VII Brazilian Symposium on Rock Mechanics – SBMR 2016
Rock Mechanics and Rock Engineering for Innovation and Development
ISRM Specialized Conference 19-22 October, Belo Horizonte, Minas Gerais, Brazil

Rockfall Hazard Rating System Adaptation Proposal for Urban Areas Through a Case Study in Mariana (MG, Brazil)

Larissa Regina Costa Silveira
Universidade Federal de Ouro Preto, Ouro Preto, Brazil, larissacbq@hotmail.com

Laura Elisa da Cunha
Universidade Federal de Ouro Preto, Ouro Preto, Brazil, lelisacunha@hotmail.com

Pedro Alameda Hernández
Universidade Federal de Ouro Preto, Ouro Preto, Brazil, pedroalameda@gmail.com

Milene Sabino Lana
Universidade Federal de Ouro Preto, Ouro Preto, Brazil, milene@demin.ufop.br

Tatiana Barreto dos Santos
Universidade Federal de Ouro Preto, Ouro Preto, Brazil, tati.barreto12@gmail.com

SUMMARY: The uncontrolled growth of urban areas causes the occupation of geotechnical hazard zones. This work addresses the geotechnical characterization of a large and steep rock slope in a recently inhabited zone in the Cabanas neighborhood, municipality of Mariana. The slope is composed of a quartzite in the Itacolomi Group and exhibits unstable blocks. The downstream area is occupied, suffering a considerable rockfall risk. For a rockfall hazard evaluation, the Rockfall Hazard Rating System (RHRS) was applied, which was originally conceived for roadway slopes, in order to select those sectors with remediation priority. Therefore, the original method has been adapted in this work for urban slopes. For this reason, some of the parameters used in the original method were modified and adapted to the new situation. Other parameters were not considered, due to their non-applicability. This work applies the Rock Mass Rating System (RMR), instead of the original geological feature parameter, to represent the mechanical behavior of the rock mass and addresses a detailed characterization of the block catchment areas. The slope was divided into sectors, and for each sector the RMR and the block falling index were assessed. The calculation results showed that the height of the slope and the catchment area characteristics were the determining factors in the rockfall hazard.

KEYWORDS: Hazard Rating System, Rock Rating System, urban areas.

1 INTRODUCTION

In the town of Mariana, Minas Gerais, as well as in several Brazilian cities, the fast population expansion without a correct planning, leads to unsafe conditions in urban occupation.

The main objective of this work is to make an assessment propose an adaptation of the Rockfall Hazard Rating System (RHRS) (Pierson et al., 1990) for urban areas.

In the RHRS system nine parameters are evaluated, resulting in a range between 3 (favorable situation) to 81 (unfavorable situation). They are: height of the slope; effectiveness of the catchment area; average vehicle risk; percent of decision sight distance; roadway width; rock block volume or size; geologic and geotechnical characteristics; weather conditions and rockfall history. Hence, this work shows an adaptation of those traffic parameters and a close examination of the others.

The chosen area for this study is a rock slope located in Cabanas district of Mariana (Minas Gerais, Brazil), whose coordinates in UTM are 665096/7743423, for point 1 (PR1) and 664744/7743199, for point 2 (PR2) as shown in Figure 1.

Figure 1: Geographic location of the rock slope, showing the survey points (Google earth).

The main failure type in this cliff is rockfall. Rock-falls are difficult to predict in their timing and dimension, especially without any kind of instrumentation. In densely inhabited mountainous regions falling rocks constitute a major hazard that can give rise to casualties, damage and injuries. As a consequence, the assessment of hazards in prone areas has become a major research task worldwide (Bauer & Neumann, 2011).

2 METHODOLOGY

This work consisted of two stages, field work and evaluation of RHRS. At the field, data acquisition was performed selecting the survey areas according to their accessibility, represented by PR1 and PR2 shown in Figure 1.

The required parameters for the RMR were evaluated, as well as a detailed geometry of the slope, the volume of the fallen blocks, the geometry of the catchment area and the presence of vegetation. During the second stage, the field data analysis, the PR1 and PR2 surroundings were divided into sectors according to the geometric parameters including the catchment area. Each sector was evaluated based on the classification proposal, with some adaptations according to the local conditions. The parameters related to the traffic in the RHRS were removed.

2.1 RHRS adaptation

The methodology of this work was based on Gomes (2009). First, a visit to the slope was done to determine accessible areas for field surveys.

The RHRS parameters were adapted for an application in urban areas. The methodology is used to select slopes for priority of remediation therefore, creating a hazard hierarchy. Thus, the method does not have maximum or minimum values, it is comparative, which means the removal of some parameters does not impact the results.

The modifications were carried out considering the geometry of the slope, including the catchment area as well as its geological and geotechnical aspect. Each parameter was scored with values between 3 and 81 points, increasing along with danger.

The Rockfall Index (I_{RF}) defined by Equation 1 is given by the sum of the scores of each parameter.

$$I_{RF} = I_{HT} + I_{EC} + I_{BS} + I_{GC} + I_{CC} + I_{H} \quad (1)$$

Where:
I_{HT} = index related to slope height parameter;
I_{EC} = index related to the effectiveness of the catchment area;
I_{GC} = index related to the geotechnical characteristics;
I_{BS} = index related to the block size;
I_{CC} = index related to the climatic conditions;
I_{H} = index related to the fall history.

2.1.1 Slope Height Index (I_{HT})

The higher the slope is, the greater the potential energy of the rockfall. The Pierson and VanVickle original proposal (1993) considers that greatest height for slopes equal to 30 m, but in natural cliffs, this height may be greater.

This parameter was valuated according to the equation 2, adapted from Gomes' proposal (2009), where H is the height of the slope, measured with a laser tape.

$$I_{HT} = e^{0,05494H} \quad (2)$$

Table 1 shows the adapted Slope Height Index (I_{HT}) rating distribution.

Table1. I_{HT} rating distribution.

H	**20m**	**40m**	**60m**	**80m**
$\mathbf{I_{HT}}$	3 points	9 points	27 points	81 points

2.1.2 Catchment Area Index (I_{EC})

In roads, the catchment area is projected and built to hold rocks. In urban areas, the catchment area is simply the distance between buildings (e.g. houses) and the foot of the slope.

This work considers that the effectiveness of the catchment area depends, mainly on vegetation, between slope and buildings and its inclination angle. The catchment inclination angle in this case relates to the inclination of the small slope observed in front of the cliff. Table 2 shows the rating of these parameters, based on the characteristics referred above.

Table 2. I_{EC} rating distribution.

Good	**Moderate**	**Limited**	**Bad**
3 points	9 points	27 points	81 points
Great distance, low inclination angle and abundant vegetation	Moderate distance and low inclination angle, or abundant vegetation	Low distance and moderate inclination angle. Little vegetation.	Low distance, high inclination angle. Little vegetation.

2.1.3 Geotechnical characteristics index (I_{GC})

In this work, this parameter is linked to RMR, according to Table 3.

Table 3. I_{CG} rating distribution

RMR	100 - 81	80 - 61	60 - 41	40 - 0
I_{GC}	3 points	9 points	27 points	81 points

2.1.4 Block Size Index (I_{BS})

The size of blocks is obtained by the equation 3, according to Budetta (2004), where Db is the dimension of the block and Vb the volume.

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

Pierson and Van Vickle (1993) consider on their proposal blocks between 2.3 m³ and 9.2 m³. But the blocks found in the slope of the Cabanas district are greater than 9.2 m³. Therefore, this parameter has been valuated according to the equation 4, adapted from Gomes (2009).

$$I_{BS} = e^{1,465Db} \quad (4)$$

Table 4 shows the Block Size Index (I_{BS}) rating distribution.

Table 4. Size of Blocks Index rating distribution.

Db	**0.75**	**1.50**	**2.25**	**3.00**
I_{BS}	3	9	27	81

2.1.5 Climatic Conditions Index (I_{CC})

The climatic condition was replaced by the presence of water in the slope, see Table 5.

Table 5. Climatic Conditions Index rating

Water in the slope	Dry slope	Little humidity	Presence of water	Slope spouting water
I_{CC}	3	9	27	81

2.1.6 Fall History Index (I_H)

This parameter is very difficult to analyze, because it needs constant monitoring. But it is very important and was considered in this work. Table 6 shows its value distribution.

Table 6. Fall History Index

Fall History	**Little falls**	**Casual falls**	**Many falls**	**Constant falls**
I_H	3	9	27	81

2.1.7 Traffic parameters

The parameters related to the traffic in the RHRS, like average vehicle risk, percent of decision sight distance and roadway width were neglected, because they have no possible application in urban constructions. As far as the method has no maximum or minimum values, it is comparative; parameters removal causes no drawback to the final proposal.

3 GEOLOGICAL AND GEOTECHNICAL CHARACTERISTICS OF THE SLOPE

The slope located in the Cabanas district is composed of quartzite of Itacolomi Group. The rock mass is extremely fractured, as shown in Figure 2. The mineralogical composition revealed quartz, sericite, biotite and muscovite.

Figure 2. Slope in the Cabanas district.

Both PR1 and PR2 present three sets of discontinuities. Table 7 shows the average orientation (dip/dip direction) of each set in each point and the orientation of the slope face. These data were obtained from the software Dips 6.0 (Rocscience Inc.).

Table 7. Discontinuity sets

Point	**Set**	**Orientation**
1	1(foliation)	21/139
1	2 (joint)	60/337
1	3 (joint)	62/038
1	Slope face	67/317
2	1(foliation)	27/117
2	2 (joint)	82/339
2	3 (joint)	55/280
2	Slope face	70/318

4 RESULTS AND DISCUSSIONS

4.1 Geometry of slope and catchment area

The slope was divided in homogenous zones according to the geometry of the slope and the characteristics of the catchment area, shown in Table 8 and 9 respectively. The rockfall hazard analysis was done for each sector.

Table 8. Geometry of the slope.

Sector	Height (m)	Inclination Angle (º)	Lateral Extension (m)
Sector 1A	55	75,6	60,4
Sector 1B	30,7	68,1	25,6
Sector 1C	29,1	57,8	35,2
Sector 2A	80	67,3	28,6
Sector 2B	68	67,4	32,5
Sector 2C	59,8	72,7	19,1
Sector 2D	78	73	28,3

Table 9. Geometry of the catchment area.

Catchment Area	Inclination Angle (º)	Lenght (m)	Vegetation
Sector 1A	18,1	24,8	Not relevant
Sector 1B	15,6	16,7	Not relevant
Sector 1C	41,8	9,2	Not relevant
Sector 2A	20,7	39,6	Not relevant
Sector 2B	22	41	Relevant
Sector 2C	25	45,3	Not relevant
Sector 2D	11,5	50	Not relevant

The geometry of the catchment area and the vegetation are very important in rockfall hazard analysis, because they may be determining for a rock block to reach or not a building. For example, great lengths and low inclination angles represent safer conditions. Vegetation can reduce the kinetic energy of the block, because it behaves like a shock absorber. Figure 3 shows the sector 2D, with the highest height slope and no relevant vegetation, but with a large catchment area.

Figure 3. Sector 2D.

4.2 Block size

For this parameter it was considered the volume estimated by the dimensions (height x width x length) of fallen blocks found in the catchment areas of sectors, rather than the volume calculation based on the spacing between fractures.
It represents the worst situation (events with larger blocks), because the block volumes found using the Palmström proposal (1995), which considers spacing and angles between families of fractures, were considerably smaller than the volumes of fallen blocks found in the catchment area. Table 10 presents the volume of fallen blocks measured directly in the field and calculated according to Palmström proposal (1995).

Table 10. Block size

Point	**Fallen Blocks**	**Palmström (1995)**	**Db**
PR1	10,9	2,25	2,2
PR2	24,6	0,44	2,9

4.3 Geological and geotechnical characteristics

This parameter was replaced by RMR. The RMR calculation needs estimation of rock strenght, fracture spacing, Rock Quality Designation (RQD), characteristics of the joints and water in the rock mass.

The strenght was estimated using the geologic hammer. The results, thorough all the rock mass, was resistant to extremelly resistant.

The average spacing of each set was obtained from field work and calculated by software Dips 6.0. Table 11 contains the average values of spacing, Jv and RQD for each initial points, PR1 and PR2.

Table 11. Spacing, Jv and RQD.

PR	F1 spacing (m)	F2 spacing (m)	F3 spacing (m)	Jv	RQD
1	0,42	1,43	0,76	4,39	100,00
2	0,24	0,44	0,76	7,76	89,39

The characteristcs of the joints are shown in Table 12, for each sector in the slope.

Table 12. characteristcs of the joints.

Sector	**Roughness**	**Opening**	**Fill**
1A	Slightly rough	Millimetric	-
1B	Slightly rough	1-5cm	Smooth
1C	Slightly rough	1-10cm	Smooth
2A	Slightly rough	Millimetric	-
2B	Slightly rough	Millimetric	-
2C	Slightly rough	Millimetric	-
2D	Slightly rough	5 cm	Smooth

From these data, it was possible to calculate the RMR, considering a dry slope, because the water is already included in the RHRS. Table 13 shows the result for each sector.

Table 13. RMR for each sector.

Sector	1A	1B	1C	2A	2B	2C	2D
RMR	85	75	75	82	82	82	62
Class	I	II	II	I	I	I	II

4.4 Climatic Conditions

The slope of the Cabanas district was observed for a period of approximately 8 months. Water draining in the slope was observed in some points, especially in rainy periods. For this parameter it is impossible to establish a variation throughout the region.

4.5 Rockfall History Conditions

A database showing the history of falls and events would be really helpful to know the behavior of a rock mass. This tool would make possible to infer relations among rainfall events and rockfalls, for example. The parameter is easily noticeable at roads, but in urban areas it needs continuous monitoring or community collaboration for reporting rockfall events.

During fieldwork some inhabitants were asked about recent rockfalls occurrence. Some of them said they had never seen any fall, however during the fieldwork evidences showing recent falls were found; blocks being little or no coverage by soil and vegetation.

4.5 Rockfall Index (I_{RF})

The sectors were scored for the block fall hazard classification system in urban areas according to the equation 1. Table 14 shows the values of indices obtained and the calculated value of I_{RF}.

Table 14. Rockfall index (I_{RF}) for each sector.

	I_{HT}	I_{EC}	I_{GC}	I_{BS}	I_{CC}	I_H	I_{RF}
1A	20,5	27	3	25,1	27	9	111,6
IB	5,4	27	9	25,1	27	9	102,5
1C	4,9	81	9	25,1	27	9	156,0
2A	81,0	27	3	70,0	27	9	217,0
2B	41,9	27	3	70,0	27	9	177,9
2C	26,7	9	3	70,0	27	9	144,7
2D	72,6	3	9	70,0	27	9	190,6

Among the subsectors, the S2A was considered the most critical, being different from the others because it has no flat area or vegetation that could cushion the block movement.

It was expected that due to the S2D catchment area characteristics, low inclination angle and great extent, the value of rockfall index would have been low, when compared to the others, but its slope height and the lower quality of the rock mass (compared to others) meant that the final value was relatively high.

Regarding PR1, the S1C sector has the worst characteristics concerning the rockfall hazard, and the conditioning factor is the geometry of its catchment area. The catchment area of this subsector is practically a “new slope” formed by the stacking of fallen blocks.

5 CONCLUSIONS

The geomechanical classification system presented in this work can be applied for rockfall hazard estimation in any urban area. It comes from an adaptation of the Pierson and Van Vickle (1993) Rockfall Hazard Rating System proposal for roads.

This tool offers hazard comparison among different areas in order to establish a priority order in the interventions to be performed by government agencies in hazardous zones.

Two particular areas in the large slope analyzed were found to be especially hazardous, revealing that the slope height is a crucial parameter.

ACKNOWLEDGEMENTS

The authors thank the Brazilian government organism CAPES and the mining engineering graduate program from the Federal University of Ouro Preto (PPGEM) for their economical support.

REFERENCES

Bauer, M. & Neumann, P (2011). A guide to processing rock-fall hazard from field data.-In: Vogt, Geotechnical Safety and Risk, Proceedings of the 3rd International Symposium on Geotechnical Safety and Risk, June 2011: 149-156

Budetta, P. (2004). Assessment of rockfall risk along roads. Natural Hazard and Earth System Sciences 4: 71-81.

Gomes, G. J.C. (2009). *Avaliação do perigo relacionado à queda de bloco em rodovias*. Dissertação (mestrado). Escola de Minas, Universidade Federal de Ouro Preto, Ouro Preto- MG.

Palmström, A. (1995). RMi – *a rock mass characterization system for rock engineering purposes*. Ph.D. thesis, Oslo University, Norway, 400 p.

Pierson, L. A.; Davis, S.A. Van Vickle, R. (1990). Rockfall Hazard Rating System Implementation Manual Federal Highway Administration (FHWA),

Report FHWA- OR- EG-90-01, FHWA, U.S. Dep. Of Transp.
Pierson, L. A., Van Vickle, R. (1993). Rockfall Hazard Rating System, Transportation Research Record Nº 1343, Nacional Record Board, Washington, D. C.
Rocscience Inc. 2012, Dips Version 6.0 - Graphical and Statistical Analysis of Orientation Data. www.rocscience.com, Toronto, Ontario, Canada.