana open-pit

The North Pesteana mining perimeter is part of the Rovinari Mining Basin and includes a lignite open-pit, the external dump and the inner dump. The external dump is in the process of revegetation, the sterile material being deposited in the inner dump. Exploitation and dumping works are performed in 4 steps (Fig. 3).

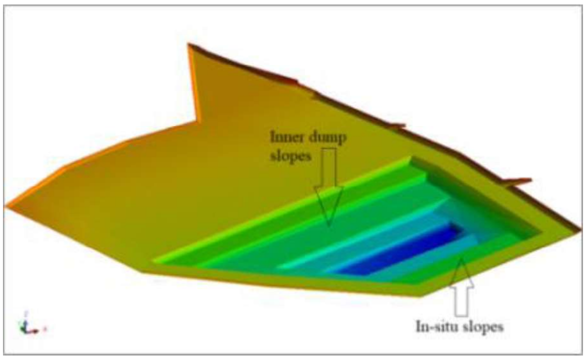


Fig. 3 *North Pesteana open-pit steps (Apostu and Florea, 2018)*

The geometric elements (slope height and slope angle) characteristic to the in-situ and dump steps are shown in table 1.

Table 1. *Geometric elements of the slopes*

Step	Dump		Open-pit	
	H [m]	α [°]	H [m]	α [°]
I	10,2	25	20,1	46
II	15,1	26	19,7	36
III	14,8	27	20,1	40
IV	14,9	26	14,2	36

The values of the geotechnical characteristics of the rocks, some resulting from the laboratory test and some taken from specialized studies (Nyari Apostu, 2019; ***, ICSITPML, 2007), were subjected to statistical-mathematical processing, determining the minimum, maximum, average values, the average square deviation (σ), average - σ and average + σ.

The degree of membership to the ensemble of dump 1 was granted for the values between the average - σ and the average + σ, respectively the degree of membership 0 to the minimum and maximum values, thus obtaining four sets of values (table 2).

Table 2. *Sets of values subject to stability analysis*

Values	Mixture of waste rocks			In-situ rocks			
	γ_a $\frac{KN}{m^3}$	c $\frac{KN}{m^2}$	ϕ °	Nature of rocks	γ_a $\frac{KN}{m^3}$	c $\frac{KN}{m^2}$	ϕ °
Minimum	16,12	7,68	16,06	Boulders, gravel	20,1	0	35
				Sands	16	4	20
				Clays	17,5	20	8
				Marls	16,73	26	12
				Vegetal soil	13,7	19	18
				Lignite	11,7	120	25,7
Average - σ	16,33	8,93	19,41	Boulders, gravel	20,33	0	35
				Sands	18,45	4,76	23,36
				Clays	18,74	27,48	13,11
				Marls	18,32	24,81	15,57
				Vegetal soil	13,7	19	18
				Lignite	11,92	151,88	25,99
Average + σ	19,40	17,98	27,52	Boulders, gravel	22,49	0	35
				Sands	20,42	10,39	31,96
				Clays	20,54	54,65	25,75
				Marls	19,92	61,04	24,09
				Vegetal soil	15,7	29	22
				Lignite	12,74	271,5	44,89
Maximum	21,37	22,80	31,43	Boulders, gravel	23,8	0	35
				Sands	20,6	12	38
				Clays	21,7	65	34
				Marls	20	93	27
				Vegetal soil	15,7	29	22
				Lignite	13,9	274,5	49

The statistical-mathematical processing was carried out in order to obtain representative values, which would characterize the in-situ rock layers depending on their nature, respectively the entire dump as a mixture of rocks.

According to the report made by the Ministry of Energy in 2016, the North Pesteana open-pit will cease its activity starting with 2023, as a result of the exhaustion of the lignite reserve within the license perimeter. (***, 2016) According to the studies performed, once the exploitation activity ceases and the dewatering systems are stopped, the remaining gap of the North Pesteana open-pit will be flooded in approx. 10 years. This process will lead to the occurence of an open-pit lake. (Nyari and Lazar, 2017; Apostu and Florea, 2018)

For these reasons and knowing the current conditions (natural and artificial drainage of aquifers) and future ones (restoration of aquifer resources with the cessation of dewatering systems), it is necessary to assess the stability of slopes in both situations in order to raise the security of objectives in the areas of influence.

Stability calculations were performed for natural humidity conditions, given that the geometry of the in-situ steps, the geometry of the dump steps, the nature and granulometry of the materials facilitate the drainage of groundwater and for saturated rock conditions considering the restoration of groundwater to the roof of aquifers.

Regarding the dumped material, the saturation of the whole rock mixture is impossible as the nature of the rocks and the degree of loosening ensure the good drainage of the water from the dump.

The stability coefficients were calculated using the specialized software presented above and the results of the stability analyses are presented in Tables 3 - 4.

Table 3. *Stability coefficient values for waste rocks*

Humidity conditions	Stage	Stability coefficient, Fs			
		minimum	average - σ	average + σ	maximum
Natural	I	1,151	1,371	2,150	2,338
	II	1,014	1,219	1,784	1,935
	III	1,179	1,430	2,160	2,461
	IV	0,978	1,179	1,803	2,111
Saturated	I	1,010	1,199	1,901	1,875
	II	0,759	0,916	1,434	1,571
	III	0,779	0,944	1,564	1,838
	IV	0,724	0,871	1,427	1,705

Table 4. *Stability coefficient values for in-situ rocks*

Humidity conditions	Stage	Stability coefficient, Fs			
		minimum	average - σ	average + σ	maximum
Natural	I	0,664	0,876	1,528	1,582
	II	0,949	1,185	2,010	2,381
	III	0,838	0,957	1,568	1,952
	IV	1,126	1,168	2,151	1,612
Saturated	I	0,648	0,858	1,154	1,242
	II	0,732	0,895	1,573	1,868
	III	0,463	0,561	1,016	1,296
	IV	0,543	0,657	1,198	1,469

Based on the values presented in tables 3 and 4, graphs were constructed which qualitatively estimate the degree of stability of the quarry and dump steps. The interpretation of the results can be followed in the Figures 4 - 7. The presented cases were chosen according to the less favorable geometric elements, respectively heights and slope angles with the highest values.

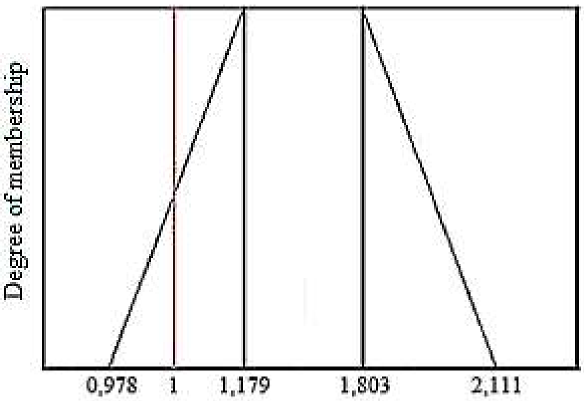


Fig. 4 *Qualitative estimation of the stability of the IVth step of the inner dump under natural water drainage conditions*

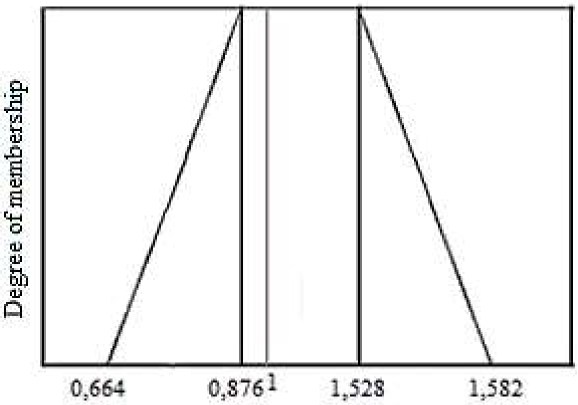


Fig. 5 *Qualitative estimation of the stability of the Ist step of the open-pit under natural water drainage conditions*

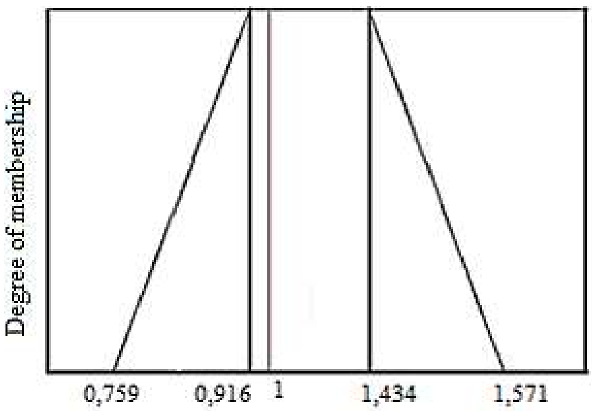


Fig. 6 *Qualitative estimation of the stability of the IInd step of the inner dump under the conditions of restoration of aquifer resources*

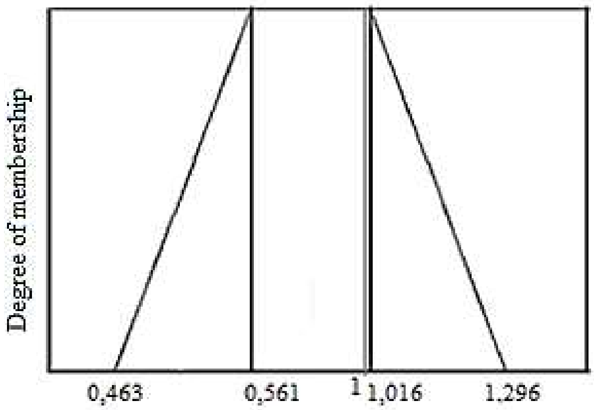


Fig. 7 *Qualitative estimation of the stability of the IIIrd step of the open-pit under the conditions of restoration of aquifer resources*

The same stages were followed to determine the degree of stability for the other steps. Thus the following results were obtained:

❖ *natural water drainage conditions:*
- stable steps: IVth in-situ step and Ist, IInd and IIIrd dump steps;
- medium stability steps: IInd sin-situ step and IVth dump step;
- low stability steps: Ist și IIIrd in-situ steps;

❖ *restoration of aquifer resources:*
- stable steps: Ist dump step;
- medium stability steps: IInd in-situ step and IVth dump step;
- low stability steps: all the in-situ steps and IInd, IIIrd and IVth dump steps.

According to the results, stage IV of the dump under conditions of natural drainage of water from rock pores has medium stability (see Fig. 4), and possible movements can be limited by exploitation technology.

The low stability of Ist and IIIrd in-situ steps in conditions of natural drainage of water (see Fig. 5) can be explained by the presence of aquifers, sands with low resistance characteristics (cohesion and internal friction angle) and/or the geometric elements of the in-situ steps, especially the slope angles that reach high values of 40 - 46 °.

Comparing the situations presented in Figures 6 - 7, it is observed that, although the two analyzed steps (under saturated conditions) have a low degree of stability, one is more stable than the other. Thus, the consolidation works are a priority for the most unfavorable situation, namely for the IIIrd in-situ step. Thus, the qualitative estimation of the degree of stability allows the construction of a hierarchy, prioritizing the necessity to consolidate the slopes.

The increase of the rock humidity determines the reduction of the stability reserve due to the manifestation of the pore water pressure. Under these conditions, all steps have low stability, according to the qualitative analysis based on the fuzzy theory, except for the Ist dump step which is stable both in conditions of natural water drainage and in the conditions of restoration of aquifer resources. First dump step is stable mostly due to the favorable geometric elements, especially the low height, but also because the nature of the rocks and the degree of loosening do not allow the saturation of the rocks.

The restoration of aquifer resources up to the roof of aquifer formations is unlikely, but the results are not to be neglected, especially if the analyzed slopes show a doubtful stability even without the negative influence of water.

First and third in-situ slopes require interventions to increase the stability reserve, which may involve redesigning the geometric elements of the slopes, adapting the exploitation technique to reduce the slope angle, maintaining the dewatering systems to prevent rising rock humidity and pore water pressure.

5. Conclusions

The fuzzy method was applied to verify the stability of 8 different slopes in terms of geometric and geotechnical characteristics. The input parameters taken into account are the slope height, the slope angle, the volumetric weight of the rocks, the cohesion, and the internal friction angle, and the output parameters are the stability coefficients.

The described procedure is easy to apply, provides fast results with high degree of reliability and indications on the necessity of slope consolidation work.

It was found that, in the analyzed case, the in-situ steps are more prone to slide regardless of the humidity of the rocks. This can be explained by the presence in the lithological structure of aquifers, consisting of sands whose strength characteristics are low, as well as by an unfavorable step geometry in terms of stability. Instead, the mixture of waste rocks in a loose state facilitates the drainage of water, and the geometry of the steps is favorable to stability.

The negative influence of water on the rocks was highlighted and it was found that all steps, except for the Ist dump step, have a low degree of stability under these conditions.

In the case of slopes with medium stability, possible displacements may be limited by arrangements or exploitation technology, while in the case of slopes with low stability more complex consolidation work are required.

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