ROCKFALL HAZARD ASSESSMENT AND GEOLOGICAL-GEOTECHNICAL CHARACTERIZATION OF A ROCK SLOPE IN BR-356

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ABSTRACT

The rockfall hazard assessment for roads is very important in geotechnical engineering business. As the process is very fast and complex, a hazard analysis is of fundamental importance for the adoption of preventive action plans and mitigation of potential impacts. Therefore, this article presents a hazard analysis for rockfall and the geological-geotechnical characterization of a rock slope on the BR-356, Ouro Preto, Minas Gerais, Brazil. In the methodology, parameters related to the geotechnical characterization, geometry and slope characteristics were inserted, as signs of block fall activity, impact of external influences and characteristics of the catchment area. According to Rock Mass Rating (RMR), the rock slope was classified as Very Good (Class I). The hazard classification for the slope analyzed varies from low to high. When the rainfall of the rainy season is considered, the slope is classified as a high hazard, while in the dry season, it is classified as low hazard. The study revealed that even if the hazard class is low, the slope deserves attention, since there is not enough space for rock blocks to be deposited before reaching the road, which can generate damages and temporarily paralyze the activities of the road.

KEYWORDS: rockfall, geological-geotechnical hazard, geological-geotechnical characterization, highway, Bação Complex.

AVALIAÇÃO DE PERIGO DE QUEDA DE BLOCOS E CARACTERIZAÇÃO GEOLÓGICO-GEOTÉCNICA DE UM TALUDE ROCHOSO NA BR-356

RESUMO

A avaliação de perigo de queda de blocos para rodovias é um tema muito importante no ramo da engenharia geotécnica. Como o fenômeno é muito rápido e complexo, uma análise de perigo é de fundamental importância para adoção de planos de ação preventiva e mitigação de impactos potenciais. Posto isto, este artigo apresenta uma análise de perigo de queda de blocos e a caracterização geológico-geotécnica de um talude rochoso, localizado às margens da BR-356, na cidade de Ouro Preto, Minas Gerais, Brasil. Na metodologia, parâmetros relacionados à caracterização geotécnica, geometria e características do talude, assim como indícios de atividade de quedas de blocos, impacto das influências externas e características da área de captação de blocos. Segundo o Rock Mass Rating (RMR), o maciço rochoso foi classificado como muito bom (Classe I). A classificação de perigo para o talude analisado varia de baixa até alta. Quando a precipitação da estação chuvosa é considerada, o talude é classificado como de perigo alto, enquanto em épocas de estiagem, o talude é classificado como perigo baixo. O estudo revelou que mesmo a classe de perigo sendo baixa, o talude merece atenção, visto que não há espaço suficiente para blocos de rocha se depositarem sem atingir a plataforma rodoviária, podendo gerar danos e/ou paralisar temporariamente as atividades da rodovia.

PALAVRAS-CHAVE: queda de blocos, avaliação de perigo, caracterização geológico-geotécnico, rodovia, Complexo do Bação.

1 INTRODUCTION

Geotechnical problems such as landslides on slopes occur frequently in various parts of the world with different causes. Among the various types of landslides, there is rockfall. According to Hoek and Bray (1981), rockfall corresponds to the detachment of a rock block from a slope, with little or no shear rupture of the rock bed. These blocks can have variable sizes and shapes, according to the orientation, spacing and persistence of the discontinuities present in the rock mass.

In urban areas, the natural characteristics are very important factors for the triggers of landslides, however, these agents are boost, often by anthropic action, which has intensified in recent decades (Effgen & Marchioro, 2017). Rockfall upon reaching the road surface can cause traffic stoppage and road bans, compromising the flow of cargo and/or passengers. The rockfall process is fast and difficult to predict, so a hazard analysis is of fundamental importance for the adoption of preventive action plans and mitigation of potential impacts.

Fell (2008) defined hazard as the description of the magnitude and probability of occurrence of the landslides. In case of rockfall the hazard analysis includes the estimation of the probability of occurrence and the intensity of the event.

This article presents a rockfall hazard assessment and a geological-geotechnical characterization of a slope located in BR-356, between the km 72 and 74 of the road, in the town of Ouro Preto, state of Minas Gerais, Brazil. The BR-356 highway is located in the states of Minas Gerais and Rio de Janeiro, and can be considered a strategic highway for the flow of materials and passengers, promoting the economy and mobility in Brazil. As it is an alternative link between the metropolitan area of Belo Horizonte and the northwestern region of Rio de Janeiro, a slope on a stretch of BR-356 highway was chosen for geological-geotechnical characterization and hazard analysis for the rockfall.

The slope is in the southeast portion of the Bação Complex, coordinates UTM 0637909/7750176 (Figure 1). The Bação Complex is comprised of approximately 385 km2 and is located in the southeast of the Quadrilátero Ferrífero, in the state of Minas Gerais, Brazil. According to Figueiredo et al. (2004) this Complex constitutes the crystalline basement granite-gneissic-migmatitic of the geological units of the Quadrilátero Ferrífero.
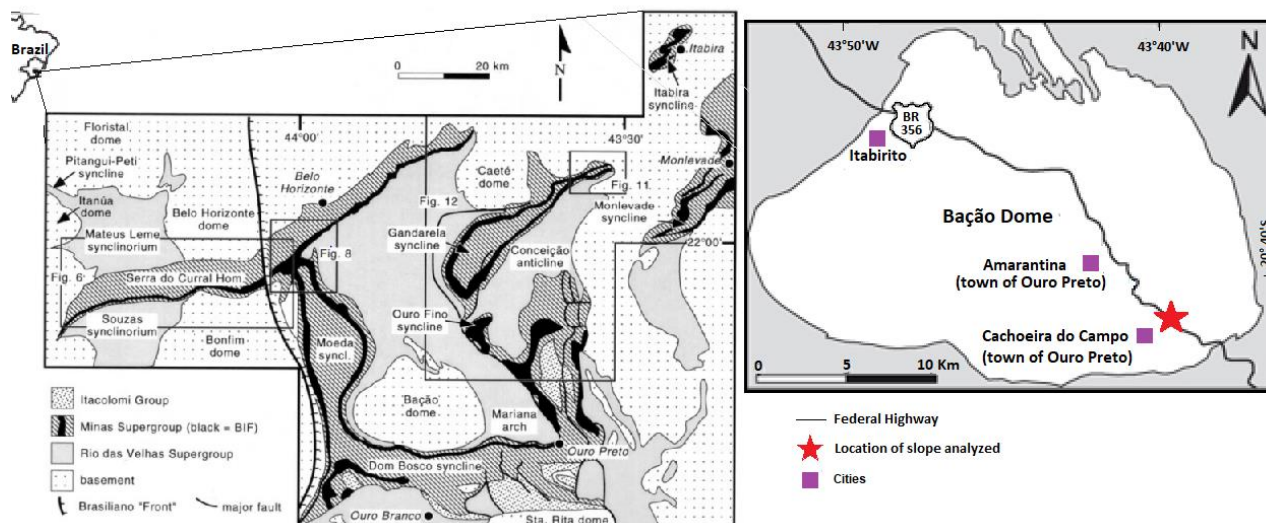
Figure 1: Geological map of the Quadrilátero Ferrífero and location map of slope studied (modification of Alkmim and Marshak, 1998; Fonseca and Evangelista, 2013).

2 MATERIALS AND METHODS

The development of this study was based on the use of a geological-geotechnical survey and geometric parameters of a rock slope found on highway BR-356 in the section comprised in the district of Cachoeira do Campo, Minas Gerais, to determine the geomechanical classification of this slope and the rockfall hazard assessment.

The geological-geotechnical characterization model adopted for analysis was according to Santos et al. (2017). For the geological-geotechnical characterization of the slope, the RQD of the rock masses was determined by means of the relationship proposed by Palmström (1982), Equation (1). For determination of the volumetric joint count (Jv), the mean spacings of discontinuity families (Si) by means of Equation (2), as proposed by Palmström (1982) were used.

$$RQD = 115 - 3,3\,J_V \tag{1}$$

$$J_V = \sum \frac{1}{S_i} \tag{2}$$

The RMR determination was performed according to Bieniawski (1973), using the parameters of intact rock compressive strength, RQD, as spacing, discontinuity conditions and water condition.

For rockfall hazard assessment, the methodology proposed by Silveira (2017) was used. Silveira (2017) adjusted the methodology of Bauer and Neumann (2011) to Brazilian environmental conditions. In this methodology, the level of hazard is provided by means of a probability matrix (Figure 2A) versus intensity. The probability of rock falls is from the

susceptibility analysis. One of the characteristics that is being presented in the geotechnical characteristics of the slope is the catchment area of the blocks; analysis of indicators of recent activity and external influences such as precipitation and seismic effects. The intensity of the rockfall is given based on the total volume of fallen blocks in the catchment area. The rockfall hazard matrix can be viewed in the Figure 2B. The Tables 1, 2 and 3 show in detail, the classification of each of the characteristics observed in the field, an assigned score and also the weight, according to that proposed by Silveira (2017).
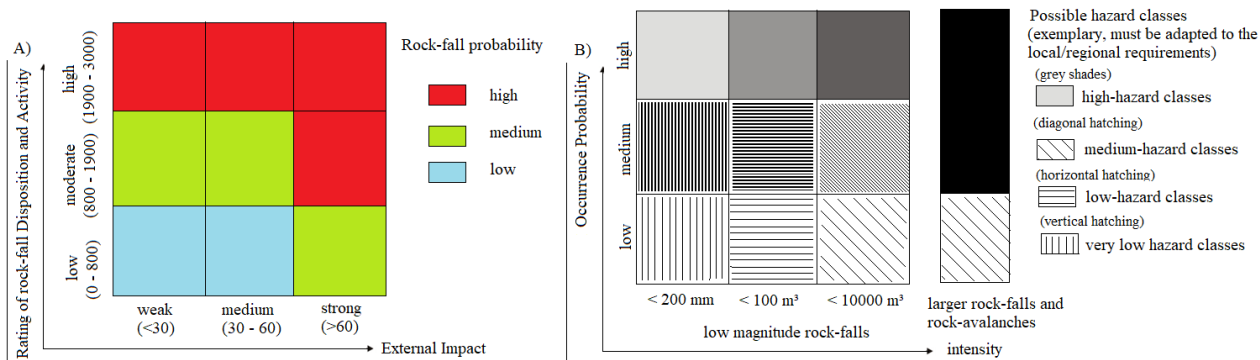

Figure 2: A) Rockfall probability matrix e B) Rock-fall hazard matrix (adapted by Bauer and Neumann, 2011).

Table 1: Table for calculation of the susceptibility to the rockfall (Bauer and Neumann, 2011; adapted by Silveira, 2017).

1) Orientation of discontinuities	Unfavorable	Fair	Favorable
Characteristic	Adverse or slope-parallel	Horizontal	Inward or vertical
Probability estimation	High	Medium	Low
Rating (Valuation = 17%)	500	200	0
2) Weathering degree	**Strong weathering (W4 to W5)**	**Slight weathering (W1 to W3)**	
Probability estimation	High	Low	
Rating (Valuation = 7%)	200	0	
3) Structural configuration of discontinuities			
Persistence	> 10m extent (high)	1-10m extent (medium)	< 1m extent (low)
Rating (Valuation = 7%)	200	100	0
Degree of transection	No or subordinate mineral bonds	Mineral bonds existent	
Rating (Valuation = 7%)	200	0	
Open width/ Aperture	Open (>1 cm)	Slightly open (0.5mm - 1 cm)	Closed (<0,5 mm)
Rating (Valuation = 7%)	200	100	0
Condition of surfaces	Slickensides	Rough	
Rating (Valuation = 7%)	200	0	
4) Degree of Loosening (alternative for category	**Clear indications available: wide open**	**Only subordinate indications**	**No indications give (low)**

3)	gaps and fractures, neck valleys etc. (high)	(medium)	
Rating (Valuation = 28%)	800	400	0

Total: Rock mechanics (1+2+(3 or 4))

5) Slope height	80m	66m	57m	10m
Probability estimation Rating (Valuation = 20%)	Very high 600	High 200	Medium 100	Low 0
6) Slope angle	Inclined plane (favorable to rockfall)	Subvertical or vertical slope with features of launch	Below 30 ° or almost 90 °; (unfavorable rockfall)	
Probability estimation Rating (Valuation = 7%)	High 200	Medium 100	Low 0	
7) Catchment area	Small distance, high slope, with little or no vegetation	Distance and/or moderate slope. Little or none vegetation	Long distance, low slope, with or without vegetation	
Probability estimation Rating (Valuation = 7%)	High 200	Medium 100	Low *0*	

Total: Slope Geometry and catchment area (5+6+7)

8) Initial activity	Active	Not active	
Rating (Valuation = 14%)	500	0	

Total: Activity [1+2+(3 or 4)+5+6+7+8]

Probability estimation Classification	High 1900 a 3000	Medium 800 a 1900	Low 0 a 800

Table 2: Table for determining the impact of external influences and calculating the probability of rockfall (Bauer and Neumann, 2011; adapted by Silveira, 2017).

1) seismic effects	Tectonic seismic effects	Mine, karsts regions and heavy traffic	without seismic effects
Probability estimation Rating	High 50	Medium 20	Low 0
2) precipitation	> 129 mm/6 dias	48.2–129 mm/6 dias	< 48.2 mm/6 days
Probability estimation Rating	High 50	Medium 20	Low 0

Total: Extern impact (1+2)

Classification Impact degree	*High (> 60) Strong*	*Medium (30 a 60) Medium*	*Low (< 30) Weak*

Table 3: Table for determining the intensity of rockfall (Bauer and Neumann, 2011; adapted by Silveira, 2017).

Intensity	High-magnitude Rockfalls		Low-magnitude Rockfalls		
Total volume	Rock avalanche	Large rockfall	Medium rockfall	Small rockfall	Single blocks

Distinction	Total rock mass volume > 1000000 m³	Total rock mass volume of about 1000000 m³	Total rock mass of about 10000 m³	Total rock mass of about 100 m³ and/or rock fragments with more than 200 mm	One or few single fragments < 200 mm

3 RESULTS AND DISCUSSIONS

The studied rock mass is inserted in the Bação Complex, which consists predominantly of gneisses of tonalitic and granodioritic composition (Gomes, 1986; Gomes, 1987). In addition, the Bação Complex composes the basement of the supracrustal rocks of the greenstone belt Rio das Velhas, which surround it; subordinately, pelitic derivation shales and amphibolites (Fonseca and Evangelista, 2013). The gneisses belonging to the Bação Complex frequently show a well developed compositional banding, with dark micaceous bands alternating with clear quartz–feldspatic ones (Bacellar et al., 2005).

The rock that constitutes the rock mass marginal to highway BR-356, is gnaisse of fine to average granulometry, with milimetric to centimetric bundles with felsic and mafic layers that sometimes are folded. The mineralogy is predominantly quartz, feldspar and biotite.

Figure 3: Apertures in the discontinuities present in the rock mass.

The basic parameters for the geotechnical characterization of the rock mass were collected in the field. The basic Rock Mass Rating was determined in order to allow a classification for the rock mass that composes the slope studied. Figure 4 presents the slope studied and allows to observe the distribution of discontinuity families giving rise to the blocks of rock present in the rock mass. Another important point to observe in Figure 4 is the proximity between the highway and the slope.

Figure 4: Slope study in the Rodovia dos Inconfidentes (BR-356) with highlight for the formation of blocks.

The geological hammer test was used in the rock mass with the objective of intact rock compressive strength on the classification proposed by ISRM in 1981. The hammer test was applied to several points of the rock mass presenting similar results with flakes after successive hammer blows, resounding when struck by the hammer. The rock mass was classified as R6 implying an extremely high resistance, bigger than 250 MPa.

Regarding the discontinuity families, the values of persistence and spacing were determined. Due to the homogeneous behavior of the measurements for spacing and persistence, Their means were selected for the analysis. Table 4 summarizes the data collected.

Table 4: Mean values of persistence and spacing.

Family	Medium persistence (m)	Medium spacing (m)
1	3.90	2.29
2	1.19	0.95
3	3.90	2.29

Observing the average values of spacing, it is possible to conclude that the rock mass presents a low degree of fracturing, reflecting in a high RQD value. Due to the spacing values being in bands greater than 1 meter it is not possible to calculate the spacing using the equations proposed by Hudson and Harrison (1997) and Palmström (1982). Besides that, the visualization of the rock mass in the field lets confirm to conclude that the rock mass presents a low degree of fracturing. Thus the selected range of RQD for the mass in study is between 90% and 100%.

Figure 3 presents the image of part of the slope where it is possible to evaluate the parameters related to the discontinuities, such as aperture, filling and roughness of the rock mass. Apertures of the discontinuities between the values of 1 and 5 millimeters were identified,

with no filling. Regarding the roughness, it was concluded that the discontinuities in rock mass presentsa slight roughness.

Regarding the weathering of the rock mass, irrelevant bands were identified slightly weathered in points along the slope, but the absence of weathering is predominant in the rock mass. Therefore the rock mass was classified as not weathered.

The survey of the parameters allowed classification according to the Rock Mass Rating - RMR. The rock mass was classified as very good, presenting value of 88 for the basic RMR. Table 5 presents the results.

Table 5: Basic RMR results for the rock mass.

Parameter	Condition		Range of values	
Intact rock stregth	> 250 MPa		P1	15
RQD	90 – 100%		P2	20
Discontinuity spacing	0.6 – 2 meters		P3	15
Discontinuity condition	Persistence	4	P4	23
	Aperture	4		
	Roughness	3		
	Filling	6		
	Weathering	6		
Presence of water	Dry condition		P5	15
Classification				
Basic RMR	88		Class I	

From the parameters collected in the field, it was possible to perform the susceptibility analysis to rockfall according to the methodology proposed by Silveira (2017) for the studied slope. Table 6 presents the parameters analyzed and the score given for susceptibility analysis.

Table 6: Susceptibility to rockfall according proposed by Silveira (2017).

Parameter	Score	Classification
Orientation	500	
Weathering	0	
Persistence	100	
Degree of transection	200	
Aperture	0	
Roughness	0	
Slope Height	2	
Slope angle	100	
Catchment area	100	
Activity	500	
Susceptibility (total)	1502	High

The analysis showed that the studied slope obtained a score of 1502 for the susceptibility, which encompasses the parameters related to rock mechanics, slope geometry and activity indications. The susceptibility to rockfall of the studied slope is between the range of score of 800 to 1900, being classified as Medium Susceptibility. The lowest scores occurred in the parameters of weathering and in the structural configuration of the rock mass (apertures and roughness of

the discontinuities) due to the good conditions of the rock mass, which is competent and little weathered. However in this slope, the presence of minerals bonds was not identified, which culminated in the maximum score for the transection degree of the slope analyzed.

The parameters that most influenced the susceptibility to rockfall in this slope was a favorable orientation to the formation of blocks and signs of activity. The signs of activity were identified directly in the field, from fallen blocks, fractures in the rock mass, open and displaced joints and presence of vegetation between the discontinuities. Figure 5 shows the studied slope, as well as its discontinuities.

Figure 5: Marginal slope to BR-356 highway with its discontinuities.

The probability of rockfall was analyzed considering the susceptibility to rockfall and the impact of external influences, such as seismic effects and precipitation. In the case of the BR356 highway, an important highway linking the capital of Minas Gerais to the historic cities of Ouro Preto and Mariana, it is exposed to the vibrations generated by the intense traffic of cars and heavy vehicles. Thus, the region studied is generally in a zone of medium seismicity, so the score in this parameter was 20 points.

The values for rainfall were obtained through studies that related the pluviometric index with mass movements in the region of Ouro Preto. Castro (2006) points out that five-day accumulated rainfall is considered to be the most effective in the landslide process, when the accumulated five-day rainfall is above 22 mm. For precipitation above 128 mm/5 days, the probability of occurrence of more severe landslides becomes greater. According to Silva (2014), the minimum cumulative precipitation required to cause geotechnical accidents is 48.2 mm/6 days. From 129 mm/6 days, the region is in a state of attention.

Although Castro (2006) and Silva (2014) relate rainfall to landslides, these data were used in this analysis of rockfall hazards because there are situations in which these events are associated. In addition, as Silveira (2017) emphasizes, there is not enough data to associate

rockfalls to rainfall, since it is a phenomenon that has not been studied so much in the region of Ouro Preto.

In order to analyze the behavior of the slope in both dry and wet periods, the probability of rockfall occurrence was calculated taking into account the maximum and the minimum precipitation of the region. For the maximum precipitation, the score was 50 points and for the minimum precipitation, the score was 0. Table 7 presents the scores for the impact of external influences according to the Silveira (2017) proposal.

Table 7: Impact of external influences according to Silveira (2017).

	Maximum	Minimum
Precipitation	50	0
Seismic effects	20	20
Total external impact	70	20
Impact degree	Strong	Weak

Table 8 presents the probability of occurrence of rockfall in the analyzed slope. The maximum probability is represented by the rainy periods and the minimum probability is represented by the dry periods. The probability of rockfall occurrence was given by the probability matrix presented in Figure 2a.

Table 8: Rockfall probability occurrence according to Silveira's proposal.

	Maximum	Minimum
Susceptibility	Medium	Medium
Impact degree	Strong	Weak
Probability	High	Medium

From the previous tables, it was possible to perceive that precipitation exerted a major influence on the result of the impact degree of the external influences and, consequently, on the final probability of occurrence of rockfall. High rockfall probability occurrence in the rainy season. The analyzed slope obtained a high rockfall occurrence probability for the rainy season. With this, it is possible to affirm that the impact degree of external influences was the parameter that most influenced the result of this analysis.

The intensity of the rockfall is measured by the volume of material that falls from the slope. In the analyzed rock mass, it was possible to verify falls on a small scale, with fragments having a diameter greater than 200mm and blocks with a volume of up to 100 m3. However, due to the fact that it is a highway with intense traffic, it is possible to consider the possibility of a rockfall occurrence, causing damage to the highway, paralyzing traffic and, possibly, causing accidents involving fatalities.

Knowing the probability of rockfall and the intensity of the event for the slope, it was possible to classify its hazardous degree. This result was obtained by means of the hazard matrix of Figure 2B given above and presented in Table 9.

Table 9 - Classification of the rockfall hazard to the marginal slope of the BR356 highway, according to the adaptation proposed by Silveira (2017).

Seasons	Probability	Intensity	Hazard Class
Drought	Medium	Up to 100m³	Low
Rainy	High	Up to 100m³	High

The hazard classification for the analyzed slope varies from low to high. When the precipitation is that of the rainy season, the probability of rockfall occurrence in the place is high, consequently the hazard is high, since the impact degree of external influences indicated by this methodology is strong. At the time of year, when drought occurs, when precipitation is minimal, the probability is medium, consequently the hazard is low.

With regard to the characteristics used for the susceptibility analysis, it is possible to cite as a differential, the orientation of the discontinuities, transection degree, activity of the rock mass and mainly the lack of a catchment area. This slope is susceptible to rockfall, which in this case the rocks are bulky. If there is a fall, these blocks would have little time to loose energy and speed, since the distance between the slope and the highway is small.

4 CONCLUSIONS

Studies of rockfall hazard analysis in highways are important, especially in highways with a high flow. The rock mass of the slope studied is a gneiss of small to average grains, very fractured, verified by the presence of discontinuities, with unfavorable orientation. The RMR was applied, and the rock mass was classified Class I. The hazard classification for the slope analyzed varies from low to high, according to the precipitation considered.

The study presented a considerable probability of detachment of blocks, especially in the rainy season. Thus, there are alternatives for hazard reduction, such as the installation of rockfall protection barriers, instalation of bar anchors in critical blocks or the removal of the larger blocks by fragmentation. In addition, on highways where there are hazard of detachment of blocks, it is necessary to have "hazard signs".

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