

Evaluation of Rockfall Hazard Along Brazil Roads

Guilherme José Cunha Gomes, Frederico Garcia Sobreira, Milene Sabino Lana

Abstract. The Brazilian road network is constructed in a highly heterogeneous geological environment and some stretches cross through discontinuous rock masses that have uncertain or even ignored geotechnical characteristics. Rock slopes are potentially unstable surfaces and as such are susceptible to rockfalls that affect the highway's user safety, transportation infrastructure and surrounding environment. The geomechanical behavior of rock masses and also the geometric and traffic conditions of highways are fundamental aspects of rockfall evaluation. This research presents a case study of rockfall evaluation for slopes bordering highway sections, aiming to classify them and determine a hierarchy for intervention, based on defined criteria. The presented method could be used as a first step in the study of stabilization techniques for problems caused by rockfalls from highway slopes. In order to use this approach, field investigations including geomechanical classification of rock mass are necessary. In this context, twelve slope sections containing rock slopes in Espírito Santo's road network were investigated. The slopes were analyzed individually and the influence of each parameter in the global rating was evaluated. Parameter effectiveness in the proposed method was also evaluated. The slopes were classified to define priority measures to minimize roadway problems in each place.

Keywords: rockfall, slope, highway.

1. Introduction

The Brazilian road network is constructed in a relatively heterogeneous geological environment, amidst different kinds of discontinuous rock masses with uncertain or even ignored geotechnical characteristics. The user safety and environmental preservation require tools to ascertain an acceptable degree of rockfall hazard along highway slopes, based on rational methodology.

In the highway engineering context, rock slopes are potentially unstable surfaces and as such are susceptible to rockfalls that affect highway user safety, transportation infrastructure and the surrounding environment.

Due to the seriousness of the problem and the difficulties encountered in investigating and analyzing rockfall along hundreds of kilometers of mountainous highways, several countries have developed classification systems for slopes that could be obtained through field investigations and simplified calculations. The objective of these classifications is to identify and distinguish particularly dangerous places requiring urgent stabilization measures or further studies, and therefore, enabling agencies or highway departments to take remedial action.

Rockfall evaluation methods along highways are important tools to monitor potentially unstable slopes. These methods use studies and investigations of directly linked characteristics to the events. Analyses of road sections with great geotechnical and geometric problems, allied to an elaborated database obtained in a discerning way, can be

helpful for road managers to choose remedial measures in places of potential hazard.

2. Highway Rockfalls

A rockfall corresponds to the detachment of a block rock mass from a steep or scarp slope (Giani, 1992), with little or no shear failure (Hoek & Bray, 1981), without structurally controlled planar and wedge failures. The displacements are rapid, and usually involve free fall, rolling or bouncing (Ahrendt, 2005). Individual blocks subjected to falls have varied geometric dimensions, and can be in the form of cubes, plates, among others (ISRM, 1978; Palmström, 1995).

According to Giani (1992), the beginning of a rockfall phenomenon at a slope involves initially unstable conditions, which cause the movement of a mass induced by slope failure. The main factors in slope instability induction are: joint pore pressure, earthquakes or vibrations due to blasting, joint pressure due to ice formation and excavation.

Ritchie (1963) studied various factors that influence block trajectory during a rockfall event. Some of them were: block size and shape, slope height and angle, hill surface characteristics, joint pattern and rock type. He carried out pioneer research about rockfalls onto roads by studying highways in Washington, USA. His work included the observation of hundreds of falls from rock slopes and highway talus, measuring and recording block paths and the distances they reached beyond the slope. The study culmi-

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nated in developing a practical design criterion to estimate the width of rockfall catchment areas based on rock slope height, rock slope angle and depth of the catchment area. A rockfall catchment area is defined as the area between the highway edge of the pavement and the base of a road slope that is designed to avoid rockfalls from reaching the roadway (Pierson *et al.*, 2001).

Ritchie's design criteria has become a practical method for estimating ditches in rock cuts, frequently used by roadway engineers, mainly in North America, even though it was proposed four decades ago (Pierson *et al.*, 2001). Later, this criteria was modified to a chart form (Fig. 1), published by the Federal Highway Administration – FHWA (1989), improving data manipulation by roadway engineers.

Geomechanical slope behavior is constantly being evaluated by geotechnical engineers, using data concerning slope stability, orientation and shape of discontinuities and

infilling material. Rock mass geomechanical classifications can be used for this evaluation. Gomes (1991) restated the concept that geomechanical classifications are oriented systems seeking to separate rock masses into classes with similar geomechanical characteristics. He did this by allotting ratings for them, based on geological, mechanical and geotechnical parameters, and in doing so, homogenized segments with the same behavior.

From among the main geomechanical classifications, the Bieniawski (1973, 1989) and Romana (1985) systems became the base for the development of highway rock slope classifications. *RMR* (Rock Mass Rating), proposed by Bieniawski (1973, 1989), includes six parameters that are used to classify a rock mass: strength of intact rock material; drill core quality or rock quality designation (*RQD*); spacing of discontinuities; condition of discontinuities; groundwater and discontinuity orientation. *SMR* (Slope Mass Rating) proposed by Romana (1985) is obtained from an adjustment of Bieniawski's *RMR*, to which is added a factorial term dependent on the slope – joint orientations and the excavation method.

Block size is a very important index for rock mass quality evaluation, but its determination is not an easy task. This dimension is calculated through discontinuity spacing and persistence, as well as from the number of joint sets that delimit potentially unstable blocks (ISRM, 1978). Palmström (1995) also affirms that there are many ways to calculate block volume in a rock mass. Beyond field observations, Palmström (1995) describes some relationships to estimate block volume in rock masses with different joint sets.

Traffic and geometric characteristics of road sections also must be considered in highway rockfall evaluation. Among these characteristics, average traffic per day represents the average number of vehicles traveling on a roadway section per day (DNIT, 2006). The posted speed limit, defined in the road project, is the larger speed allowed in this segment with appropriate safety conditions, even with wet pavement, without traffic influence. Another roadway characteristic, sight distance, can be understood as a vision pattern given to the driver, in a way that there is always time to safety decisions.

The first inventory of problematical rockfall areas was developed by Brawner & Wyllie (1975). Since then, highway rock slope classifications have been developed in order to assist in the management of critical roadway areas.

In the beginning of the 90's, a highway rock slope classification system was developed by Pierson *et al.* (1990), based on a previous study, and named *Rockfall Hazard Rating System* (RHRS). This method, implanted in the State of Oregon (USA), has proved to be an important tool for analysis and prevention of rockfall problems involving roads. It has provided significant innovation by improving the identification, evaluation and mitigation

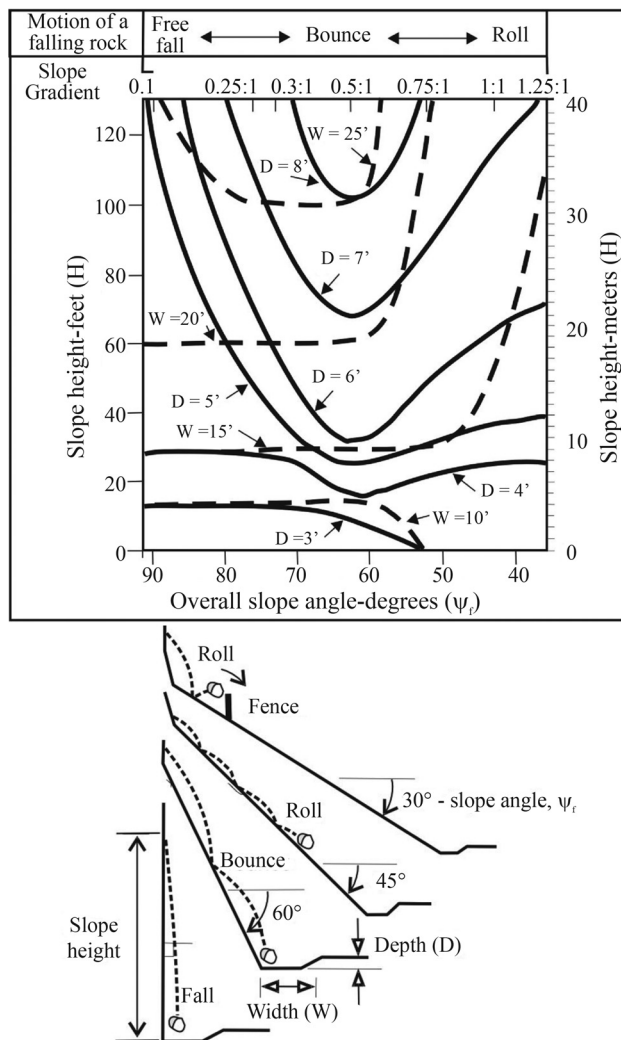


Figure 1 - Modified Ritchie's design chart to determine required width (*W*) and depth (*D*) of rock catchment areas in relation to height and slope angle (after FHWA, 1989; Hoek, 1998).

processes of potentially unstable rock masses. The RHRS system is a highly-used technique employed for quickly establishing which rock slopes offer risks for the users. The nine categories of this system are framed in four different ratings. Categories between the established ratings can be interpolated. The criterion to interpolate ratings increases exponentially from 3 to 81, making it possible to distinguish which slopes are more problematic or dangerous. Slopes with the largest ratings need priority intervention.

Budetta (2004) evaluated the rockfall problems of Italian roads based on the RHRS method (Pierson *et al.*, 1990). The author modified the method, adapting it to the geological and road context of that country. The main modification proposed by Budetta (2004) was the incorporation of the *SMR* (Romana, 1985) into the geological evaluation of rock masses.

Several other authors also have studied highway rockfalls all over the world, for example, Bunce *et al.* (1997), Hadjin (2002), Hopkins *et al.* (2003), Rose (2005), Eliassen & Springston (2007), among several others.

3. Work Development

This research developed and applied a method for rockfall evaluation of slopes bordering highway sections, aiming to classify them and determine a priority intervention hierarchy. For this, existent data, as well as collected data in the area, was analyzed. This resulted in the definition of a field investigation area involving twelve highway-bordering rock slopes in the State of Espírito Santo, Brazil (Fig. 2). Due to map scale, two investigated slopes that are very close do not appear in figure.

The applied rockfall hazard evaluation method then used the data from the geological and geotechnical slope investigation, as well as traffic and geometrical highway section assessment. Geomechanical rock mass classification systems were applied as a geotechnical tool for evaluating the slopes, adjusting rockfall hazard assessment methods internationally proposed for Espírito Santo roads. Slopes with the highest intervention priority were defined.

The application of the methodology, added to professional's experience in problem diagnosis, represents a contribution to highway departments for road safety increment

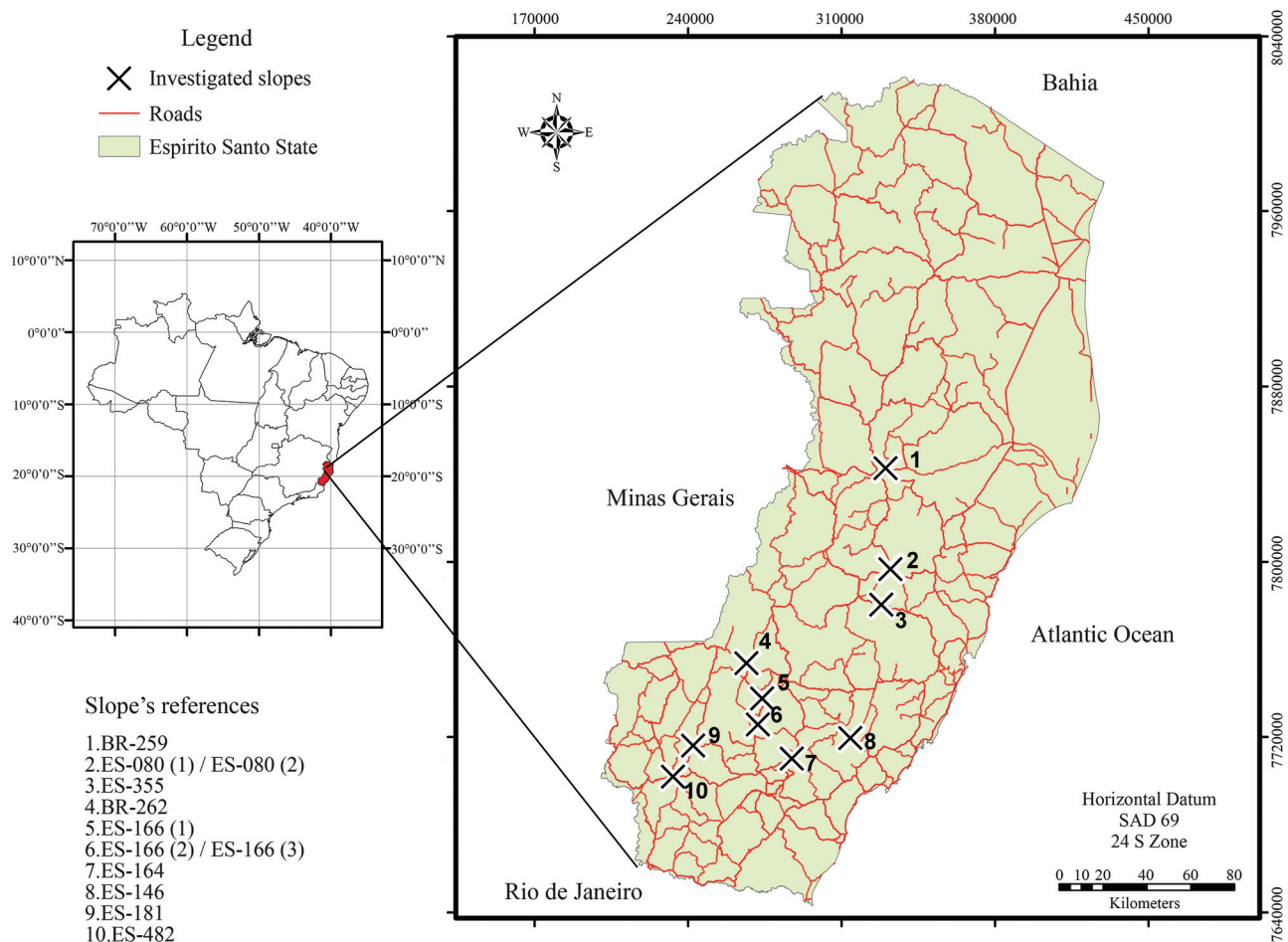


Figure 2 - Investigated rock slopes distribution (Espírito Santo State, Brazil).

when adding the acquired results to roadway rehabilitation and improvement projects.

In this method, pavement widths, posted speed limit, decision sight distance, slope height and extension, catchment area and the longitudinal ramp of slope extension are determined in order to characterize the traffic conditions along the road sections and the geometry of each studied area.

For the characterization of the basic structural model for each slope, an overall rock mass analysis is performed and the surveyed data registered in a standard field sheet. The geological and geotechnical characterization is achieved by surveying the physical and geometric characteristics of rock mass discontinuities, as proposed by Bieniawski (1973, 1989), ISRM (1978), Romana (1985), Pierson & van Vickie (1993) and Palmström (1995).

For the discontinuity characterization, the following parameters are used: orientation, spacing, persistence, roughness, opening, infilling, water flow, joint sets and block size.

The collected information in the field of jointing rock mass was treated to obtain values concerning geomechanical quality of the slopes studied. The application of classification Bieniawski (1989) was conducted from field surveys and in literature data. Initially, we defined the most important families of discontinuities that control rock mass behavior.

As the characteristics of the rock masses studied were composed by crystalline rocks (granites and gneisses), values between 100 and 250 MPa for strength of rock material were considered, in accordance with Palmström (1995) and Bieniawski (1984) work's. It may also be added that due to operational conditions no samples were collected for uniaxial compression test. Therefore, ISRM (1978) proposal was used and as a result, the rocks were considered as very

resistant, requiring many hammer blows in order to be fractured.

For RQD index, as no borehole was available, Priest & Hudson (1976) proposals were used. This method correlates RQD with joint spacing by using the following equation:

$$RQD = 110 e^{-0.1/S} \left[\left(\frac{0.1}{S} \right) + 1 \right] \quad (1)$$

being S the average spacing between discontinuities in meters.

The joint spacing average of every family was taken into account in each slope. Joint condition, which involves opening characteristics, persistence, roughness, alteration in the walls and filling material conditions, it was calculated by averaging the magnitudes analyzed. For the influence of groundwater, a year length visual observations were made mostly during the rainy season, in order to define the state conditions such as the dry, damp, wet, dripping and flowing occurrences.

Bieniawski joint orientation was not considered in *SMR* classification, as proposed by Romana (1985). In this case, the joint and slope dip and dip direction were recorded for application of the *SMR* model.

4. Slope Rating Evaluation Methodology

Eight parameters are adopted for the evaluation of the slopes, as shown in Table 1. Each parameter receives a rating ranging from 3 to 81, where the smallest values correspond to the best highway safety conditions.

Pierson & van Vickie (1993) have proposed a practical field method for the calculation of average slope heights. Due to access difficulties to the top of most of the slopes, the cut height is obtained with a measuring tape and

Table 1 - Parameters for classification of the evaluated rock slopes.

Parameter	Criteria and rating			
	3 points	9 points	27 points	81 points
Slope height	6.0 m	12.0 m	18.0 m	24.0 m
Ditch effectiveness	Good catchment + Ritchie's chart conformity + protection	Moderate catchment + Ritchie's chart conformity	Limited catchment + Ritchie's chart disconformity	No catchment
Average vehicle risk	25% of time	50% of time	75% of time	100% of time
Percent of sight distance (DV)	100% (Appropriate DV)	75% (Moderate DV)	50% (Limited DV)	25% (Very limited DV)
Roadway width	13.2 m	10.8 m	8.4 m	6.0 m
Block size	0.30 m	0.60 m	0.90 m	1.2 m
Climate condition	Low annual rainfall < 1,150 mm	Medium annual rainfall 1,150-1,450 mm	Large annual rainfall 1,450 - 1,750 mm	High annual rainfall > 1,750 mm
Geologic characteristic (<i>SMR</i>)	80	70	60	50

a clinometer, using the relationship between the angle formed by the observation point and the slope surface:

$$H = X * \tan \alpha + AC \quad (2)$$

where X is the distance, in meters, of the measurement point (pavement edge); α is the angle measured by clinometer and AC is the clinometer height. Slope height is a fundamental characteristic in stability analyses. This parameter has shown to be effective in the geometric diagnosis of slopes, because a high slope will probably have discontinuity occurrences that induce rockfalls. The values of 6, 12, 18 and 24 meters shown in Table 1 were defined according to the variation of slope heights found on the worked area, aiming at establishing an adequate indicator to this category.

The ditch effectiveness parameter measures the efficiency of the catchment area to prevent rockfalls from reaching the roadway pavement (Ritchie, 1963). This highway section characteristic have been rated from Budetta (2004), that modified Pierson & van Vickie's (1993) qualitative evaluation, improving the pioneering geometric aspects proposed by Ritchie (1963).

According to Pierson & van Vickie (1993), the average vehicle risk (RV) measures the percentage of time that vehicles have been exposed to a dangerous rockfall zone. The percentage is obtained from equation below. Average vehicle risk meaning is similar to that used by the RHRS method.

$$RV = \frac{ADT \times CE}{PSP} \quad (3)$$

where ADT is average daily traffic (cars/h), CE is the cut extension (km) and PSP is the posted speed limit (km/h). Average vehicle risk is determined in percentage terms. In this case, the smaller the percentage of vehicles in rockfall hazard areas is, the smaller the index rating of the road section under consideration will be.

Percentage of sight distance (DV) is used to determine the highway length available to the driver for taking an instantaneous decision. This category is considered critical when roadway obstacles are difficult to notice, or when an unexpected move is requested (Pierson & van Vickie, 1993). Percentage of sight distance is an important parameter for evaluating rockfall hazard. This is because it is intimately related to the probability of the occurrence of automobile collision with any object present on the road. The calculation is based on the relationship between actual sight distance (ASD) and designed sight distance (DSD), measured in meters:

$$DV = \frac{ASD}{DSD} \times 100\% \quad (4)$$

DSD is designed by engineering project, usually established by the highway department. ASD is obtained in the

field, changing in each road meter. Due to several operational reasons involving technical and financial resources, some road extensions are built without considering project sight distance. This fact is perceptible in highways that transpose mountainous or sinuous extensions.

The parameter roadway width represents the paved band extension, including the shoulder, and is measured perpendicularly to the central road line. It represents the space a driver has to maneuver. Most highway rockfall evaluation methods, based on Pierson *et al.* (1990) proposal, maintain the pavement width as an essential category or parameter because this is considered an important geometric aspect for safety.

In the investigated sections, frequently less than 3 joint sets were identified, so the calculation of the equivalent block volume proposed by Palmström (1995) was considered convenient, see Eq. (5). This relationship determines block volume from the volumetric joint count (J_v) and block shape factor (β), which is a function of the largest and the smallest joint spacing (S_{max} e S_{min}) and the number of joint set indexes (n_j):

$$Vb = \beta \times J_v^{-3} \quad (5)$$

$$\beta = 20 + 7 \left(\frac{S_{max}}{S_{min}} \right) \left(\frac{3}{n_j} \right) \quad (6)$$

In which $n_j = 3,0$ to 3 joint sets; $n_j = 2,5$ to 2 joint sets and random sets; $n_j = 2,0$ to 2 joint sets; $n_j = 1,5$ to 1 joint sets and random sets; $n_j = 1,0$ to 1 single joint set.

The J_v index, according to Palmström (1995), is equal to the number of joints in a unitary rock mass volume. After calculation of Vb , Budetta's proposal (2004) is used to calculate block size (Db), measured in meters:

$$Db = \sqrt[3]{Vb} \quad (7)$$

Several methods of rockfall hazard evaluation in roadway rock slopes, especially those adopted in developed countries, use combinations between the period when there is water in the slope and when it snows. But, as the presence of snow would be a rare event and the slope water condition has been already used in *SMR* classification, this parameter is rated as a function of incident annual rainfall in the studied places. The most important climatic factor in Brazilian slopes is the rainfall, because the water, flowing on discontinuities, leads to rock mass shear strength reduction (Bieniawski, 1984 and Palmström, 1995), among other aspects. As this aspect has already been considered in the *RMR* classification, Budetta's proposal (2004) was adopted, which uses annual rainfall values for the studied areas. Then values of rainfall were obtained from historical series of Espírito Santo state. Low annual rainfall (< 1.100 mm) represents points of minor influence of water on the slope. On the other hand, high annual rainfall (> 1.750 mm) represents water's major contribution to slope instability.

Due to the geotechnical characteristics of the investigated slopes, the geological characteristic adopted by Pier-

son and Van Vickle (1993) was not used. The author's method, as quality is concerned, is better suited for regions on which lithologic structure vary greatly (Gomes & Sobreira, 2008).

The geological characteristic parameter is evaluated according the *SMR* index (Romana, 1985). Budetta (2004) proposed *SMR* incorporation, whose value is inversely proportional to the Pierson *et al.* (1990) rating. *SMR* values have been adjusted in this work to provide a better understanding about the mechanical behavior of the slope. Values of *SMR* smaller than 50 can be considered critical, hence they have a high value in this parameter.

The parameter ratings are exponential, according to the Pierson *et al.* (1990) proposition. Slopes with a larger rating are hazardous and they must be given priority for immediate interventions. All parameters, except ditch effectiveness, can be put in equation form, according to Ritchie (1963), ISRM (1978), Romana (1985); Bieniawski (1989), Pierson & van Vickle (1993), Palmström (1995), Budetta (2004) and DNIT (2006). The equations to aid the parameter calculations and the symbology adopted are presented in the Table 2.

After the calculation of the parameter values for each slope, a value that represents the rockfall hazard index (I_{QB}) is determined by the equation:

$$I_{QB} = I_{AT} + I_{AC} + I_{RV} + I_{DV} + I_{LP} + I_{DB} + I_{CC} + 2I_{CG} \quad (8)$$

where I_{AT} = slope height parameter; I_{AC} = ditch effectiveness parameter; I_{RV} = average vehicle risk parameter; I_{DV} = sight distance parameter; I_{LP} = roadway width parameter; I_{DB} = block size parameter; I_{CC} = climate condition parameter; I_{CG} = geologic characteristic parameter. The I_{CG} index was multiplied by a weight of 2 in order to value the influence of geological-geotechnical characteristic in instability rockfall processes.

5. Results and Discussions

The slope sections selected for the study are located in different areas to encompass the aspects desired for the analysis. Places with differences in the traffic conditions,

ramps, geometry, speed limit, among other intrinsic road project aspects were chosen, since the geological characteristics in the studied area didn't vary significantly. Twelve slopes were selected, two of which are federal highways subject to larger loads and greater traffic. The other ten are regional highways.

Basically, the rock masses are highly metamorphic crystalline rocks (Meneses & Paradella, 1978). There is also gneiss, essentially composed of quartz, feldspar, biotite and garnet that is well-oriented by the centimetric alternation of the banding. The foliation presents concordance with the banding.

Each slope was evaluated, increasing the understanding of the most problematic places per parameter. The rating of each parameter, following the model developed by Pierson *et al.* (1990), varied exponentially (see Table 1). The graphs in Fig. 3 show the indexes versus parameters rating relation.

Fig. 3 (h) shows the relationship between the I_{CG} index and the *SMR* value, as well as the distribution of the values obtained for each slope. It can be noticed that the I_{CG} rating is inversely proportional to the *SMR* index.

From Fig. 3 (h), it is possible to observe that *SMR* values above 60 result in low values of I_{CG} . Therefore, a rock slope must have a low value of *SMR* to present a significant influence on the I_{CG} index in the method proposed by Budetta (2004). On the other hand, if the I_{CG} value is multiplied by 2, the geological-geotechnical characteristic will have a larger contribution in the determination of I_{QB} .

Table 3 presents the summary of index values and total rating for each slope analyzed. The most problematic slopes in relation to rockfall hazards have larger values of I_{QB} .

In spite of the high *SMR* values, it is observed that four slopes can be considered less stable: ES-080 (1), ES-146, ES-164 e BR-259. As previously informed, the distinction between the geological characteristic indexes was only possible due to *SMR* use, which is more sensitive to changes in relation to the initial proposal of RHRS for that parameter. The RHRS original rating was modified due to two basic aspects: its evaluation is merely qualitative and it's difficult to distinguish between the crystalline rock mass being investigated. Gomes and Sobreira (2008) went into detail about this discussion.

As it can be seen in Table 3, the slope ES-164 was considered the most critical concerning rockfalls, receiving the largest I_{AT} . Besides the highway's geometric factor, due to the absence of ditch or catchment area in the basis of the slope, geotechnical factors were decisive for its classification in a critical category. The large slope height, with rockfall hazard, was the first geotechnical aspect considered in the rock mass evaluation.

The slope ES-164 has a jointing pattern that leads to loss of support at its base, favoring instability of the upper blocks. The 30° dip average of the main joint set, formed by

Table 2 - Symbols and equations used to each parameter of slope evaluation.

Parameters	Symbol	Equation
Slope height (<i>H</i>)	I_{AT}	$I_{AT} = e^{0.1831.H}$
Ditch effectiveness	I_{AC}	-
Average vehicle risk (<i>RV</i>)	I_{RV}	$I_{RV} = e^{0.0439.RV}$
Percent of sight distance (<i>DV</i>)	I_{DV}	$I_{DV} = 243e^{-0.0439.DV}$
Roadway width (<i>LP</i>)	I_{LP}	$I_{LP} = 1262.7e^{-0.4578.LP}$
Block size (<i>Db</i>)	I_{DB}	$I_{DB} = e^{3.662.Db}$
Climate condition (<i>P</i>)	I_{CC}	$I_{CC} = 0.0048e^{0.0054.P}$
Geologic characteristic (<i>SMR</i>)	I_{CG}	$I_{CG} = 243e^{-0.055.SMR}$

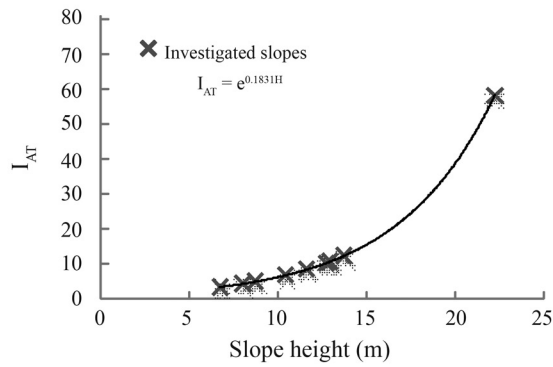
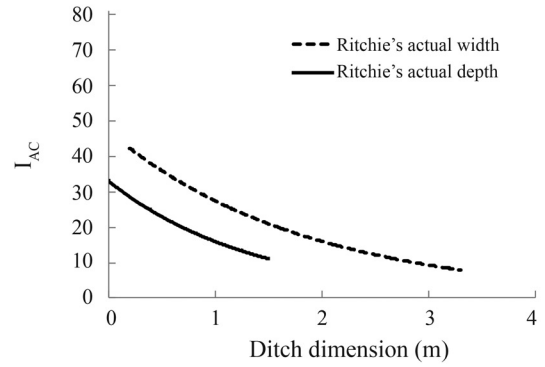
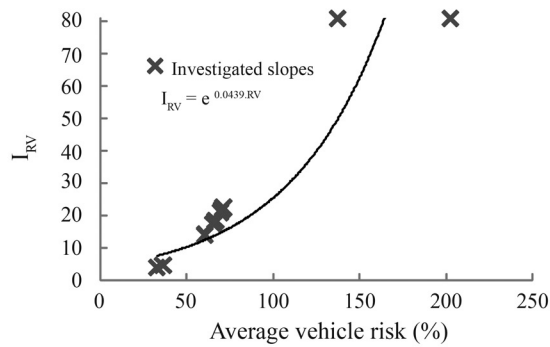
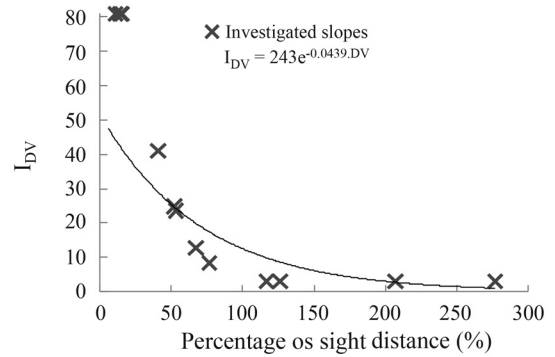
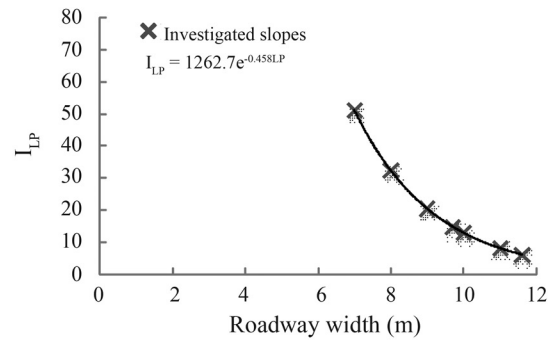
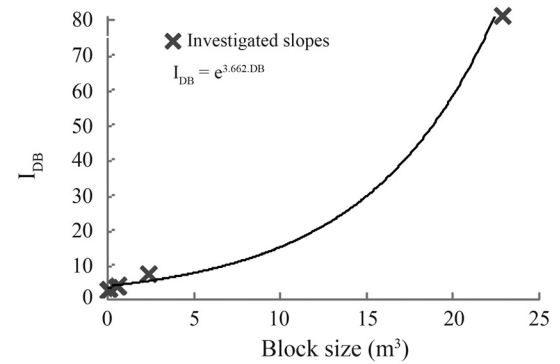
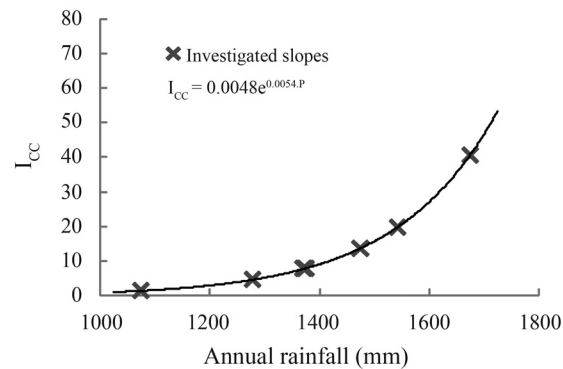
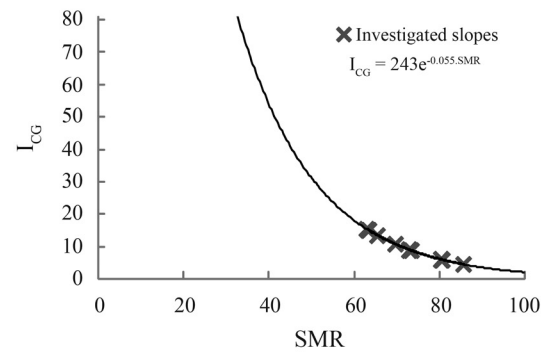

 (a) Relation between I_{AT} index and slope height

 (b) Relation between I_{AC} index and Ritchie's ditch dimension

 (c) Relation between I_{RV} index and average vehicle risk

 (d) Relation between I_{DV} index and sight distance

 (e) Relation between I_{LP} index and roadway width

 (f) Relation between I_{DB} index and block size

 (g) Relation between I_{CC} index and climate condition

 (h) Relation between I_{CG} index and SMR

Figure 3 - Relation of the eight parameters adopted in the investigated slopes. The smallest value of indexes corresponds to the best highway safety conditions.

gneiss rock banding that dips into the rock mass slope, frequently becomes smaller, due to folds or layers of different strength in the slope. However, due to different erosion rates of materials in the rock mass, several points below loosened blocks suffer erosion, creating ideal conditions for the beginning of falls. In spite of the fact that the main discontinuities, originating from gneiss banding, dip favor-

ably (inside the slope face), there are some joints with a dip smaller than the slope face, dipping inside it. This is relevant because this latter discontinuity pattern creates support loss for some blocks, and due to the lack of a catchment ditch, any rockfall tends to reach the pavement. Fig. 4(a) shows detail from the ES-164 slope.

Table 3 - Index values for each investigated slope.

Slope	I_{AT}	I_{AC}	I_{RV}	I_{DV}	I_{LP}	I_{DB}	I_{CC}	I_{CG}	I_{QR}
ES - 080 (1)	3.4	27.0	4.2	12.7	51.2	18.2	8.0	18.5	143.2
ES - 080 (2)	12.3	27.0	4.2	81.0	51.2	20.1	8.0	3.0	206.8
ES - 146	8.4	9.0	18.6	23.6	20.5	81.0	20.0	19.2	200.3
ES - 164	58.3	81.0	22.6	24.8	20.5	3.0	41.0	14.8	266.0
ES - 166 (1)	4.9	27.0	17.6	41.1	8.2	3.0	8.0	3.0	112.8
ES - 166 (2)	5.7	27.0	14.1	8.4	8.2	3.0	8.0	3.8	78.2
ES - 166 (3)	6.5	27.0	21.9	3.0	8.2	10.5	8.0	5.3	90.4
ES - 181	4.3	27.0	4.9	3.0	14.9	81.0	8.0	3.0	146.1
ES - 355	10.2	27.0	21.2	81.0	51.2	3.0	8.0	6.1	207.7
ES - 482	6.7	27.0	14.3	81.0	32.4	3.7	5.0	6.4	176.5
BR - 259	4.9	9.0	81.0	3.0	6.2	3.9	3.0	18.4	129.4
BR - 262	10.6	9.0	81.0	3.0	13.0	81.0	14.0	9.2	220.8

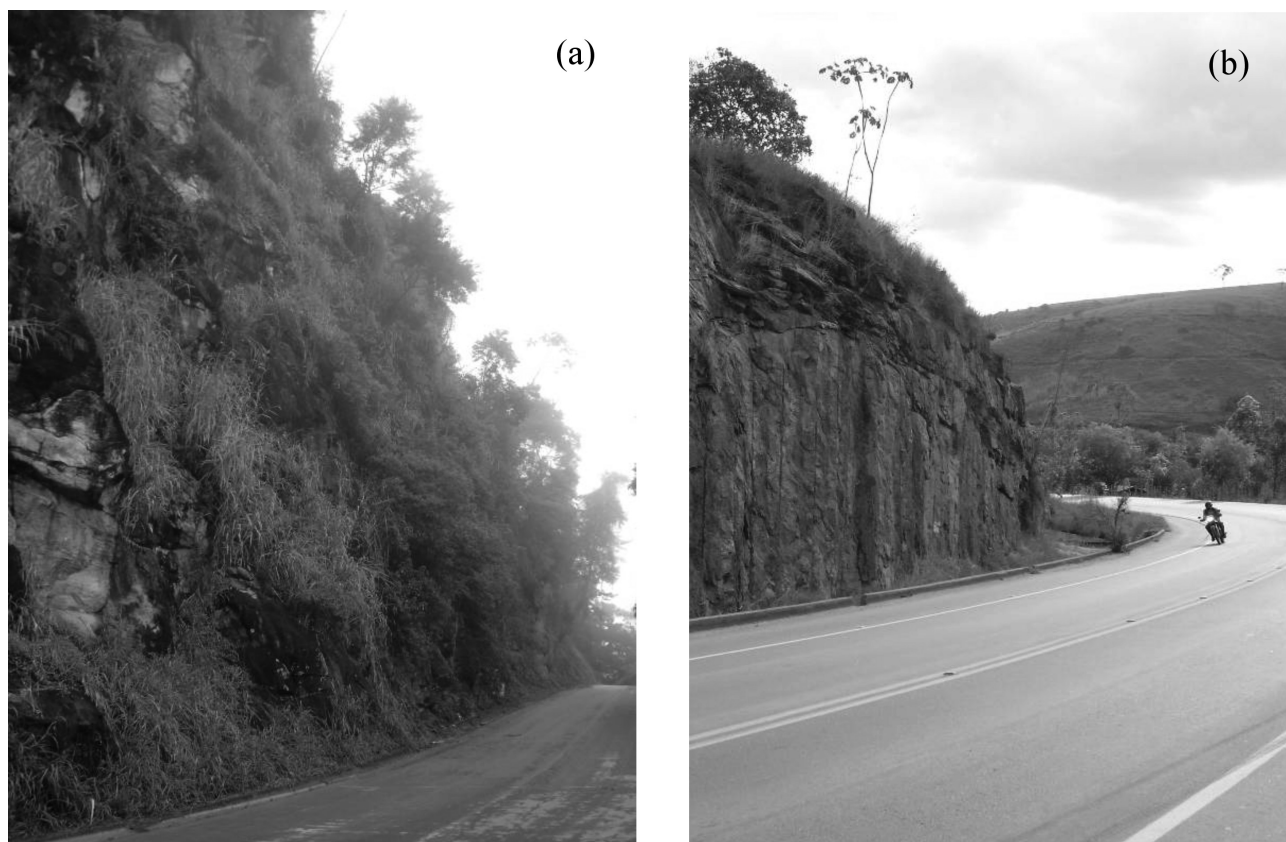


Figure 4 - (a) ES-164 slope. Due to the lack of a catchment ditch, any rockfall tends to reach the pavement. (b) BR-259 slope. Ditch designed according Ritchie's chart.

Due to a geotechnical problem, most of the catchment areas were not sized according to the Ritchie criterion for road safety. In relation to depth, only the two federal highways match Ritchie's chart. It can be observe in Fig. 4(b).

In slope ES-146, there is an abundant presence of water, even in dry periods, and its large block volumes can generate problems (Fig. 5 (a)). At the base of slope ES-355, several blocks in the ditch indicates regular rockfall problems (Fig. 5 (b)). The beginning of the slope is close to a horizontal curve and considering the traffic near the rock mass will result in high I_{DV} values.

Table 3 also displays other road segments with a high I_{QB} index. Slope ES-080 (2) has good geotechnical properties, but presents a high value for I_{QB} , related to inadequate driver-visibility distance and to unfavorable geometric characteristics.

The average dimensions of the blocks in each slope were systematized in the Table 4.

The block size index, I_{DB} , in spite of being an estimate, expressed the rockfall danger of big block failure in BR-262 slope. In this slope the only identified joint set has a large spacing. In case of another slopes, the less spaced fractures and the largest number of joint sets result in

smaller block volumes, consequently the I_{DB} index decreased. Fig. 6 shows block format found in ES-166 (2) slope.

Table 4 - Values obtained for dimension of blocks and adopted terminology.

Slope	Block volume (m ³)	Description (Palmström, 1995)
ES - 080 (1)	0.496	Very large blocks
ES - 080 (2)	0.550	Very large blocks
ES - 146	2.358	Very large blocks
ES - 164	0.023	Moderate blocks
ES - 166 (1)	0.002	Small blocks
ES - 166 (2)	0.026	Moderate blocks
ES - 166 (3)	0.266	Large blocks
ES - 181	2.358	Large blocks
ES - 355	0.002	Small blocks
ES - 482	0.045	Moderate blocks
BR - 259	0.052	Moderate blocks
BR - 262	22.867	Very large blocks



Figure 5 - (a) ES-146 slope. Presence of water is constant even in dry periods. (b) ES-355 slope. Several blocks in the ditch indicates regular rockfall problems.



Figure 6 - Format of block in ES-166 (2) slope.

6. Proposition of Priority Interventions

The results of the classification presented in this paper can be used as a tool for road administration. Larger values of RHRS mean that the slopes must have priority in intervention measures. The proposed classification also allows ranking, for practical purposes, of the highway's characteristics that need to be improved or remedied when seeking user safety. The summary of the most critical aspects, besides interventions proposed for each rockfall section, is presented in the Table 5.

The measures to be taken were simply proposed as a way of minimizing the main problems observed in the field

and confirmed after determination of the values for each parameter. The suggested measures include:

- Removal or stabilization of unstable blocks;
- Geometric improvements of the road and platform;
- Vertical warnings close to unstable slopes;
- Elaboration and execution of a rock mass stabilization project;
- Kinematic analysis for definition of potential failures.

7. Conclusions

The evaluation method proposed in this work is a preliminary tool for identifying hazardous points in highways as related to rockfall. It permits specific geotechnical diagnostics and is the first step towards problem correction in highway slopes when the problem is related to rockfalls.

Field investigations, including the application of geomechanic classification systems to crystalline rock masses that constitute the rock types studied, were very important. The geomechanical behavior of the slopes was similar, indicating that the intact rock had good geotechnical properties, in spite of the fact that most of the discontinuity orientations were unfavorable to slope stability.

The determination of the traffic and geometric characteristics of the road sections in this study was fundamental for the evaluation of the rockfall hazards. Highway rock slopes with high traffic or inadequate sight distance due to sinuous geometry should be studied carefully by the government, and appropriate interventions should be implemented in these places. This is the case of the slopes investigated in ES-355 and ES-482 roads that need geomet-

Table 5 - Summary of the most critical aspects and priority interventions proposed.

Slope	Critical(s) parameter(s)	Priorities in interventions
ES - 080 (1)	• geological characteristic	• removal or stabilization of unstable blocks
ES - 080 (2)	• decision distance	• geometric improvements of the road and platform
ES - 146	• geological characteristic • average vehicle risk • climatic condition	• removal or stabilization of unstable blocks • vertical warnings close to slopes
ES - 164	• geological characteristic • slope height • ditch effectiveness • climatic condition	• elaboration and execution of a rock mass stabilization project • geometric improvements of the road and platform • vertical warnings close to slopes
ES - 166 (1)	• ditch effectiveness	• geometric improvements of the road and platform
ES - 166 (2)	• ditch effectiveness	• geometric improvements of the road and platform
ES - 166 (3)	• ditch effectiveness	• geometric improvements of the road and platform
ES - 181	• geological characteristic	• removal or stabilization of unstable blocks
ES - 355	• sight distance	• geometric improvements of the road and platform
ES - 482	• sight distance	• geometric improvements of the road and platform
BR - 259	• geological characteristic	• removal or stabilization of unstable blocks
BR - 262	• block size	• kinematic analysis

ric improvements that would provide a safe sight distance for users.

A factor of great influence in rockfall mitigation is the existence of a ditch (catchment area). Even when the structure is not appropriately constructed, as in the vertical slopes studied, there is a great tendency for blocks to be captured by the structure between the limit of the pavement and the slope base. Road projects should contemplate a budget for the construction of that structure, which also has the important function of superficial drainage.

Rock block volume determination of the slopes can be considered the most arduous task during field surveys. It is difficult to identify some joint sets because of fractures caused during rock mass excavation. This influences the determination of joint spacing and the block shape. However, empirical relationships were used seeking the calculation of the average block dimensions because this characteristic is fundamental for rockfall hazard evaluation.

Another problem faced in this work, that is also an obstacle for most geotechnical investigations, was the difficulty of expressing a rock mass quality with a single index, due the variability of the structures, materials, etc. The studied slopes are heterogeneous, with distinct behavior in some places. Therefore, many times, it was necessary to represent the overall rock mass quality or, in some cases, the worst observed scenario. Although the index used may take into account many factors, it is not an easy task to have represented all of the rock mass complexity through one sole number, as the environment variability admits, sometimes, different values when rating the parameters which compose this index.

The method used in this research (rating system) satisfactorily represented the slope characteristics related to rockfall problems. The intervention hierarchy of the slopes matched the conditions observed in the field. The alterations proposed aimed to adapt internationally used criteria to the geotechnical and road characteristics encountered. In addition, the proposed alterations contributed to eliminate a certain subjectivity of some of the parameters.

The investigated slopes are placed in the same geological and climatic environment. This is fundamental for the viability of the application of the rockfall hazard evaluation method proposed in this research. Even though this methodology is not being used in Brazil, a highway rockfall assessment system could be adapted for the geological-geotechnical and climatic aspects presented in the area. Besides, geometric and traffic characteristics of the highway are essential parameters for these analyses, and should always be considered.

After obtaining the list of problematic roadway slopes, the government needs to implement this methodology, so that during the rehabilitation services or road restoration, the costs of improvement can be estimated.

Other geotechnical methods of slope classification can be used in the evaluation of the rockfall hazard along

highways providing they are in accord with the rock mass structural model and failure conditions. Standard methods in engineering geology, like RMR and SMR, can be adapted for peculiar geomechanical conditions.

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List of symbols

- AC: Clinometer height (L)
 ADT: Average daily traffic
 ASD: Actual sight distance (L)
 CE: Cut extension (L)
 D: Depth of rock catchment areas (L)
 Db: Block size (L)
 DSD: Designed sight distance (L)
 DV: Percent of sight distance
 H: Slope height (L)
 I_{AC} : Ditch effectiveness parameter
 I_{AT} : Slope height parameter
 I_{CC} : Climate condition parameter
 I_{CG} : Geologic characteristic parameter
 I_{DB} : Block size parameter
 I_{DV} : Sight distance parameter
 I_{LP} : Roadway width parameter
 I_{OB} : Rockfall hazard index
 I_{rv} : Average vehicle risk parameter
 J_v : Volumetric joint count (L^{-1})
 LP: Roadway width (L)
 n_j : Number of joint set indexes
 P: Annual rainfall (L)
 PSP: Posted speed limit (LT^{-1})
 RV: Average vehicle risk
 RMR: Rock mass rating
 SMR Slope mass rating
 RQD: Rock quality designation
 S: Average joint spacing (L)
 S_{max} : Largest joint spacing (L)
 S_{min} : Smallest joint spacing (L)
 X: Distance of the measurement point (pavement edge) (L)
 W: Width of rock catchment areas (L)
 α : Angle measured by clinometer
 β : Block shape factor