Application of the limit equilibrium method to determine the safety factor for ornamental rocks

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Abstract

The state of Espirito Santo is the most important producer and exporter of ornamental quarry stone. In its various quarries, it uses bench heights that range from 5, 20, 50 and 100 meters. The high altitudes raise concerns about the stability of the slopes. Therefore, the study focuses on determining the value of the safety factor (SF) for these heights using the limit equilibrium method. To make this possible, the values of simple uniaxial compression, Geological Strength Index (GSI), the disturbance factor, and intact rock parameter must be obtained. To obtain the GSI, it is necessary to establish a correlation with the Rock Mass Rating, the values of which are determined using a scan line. The uniaxial compression values were treated statistically, obtaining classes at 75, 100, 125, 150, 175, and 200 Mpa. The 2D slide software was used to obtain the SF values for the respective heights. With the results obtained, these rocks do not present stability problems. The correct choice of GSI is of paramount importance for a good analysis, as it directly affects the results. Using this technique to determine safety factors is appropriate, but it is necessary to analyze more robust methods to compare the results.

Keywords: ornamental quarry stone, slope stability, bench height, limit equilibrium method, safety factor.

1. Introduction

The southeastern region of the country has a strong aptitude for producing ornamental rock, yielding 60.65%, which is more than half of the national production, with the state of Espírito Santo standing out as its main producer with 36.96%. This sector was responsible for exporting US $ 1.07 billion in 2017, with Espírito Santo responsible for 81.7% of the total of this value (Chiodi Filho, 2018).

Among the Brazilian states, the largest exporters are: Espírito Santo, Minas Gerais and Ceará occupying more than 90% of the volume of exported rock. From January to June 2019, the volume of rock exported exceeded 980 thousand tons of rock of different lithologies and degrees of industrialization (Chiodi Filho, 2019).

Increased productivity and reduced costs are recurring concerns in the business world, which leads to the search for new technologies or a new operational standard. In the sector of ornamental rocks, the aim of these changes is to increase the height of countertops, which can lead to greater instability in the rock mass. On the other hand, this change has brought great benefits, including increased productivity by reducing the time cycle of operations and reduction cost (Silva *et al*., 2019).

The mining of ornamental rock can be performed by the method of boulders or rock mass. In the latter method, it was possible to divide it into low countertops with a height of up to 5 meters, high benches with heights of up to 20 meters and ultra high countertops that already exceed 100 meters (Vidal *et al*., 2013).

As the height increases, problems with slope stability arise, causing concern to researchers. They propose several methods to ensure slope stability. These are divided into four types: kinematic analysis, limit equilibrium, numerical modeling, and empirical methods (Basahel and Mitri, 2017).

In this study, the limit equilibrium method is used, which compares the driving and resisting forces along the slip plane to determine the safety factor (SF) (Basahel and Mitri, 2017) when evaluating the stability of ornamental rock slopes with heights from 5 m to 100 m, since greater heights raise concerns about worker safety. Therefore, checking the stability of the slopes in the ornamental quarry stone mining is of great importance to the operation, since it is directly related to the safety of workers, the environment and the company's assets. The stability of the rock mass is given by a safety factor, which takes into account the resistive forces and the shear forces, as can be seen in equation 1 (Vallejo *et al*., 2002).

$$Safety\ Factor = \frac{\Sigma\ Resistive\ Forces}{\Sigma\ Shear\ Forces} \quad (1)$$

According to Read and Stacey (2009) and Wyllie and Mah (2004), the value of SF for mining slopes should be between 1.2 and 1.4 to ensure stability of the rock mass at the surface. According to Vallejo *et al*. (2002), geometry and geology directly affect stability. Safety values for permanent slopes should be between 1.5 and 2.0 and for temporary slopes about 1.3. In order to analyze slope stability using the limit equilibrium method, it is necessary to classify the rock mass, such as according to Bieniawski's Rock Mass Rating (RMR). In this classification, the characteristics of the rock mass are analyzed and weighted with the respective weights, obtaining a value.

In addition to the RMR, Hoek and Brown's Geological Strength Index (GSI) can also be used. The GSI can be applied both in its empirical form, using an appropriate table, as shown in Figure 1, and in its equated form as shown in Equation 2, which combines the values of the RMR and GSI (Basahel and Mitri, 2017).

$$GSI = RMR_{1986} - 5 \quad (2)$$

According to Hoek and Marinos (2007), the experimental value of the GSI must be chosen by the user, taking the value that best describes the various types of rocks exposed in their geological environment. These values must be chosen in a line that will determine the disturbance in that geological environment, allowing the user to make his own judgment on how much to reduce the GSI value to explain the loss of strength as seen in Figure 1, but it must follow a criterion so that conservative or insufficient data is not found.

This method is well accepted and there are numerous projects where it is used (Hoek *et al*., 2002), although it has its limitations, including its use in slope and gallery stabilization models (Hoek and Brown, 2019).

According to Hoek *et al*. (2002), the D factor depends on the degree of disturbance suffered by the massif, either by dismantling rocks with explosives, or by relieving tensions caused by excavation. This value is 0 for intact *in situ* rocks or 1 when the massif is very disturbed, this criterion must be used with care.

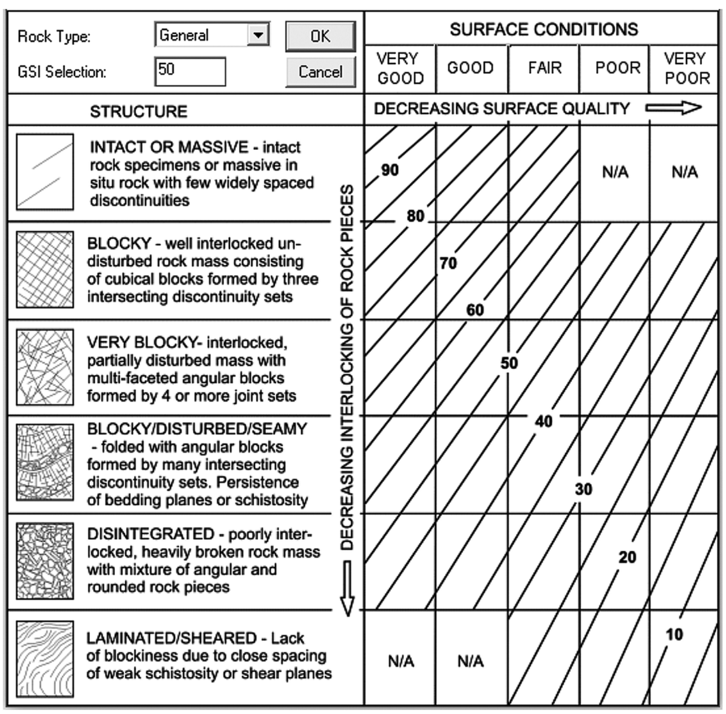

Figure 1 – Determination of GSI index (Source: Hoek and Marinos, 2007).

Since the ornamental quarry stone sector uses this technique to determine the SF on its slopes, even if it is not the most appropriate technique, this study creates a theoretical model that will later be compared with theoretical models using the finite element method in a second phase of this study, allowing the establishment of a correlation between them.

2. Methodology

In this study, information from the Catalog of ornamental rocks of Espírito Santo (Sardou Filho, 2013), subsection Granites and marbles, which has more than 100 catalogs, is being used. The information was placed in a simulation software that used the limit balance method to determine the safety factor associated with ornamental stone benches. Safety factors are simulated for bench heights of 5, 20, 50 and 100 meters, which are being used in Brazil.

Slide® software, available at the UFRGS rock mechanics laboratory at LPM, was used to model and record the SF. Uniaxial compressive strengths of intact rocks were taken from the Catalog of Ornamental Rocks of the State of Espírito Santo (Sardou Filho *et al.*, 2013) and treated with univariate statistics and treated as silicate rocks only.

To estimate the parameters of the rock masses with certain reliability, the software in question uses the general Hoek-Brown rupture criterion. Among them, parameters such as the compressive strength of intact rock (UCS), the geological strength index (GSI), the damage factor in dismantling (D) and the parameter of intact rock (mi) are used, as the software provides the results. Rock mass parameters: mb, s, a, and Erm, penalizing the characteristics of the joints and operational effects as can be seen in Figure 2 below.

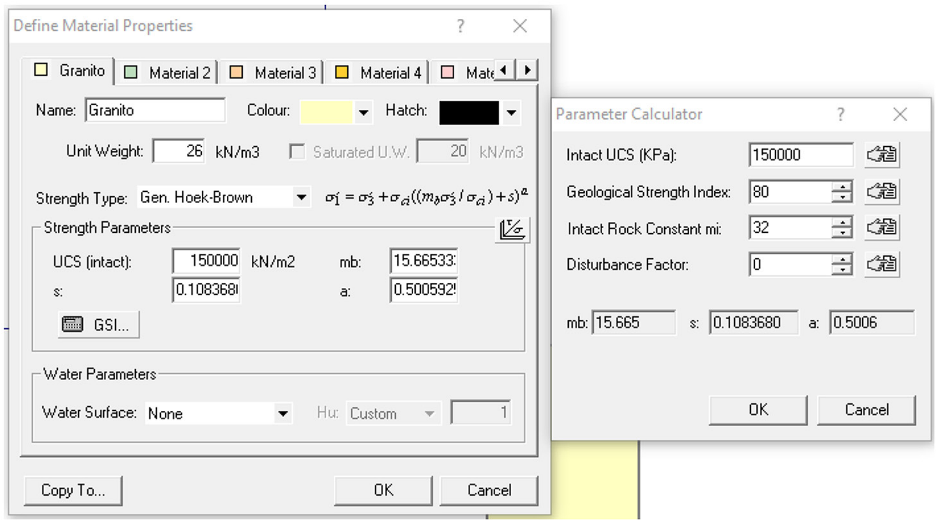

Figure 2 - Screen for entering data from Slide 2D.

With the data obtained in Figure 4, it was possible to select the average UCS values to be used. In order to obtain the GSI value, it is necessary to perform a scan line in the extraction front, as shown in Figure 3 for silicate rocks, which allows to obtain the RMR values developed by Bieniawski (1989), as shown in Table 1.

Figure 3 - Silicate rock with a 10 m scan line.

With scan line analysis in the extraction fronts, it was possible to verify the distance of the discontinuities, their conditions, their RQD, and whether there was water in the discontinuities. Using this information, their weights were compiled in Table 1 below.

Table 1 – RMR Classification System (Source: Adapted Bieniawski, 1989).

CLASSIFICATION PARAMETERS AND THEIR WEIGHTS								
Parameters	Values							
1	Intact Roc Res. (UCS) (in MPa)	> 250	100-250	50-100	25-50	5-25	1-5	<1
	Weights	15	12	7	4	2	1	0
2	RQD (in %)	90 – 100	75 – 90	50 – 75	25 – 50	< 25		
	Weights	20	17	13	8	3		
3	Discontinuity spacings (in m)	>2	0.6–2	0.2-0.6	0.06–0.2	<0.06		
	Weights	20	15	10	8	5		
4	Discontinuity conditions	Very rough Surface, non-persistent, closed, no change	Smooth Surface, <1mm opening and slightly altered wall	Smooth Surface, <1mm opening and heavily altered wall	Striated Surface, filling <5mm or opening from 1 to 5mm persistent	Filling >5mm or opening >5mm persistent		
	Weights	30	25	20	10	0		
5	Water general conditions	Dry	Humid	Wet	Trickling	Abundant flow		
	Weights	15	10	7	4	0		

Based on the weights, Table 2 below was prepared. For this purpose, all the weights of the items collected at the extraction front were recorded and then summed to obtain the RMR and GSI values, the UCS value to be applied in Table 1, and the average value of the silicate rocks when its weight is selected.

Table 2 - RMR and GSI value, calculated by using figure 3.

RMR	
Tabela	Peso
1 - Intact Roc Res. (UCS)	12.00
2 – RQD	20.00
3 - Discontinuity spacings	20.00
4 - Discontinuity conditions	25.00
5 - Water general conditions	15.00
TOTAL	92.00
GSI	87.00

The parameter used for intact rock (MI) is given in the software for granitic rock, while the value 0.0 was used for D because an ornamental rock has little or no disturbance and the failure mode analyzed is non-circular.

3. Results and discussions

The uniaxial compression values, taken from the ES catalog for ornamental rocks were ordered and shortly after subjected to a univariate statistical treatment that allowed the creation of a bar chart in which they were divided into 7 classes of values.

Silicatic rocks have uniaxial compression values ranging from 60 to 221 MPa,

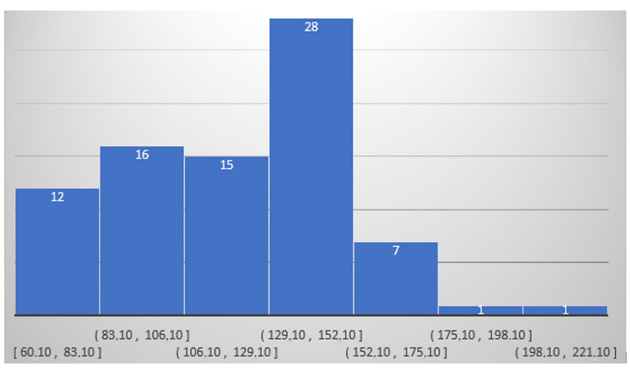

Figure 4 – Bar graph with uniaxial compression values of silicate rocks.

as can be seen in Figure 4. The standard deviation is 31 MPa, with an average of 119.58 MPa, the median is 122.34 MPa, and the mode is 95 MPa.

Figure 4 shows six well-defined classes of values, since there are two extreme values that are grouped in the same class. To simulate rock slope stability, the uniaxial compressive strength (UCS) chosen were 75, 100, 125, 150, 175 and 200 MPa.

After defining the UCS values, used in the ornamental rock quarries and their benches, which vary between 5, 20, 50 and 100 meters, the slope stability analysis was performed for each scenario.

The safety factor (SF) shown in Figure 5 is obtained from the ratio between the sum of the forces resisting shear and the sum of the forces causing the shearing, and can also be defined in terms of acting and resistive moments with the aid of the Slide® software and using a generic topography.

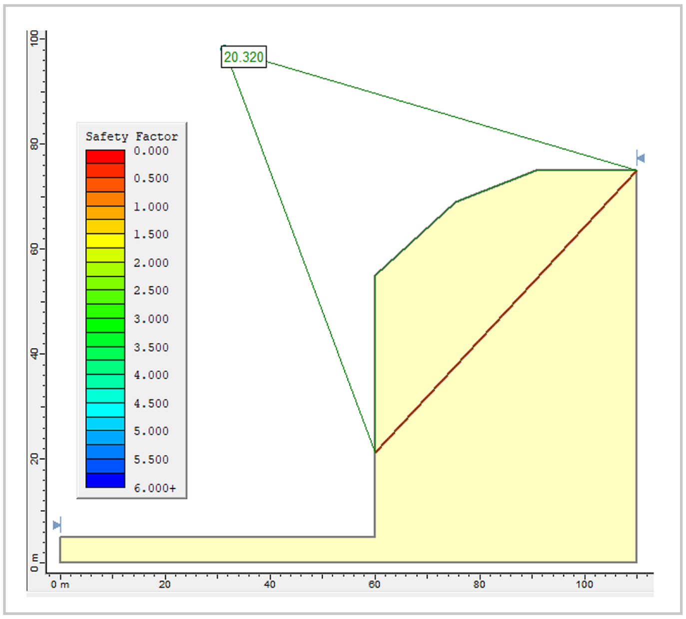

Figure 5 – Image obtained using the slide software, with a bench height of 50m and uniaxial compression values of 125 MPa.

Despite the use of a generic topography for bench heights of 5, 20, 50, and 100 meters, it does not affect the analysis, since the fracture surface of the planar type is included in the model and the GSI, UCS, and MI are considered to perform the general analysis of Hoek and Brow and to obtain the SF and consequently the stability of the rock mass with the four heights already mentioned.

Due to this type of stability, some situations already mentioned in the methodology were analyzed, and at the end of these, it was possible to generate Table 3, where the safety factors estimated in this study are found. With this table, it can be determined that there is no stability problem for the rock masses, since their safety factors do not approach 1.

Table 3 – Safety factor values, related to bench height, uniaxial compressive strength value and rock quality by GSI.

	SF			
UCS (Mpa)	5 m	20 m	50 m	100 m
75	56.94	19.61	13.19	7.89
100	74.96	25.36	16.76	9.83
125	92.98	31.11	20.32	11.76
150	111.00	36.85	23.88	13.68
175	129.02	42.59	27.43	15.60
200	147.04	48.32	30.98	17.51

When observing Table 3, there is a major change in the safety factor of the benches with 5m for the others, which leads to the assumption that there are no problems with this type of bench height; its height being limited to the fracture plans found in the rock.

As for the other heights, the change in SF values is smaller, but the fact that the higher the height, the lower the safety factor is confirmed. Taking as an example, the values of the 100m bench and the data of the simple uniaxial compression value analyzed, there is an increase in the safety of the bench, even if this improvement is small and has no influence on the choice of the slope height.

Table 4 shows a more significant change in the values of the safety factor when comparing values other than the GSI, showing that the choice of this value is fundamental for this type of analysis. Thus, to obtain the appropriate GSI value, it is necessary to use Equation 1, which correlates the values of the classification of the rock mass through the Rock Mass Rating - RMR, which was developed by Bieniawski (1974).

Table 4 - Safety factor values, related to bench height, uniaxial compressive strength value and rock quality by GSI with 82 and 70.

	SF			
UCS /				
150 MPa	5 m	20 m	50 m	100 m
GSI 82	111.00	36.85	23.88	13.68
GSI 70	38.96	14.13	9.95	6.25

From the results of Table 4, it is clear that the quality of the massif and its subsequent classification are of paramount importance for the stability of the slope under study.

A tendency can be seen in Figure 6: the SF curve for a constant. This means that the value of the safety factor decreases uniformly as the height of the bank increases and never tends to zero in this situation.

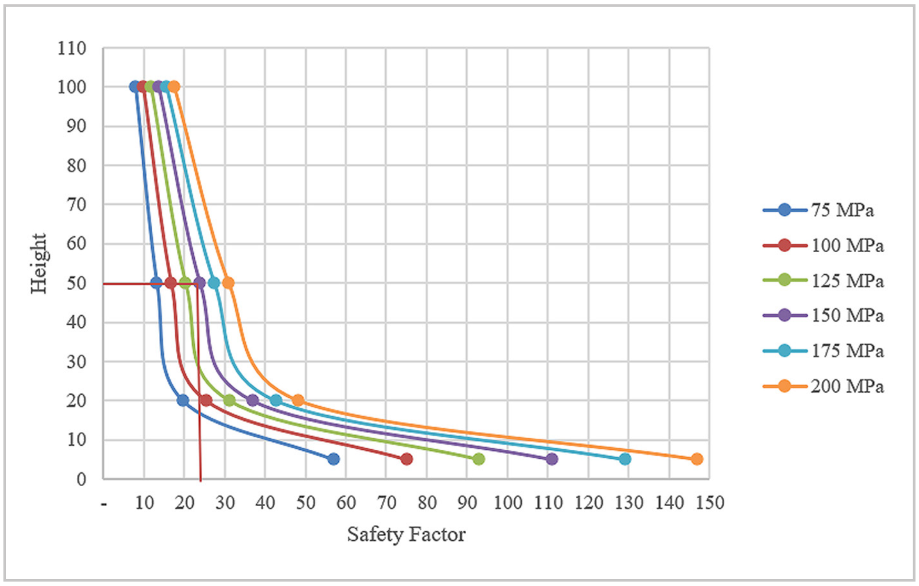

Figure 6 – Correlation chart between safety factor and bench height, for silicate type rocks.

By analyzing the diagram in question, it is possible to estimate SF. For a rock of 150 MPa and a bench height of 50 meters, the safety factor is about 25, which corresponds to the value found in Table 3, which is about 24.

The factor of safety indicates how stable the slope is. It is important to emphasize that this is an exponential scale, where SF = 1 (one) represents the limit safety factor, and the higher this value is, the more stable the slope studied is.

4. Conclusion

The SF found by the method of limit equilibrium for dimensional stones shows us that we have no instability problems with respect to the height of the bench. With the constant increase of heights in search of better productivity, a new nomenclature for them becomes necessary, proposing here that heights up to 5 m should be considered as low benches, heights up to 20 m as medium benches, heights up to 50 m as high benches, and heights above 50 m as ultra-high benches.

The choice of the GSI is a determining factor to carry out the study of the slope stability, and its value should not be determined only by the experience of the person who is doing the study, since less experienced people may make mistakes in determining the value, and should therefore use the classification of the rock massif developed by Bieniawski which is the RMR and correlate it with the GSI values.

Due to the high values of the safety factor, we must evaluate the choice of the limit equilibrium method, because although it is simple to use, it admits simple rupture surfaces of the circular, flat, polygonal and mixed types, making all the points analyzed reach the calculated safety factor. Thus, it may not be the most appropriate method to determine the SF of ornamental rocks.

This preliminary analysis using the method of limit equilibrium shows that the ornamental stone benches, despite their great height, do not present stability problems, which is due to the fact that this technique assumes a homogeneous distribution of forces along the massif, while more robust techniques that take into account such a distribution in a non-homogeneous way are necessary.

The height of the benches must depend on the geotechnical factors studied, since these distinctions will be the best criteria for ensuring the stability of the rock massif throughout the life of the mine.

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