Rockfall risks along highways - a case study in the Serra do Mar mountain range (São Paulo, Brazil)

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ABSTRACT: Previously obtained RHRS results were complemented with trajectory simulations of potentially detachable blocks at mountain slopes that margin a segment of the SP-055 (or BR-101) highway. The study area is located in the city of São Sebastião, northern coast of the São Paulo State (Brazil) which has been historically affected by mass movements and rockfalls. This work details the risk analysis regarding the users of the highway presented by Castilho et al. (2018) combining RHRS risk assessment (Budetta 2004) with computer simulations of rockfall trajectories. The RocFall® software analyses demonstrate that even segments without rock outcrops at the road margins are prone to rockfalls in cases of detachment or landslide. Results show that in most cases the rocks strike the highway with a kinetic energy sufficiently high to inflict damage to its infrastructure and users. This work can be used by highway authorities to plan geotechnical measures and future surveying.

1 INSTRUCTION

1.1 *Geological risks and transport corridors*

Highways bordering rugged mountainsides suffer with slope stability problems worldwide, causing several physical, material and financial damage to their users and adjacent communities.

According to Ranh (1986), a risk (geological or else) is defined as a potential hazard to human life and properties. This definition implies that a natural event regardless of the damage level should not be considered risky if there is no possibility of accident, that is, the human presence transforms an event into a risk. The possibility of accident occurrences – induced by human activity or not – endangers all the people and properties involved. In this case, a risk situation is only characterized whether geological information are linked to social and economic circumstances (Bolt et al. 1975).

In case of transport corridors such as highways and railways, a natural event would certainly result into some level of risk considering that human lives and the infrastructure itself would be compromised. Another aggravating feature in this scenario is that the individuals are in motion. A car driver or the passenger of a train could be at a speed that increases the danger situation, so the risk, or the potentiality of an accident, is bigger. Risk evaluations are performed in order to anticipate or prevent hazards and to mitigate the effects.

The Rockfall Hazard Rating System (Pierson et al. 1990; Budetta 2004) is a method used to assess the risk of rockfalls in highways. The risk is quantified taking into account instability susceptibility (physical environment, geologic information) and road features such as traffic density, sinuosity, speed limit, distance from road shouders etc. Thus, the RHRS allows to establish which segments are high-priority for remedial works. The RocFall® 4.0 software (Rocsiense Inc 2002) generates probabilistic simulations of failing rock trajectories along with other parameters such as the endpoints and kinetic energy of the blocks. The RHRS and RocFall® data combined provide a more accurate behavioural model on the block movements of the studied region.

1.2 *Localization and occurrence history*

The study was performed on the hillsides of the SP-055 (Rio-Santos) highway in the city of São Sebastião (northern coast of the State of São Paulo – Fig. 1). The delimited segment is 1095 meters long with rock slopes close to the pavement and exposed boulders at the highest parts of the hill. The segment is also characterized by intense vehicle traffic (cars and trucks), one lane for each direction and narrow shoulders. The northern coast of São Paulo State has been historically affected by landslides and rockfalls. Although there are no official records, the local press has registered several cases of slope failure in the past years that resulted in big rock masses striking the Rio-Santos highway in areas nearby the studied segment (Fig. 2).
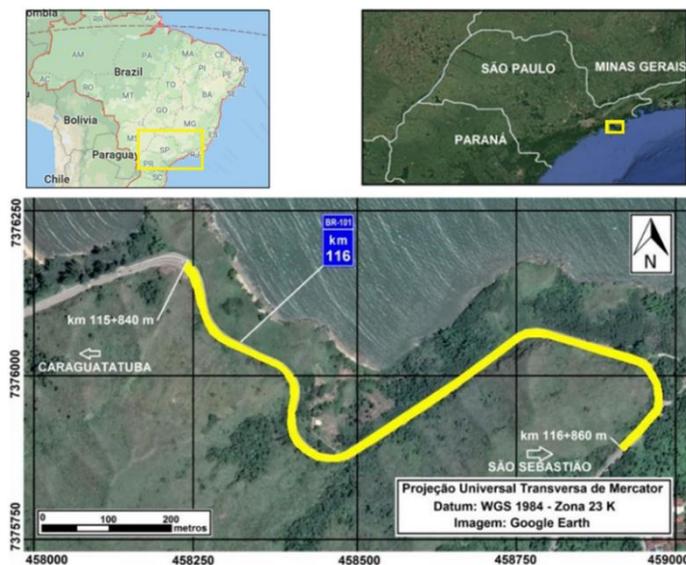

Figure 1. Geographical location of the study area.

Figure 2. Examples of rockfalls occurred in the past years on the SP-55 and registered by local press: (a), km 117, Folha do Litoral Norte 2015a; (b), km 120, Portal Fotos Públicas 2016; (c), km 119, Portal G1 2015; (d), km 119, Folha do Litoral Norte 2015b.

2 THEORETICAL ASPECTS

2.1 *Geologic and geotechnical insights*

The study area is inserted in the Costeiro Complex (Bistrichi et al. 1981) of Neoproterozoic age (Campos Neto & Figueiredo 1985, Dias Neto 2001), located in the central Mantiqueira Province (Almeida et al. 1981), composed mainly of gneissic-migmatitic rocks and granitic bodies that fit the geostructural Gneissic-Migmatitic Complex (Maffra 2000; Fig. 3). The segment comprises banded biotite gneisses of fine to coarse-grained granolepidoblastic texture constituted of quartz, biotite, muscovite, plagioclase, K-feldspar with local garnet concentrations. The foliation is defined by the preferred orientation of micas (and sillimanite in minor amounts) that gives a schist-like aspect in mica-rich portions. Locally occur layers enriched in quartz and feldspar and/or more migmatized ones with coarser granulation.

The foliation presents a ENE-WSW direction concordant to the general structure of the Brazilian southeastern platform where prevail large shear zone systems. Dip directions vary within 50° and 70° NW representing the most frequent discontinuity. The rock mass is general non-weathered with few weathered portions mostly associated to fractures.
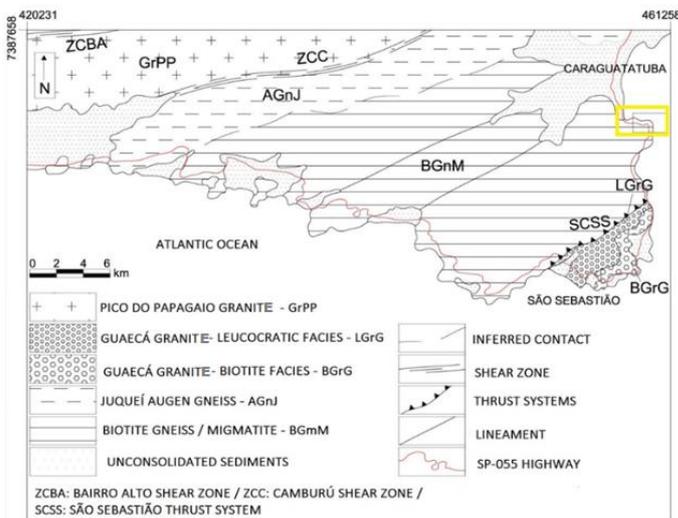

Figure 3. Regional geologic map (Maffra 2000). Yellow rectangle shows the study area of this work.

2.2 *Kinematic analysis*

The study site was divided into different sections or slopes, because of slopes face strike variations. Each one of the slopes presents at least some probability of failure, mainly the wedges formed by the intersection of FR-2 and FR-5 fracture sets and by the ones related to the FL-1 foliations (Table 1). Failures associated to foliations are solely possible in NW-dip slopes (majority of the sampled slopes) which therefore represent the most problematic discontinuity set. Approximately 80% of the potential wedge and 70% of the planar failures relate to FL-1 foliations.

2.3 *Rockfall Hazard Rating System (RHRS)*

For risk assessment using RHRS, modified by Budetta (2004), nine parameters should be analyzed including geostructural data that consider the characteristics of the route. Each analysed parameter is given a weight grade. The final sum of each slope indicates the hazard magnitude concerning the highway users in case of rockfalls. The detailed description for the RHRS use in this study site can be found at Castilho et al. (2018).

Thereby a thorough knowledge of the structural and geomechanical behaviour of the analysed rock mass is needed to achieve the final scope. The RHRS method, although engages several

theoretical concepts, might be considered a first approach to the geological risk assessment in highways because of its practicality.

Table 1. Studied failure types and the most common discontinuities involved in the possibilities of failures

Failure Type	Possibilities of failure	Amount of discontinuity families involved	Quantity of times that a discontinuity family is involved in a possibility of failure
Planar	7	FL-1	5
		FR-5	2
Swedge	24	FL-1	19
		FR-2	13
		FR-5	9
		FR-4	9
Topling	7	FR-2	6
		FR-5	1

FL – Foliation family. FR – Fracture family.

3 ROCFALL ANALYSIS

3.1 Introduction to RocFall® 4.0

Eighteen cross sections were analyzed using RocFall® 4.0 in order to determine the trajectory of rocks detached from the outcrops and isolated boulders from the highest levels of the hill. As a pattern of the software, fifth simulations are performed for each detachment point. Two-dimensional trajectory simulations and probabilistic models were calculated to better comprehend the different rockfall and rolling scenarios in the affected area. The obtained results allowed to estimate the kinetic energy from the block movement and respective endpoints which are key-data to estimate the damage magnitude. In RocFall®, the calculations are executed assuming the rock mass is entirely concentrated in one extremely small circle. In this model, called Lumped Mass, a single rock is represented by a point with a mass simply used to compute the energy involved (Taga 2006) neglecting the size and shape of the falling object –features that could influence its trajectory.

3.2 Input parameters

The major challenge in the modelling process relies on the characterization of a handful of variables involved such as lithology, description and definition of the surface of impact, friction angle between object and slope and the size and shape of the block. However, the terrain geometry and coefficients of restitution are more relevant factors in block movement simulation models (Sweigl 2002).

According to the reaction and resistance coefficients of materials encountered along the rock trajectory, the normal (Rn) and tangential (Rt) components of velocity are modified when in contact with the surface (Sweigl 2002). The coefficient of restitution is a mathematical expression that translates the retardment capacity of a surface against a falling or rolling object.

Therefore, surfaces with short or absent vegetation are more dangerous since they contribute to the bouncing effect, especially on outcrop surfaces (Youssef 2012). Thus, the values of normal and tangential restitution will depend on the material type of the surface impact.

The studied segment lacks detailed information on the local rockfall phenomena and traces of past rockfalls are not sufficiently recognizable to run retrospective analyses. Therefore, the coefficients of restitution used for the simulations were taken from Pfeiffer & Bowen (1989) that proposed values corresponding to different scenarios through retrospective analyses of rockfalls occurred in the United States of America. Table 2 lists the coefficients of restitution used for the analyses.

Table 2. Coefficients of restitution applied for rockfall simulations (Pfeiffer and Bowen, 1989).

Material type	Rn	Rt	Code
Hard surface paving	0.37-0.42	0.87-0.92	rc1
Soft soil Slope with little vegetation	0.28-0.32	0.8-0.83	rc2
Vegetaded Soil Slope	0.28-0.32	0.78-0.82	rc3
Bedrock or boulders with little soil or vegetation	0.33-0.37	0.83-0.87	rc4

In Figures 1, 4 and 5, we note that the original vegetation upstream the studied segment has been dominated by bushy ground vegetation. The difference between the vegetated and denuded areas is noticeable and helps expose rock outcrops and boulders.

The friction angle was estimated from the assumed tangential coefficient of restitution, described in equation 1. This method is convenient because it reduces the number of parameters necessary when the friction angle is difficult to determine (Rocscience Inc 2002).

Equation 1:

$$Friction\ Angle = \frac{(1 - Rt)}{Rt}$$

Where Rt is the Tangencial Coeficient of Restituiton

Access issues due to the steepness of the slopes prevented us from mapping the exact location of the rock boulders. Considering the blocks and outcrops were scattered, two setups were used for each chosen section – one with a detachment point at the highest position and another at an intermediate position (Figure 4), totalizing eighteen cross-sections simulated. Despite the lack of accurate historical reporting on rockfalls, the most reliable data on rockfall volume were collected from the last reported events. Hence, the trajectories were calculated assuming block masses of 1 ton – average value of the real masses of fallen blocks in the studied segment and vicinity.
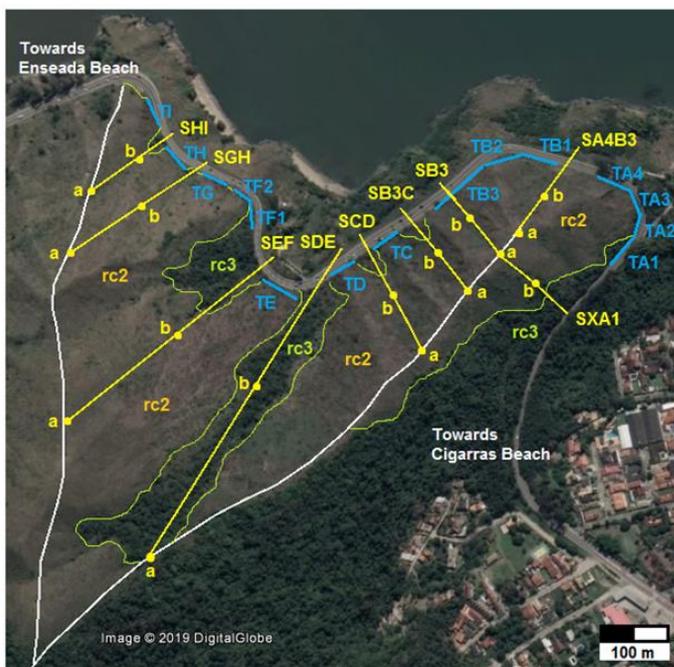

Figure 4. Yellow: Rock fall sections simulations and its detachment points (a: highest point / b: intermediate point) / Blue: Cut slopes in rock / Green: Restitution coefficient rc3 area / Orange: Restitution coefficient rc2 area.

3.3 *Results*

The rocks from the northern side of the hill might have originated from rockmass failures uphill or from boulder isolation and afterward instability. The endpoints and kinetic energy were assessed for each trajectory in which the highway was an endpoint, whenever applicable (Table 3). The lowest rates of kinetic energy correspond to the starting point of the trajectory at which the blocks move mainly by rolling over the surface. On the other hand, the highest rates were registered whenever shifts on the topographic gradient occur, due to energy gain from free fall and/or rebound.

For most cases, the simulated trajectories show that the first impact occurs on the highway margins near the hillside and involve a kinetic energy peak, secondary rebound and rolling until the final point with a gradual reducing of energy. The kinetic energy of blocks that crossed the highway varies between 12.3 and 67.9 kJ. The final points are situated on the highway or beyond it, in sixteen out of eighteen cross sections simulated.

Table 3. Results of rockfall simulations. For each cross-section fifth simulations were performed.

Cross Section	Detachment point	Detachment Height (m)	Distance from the highway (m)	Endpoints positions			
				Before the highway	On the highway	Beyond the highway	Maximum Kinetic energy on the road (J)
SXA1	a	85	135	3	3	44	33420
SXA1	b	50	67.5	17	18	15	25121
SA4B3	a	68	150	42	1	7	20750
SA4B3	b	43	75	0	24	26	25019
SB3	a	90	148	0	13	37	63674
SB3	b	50	74	0	0	50	67964
SB3C	a	105	210	0	37	13	29356
SB3C	b	56	105	0	44	6	13027
SCD	a	95	190	1	47	2	30020
SCD	b	47	95	0	42	8	32705
SDE	a	220	595	50	0	0	NA
SDE	b	87	297.5	50	0	0	NA
SEF	a	207	425	50	0	0	NA
SEF	b	148	212	0	0	50	51997
SGH	a	222	460	38	0	12	31565
SGH	b	124	230	0	22	28	40560
SHI	a	90	172	0	38	12	12451
SHI	b	58	86	0	37	13	12271

4 DISCUSSION

This study infers that the geological context contributes to slope instability since the tectonic history is responsible for the several fracture systems that combined to the foliation helped individualize rock boulders. The acquired results are concordant to the field observations – the highest RHRS segments are the ones that already display fallen rock masses of metric dimensions near the highway shoulders. The possibility of block rolling from the hillsides exists even at highway margins without slopes.

The RocFall® outputs show that the kinetic energy rate of blocks that cross the route is high and has the potential of damaging a vehicle therefore causing human and material damage. The sinuosity of the road segment adds to the hazard potentiality since the driver's reaction time would be considerably reduced against unexpected obstacles. The main aggravating factor of this analysis is that the vegetation of the northern hillside was supressed. The presence of native vegetation such as in the southern region is key to prevent movement of detached blocks due to alterations of the restitution parameter.

As observed in previous rockfall phenomena, these events tend to occur preferentially during the wet seasons of the year indicating that they could be induced by ground movements. Additionally, boulders also occur in the subsurface surrounded by thin layers of soil which could destabilize in case of saturation. Figure 5 shows the integrated results of RHRS analysis and Rocfall simulations.
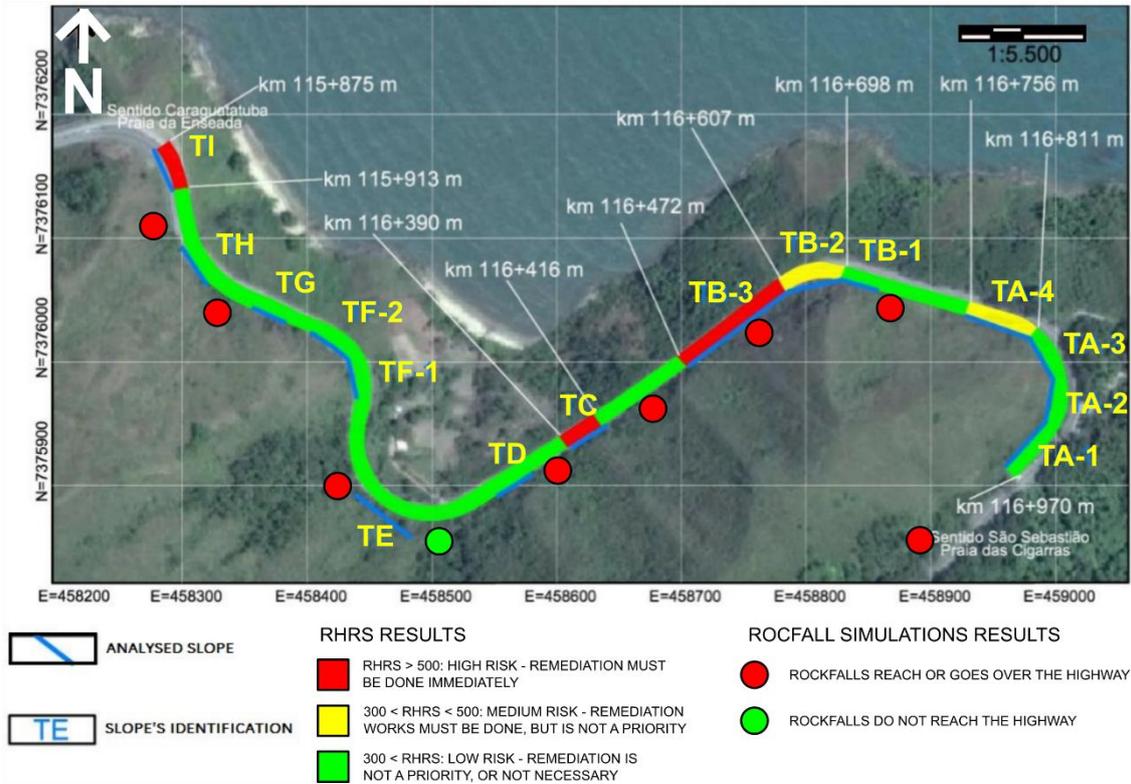

Figure 5. SP-55 Highway hazard distribution between Cigarras and Enseada Beaches, combining the scores obtained by RHRS (Castilho et al. 2018) and rockfall analyses.

5 CONCLUSION

The trajectory simulations of rock blocks identified at the peak of the hill evidentiate kinematics linked to potential block rolling and complement the risk study of rock outcrops via RHRS on the entire analyzed segment.

As expected, the rolling zone next to the hill (towards Cigarras Beach) classifies as the most dangerous not only due to the high RHRS (Castilho et al. 2018) but also because rocks that strike the highway concentrate the highest rates of kinetic energy. The present study suggests that rock blocks located on the hillsides – where the native vegetation was extinguished – should be systematically mapped to evaluate the hazard potential related to ground movements.

The map presented in Figure 5 can also be used as a base for a standard presentation of results when studies of this type are carried on, because it summarizes the results in an easy and fast to understand way.

The RocFall® simulations added another layer of analysis on top of the RHRS result. With the combination of RHRS and RocFall® simulations, two methods with different purposes, an interesting and broad knowledge can be obtained. This work should assist the highway authorities on making life-saving decisions in an area that is already known to suffer frequent rockfall phenomena.

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