Energy Map as a Subsidy to the Project of Dynamic Rockfall Barriers

Marcelo Heidemann
Universidade Federal de Santa Catarina, Joinville, Brazil
marcelo.heidemann@ufsc.br

Felipe Gobbi Silveira
Geobrugg AG, Porto Alegre, Brazil
felipe.gobbi@geobrugg.com

Bruno Denardim da Rosa
FGS Geotecnia, Porto Alegre, Brazil
bruno@fgs.eng.br

Victor Hugo Duarte de Andrade
Universidade Federal de Santa Catarina, Joinville, Brazil
victor_hgda@hotmail.com

Anderson Fonini
FGS Geotecnia, Porto Alegre, Brazil
fonini@fgs.eng.br

Álvaro Pereira
FGS Geotecnia, Porto Alegre, Brazil
alvaro@fgs.eng.br

Abstract

This paper presents the methodology used in the construction of an energy map that served as a tool to define the proper alignments to install rockfall barriers to protect an ore plant. The calculations of the energy levels were made through simulations of rock fall in several topographic sections, using the Software Rockfall Dr. Spang 6.1. This software simulates rock fall events, and it has as input data the topographic section, boulders size and position, and the parameters of elastic restitution of the surface along the slope. In addition to the energy levels, it is evaluated the trajectory and height of rock boulders along its way downslope. The definition of restitution coefficients was carried out through parametric and back analysis. The positions of the blocks were verified in-situ and confirm that parameters used in analyses are reliable. Multiple analysis for 7 topographic sections were carried out. Analyses were executed for rock boulders of jaspilite/quartzite with density of 2.7 ton/m³. The initial position was the crest zone of each section, varying ±150 m. Each rockfall simulation considered 100-300 rock boulders with 3 m³ in volume, 0.9 m radius and 81 kN weight. The map was built by interpolation of the results obtained in each section using the "nearest neighbor" method. The simulations showed that the maximum energy developed by the boulders ranges between 600 kJ and 1000 kJ, and the maximum levels of energy involved in the problem were verified in the top of the slope, which are greater than 3000 kJ. There is a progressive reduction of energy as the blocks reach the lowest elevations. From the analyses it was recommended the installation of a rockfall barrier with 4 m height and capacity to absorb energies up to 1500 kJ.

1 INTRODUCTION

Rockfalls are quite common in areas where the rock was cut and in slopes with boulder outcrops. Rockfall is an important type of landslide and it is reported in many classifications systems, e.g. Cruden & Varnes (1996), Hutchinson (1988), Guidicini & Nieble (1984) and Augusto Filho (2001).

The geological-geotechnical conditions of the Serra Azul region, in Minas Gerais state, Brazil, is characterized by elevations covered by residual soils that are a product of weathering of jaspilite and ferrous quartzite rocks Afterward, the residual soil is eroded and many boulders were exposed. These massive rock blocks are partially or slightly altered and constitute masses susceptible to instability.

This condition is quite common in the region known as Quadrilátero Ferrífero, an area of remarkable iron ore reserves in Minas Gerais state, southeast Brazil. In this region a plant to process iron ore was built in the base of a steep hill, which is susceptible to rockfalls. Rock boulders are prone to hit the plant areas and cause damage to human lives and to infrastructure.

To protect the future installations, it was assessed the construction of physical barriers to intercept and stop any rock boulders if they become unstable. Such protection system could be constituted of dynamic barriers, that when hit by the unstable mass, which can be rock blocks or soil, absorb the impact energy of these materials, suffering controlled deformations to reduce the loads. Through special devices they dissipate the energy transmitted to the barrier, until the boulder movement ceases.

The project of dynamic barriers requires the understanding of the energy levels reached by the mass on the instant that it impacts the barriers, besides the heights reached in the case of rock blocks bounce. Thus, the barriers are preferable installed in the areas where the energies along the trajectory of the moved mass reach the minimum levels and the height reached by the blocks would be short.

When moving downhill the blocks transform gravitational potential energy in kinetic energy, which is directly proportional to the size of the blocks. Depending on the characteristics of the ground materials whereupon the movement will take place, the rock mass energy will be dissipated, in a more or less effective manner. When topographic characteristics make the rock to bounce and the surface of the ground is rigid, as in the case of fresh rocks, the energy levels are kept higher, while in grounds covered by soils and vegetation there is a higher dissipation of energy. The potential of the materials that covers the slope surface to not absorb energy is given by the restitution coefficients (normal and tangential), the friction angle between the block and the surface (static and dynamic) and the rolling resistance.

When the problem is given by a specific boulder and a clear rolling path, the energy estimation is made for each scenario, individually. However, that definition of energies is not simple in extensive areas or when exists many potentially unstable boulders, as in the reported slope.

In this sense, this work shows the methodology used to create a map that summarizes the energy levels reached by unstable rock blocks along the studied slope. This map was built with basis in results of rockfall simulation in multiple topographic sections.

2 DESCRIPTION OF THE STUDIED AREA

This study was conducted in an area located near to Brumadinho and Igarapé towns, in Minas Gerais state, Brazil.

In this area the weathering of the rocks and the subsequent erosion of residual soils exposed many boulders partially or little altered, which are potentially unstable. This condition is illustrated in Figure 1 that shows the upslope area of implantation of the industrial plant, and the catchment area, from where the blocks come.

Figure 1 Studied slope showing the catchment area and falling blocks.

Although there is reasonable distance between the catchment area and the area to be occupied, the existence of many blocks in the base of the elevation confirms the possibility that the blocks in the upper part of the slope can move far downwards. To get the condition worse, on the opposite side of the slope, there is an active mining area. So, there is the risk that chock waves from blasting in the mine can activate the motion of the blocks in the studied slope. Figure 2 shows a satellite image from the studied area indicating the mentioned areas.

However, measure the acceleration caused by blasting and simulate their effects as landslide triggering agent is a complex issue.

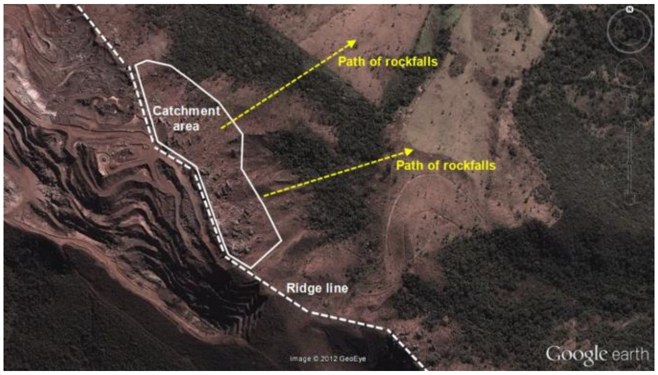

Figure 2. Satellite image of the studied area.

The area effectively analyzed is about 940,000 m², considering the slope area and the region where the industrial facilities will be built. The slope is covered by a thin soil profile, and in some areas by rock outcropping. According to the measurement made in-situ the volume of blocks ranges from 1 m³ to 10 m³.

3 METODOLOGY

The main tool used for the generation of the energy map is the software Rockfall Dr. Spang 6.1. The input data to simulate the rockfalls are the 2D topographic section, the size and weight of the blocks, their initial position and the parameters of restitution and dissipation of energy of the materials that cover the ground. The outputs are the energies and heights reached by the blocks along their way downhill slope. In this study 7 representative topographic sections were extracted from a map of contour lines.

The definition of the input parameters for the restitution coefficients is not a simple task. To define the most suitable values for restitution coefficients a parametric analysis was carried out. Several analyses were run with different combinations of restitution coefficients. After the parameters were refined through back analyses and the most probable set of parameters were used to simulate the movement of specific blocks found in the area. It aimed to verify if the proposed parameters combination matches with the positions of the blocks that had previously fallen in the slope and were observed downhill in the study area. The section 3 (Figure 3), was used in these analyses because it was judged as the most critical considering its inclination and length.

In the preliminary analyses the rock was assumed as a jaspilite/quartzite, with density about 2.7 ton/m³. The geometric characteristics adopted to the blocks were perfect spheres with radius = 0.9 m; volume = 3.0 m³; weight = 81 kN. The initial position of the blocks is the ridge line (water parting). The simulation considered that the blocks move by rolling or sliding.

As the boulder is simplified to a 2D circle, it will stop due to a rolling resistance parameter, that has particular importance in gentle slopes, or if topographic features restrain the movement (as a barrier).

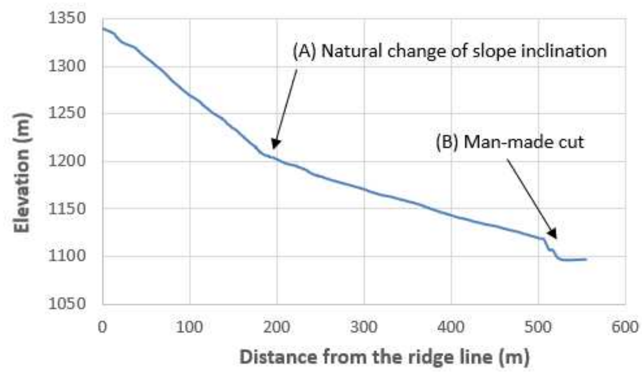

Figure 3. Topographic section 3.

The key question to be analyzed in this preliminary stage refers to the most suitable distribution of the interaction parameters between the block and the natural ground, which impacts in the amount of energy restituted during the movement. So, 3 scenarios were tested:

- Combination 1: the entire surface of the slope is characterized by coefficients related to only one material (fresh rock). This combination was used to characterize the most critical condition, with low levels of energy dissipated in the terrain, allowing the blocks to reach high velocities and bounce heights, and consequently high energies. This condition showed up conservative and do not match the real conditions.
- Combination 2: the upslope region the relief transition zone (about 180 m from the ridge line) was considered fresh rock, while the region downslope the relief transition was assumed to be covered by a rock of intense roughness. The results

obtained from these analyses were similar to the observed in the field, considering that they predict the deposition position of the boulders in accordance with in-situ observations.

- Combination 3: the region upslope the relief transition zone (about 180 m from the ridge line) is composed by fresh smooth rock and the region downslope the relief transition is considered covered by a thin soil layer. This combination matches with the slope coverage observed in situ. Most of the energy from the blocks is dissipated in the region covered by soil. Despite this choice correspond to the in-situ cover, the use of these data as input parameters does not allow to achieve reasonable results considering the paths and positions of rock blocks observed in-situ.

The interaction parameters between the ground and the blocks used in the analyses are showed in Table 1.

Table 1. Elastic restitution coefficients.

Parameter	Fresh rock (smooth)	Fresh Rock (rough)	Soil
Rg	30°	30°	15°
Rh	40°	40°	30°
Dn	0.06	0.06	0.035
Dt	0.93	0.93	0.8
Rw	0.02	0.05	0.1
Oa	0.1	0.3	0.2
Of	1.0	2.0	1.0

Where: Rg – dynamic friction angle block/surface; Rh – static friction angle block/surface; Dn – normal absorption coefficient; Dt – tangential absorption coefficient; Rw – rolling resistance; Oa – maximum rough amplitude; Of – maximum rough frequency.

A set of rockfall simulation were carried out for seven topographic sections using the most suitable combinations of materials and their properties. Figure 4 shows the positions of the sections.

These analyses were carried out for rock boulders of jaspilite/quartzite with density of 2.7 ton/m³. The initial position of the blocks is the top of the section and vary ± 150 m from this point, (when possible since that in some sections the top coincides with the riding line). One simulated the fall (by rolling or sliding) of 100 to 300 rock blocks with 3.0 m³ volume, 0.9 m radius and 81 kN weight.

These simulations allowed to estimate the maximum energies reached and the height reached by the blocks in its movement along the slope. As the data of maximum energy and height are taken for each section, the results for the slope area between the cross sections were estimated by interpolation, applying the "nearest neighbor" method. This method is implemented in a Geographic Information System software.

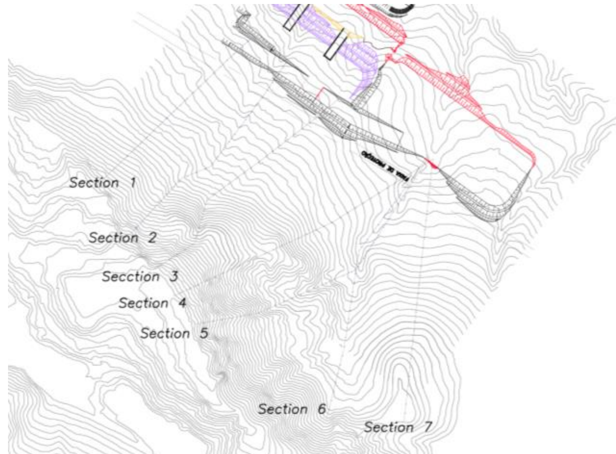

Figure 4. Location of the topographic sections.

4 RESULTS

Figure 5 shows the results of the rockfall simulations for section 3, considering the input parameters given by "Combination 2".

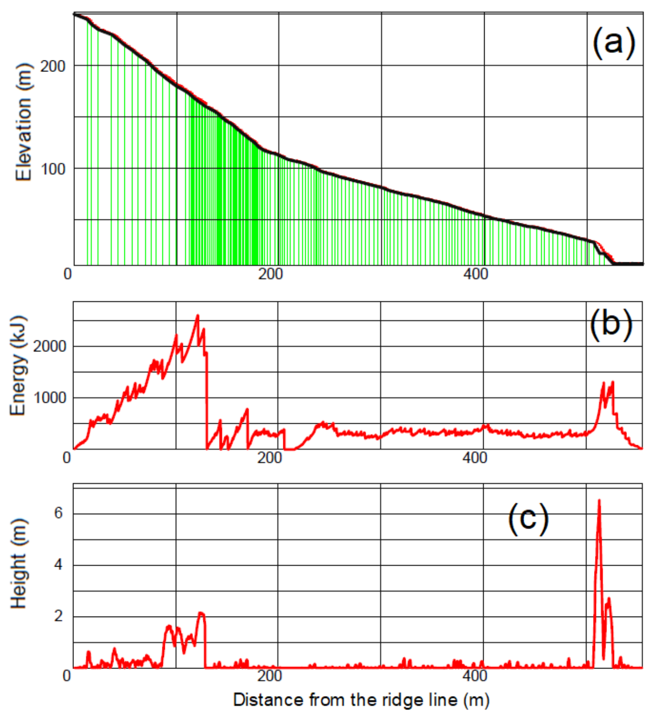

Figure 5. Results of the analyses to the section 3 (a - surface profile and rock path; b – energy; c – bounce height).

The Figure 5a shows the trajectory of the blocks along the slope surface. The Figure 5b and c shows the distribution of the energies and bounce height, respectively, with reference to the position of the block along the slope. Based in these data the alignment to install the barrier, its height size and energy capacity can be decided in a reasonable way.

The Figure 6 and 7 show the energy levels and the bounce heights obtained through analyses in the same cross section, but with the input data related to the "Combination 1" and "Combination 3".

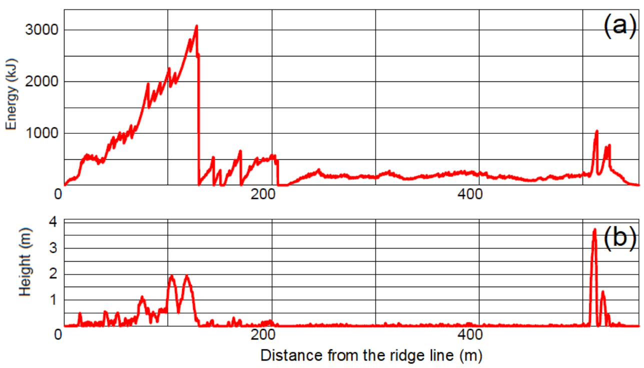

Figure 6. Results of the analyses to the section 3, using properties given by the Combination 1 (a – energy; b – bounce height).

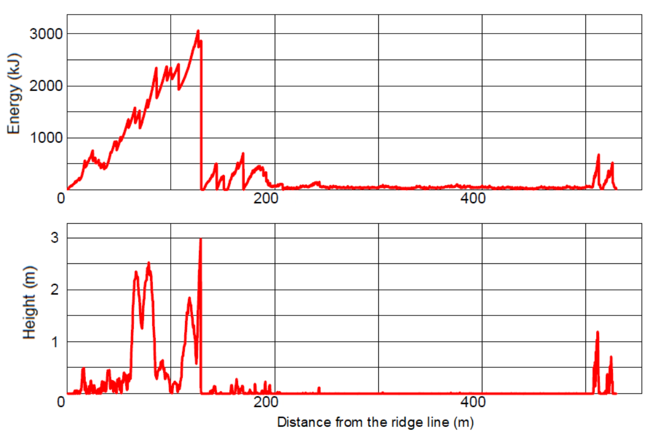

Figure 7. Results of the analyses to the section 3, using properties given by the Combination 3 (a – energy; b – bounce height).

The results obtained in this preliminary analysis indicated coherent project premises in relation to the energy levels achieved, what can be assessed by the position in which blocks stop along the slope and the paths that can be followed. The analyses revealed that Combination 2 was the one that best represent in-situ conditions. Section 1 was the most conservative (high energies) and Section 3 appears to underestimate the energies and distance reached. Analyses in multiple sections.

The simulations showed that the maximum levels of energy developed by the rock boulders vary from 300 kJ up to 3000 kJ, however energy levels between 500 kJ and 1000 kJ are the most frequent.

The simulations carried out considering the seven slope cross sections allowed the elaboration of a map that shows the magnitude of energy reached by the blocks when they move. Figure 8 shows the energy map developed from these results. The maximum levels of energy and higher velocities occur in the upper part of the slope. There is progressive reduction of the velocity as the blocks reach the lower elevations. The natural change in topography that occur 200 m far from the initial position also marks the change in surface properties (point A, see Figure 3).

After the reduction of energy levels that occur after the point A, the energy increases in the end of the sections (around 510 m in section 3). This is due to a cut executed in the slope (see point B in Figure 3) for the construction of an access road. This cut results in an increase of velocity for the material that reflects in the increase of energy observed in the analyses.

Therefore, it is interesting to install the barrier in the region immediately before this cut in the slope. It will prevent a new increase of energy, and it will also protect the road, the users, and the structures downslope.

Based on the energy map the barrier should be positioned in the region just upslope to the road, as shown in the Figure 9.

Complementary analyses considering the barrier in the proposed position allowed a statistical evaluation of energy levels, the velocity, and the impact height of the boulders. The results of these analyses are shown in the Figure 10.

From the energy map and the specific analyses from section 3 one can conclude that for the barrier in the indicated position, the maximum energies are about 500 kJ and the impact heights not higher than 1 m.

However, the energy map shows that along a wide region, beyond the region of influence of section 3, blocks with energies between 500 kJ and 1000 kJ can hit de barrier. Therefore, barriers able to support kinetic energies up to 500 kJ are not proper to these regions.

Consequently, it was suggested as a safest solution the use of dynamic barriers 3 m height and able to absorb kinetic energies about 1000 kJ. Such barriers should be installed along the entire slope as shown in Figure 9.

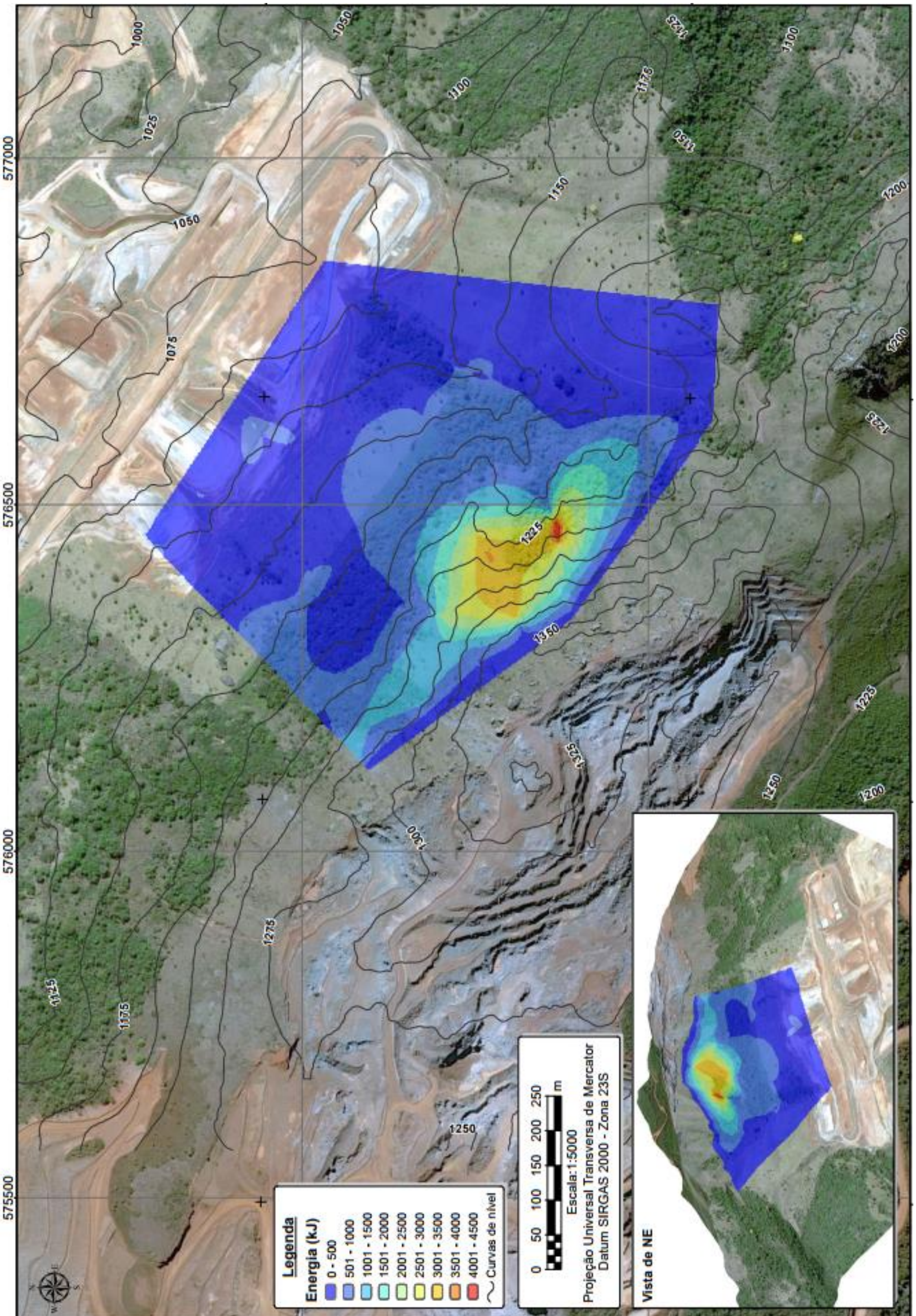

Figure 8. Energy map of the studied slope.

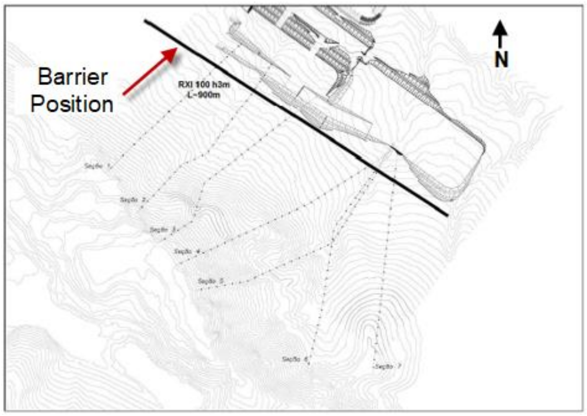

Figure 9. Proposed position to the installation of the barrier.

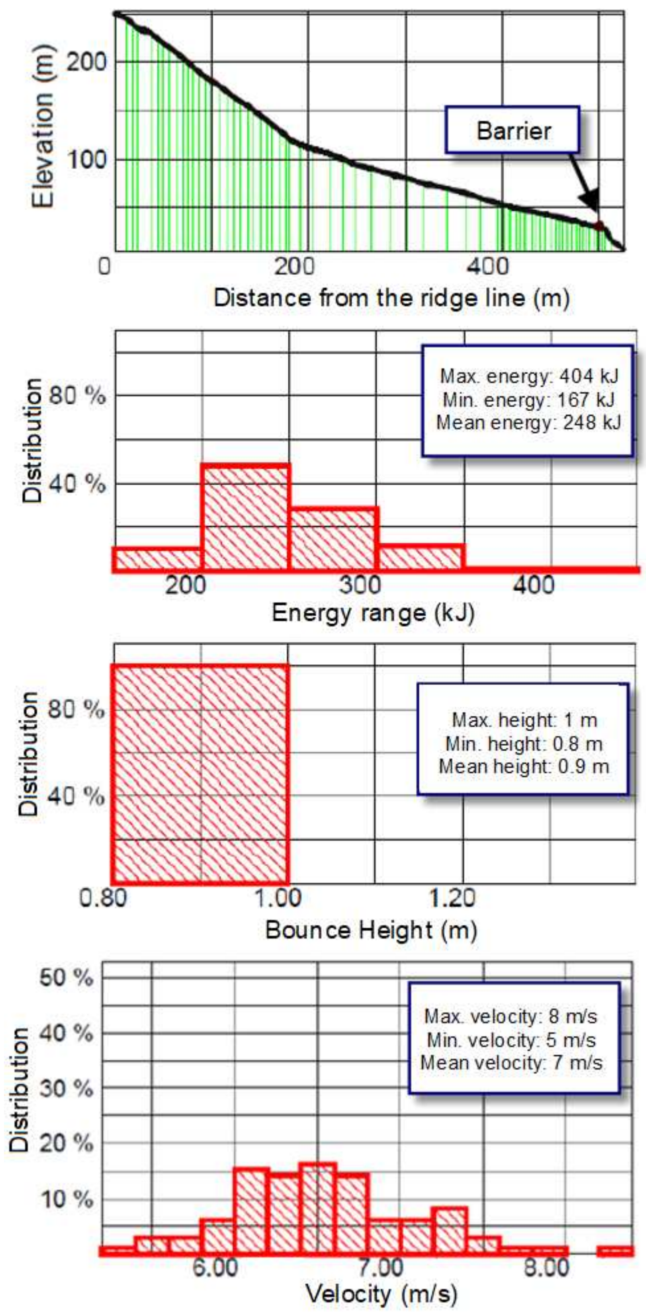

Figure 10. Results of the statistical analyses of energy, impact height and velocity for section 3.

5 CONCLUSIONS

The occupation of areas downslope the studied slope created a rockfall high-risk zone. In order to protect people, the plant structure and the facilities a dynamic barrier can be a suitable solution.

The design of such barriers must consider that they need to be safe, but not excessively robust and costly. As the study area is wide, it was not clear in the preliminary design phase the best position to install the barrier. In this sense, the energy map was useful to define the most efficient position to install the dynamic barrier. The solution was proposed with basis on the energy reached by the blocks and the bounce height.

In the same way, based in this map one defined the use of dynamic barriers 3 m height and able to absorb kinetic energies about 1000 kJ.

The methodology to produce the energy map is relatively simple and produces consistent results. Such maps can be used in similar situations as a support tool in the designing of dynamic barriers for rockfalls.

6 ACKNOWLEDGMENTS

The authors thank the Geobrugg AG and FGS Geotecnia to support this study.

7 REFERENCES

Augusto Filho, O. (2001) *Carta de risco de escorregamentos quantificada em ambiente SIG como subsídio para planos de seguro em áreas urbanas: um ensaio em Caraguatatuba (SP)*, Tese de Doutorado em Geociências, Instituto de Geociências, Universidade Estadual Paulista, Rio Claro, 166 p.

Cruden, D.M., Varnes, D.J. (1996) Landslide types and processes, In. Special Report 247: *Landslides: Investigation and Mitigation* (A.K. Turner e R.L. Schuster, eds.), TRB, National Research Council, Washington, D.C. pp 36-75.

Guidicini, G. Nieble, C.M. (1984) *Estabilidade de taludes naturais e de escavação*, Edgard Blücher, São Paulo, 194 p.

Hutchinson, J.N.O (1988) Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology, In: *Proc. 5th International Symposium on Landslides*, Lausanne, pp. 3-36.