Use of rockfall dynamic barrier as hydroelectrical power plant access protection

Lucas Defalco Marcomini, Darwin José Guillón Mata, Ginna Marcela Torres Rodrigues

Maccaferri do Brasil; Maccaferri de Centro America; Maccaferri de Colombia;

l.marcomini@maccaferri.com; *d.guillon@maccaferri.com*; *g.torres@maccaferri.com*

Abstract

A hazardous event happened in 2013 which put in risk those who works at the underground power house unit of Henry Borden Hydroelectrical power plant when a block of approximately 2 tons fell into the access path of the power house facilities. After an on-site investigation, was detected the presence of several loosing blocks of rock, with dimensions from hand carrying blocks up to boulders of almost 1.8 m³. Immediately, the presence of people under the risk area was suspended until a permanent solution was installed. Many possibilities have been considered, however, the dense native vegetation in addition to the huge area of intervention led to the election of an environmentally friendly solution as well as efficient solution regarding economical aspects. A rockfall dynamic barrier has been chosen and designed to work at serviceable state conditions by methods suggested by European guideline ETAG 027 and the Italian normative UNI 11211-4:2012.

1 INTRODUCTION

Henry Borden hydroelectrical power plant, situated at Cubatão, São Paulo, Brazil had it first power house constructed at the 1920's with the goal to supply enough and clean energy to the city of São Paulo, which was having an increase of electric power consumption year by year. This power plant had your position strategic defined at the foot of Serra do Mar, which is a mountain group parallel to the sea, to use its 720m water drop to generate energy by the spinning of eight Pelton turbines.

At the 1940's the increasing use of electric power by São Paulo city and aerial attacks against the power house, made "Light", the Canadian company that was in charge to manage the power plant at this time, in partnership with the government of São Paulo to design a new power house, to increase the amount of energy produced as well as be safer in case of eventual other attacks. Subsequently, another power house with six generating units has been constructed at the 1950's inside an artificial cave, excavated using explosives on a Gneiss rock matrix. This building process caused lots of cracks on the rock, which became a problem when the vegetation roots started to grow inside of the space between the rocks in the future years.

Henry Borden Power Plant facilities Layout may be better understood by looking at the perspective, shown in figure 1.

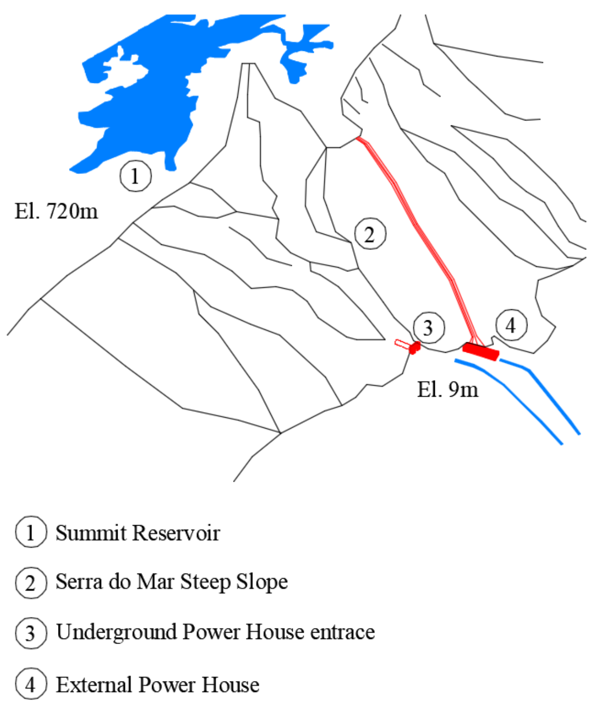

Figure 1 - Henry Borden Power Plant Facilities General Layout

The main access to the cave, that takes to the underground power house (Number 3 shown at figure 1) has a steep rocky slope at the entrance. Undoubtedly in 2013 a block of approximately 2 ton fell right on the access path, threating those who use the access at change of shafts and meal time. This event caught the attention of the safety team of EMAE (*Empresa Metropolitana de Águas e Energia*) which is the current manager of Henry Borden Power Plant facilities. After this rockfall, the team immediately suspended all the activities of maintenance at the power house entrance roof in addition to start to planning a viable economic solution as well as environmentally friendly.

2 GEOTECHNICAL PROBLEMS AND RISK ASSESSMENT

The municipality of Cubatão has been grown between the steepest slopes of Serra do Mar. This city has an important industrial area in addition of a petrochemical complex. Through Cubatão also pass the main highways and railways that ensure manufactories transport from state's countryside to the Port of Santos, one of the main Brazilian's route of exportation. These facilities have previously been affected by the same hazardous events faced by Henry Borden Power Plant.

According to Ribeiro (2003), these slopes of Serra do Mar are naturally susceptible to natural hazards, such as landslides, rockfall, debris flow and mudflow, due to among other factors the steep slopes and the high rainfall at summer period.

From the geological point of view, Serra do Mar is composed mainly by metamorphic rocks from Pre-Cambrian period (gneiss, granite, mica schists). (Massad, 2009).

The geologic formation in addition to the new power house building process triggered the formation of blocks of rock from hand carrying dimensions up to 1.8 m³, which gives a mass of approximately 4.860 kg. These blocks are formed by the rock mass fractures, that was being developed through the years and have been increased due to the use of explosives during the cave entrance excavation at 1950's.

During earlier on-site inspections, these blocks were found and it's dimensioning was visually estimated. On the figure 2, taken while the site was being cleared, is possible to see the biggest block found.

Figure 2 - Big block of rock, around 1.8m³

The rockfall, happened in 2013, occurred after a heavy rainfall, this event probably has been caused due the leaching of the poor portion of residual soil among the rock cracks, caused by the water. Based on these observations made during on-site inspections was clear that another rockfall could suddenly happen, exposing workers and visitors of the Power Plant at risk. To minimize that risk and guaranty safe conditions for those who use the facilities a solution was mandatory.

The instability area occurred right above the main entrance of underground power house, fact that enlarge even more the risk of exposure, as the access path was populated quite often. The figure 3 gives a general idea of the positioning of the access in relation to the instability area.

Figure 3 - Overview of underground power house entrance

Moreover, the highly dense vegetation, present in the whole slope helps to hide the blocks of imminent risk of fall, leaving behind any chance to prevent the damages.

3 PROPOSED SOLUTIONS

The main goal of the solution proposed was to project the entrance, reducing the risk of falling blocks to reach the access path as much as possible, besides being economical viable, concerning some conditions imposed by the nature of the intervention.

The upslope area, that may contain unstable blocks, extends up to about 50m above the entrance, which gives a relatively large intervention area, leading to an excessive amount of resources involved as well as intervening at the forest in a non-ecological way.

Regarding rockfall solutions, there are two main kinds of intervention: Active and Passive. Active solutions are designed to work directly upon the instability, with the aim of stabilizing the loosened blocks of rock, avoiding the triggering of any movement. This type of solution, in their majority, requires less maintenance, once the load applied is only static and not dynamic. On the other hand, passive solutions are engineered with the purpose to allow the loosing material movement to happen, and at some point, being stopped by the intervention. Passive solutions, in most cases works with dynamic loads, which requires specific properties from the materials as well as maintenance. This concept works appropriately when facing big areas of unstable material, once the price of the passive solution is relatively constant whereas the cost of active solutions is given in function of the unstable area, as shown in figure 4.

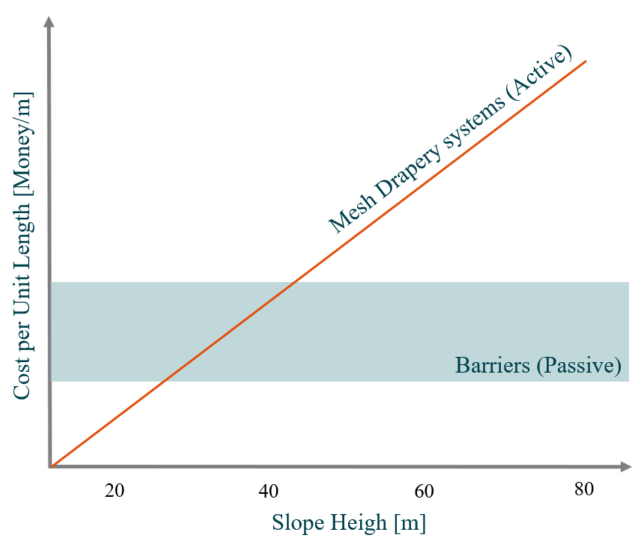

Figure 4 - Economical aspects when facing active (mesh systems) and passive (barriers systems)

As mentioned in previous chapter, the job site is situated at Serra do Mar, which is an outstanding area of Mata Atlântica. According to Mori, et al. (1983) this biome is the most threated tropical forest in the world, which through the years lost a huge quantity of area, currently only has about 7,3% of its original area, thus, is mandatory that the solution applied must have as minimal environmental impact as possible.

Once the underground access has a high slope fulfilled with native vegetation of Mata Atlântica, the solution should regard an intervention as light as possible, the first idea that comes to EMAE safety committee was to expand the entrance tunnel approximately 50m, creating a kind of false tunnel in order to protect those who use the path from the falling blocks, as shown at figure 5.

Figure 5 - False tunnel, initially considered as a solution

Nevertheless, some issues were carried on in the false tunnel solution. At the side of entrance, there is a parking area, which serves the operational vehicles and visitors' buses, who often visit power plant facilities, and the tunnel wouldn't protect that area. As seen at figure 4 and 6, there is a considerable amount of vegetation upon the entrance roof, which wasn't a usual situation until the maintenance at this area be suspended until the solution be installed, neither for the roof the tunnel would offer protection.

Moreover, the behavior of rigid elements placed as rockfall protection structures requires a higher resistance of it, as described by Agostinacchio and Olita (2002).

At the figure 6, two graphics of force x elongation are shown. At these graphics, A1 is equal to A2 which are as well equal as the kinetic energy of falling mass, although the forces F1 and F2 are significantly different between each other, due the fact that the body A1 is more rigid than the body A2, and the low level of deformation of a rigid body gives to a higher force to absorb the impact of the same block at the same Kinect energy.

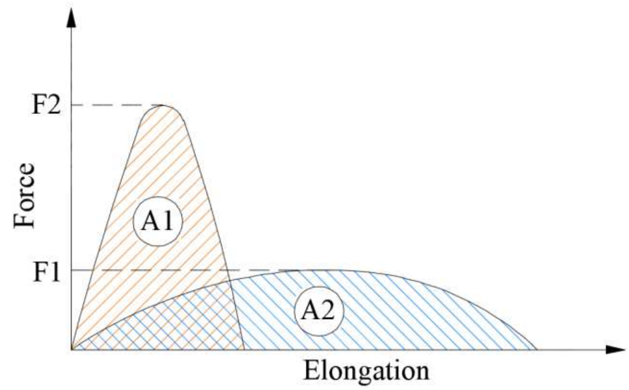

Figure 6 - Force applied on the interception structure (Adopted from Agostinacchio and Olita, 2002)

Higher forces applied on the structure leads to stronger structures and thus, more expensive ones. According to Agostinaccio and Olita (2002), the rigid structures are reliable, from the technical point of view, and shall be used under extreme conditions, but for the most part of cases, flexible structures fulfill the requirements, beside to be lighter, cheaper, and easier to install.

Therefore, under all project conditions, the adopted solution for underground power house entrance protection have been the use of Rockfall Dynamic barriers, which are flexible structures installed in a line, giving to the project a quick on-site chronogram besides the fact of the minimum amount of vegetation should be cleared, reducing the project footprint.

4 ROCKFALL DYNAMIC BARRIER DESIGN

Rockfall dynamic barriers, or deformable barriers are classified as passive solutions, once they are placed not at direct contact to the instability, but at a strategic position to intercept falling blocks trajectories. (Grimod and Giacchetti, 2014) According to the European Guideline ETAG 027 (Guideline for European technical approval of falling rock protection kits), issued by EOTA (European Organization for Technical Assessment) defines a rockfall barrier as a kit of different elements that must be able to stop a block at the impact against it. The main goal of the design is to check if the characteristic energy of the barrier can stop a falling block with its Kinect energy.

ETAG 027 was created with the main objective to understand and compare the behavior of such structures. The guideline also standardized the testing procedure of the barriers. All barriers are tested under the Maximum Energy Level (MEL) condition that throw a block of a certain mass at a specific height in order to test the barrier according to its maximum level of energy. Another test is done, now at Serviceability Energy Level (SEL), at this test the aim is to proof the barrier behavior under two consecutive impacts under a serviceability energy of 1/3 of maximum energy level (e.g. A barrier tested under 3.000 kJ of energy at MEL is tested at 1000kJ at SEL).

The table 01 shows Maccaferri barriers properties tested under MEL criteria, and table 02 displays the data from SEL test.

Table 1 - Maccaferri barriers properties at MEL test criteria

Barrier	MEL Tested Energy [kJ]	Elongation at MEL test [m]	Residual Height at MEL
RB 100 UAF	111	2.10	81%
RMC 050 ICAT/2	534	3.40	61%
RB 750	774	4.21	58%
RB 1000	1,092	4.63	70%
RB 1500	1,637	5.80	62%
RMC 200/A	2,083	5.25	72%
ROC 200/5	2,233	5.82	63%
RMC 300/A	3,136	6.05	74%
RMC 500/A	5,254	6.50	70%
RMC 850/A	8,644	8.10	58%

Table 2 - Maccaferri barriers properties at SEL test criteria

Barrier	SEL Tested Energy [kJ]	Elongation at SEL test [m]	Residual Height at SEL
RB 100 UAF	-	-	-
RMC 050 ICAT/2	186	2.70	75%
RB 750	299	2.75	70%
RB 1000	363	3.41	77%
RB 1500	525	3.39	84%
RMC 200/A	730	3.75	84%
ROC 200/5	779	5.77	74%
RMC 300/A	1,073	5.20	79%
RMC 500/A	1,725	5.30	74%
RMC 850/A	3,149	5.60	76%

The energy carried on the block is calculated through the determination of the trajectories using probabilistic techniques. According to Grimod and Giacchetti (2014) the analysis of trajectories of potential unstable blocks are the first step to the barrier design. Such analysis is very often carried out using a commercial software and the simulations are fed with geomechanical, geological and topographic surveys. The focus of these data is to represent on-site conditions at analysis, such as block dimensions, restitution coefficients and the trajectory profile.

At Henry Borden Power Plant project, the geological and geomechanical surveys have been done by Maccaferri team, when visiting the site. At this point, block sizing and the area of intervention have been estimated. Unfortunately, because of the highly dense vegetation, the topographic survey used was from the power house's construction age (1950's) and for that reason the topography carried on a certain lack of accuracy. The the figure 7 shows the trajectories analysis done using the software Rocfall, from Rocscience.

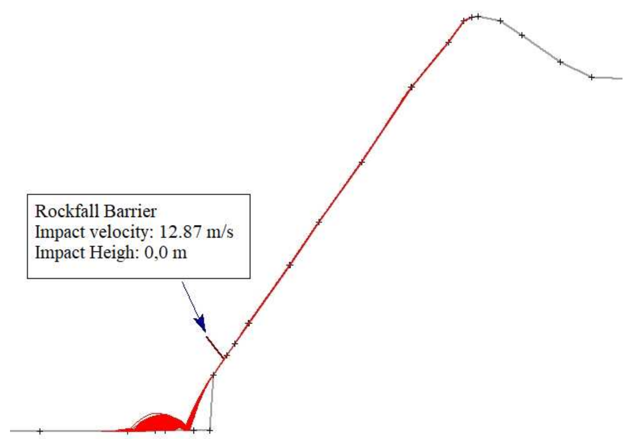

Figure 7 - Trajectories analysis using the commercial software Rocfall, from Rocscience

In the analysis, was considered a block of 1.80m³ volume, with a density of 2,700 kg/m³, leading to a total mass of 4,860 kg.

The design approach proposed by the Italian standard UNI 112122-4:2012 foresees the application of partial safety coefficients in order to cover the lack or the data inaccuracy. At the table 3, the project safety coefficients are shown.

Table 3 - Partial safety coefficients used on analysis

Issue	Symbol	Coefficient
Quality of the Topographic Survey	γ_t	1.10
Quality of block sizing survey	γ_v	1.03
Quality of block density sizing	γ_γ	1.00
Quality of rockfall simulation	γ_{tr}	1.10

These coefficients are disposed in a range, where 1.02 is most accurate data and 1.10 is for lacked data. There are also mid-values in order to classify the data accuracy

These factors are applied at the velocity taken from trajectory analysis and the block mass measured by sizing estimation, in order to consider possible variations on these variables against the security, these factors are applied as shown in Equation 1 and 2.

$$m_d = m \cdot \gamma_v \cdot \gamma_\gamma \quad (1)$$

Where m_d is the design mass, in kilogram, m is the mass estimated on site, in kilogram, and γ_v and γ_γ are coefficients described at the table 3.

$$v_d = v \cdot \gamma_t \cdot \gamma_{tr} \quad (2)$$

Where v_d is the design velocity, in meters per second, v is the velocity taken from the trajectory's analysis, in meters per second, and γ_t and γ_{tr} are coefficients described at the table 3.

Then, after these considerations, the block energy is calculated by the equation 3.

Where E is the block kinect energy of impact, in Kilojoule.

$$E = \frac{m_d \cdot v_d^2}{2} \quad (3)$$

Another concern, from UNI 11211-4:2012 standard is the occupation below the barrier, for this, the standard foresees the application of a safety coefficient (i). This coefficient increases in accordance with the vulnerability of the area usage. Places without presence of people, without historical value and with low economical value receive a lesser coefficient than a place with permanence or transit of people, high historical value, relevance for country infrastructure and/or high economical value.

The coefficient (i) range is from 1.00 up to 1.20. The description of the coefficient selection is related with the on-site condition and is better described at the table 4.

Table 4 - Human live safety coefficients accord to UNI 11211-4:2012

On-site Condition	Coefficient
Low economical value and can be easily repaired (e.g. Places without historical value)	1.00
High economical value, but can be easily repaired (e.g. places without historical value, but with relevant economical value, like storage areas)	1.05
High economical value and are hard to be repaired (e.g. places with low historical value, strategic bridges)	1.10
High economical value and cannot be repaired (e.g. Schools, dams, electric power station, high relevance historical monuments, army barracks)	1.20

As at the Henry Borden underground power house project, the aim is to protect those who use the access path, the adopted safety coefficient (i) has been 1,20. This coefficient is applied at the impact energy, as shown in equation 4.

$$E_d = E \cdot i \quad (4)$$

Where E_d is the design energy, expressed in Kilojoules.

Substituting the values previously mentioned at equations 1 to 4, the value of design energy is 728,37 kJ.

After the design energy being determined, the next step of barrier designing is to choose the energy level that will be used at the project as well as the barrier type in function of the energy.

According to Grimod and Giacchetti (2013), a typical application of a SEL-design is at the entrance of tunnel portals.

The SEL criteria is normally used in order to reduce the maintenance costs of the barrier, when the site is vulnerable to multiple impacts and a very low risk is admitted. (Grimod and Giacchetti, 2014).

Thus, for the protection of the access path, the best design procedure is SEL.

To define the barrier, it was used the calculated value of E_d (728,37kJ) and at the table 2, would be chosen which barrier would fulfill the energy requirements. This barrier was the RMC 200/A, of 2,083 kJ of resistant energy at MEL and 730 kJ at SEL.

The next step is the proofing of the barrier height. At this point, the design impact height was determined through the equation number 5.

$$H_d = H_i + B_d + F_B \quad (5)$$

Where H_d is the barrier minimum requested height, in meters, the Hi is the height of the impact, in meters, B_d is the block diameter, in meters, and F_B is the free board, given by UNI 11211-4:2012 as a minimum value of 0,50m

Substituting the values, the value of design height of the barrier is 2,25m.

RMC 200/A barrier was tested with a height of 4m, and according to ETAG 027, this barrier only can be certified if the height is about 1m higher than the tested one, therefore, the adopted barrier height was 4m.

The next step is the residual height proofing, that consists in checking if the barrier height after an impact will still fulfill the conditions. The residual height for the RMC 200/A barrier under SEL criteria is of 84% and, for a 4m height barrier is 3.37m, which fulfills the condition.

The barrier positioning should respect its MEL deformation in order to avoid impacts even after the block reach the barrier, thus, at the project, the barrier should be positioned at least 5.25m away from the entrance roof.

5 INSTALATION CHALLENGES

Originally, challenges have been found during the installation process, especially regarding the difficulties to the access, due the dense vegetation and the barrier stakeout because of the irregular topography at the beginning of works.

The vegetation didn't allow the installation team to see topographic conditions where the barrier would be located, and some photos, from the construction helped the team in order to define the best alignment of the barrier, once they have been taken with part of the vegetation cleared.

Another challenge at the stakeout process was the drops between barrier's posts. According to Maccaferri Rockfall Barrier Installation manual, the maximum drop should not be greater than 0.50m. Nevertheless, at two barrier spans, the drop was around 3.00m. These high drops could generate an excess of tension at the largest diagonal of the barrier. The solution for this was to install the posts closer than the standard of 10m, in order to dispose the barrier panel in a way which it's not overstressed.

Once the power house works 24 hours a day, and 7 days per week, the installation of the barrier couldn't just change these shafts, so extra precautions have been taken in order to guarantee the safety of the workers and visitors.

When stalled, a crane has been used to lift the components, as shown at figure 8.

Figure 8 - Rockfall barrier components lifting using a crane

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7 CONCLUSION

At this project, rockfall barriers once again proved its efficiency as a protection structure that leaves a small footprint when is installed.

For some projects that requires reliability at the solution and good economic aspects when applied at places with high intervention areas, together with environmentally concerns, dynamic rockfall barriers fulfill all aspects.

Thanks to ETAG 027 and UNI 11211-4:2012, this solution has a complete set of testing and standardized design method, what allow the designer to know exactly how the barrier will behave under the designed conditions.

At this intervention, the barriers also show its capacity of customization according to on site conditions since a group of analysis are made.

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