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Development of a risk mapping along a railway

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Case Study

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Railway risk

Abstract

The Ramal Trem Turístico (RTT), a 17 km long railway between Ouro Preto and Mariana, a centenary line, currently in operation as a tourist attraction with historical importance. The railroad was built along a steep region, with hundreds of slopes, and eventually slope instabilities compromised the tour. In linear infrastructure projects, a risk assessment is an important tool for risk management, mapping it is the first step. After slope instabilities in 2019, a risk map was elaborated early 2021 for RTT. Risk is obtained by multiplying the probability of a certain event to occur by its consequences. Define its value in a quantitative way demands geotechnical investigation, for precise failure probability. Regardless of its importance, its determination needs high resources, specially for linear infrastructure in a region with heterogeneous geology and pedology. Therefore, for the risk mapping of the RTT, a semi-empirical methodology was adopted, based on the Rockfall Hazard Rating System (RHRS), originally developed for rocky slopes, and adapted for the registration of slopes in soil and in landfill. The aim of the method is to register a series of slope characteristics to be assigned a specific score, framing the slopes within pre-defined risk classes. This methodology was applied to this 17 km railway and identified 286 slopes. In January 2022 extreme rainfall triggered slopes instabilities at RTT. A critical analysis of this event shows a satisfactory result for the applied methodology. Risk mapping is an important tool for risk management, helping to prioritize investments in mitigation measures.

1. Introduction

The cities of Marina and Ouro Preto, both located in the state of Minas Gerais, Brazil, are connected by a century-old railway line, which in the past served as the main commercial and passenger route between both municipalities. The construction of the railway line was an engineering challenge at the time, as the region's geomorphology is extremely rough, passing through different geological formations along its 17 km length. With the evolution of road and truck transportation, the railway ended up losing relevance in the region, and after a significant period of neglect, it was converted by private initiative into a tourist attraction, offering people a journey through the secular history of these two municipalities.

Although the extension is not significant, this railway work structure required the execution of cuts, embankments, and tunnels in order to keep the track inclination restricted, mainly due to the limitations of the locomotives of the time. Therefore, along the stretch, hundreds of slopes are observed, consisting of different geotechnical materials and with different geometries.

The rainy season of 2019/2020 in the state of Minas Gerais was extremely intense, with hundreds of millimeters of precipitation recorded in very short time intervals (hours and days), representing very high return periods. These extreme events were responsible for thousands of instabilities throughout the state, including the slopes that make up the section of the old railway between Ouro Preto and Mariana, resulting in the circulation interruption of the tourist attraction.

After assessing the magnitude of the ruptures, it was found that in addition to the triggered events, many slopes presented a critical stability condition. Therefore, the managers of the tourist train operation chose to close the attraction in order to ensure operational safety and the safety of its users.

For the resumption of activities, it was defined that the region should not be subject to a high level of geotechnical risk, meaning that risk mitigation measures would be implemented to ensure the safety of the users. However, even in a short extension, there are hundreds of slopes that can potentially be mobilized, and it is necessary to direct the resources following their degree of criticality, in order to allow the resumption of operation in the shortest possible time, already with the mitigated risk.

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To define the priority order e the rationalization of the resources, it was decided to develop a geotechnical risk mapping of the slopes present in the entire railway line of the Tourist Train Branch, the RTT. The geotechnical risk map aims to evaluate, define and identify the classes of geotechnical risk of each slope, categorizing them as: very high, high, medium and low risk, enabling a more assertive risk management approach.

Geotechnical risk is defined as the product of the probability of occurrence of a certain event by the consequence of this event. Equation 1 defines a numerical value for the risk:

$$R = H.E.V \tag{1}$$

where: R = risk; H = hazard; E = elements subjected to risk (individuals or infrastructure); and V = vulnerability.

Calculating the risk in quantitative terms demands a significant amount of resources and time, as it requires a detailed geotechnical investigation to support slope stability analyses and the appropriate definition of the probability of failure. In addition, the elements at risk, their spatial variability and frequency, as well as their vulnerability must be determined. Depending on the scale of the problem, this can create a demand for resources and time that are incompatible with the expectations of the parties involved in the problem.

There are simplified methodologies that aim to define the terms of the aforementioned expression qualitatively or quantitatively based on secondary data or the product of field inspections. As an example, the methodology for mapping risk areas published by Instituto de Pesquisas Tecnológicas (IPT) and widely used for mapping and classifying the risk of cities in Brazil can be mentioned. This methodology, Brasil (2007) is fundamentally qualitative and aims to classify risk sectors and areas into groups that fit specific characteristics indicated in that methodology. This type of methodology has a significant advantage over the time of application because the classification is obtained practically immediately after the field visit. However, it has as a negative point the implicit subjectivity arising from the personal judgment of the technicians involved in the mapping.

For this study, the quantitative approach was not feasible due to the extent of the analyzed railway and the deadline for generating the risk classification. Therefore, a semi-empirical methodology was employed for the risk classification, with parameters obtained primarily from the field visit and physical data of the slope but classified according to the variation of the importance of each parameter. This definition of several topics to be evaluated in the inspection, with well-defined classes and aiming to cover all occurrences related to local geomorphology, and its main objective is the reduction of subjectivity in the evaluation, reducing the influence of the technician's judgment involved in the field mapping.

In this study, the development of the geotechnical risk mapping was mainly based on the well-established and widely spread methodology, the Rockfall Hazard Rating System (RHRS). This method was developed by the Oregon Department of Transportation, USA (Pierson et al., 1990; cited in Hoek, 2006), and is a risk classification system for rock mass instabilities applied to roadways. Its basic parameters were adjusted to allow for use on both embankment slopes and natural and cut slopes. This adjustment has already been employed by the authors in linear highway works, and the version presented in this study was adapted and applied to this railway section.

This article aims to present a detailed description of the study area, the adaptations implemented in the RHRS, and the main mapping results. In addition, a comparison was made between the risk map results and different terrain characteristics (slope, materials, orientations) as well as information from open and free sources, in order to establish a correlation between the results obtained by the detailed analysis and these more comprehensive data.

2. Location and geological characterization

2.1 Location

The railway section, spanning approximately 17 kilometers, is located between the municipalities of Ouro Preto and Mariana, in the state of Minas Gerais. Known as the Tourist Train, this section can be characterized as an important tourist route, mainly due to its historical value for the state of Minas Gerais and the country. The ride provides rich historical and cultural knowledge, as well as beautiful landscapes, of the ancient gold route. Figure 1 shows a satellite image with the approximate position of the railway section.

2.2 Geological characterization

The Ouro Preto - Mariana railway is located in the context of the Iron Quadrangle (Romano & Rezende, 2017; Lobato, 2005), which is composed of an archean basement and archean and paleoproterozoic metasedimentary units, with some volcanic contribution. Figure 2 shows a cutout of the most recent geological mapping of the Iron Quadrangle, where according to Endo et al. (2019), intercalations of metasedimentary rocks are expected in the presented groups and formations, with quartzites, schists, itabirites, and phyllites commonly described along this railway stretch.

Regarding pedology, according to Embrapa (2006), the entire study region is located in areas of haplic cambisoil - soil characterized by the presence of an incipient B horizon (therefore, the soil as a whole is not usually very deep) - and, being a poorly developed soil, its characteristics vary according to the origin material.

Figure 1. Railway alignment and pluviometry stations i) Santo Antônio; ii) County of Soares; iii) Bauxita e iv) Highway Melo Frando (Image from *Google Earth*).

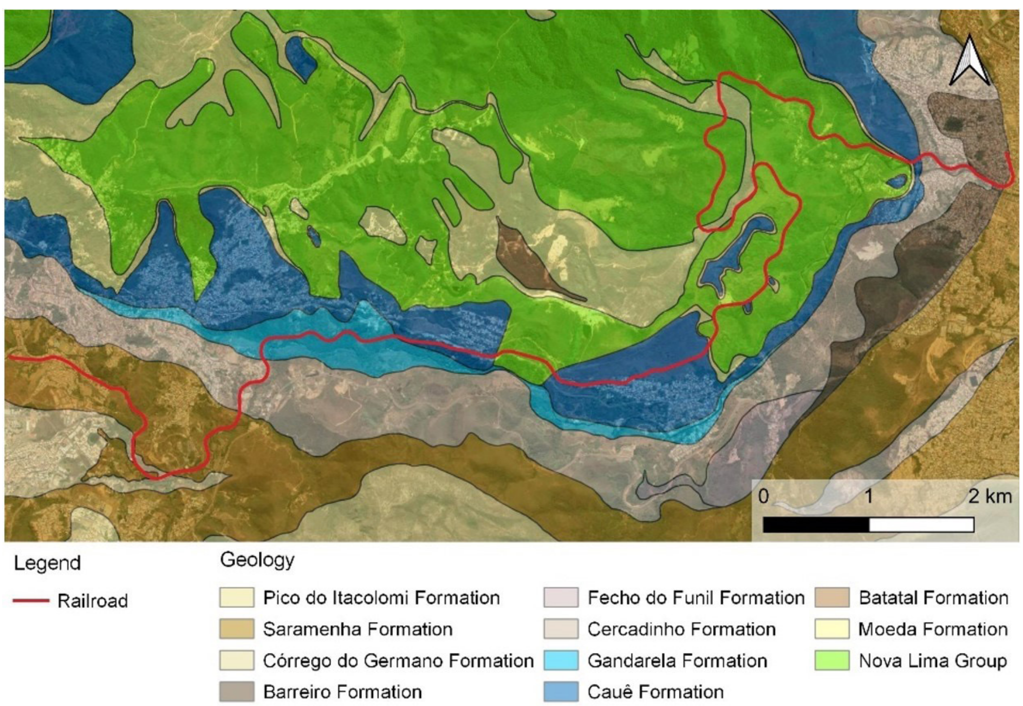

Figure 2. Geological map of the area (adapted from Endo et al., 2019).

With the basic geological and pedological characterization, it was possible to predict which materials are present in the railway section, and thus, basic geotechnical models of the railway slopes were constructed for subsequent refinement with the field survey information to be conducted.

Along this section, it was possible to evaluate the presence of cut, fill, and mixed slopes, executed according to the topographic and geometric variation of the railway, which were classified according to the main material as: fill slopes, cut slopes in rocky masses, cut slopes in soil masses, and natural slopes. This classification is fundamental for the application of the risk classification methodology defined in the project.

Initially, a visit to the region was made with the objective of a general reconnaissance of the area as well as to delineate the general characteristics of the materials to subsidize the following phases of the study.

There was no available information such as boreholes or material classification maps, and thus, for the development, it was necessary to consider that all materials within the same group are similar, assigning a specific classification according to the field observations. In addition to the type of material, this preliminary inspection aimed to preliminarily evaluate the possible instability mechanisms that can affect the local slopes.

3. Risk classification methodology

Geotechnical risk is a function of the product between the probability of an instability event and the consequence of that event, as presented in equation 1, and determining these components requires defining the properties and characteristics of each evaluated slope, a level of detail that makes application in linear sections impractical (especially in terms of time and cost). To overcome this situation, it was necessary to adopt a semi-empirical classification methodology, using an approach to quantify the risk in each mapped slope.

It was defined that the numerical risk is obtained by summing individual scores for a series of pre-established criteria, a procedure established by the Rockfall Hazard Rating System (RHRS) method, due to the large number of successful historical cases of application. As the name suggests, the RHRS was developed to assess the risk of rock fall, so it was necessary to adapt the methodology to the scenario where different materials and rupture mechanisms are present, as well as the specificities of the railway. Note that in this methodology, both the probability component of a certain event occurring and the consequence generated by it are evaluated in terms of specific parameters and scores assigned to local conditions, as will be presented below, meaning that the final score already takes into account the HxC (product presented above).

3.1 Risk classification parameters

The original methodology was used to define the concept that risk is composed of the sum of classification parameters, which indirectly represents the product of the probability and consequence of the event, in other words, a semi-empirical classification methodology. A classification table was established for soil/embankment/rock slopes, and 11 classification parameters were defined for each one, with scores growing exponentially by 3, 9, 27, and 81. The overall score for each slope is obtained by adding up the parameters, a sum that varies between 33 and 891, and the assigned risk is a function of the overall sum. Table 1 and Table 2 indicates the main concepts adopted for defining the classification parameters.

3.2 Table for risk assessment

Above, all the information that constitutes the field parameter criteria was presented and defined. Based on the above criteria, a table was developed for each of the geotechnical materials, which determine the nomenclatures of the parameters, field descriptions, as well as the score assigned to each item.

On Table 3, Table 4 and Table 5 are shown below. Based on these tables, a field mapping was carried out, which consisted of a walking inspection along the entire length of the railway, with a team consisting of a geologist and a geotechnical engineer. In addition to the information indicated in the tables, complementary records were made, mainly related to the drainage system and existing containment structures. Field inspections were restricted to the railway's right-of-way.

To facilitate field activities, these tables were loaded into a GIS environment (software QGIS), allowing all information to be recorded and the polygon of the slope area to be defined during the field inspection, generating an electronic classification table. On the field all the data was collected using a tablet, where all the presented tables were preloaded.

Table 1. Classification parameters for Consequences.

Consequence	Definition
Element and number of exposed people	Building, people, drainage
Vulnerability	Depends on the size of event, energy, potential damage
Time of exposure	Time probability of presence the exposed element at the exact moment of failure

Table 2. Classification parameters for Probabilities.

Probability	Definition
Slope type and geometry	Defines the mechanisms, energy levels, height and slope inclination
Railway geometry	Evaluates: curves, driver time of response, setback of the slope
Slope structure and signs of instabilities	Structural condition of the rockface, erosion signs, tension cracks, etc..
Drainage	Evaluate the correlation between drainage system and stability
Historical cases	Evaluates the historical data of events

Table 3. Classification parameters for rock slopes.

Risk Classification System for Rock Slopes						
		CATEGORIA	Classification and scoring criteria			
			3 Points	9 Points	27 Points	81 Points
		1.1 Elements at risk: People	Psychological effects	Minor injuries	Serious injuries	Fatality
		1.2 Elements at risk Environment	No impact	Punctual impact	Local impact	Regional Impact
		1.3 Elements at risk: Financial	>US$10M-US$100 M	>US$ 100M-US$1bi	>US$ 1 bi-US$3bi	>US$ 3 bi
		2. Exposure Time	25% of the time	50% of the time	75% of the time	100% of the time
		3. Slope height	>7.5 m	>15 m	>25 m	>30 m
		4. Presence and effectiveness of ditches	Good containment	Moderate containment	Limited containment	No containment
		5. Driver decision distance	Enough for breaking	Enough for speed reduction	Insufficient	Nonexistent
			D>1 km	0.75<D<1.0 km	D<750 m	D<250 m
		6. Distance from slope to exposed element	>13 m	Up to 10.80 m	Up to 8.40 m	<6 m
7. Geological conditions	**Case 1**	**Structural condition**	discontinuous fractures	discontinuous fractures	discontinuous fractures	Continuous fractures
			Favorable orientation	Random orientation	Unfavorable orientation	Unfavorable orientation
		Rock friction	Rough, irregular	Wavy	Flat	Clay fill, slickensides
	Case 2	**Points of erosion**	No erosion	Isolated points	Many Points	Large areas
		Variation on erosion	Small variation	Moderate variation	Large variation	Extreme variation
		8. Block size	0.3 m	0.6 m	0.9 m	1.2 m
		9. Block volume	V<3.00 m^3	3.0<V< 6.00 m^3	6<V<9.00 m^3	>9.00 m^3
		10 Movement history	Rare	Occasional	Recurrent	Frequent
		11. Water presence/ drainage system	Dry	Isolated wet points	Large areas with water, dripping	Large areas with water flow
			Drainage in perfect condition	Drainage in good condition	Drainage partially functional	Drainage compromised
		12.1 Social Impact	No Impact on local communities/culture	Impact on local community	Impact on nearby municipalities	Impact on several municipalities
		12.2 Reputation Impact	No impact to image	Local repercussion	National repercussion	International repercussion

Table 4. Classification parameters for soil slopes.

Risk Classification System for Soil Cuts						
		CATEGORIA	Classification and scoring criteria			
			3 Points	9 Points	27 Points	81 Points
		1.1 Elements at risk: People	Psychological effects	Minor injuries	Serious injuries	Fatality
		1.2 Elements at risk Environment	No impact	Punctual impact	Local impact	Regional Impact
		1.3 Elements at risk: Financial	>US$10M-US$100 M	>US$ 100M-US$1bi	>US$ 1 bi-US$3bi	>US$ 3 bi
		2. Exposure Time	25% of the time	50% of the time	75% of the time	100% of the time
		3. Slope height	>7.5 m	>15 m	>25 m	>30 m
		4. Presence and effectiveness of ditches	Good containment	Moderate containment	Limited containment	No containment
		5. Driver decision distance	Enough for breaking	Enough for speed reduction	Insufficient	Nonexistent
			D>1 km	0.75<D<1.0 km	D<750 m	D<250 m
		6. Distance from slope to exposed element	>13.20 m	Up to 10.80 m	Up to 8.40 m	<6 m
7. Geotechnical conditions	**Case 1**	Anisotropy Condition	Favorable orientation	Random orientation	Adverse orientation	Unfavorable orientation
		Anisotropy Inclination	i < 15º	15º<i<30º	30º<i<45º	i>45º
	Case 2	Probability of movement	Unlikely	Likely	Very Likely	Imminent
		Points of erosion	No erosion	Isolated points	Many Points	Large areas
		8. Unstable Thickness	t< 0.50 m	0.50<t<1.0	1.00<t<2.00	t>2.00
		9. Volume	V<2.50 m^3	2.50<V< 5.00 m^3	5.0<V<10.0 m^3	>10.00 m^3
		10 Movement history	Rare	Occasional	Recurrent	Frequent
		11. Susceptibilities to saturation / drainage system	Very little susceptible	little susceptible	Susceptible to saturation	Very susceptible to saturation
			Drainage in perfect condition	Drainage in good condition	Drainage partially functional	Drainage compromised
		12. Slope Inclination	i < 30º	30º<i<45º	45º<i<60º	i>60º
		13.1 Social Impact	No Impact on local communities/culture	Impact on local community	Impact on nearby municipalities	Impact on several municipalities
		13.2 Reputation Impact	No impact to image	Local repercussion	National repercussion	International repercussion

Table 5. Classification parameters for embankments.

Risk Classification System for embankments				
CATEGORIA	Classification and scoring criteria			
	3 Points	9 Points	27 Points	81 Points
1.1 Elements at risk: People	Psychological effects	Minor injuries	Serious injuries	Fatality
1.2 Elements at risk: Environment	No impact	Punctual impact	Local impact	Regional Impact
1.3 Elements at risk: Financial	>US$10M-US$100 M	>US$ 100M-US$1bi	>US$ 1 bi-US$3bi	>US$ 3 bi
2. Exposure Time	25% of the time	50% of the time	75% of the time	100% of the time
3. Slope height	>7.5 m	>15 m	>25 m	>30 m
4. Embankment foundation condition	No signs of problems	Containment structure in good condition	Signs of problems, Containment structure in good condition	Visible problem Containment structure precarious
5. Driver decision distance	Enough for breaking	Enough for speed reduction	Insufficient	Nonexistent
	D>1 km	0.75<D<1.0 km	D<750 m	D<250 m
6. Distance from edge of road to embankment crest	>10.00 m	Up to 7.50 meters	5.00 meters	<2.50 meters
7. Embankment Condition – **Longitudinal Cracks** – Length	No cracks	Small and isolated (Up to 1.00m)	Medium and connected (1,00 à 5,00 m)	Long and connected (>5,00m)
7. Embankment Condition – **Longitudinal Cracks** – Thickness	No cracks	Up to 1 cm	Up to 5 cm	>5cm
7. Embankment Condition – **Subsidence** – Length	Nonexistent	P Small and isolated (Up to 1.00 m)	Medium and continuum (1.00 à 5.00 m)	Long and connected (>5.00m)
7. Embankment Condition – **Subsidence** – Depth	Nonexistent	Up to 10 cm	Up to 50 cm	>50cm
8. Erosion processes	No erosion	Isolated points	Many Points	Large areas
9. Impact on road in case of failure	No impact	Reaches outer edge	Partial destruction	Total destruction
10 Movement history	Rare	Occasional	Recurrent	Frequent
11. Susceptibilities to saturation / drainage system	Very little susceptible	little susceptible	Susceptible to saturation	Very susceptible to saturation
	Drainage in perfect condition	Drainage in good condition	Drainage partially functional	Drainage compromised
12.1 Social Impact	No Impact on local communities/culture	Impact on local community	Impact on nearby municipalities	Impact on several municipalities
12.2 Reputation Impact	No impact to image	Local repercussion	National repercussion	International repercussion

This technique allowed the field teams to do a rapid data acquisition, and most important, as this information were digitalized it was possible to automatically exported all the registered slopes and polygons, simplifying and assisting all the data analysis and interpretation of the results.

3.3 Risk classification based upon a GIS approach

In addition to the risk analysis of each point, the polygons registered in the mapping along the railway were analyzed in a GIS environment, in order to determine a possible relationship between the defined risk class and: (i) the local lithology; (ii) the terrain slope. This analysis would allow a preliminary evaluation and direction of geoprocessing mapping for new areas. To approach the data along the railway axis, the risk classification and the limit of influence polygons of each point were considered according to the field survey and risk map analysis, the regional geological map, and the digital elevation model (DEM) based on ALOS PALSAR satellite data, which has a spatial resolution of 12.5 m.

4. Obtained results

Based on the methodology used and the results obtained through field surveys, it was possible to determine the risk classes, considered according to the recommendations indicated in AGS (2000, 2007) manual and the IPT (Brasil, 2007) Ministry of Cities manual, defining 4 risk classes, R1-R4, according to the score presented in Table 6.

The mapping along the railway resulted in the registration of 286 slopes (polygons in Figure 3), which were grouped according to the risk classes. The distribution of the risk levels (Table 6) of all registered elements is presented succinctly in Figure 3, graphically, by the distribution of slopes according to the risk class assigned to each of them and a map.

4.1 Results based upon the GIS approach

According to the position of the points and the regional geological map, the points within each risk class were grouped according to the lithological occurrences, indicating the percentage (%) of points registered in each unit, which are presented in Table 7

Looking at the percentage distribution in Table 7, it can be observed that the majority of high-risk polygons are located in the Barreiro and Córrego do Germano formations, while the high-risk polygons are found in the Saramenha and Moeda formations. These units are characterized by the occurrence of metasedimentary rocks such as quartzites, schists, and phyllites, with the latter two being the main lithologies found in the high-risk areas.

However, another parameter that needs to be evaluated is the spatial representativeness of each lithology. For this analysis, the occurrence of each lithology along the 18km stretch of the tourist train railway was verified. For quantitative purposes, a 30m width strip was considered, representing the same width as the risk polygons on both sides of the railway.

Table 6. Risk classes based on AGS (2007) and Brasil (2007).

Risk	Risk	Score
Low	R1	0-300
Medium	R2	300-500
High	R3	500-700
Very High	R4	>700

The table below shows the area in square meters of each lithology, as well as the percentage of the total surveyed strip area.

To eliminate the impact of spatial representativeness of each lithology, the risk by lithology index (*RL*) was evaluated using the following expression:

$$RL = \frac{\sum AR_{nl}}{\sum A_l} \quad (2)$$

where: RL = risk by lithology; AR_{nl} = area in m^2 of a specific risk class (n) in a specific lithology (l); and A_l = área in m^2 for a specific lithology (l) along the railway.

Table 8 presents the lithology of the total area along the railway and the risk areas by the different classes.

The chart presented in Figure 4 show the *RL* parameter for each lithology to the present study.

Based on the satellite Digital Elevation Model (MDE), a slope map in percentage was generated, with classifications following the recommendations of Embrapa (1979). Based on the geoprocessing values, the maximum, minimum, and average slopes were extracted, as well as the range for each risk class. The MDE with the percentage distribution per risk class is presented in Figure 5.

Table 7. Relation between risk and litology.

Name / Risk	Very High	High	Medium	Low
Moeda Formation	5.0%	20.0%	55.0%	20.0%
Cauê Formation	2.7%	5.4%	35.1%	56.8%
Gandarela Formation	0.0%	12.5%	33.3%	54.2%
Nova Lima Group	3.2%	16.1%	53.2%	27.4%
Cercadinho Formation	0.0%	4.8%	47.6%	47.6%
Barreiro Formation	20.0%	0.0%	40.0%	40.0%
Saramenha Formation	4.2%	22.9%	56.3%	16.7%
Córrego do Germano Formation	14.3%	14.3%	28.6%	42.9%

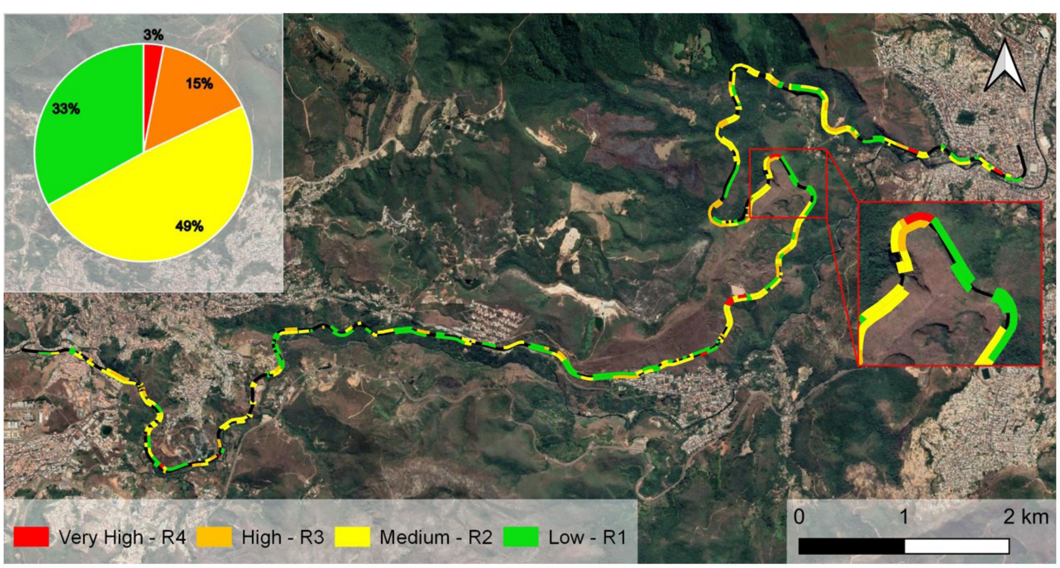

Figure 3. Risk classification of the slopes (numbers and percentage) and the risk map.

Table 8. Spatial distribution of risk and lithology.

Lithology	Total lithology area along the railway (m²)	Total R1 area (m²)	Total R2 area (m²)	Total R3 area (m²)	Total R4 area (m²)
Moeda Formation	334,572.64	93,502.38	170,066.75	60,273.45	10,730.06
Cauê Formation	43,136.34	6,805.43	25,254.10	8,427.97	2,648.85
Gandarela Formation	113,727.29	66,109.95	34,182.09	11,314.03	2,121.21
Nova Lima Group	50,712.79	28,629.75	17,386.87	4,696.17	0,00
Cercadinho Formation	11,025.86	4,034.34	4,235.25	0.00	2,756.26
Barreiro Formation	40,648.81	17,391.93	21,280.12	1,976.75	0,00
Saramenha Formation	12,866.81	7,046.33	4,879.30	480.78	460.41
Córrego do Germano Formation	96,676.57	19,239.01	58,859.57	17,239.38	1,338.62

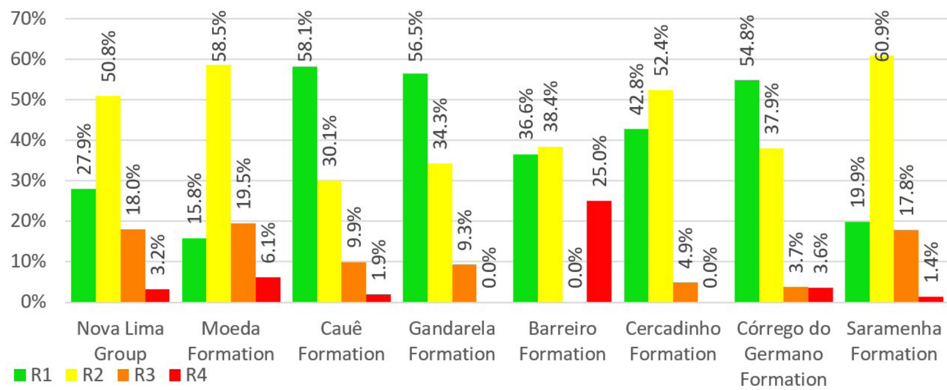

Figure 4. Chart with the lithology vs risk along the railway.

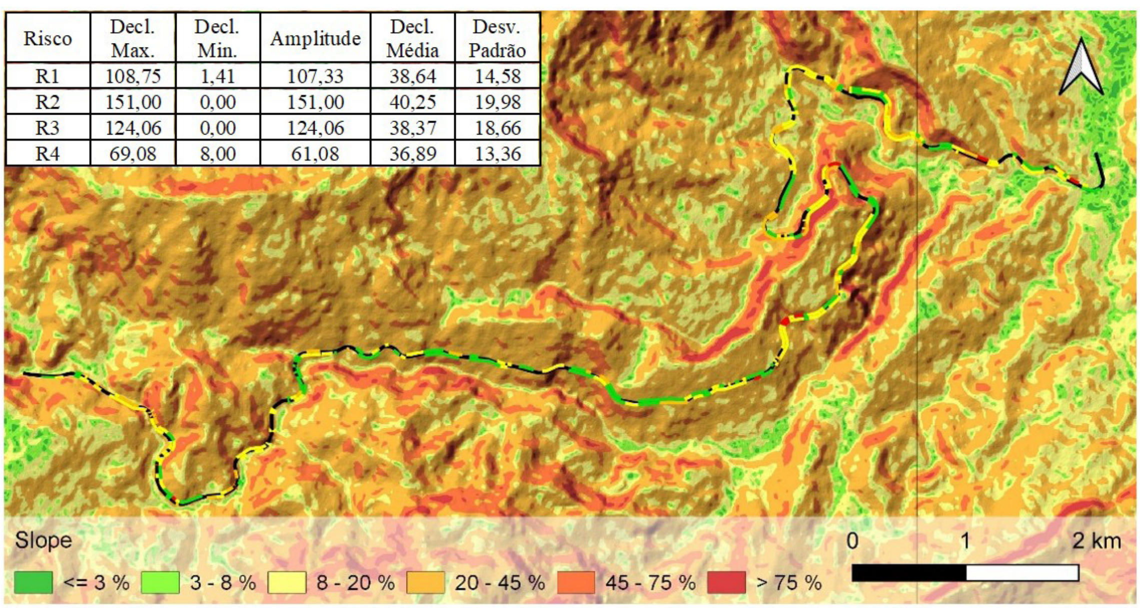

Figure 5. Slope map and % with the risk polygon on the railway.

When analyzing the statistical summary of the slope averages, it can be noted that the maximum values increase and the minimum values decrease as the risk decreases, resulting in a significant increase in the slope range. In other words, there is an increase in the variation of possible slopes according to the change in risk. This factor may be directly related to the higher occurrence of lower-risk classes. The graphic results of this analysis are presented in Figure 6.

The average of the slopes remains relatively constant, around 38%. When observing the distribution of the maximum and minimum values, it is noticed that the results do not suggest a strict pattern of relationship between the topography and the risk areas. This could be due to two factors: a) these estimates did not provide conclusive results due to the local nature of the areas, and the resolution of the available data may not be detailed enough for the level of detail in this

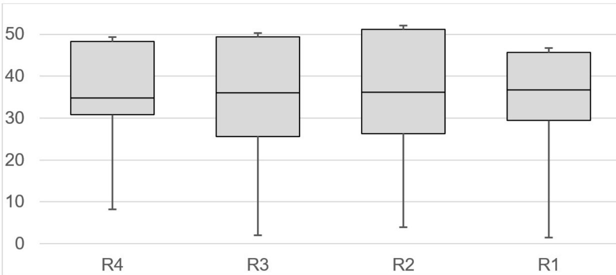

Figure 6. Boxplot chart illustrating the slop distribution for each risk class.

study; or b) the risk factors are better conditioned by the specific lithology found point by point.

4.2 Risk map evaluation after occurrence of new failures

During the rainy season of 2021/2022, specifically from January 7th to 10th, 2022, there was a period of high precipitation (return period of approximately 50/100 years), resulting in some new slope failure along the railway. To assess the accuracy of the risk map, one of the first actions taken was to evaluate the precipitation that occurred. Observational data shows that during the first half of January alone, the four pluviometry stations recorded accumulated rainfall that exceeded the historical monthly average for the month, which ranges from 300-350mm. The consulted data from the stations i) Santo Antônio with 445 mm; ii) Subdistrict of Soares with 469 mm; iii) Bauxita with 446 mm; and iv) Rodovia Melo Frando with 469.31 mm, according the CEMADEN. The rainfall data shows consistency in the spatial distribution of rainfall in the area of interest, which allows extrapolating this rainfall to the railway region. As can be seen between the 7th and 10th of January, the period when the failures occurred, there was a significant accumulation of precipitation, with daily rainfall reaching approximately 180 mm in 24 hours.

A new inspection along the entire stretch of the railway was carried out by two geotechnical engineers to identify and locate unstable points. After mapping these new points, they were cross-checked with the risk map that had been previously conducted and reclassified. Photographic records were taken for all points and compared with previous records, and the description of each point in the risk map and the current description of instability were retrieved. Additionally, actions that could be implemented were indicated for each point. Table 9 presents the results of the inspection carried out after the rainy period of 2021/2022, including the initial classification of the polygons, the reclassification of each instability point, the justification for each point's alteration, and the severity of impact on the railway. The severity was classified as low, medium, or high. Low severity means that the volume that reached the railway would not be sufficient to cause a disruption in the line, medium severity means that the volume would temporarily halt the line but could be cleared within a few hours (i.e., < 10 m^3), and high severity refers to volumes exceeding 10m^3. If the instability did not reach the railway, the severity was classified as null.

Based on the assessment of the points recorded and presented in Table 9 a total of 32 instability points were identified: 9 in high-risk areas, 18 in medium-risk areas, and 4 in low-risk areas. Two of the points occurred in locations where retaining walls were present, which had been excluded from the initial risk map. After the site visit, the points were reclassified based on the changed local conditions, it can be observed that there is a convergence between the classification assigned to the instability points and the characteristics of the actual events recorded at the site. Overall, the significant change was the escalation of medium-risk points to high risk. Only one low-risk point moved to the high-risk category, and one high-risk point moved to very high risk. It is worth noting that the two points related to retaining walls were not classified in the risk map, as it was assumed (during the development of the risk mapping) that the constructed containment structures were designed and built to withstand the predicted events throughout the structure's lifespan.

It is important to revisit the conceptual difference between risk and susceptibility. Susceptibility refers to the probability of a specific event (in this case, instabilities) occurring, while risk is the product of this susceptibility and the resulting consequence (in this case, the impact on the railway). In other words, points with records of occurrences that did not affect the railway do not indicate high-risk points but rather high susceptibility. This difference is crucial to understand to avoid misinterpretation of the relationship between the recorded events and the existing risk mapping. In other words, small events that did not impact the railway did not pose a risk to its operation. For a quantitative assessment in this regard, severity classes of the events were defined as mentioned earlier. Excluding points with null severity, there were 9 instabilities recorded in areas pre-classified as high risk, 10 in areas pre-classified as medium risk, and 1 instability in an area previously mapped as low risk.

5. Conclusion

A risk mapping of a 17 km railway section between the cities of Ouro Preto and Mariana was presented. This study identified 286 risk areas classified as low, medium, high, and very high. This risk mapping was used for railway risk management, including planning, stabilization projects, construction works, and monitoring.

Less than a year after the completion of the mapping, an intense rainfall event struck the state of Minas Gerais and caused a series of instabilities in this railway section. The instabilities occurred in high, medium, and low-risk areas: 9 in high-risk areas, 18 in medium-risk areas, 3 in low-risk areas, and 2 were not classified because the slopes already had containment structures. Locations with a high probability of an event occurrence but without significant consequences are categorized as low risk. This situation was identified in most

Table 9. Analysis results.

Point	Initial Risk	Risk post event	Hazard of railway impact	Reason to risk alteration
04	Low	Medium	Low	No field evidence was found for an event of this magnitude, suggesting that it was possibly caused by the overflow of the upstream street drainage system.
06	Medium	High	Medium	Mobilization of a previously occurred event, with the contribution of the upstream drainage system failure.
09	High	High	High	Unchanged
10	Medium	Medium	Low	Unchanged
11	Medium	Medium	Null	Unchanged
12	Medium	Medium	Medium	Unchanged
33	Medium	High	Low	Change in local conditions, after the rains and the occurrence of the rupture (which did not reach the railway), a crack was triggered, and a second event could now affect the railway, thereby altering the risk at the site.
40	Low	Low	Null	Unchanged
-	Not classified	High	Low	Unclassified because of a retaining wall existing
42	High	Very High	High	An expected critical event was predicted; however, the magnitude of the recorded event is greater than initially anticipated.
45	High	High	Low	Unchanged
46	High	High	Low	Unchanged
150	Medium	Medium	Low	Unchanged
151	Medium	High	Low	The obstruction of the drainage system at the crest of the slope
160	Medium	High	Null	As a result of the identification of a tension crack
183	High	High	Low	Unchanged
192	Medium	Medium	Low	Unchanged
193	Low	Low	Null	Unchanged
198	High	High	Low	Unchanged
213	Medium	Medium	Null	Unchanged
214	Medium	Medium	Low	Unchanged
215	Medium	Medium	Low	Unchanged
218/219	High	High	Low	Unchanged
220	Medium	Medium	Null	Unchanged
221	Medium	Medium	Null	Unchanged
226	High	High	Low	Unchanged
227	Medium	Medium	Null	Unchanged
236	Low	Low	Null	Unchanged
239	Medium	Medium	Null	Unchanged
248	High	High	Low	Unchanged
250	Medium	Medium	Null	Unchanged
256	Medium	Medium	Low	Unchanged
-	Not classified	High	Medium	Unclassified because of a retaining wall existing

of the instabilities recorded in medium and low-risk areas. Excluding points with null severity, the results were 9 in high-risk areas, 8 in medium-risk areas, and 1 in low-risk area.

The crossing of risk areas with lithology indicated that the Barreiro Formation, followed by the Córrego do Germano Formation, had the highest occurrence in the R4 class. The Saramena Formation and Moeda Formation represented the highest proportion in the R3 and R2 classes, respectively. Regarding the lowest risk class, R1, the Cauê and Gandarela Formations from the Itabira Group were the predominant lithologies.

The crossing of risk areas and slope did not show a strong correlation between topography and risk areas. This result may indicate that the topographic base does not have a resolution compatible with the detail scale of the mapping or that the predominant factor is related to lithology.

The analysis of correlations highlights that specific local factor of each slope (e.g., geometry, materials, drainage conditions) and human activities on the terrain are sometimes masked due to the scale of the available information. The higher the level of detail in the provided information, the greater the accuracy of the risk mapping.

Finally, the analysis conducted after a high rainfall event and a large number of instabilities indicated that the risk mapping showed satisfactory convergence. Additionally, a risk map is a management tool used to allocate resources and identify areas to be further studied in subsequent stages. It should be constantly updated as new information becomes available.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Felipe Gobbi: Field Mapping, original draft, Project administration, Methodology, Validation; Formal Analysis. Alvaro Pereira: Field Mapping, Conceptualization; Writing – review & editing; Formal Analysis. Bruno Denardin: Formal Analysis, Field Mapping, Writing – review & editing, Methodology. Fabiano Madrid: Formal Analysis, Software, GIS analysis; Field support. Karine Liboreiro: Funding acquisition; Project administration, resource acquisition for field mapping, result analysis and discussions. Adoniran Coelho: Funding acquisition; Project administration, resource acquisition for field mapping, result analysis and discussions.

Data availability

The datasets generated analyzed in the course of the current study were collected during the development of the present study, and all data produced or examined in the course of the current study are included in this article.

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