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Characterization and risk analysis of rockfall in underground mines in Brazil

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Article

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Abstract

One of the greatest challenges of an underground mine is minimizing the risk of rockfall occurrences in its excavations. Rockfall is defined as an uncontrolled rock fall (detachment or ejection) of any size that causes (or potentially causes) injury or damage (Minerals Council of Australia, 2003). Although it is possible to find good works on this subject internationally, in Brazil there is a scarcity of references. Adequate treatment of data related to rockfall requires, first, a database composed of important aspects that can influence its occurrence. The formation of this database represents the first constraint for the publication of works. In addition to the absence of an adequate database in mines, publication may be restricted by involving the exposure of more sensitive topics involving operations. Even in international reference works, the names of companies and mines are not disclosed. This work involves the treatment of a robust database (294 cases), formed over approximately 5 years, derived from four underground mines in Brazil. It was possible to identify, with the treatment of these data, trends and improvement aspects that should be prioritized to minimize the risk of rockfall in Brazilian mines, such as surface support application, which could prevent more than 60% of all rockfall occurrences, the importance of establishing a quality control process for reinforcement and support application, in addition to identifying the area with the highest probability of occurrence (30 m from the blasted face), thus helping to provide a safer environment for all who work in underground excavations.

1. Introduction

One of the greatest risks associated with underground mines is the uncontrolled fall of part of the rock mass, globally known as rockfall. Rockfall is defined as an uncontrolled rock fall (detachment or ejection) of any size that causes (or potentially causes) injury or damage (Minerals Council of Australia, 2003). One of the main objectives of the work carried out by geotechnical engineers in underground mines is to eliminate or minimize the risk of rockfall occurrences, which can cause accidents and material losses.

For proper management of rockfall occurrence risk, the geotechnical engineer studies the excavation design, the rock mass quality, the acting stress, and recommends, when necessary, the use of ground support. Hoek & Brown (1980) specify as the main objective of underground excavation support design to help the rock mass support itself. Even with the use of various types of ground support, whether reinforcement or support systems, and their development and improvements over time, many rockfall events still occur in underground mines.

Rockfalls are the main influencers of safety statistics in underground mines (Potvin et al., 2001). "In Western Australia between 1987–1997, the annual fatality incidence for underground mining was high, averaging 1.3 in 1000 employees. Rockfalls/rockbursts accounted for over half of these deaths (MOSHAB, 1997)". "Over the next decade, 1998–2008, records from the Minerals Council of Australia (2007) show a halving of the fatality rate in Western Australian underground metalliferous mines: 38 deaths over 10 years (Owen, 2009). Such accidents account for approximately 40% of all injuries and fatalities in underground base metal mines in China (Zhao et al., 2019). In Peru, the most common type of accident is caused by rockfalls in underground mining excavations. Between 2000 and 2007, there were 443 fatal accidents resulting in a total of 499 victims; of these, 163 accidents were caused by rockfalls, resulting in 181 fatalities and representing 37% of workplace accidents (Candia, 2011).

There are several factors that can influence the occurrence of a rockfall and this work aims, through the analysis of a robust database, with 294 events in 4 underground mines in Brazil, collected over approximately 5 years, to identify

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trends and improvement aspects that should be prioritized to minimize the risk of rockfall in Brazilian mines, thus helping to provide a safer environment for all who work in underground excavations. This type of work, with such a robust database, on rockfall in underground mines is unprecedented in Brazil.

Data collection was carried out based on the established definition of rockfall, from 2018 to September 2020. Data from previous years were evaluated, where some of these data, from the 2 years preceding the collection, 2016 and 2017, are also presented here. There were visits to the mines and verification of data with the responsible geotechnical engineers, which made it possible, in some cases, to correct the database and/or complete the data.

2. Materials and methods

To carry out this work, bibliographic research regarding the topic of Rockfall was executed. And the first challenge was to establish the definition of rockfall that should be used for data collection. There is no universally accepted definition of rockfall (Nedin & Potvin, 2005). The conceptualization of rockfall can vary considerably from one company to another, or even from one mine to another within the same company.

In general, rockfall, which is a globally known term, is conceptualized as fall of part of the rock mass. But when there is greater detail in the practical application of this concept for proper classification, several doubts begin to appear. When an operator is removing small loose rock fragments, in the activity called "scaling," is it considered rockfall? And when in this activity a small block hits them, causing an injury? And when does a block falls near the location that was previously blasted? And when a block falls during the blasting period and there are no other people in the mine except those responsible for blasting? And when a block falls in a mining area, without access to people? And when does a block falls in a location where loose material has not yet been removed after blasting? To be rockfall, is there a specific weight limit? Many discussions are generated in various companies and institutions in an attempt to have a single concept for the term rockfall.

In a work developed in Australia (Potvin et al., 2001; Nedin & Potvin, 2005), in two phases, two concepts were generated, one in each phase. In the first phase, the rockfall concept worked with was: uncontrolled rock fall of significant size in an area with access to people or a rock fall of any size that causes (or potentially causes) injury or damage. In the second phase of the project, after discussions with various entities in the mining industry, the concept was modified to: An uncontrolled rock fall (detachment or ejection) of any size that causes (or potentially causes) injury or damage (Minerals Council of Australia, 2003). In this work, the definition from phase II of the work developed in Australia was used. The clear conceptualization of rockfall represents the first step for any work to be developed, as it is through this definition that the rockfall database will be generated.

After the definition of rockfall was established, it was necessary to verify the published material available for research, in order to help in choosing the parameters to be collected that could support a more complete analysis on the subject. As previously reported, there are few works with truly relevant rockfall characterization data published in the world, which becomes even more restricted when only Brazil is considered.

One of the most complete works ever published, which involved 26 underground mines (in phase I) in Australia, in two project phases, in 2001 and 2005, did not identify the companies and mines, perhaps due to the sensitivity of the subject, as mentioned above. The first phase of the project called "Towards the Elimination of Rockfall Fatalities in Australian Mines" (Potvin et al., 2001), whose results were published at the end of 2001, and worked with 494 rockfalls (Figure 1), had as its main objective the identification of trends related to the causes and conditions that lead to the occurrence of a rockfall. The second phase of the project called "Australian Rockfall Research – Phase II" (Nedin & Potvin, 2005), with publication of results in 2005, had as its main objective, in addition to the expansion, with more data, of the previous research, to detail separately rockfall data far from the active excavation face (>50m) and near (<10m), in addition to understanding the personal exposure of workers through process mapping, performing risk analysis and control for the rockfall event in sequence.

The parameters that were collected were based on the previously cited works, mainly related to the first phase of the project carried out in Australia. In this work, the parameters were separated into specific groups:

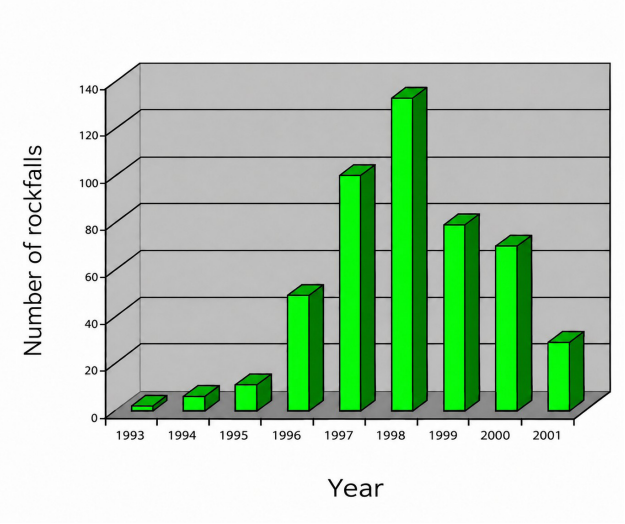


Figure 1. Rockfalls per year. The 2001 data covers only the first 9 months of the year (Potvin et al. 2001).

- Rockfall descriptors – weight, failure height, rock mass conditions, stress field, etc.
- Rockfall location and personal exposure – drift/intersection, distance to active face, frequency of use, roof/walls, etc.
- Rock mass support practices and performance – reinforcement embedment, surface support, reinforcement failure (adequacy of support system), etc.

After determining the parameters to be collected, meetings were held with the geotechnical engineers from each mine for proper alignment and training on filling out the spreadsheet. All 4 mines received the same spreadsheet to be filled out, with some small adaptations when compared to the work developed in Australia.

As mentioned before, in addition to the data that were collected over the period of almost 3 years, from 2018 to September 2020, an evaluation of rockfalls that occurred in previous years was carried out, and data from 2016 and 2017 are presented here, where it was possible to recover some important analysis parameters (weight, height of the failure, support, etc.). It is important to consider that in this period the analysis should always be carried out with reservations, as the concept of rockfall was not defined and aligned and not all parameters were collected.

3. Analysis and results

In the analysis and presentation of results, the data were grouped into specific themes, following the work carried out in Australia, mentioned earlier. The first group to be presented is the Rockfall Descriptors, where specific characteristics of rockfall are examined. The number of rockfall events for each characteristic may vary depending on the availability of the data used. The overall quantity of rockfall events over time can be seen in Figure 2. It is worth noting that for the year 2020, data were collected only up to September, and that the data from 2016 and 2017 were retrieved but with low reliability, as the definition of rockfall had not yet been established at that time.

In Figure 3, it is important to note that the majority of rockfalls, 61%, weigh up to 1 tonne, although large rockfalls, exceeding 50 tonnes, also occurred in a smaller proportion, 7%, across the 4 underground mines analyzed. These rockfalls above 50 tonnes show a greater dispersion over the years, as shown in Figure 4.

Most rockfalls occurred in schistose rocks, although in the ore drive, the majority involved sulfidic banded iron formation and quartz, which generally exhibit better rock mass quality.

Another important characteristic of rockfalls is related to the failure height into the rock mass, Figure 5, where 86% of rockfalls have a failure height of up to 1 m, and 97% have a failure height of up to 3 m, which is a good indicator for verifying the design of the support/reinforcement system.

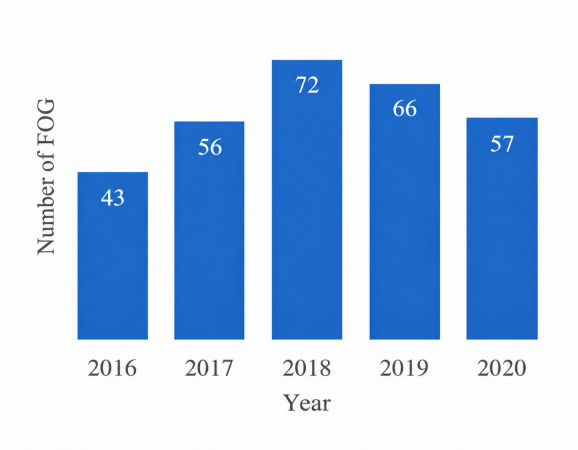


Figure 2. Distribution of rockfalls (total: 294) per year, with 2020 data collected up to September (2016 and 2017 data were retrieved with limited reliability).

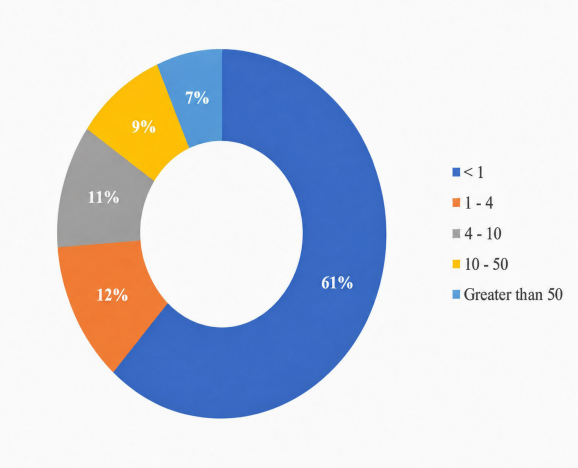


Figure 3. Distribution of rockfalls (total: 293) by weight, with 2020 data collected up to September (2016 and 2017 data were retrieved with limited reliability).

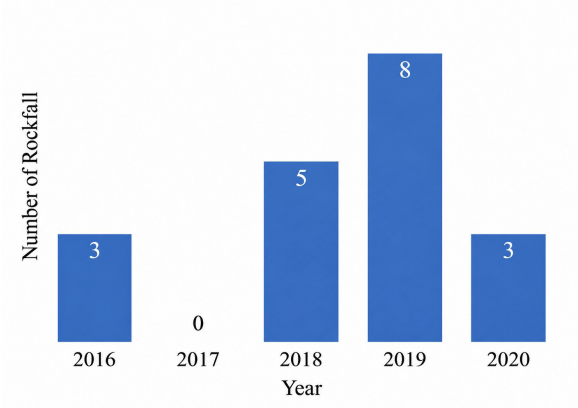


Figure 4. Distribution of rockfalls above 50 tonnes per year, with 2020 data collected up to September (2016 and 2017 data were retrieved with limited reliability).

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Another characteristic that was analyzed was the depth of rockfall occurrence (Figure 6), where a significant portion of rockfalls, 53%, occurred at depths greater than 700 m. Analyzing the variation over the years, it is noteworthy that a higher number of rockfalls, 22, at depths greater than 1,000 m, occurred in 2018.

For the Rockfall Descriptors group, we can draw some important conclusions:

- The majority of rockfalls, 61%, weigh less than 1 tonne;
- Large rockfalls, above 50 tonnes, occur in smaller quantities, 7%, and are more variable over the years;
- The majority of rockfalls, 86%, occurred with a failure height of up to 1 m;
- The majority of rockfalls occurred at depths greater than 700 m.

Another group of rockfall characteristics is the Rockfall Location and Personal Exposure, where other important aspects can also be analyzed. One of these aspects is the excavation type, as shown in Figure 7. It is important to note that the majority of rockfalls occurred in the main declines and access drives, 52%. If we consider main declines, access drives and oredrives together, this value rises to 80%. Another noteworthy finding is the increase in rockfalls in the main declines and access drives in 2018, as well as the increase in rockfalls in infrastructure drives during that same year.

Another important aspect is related to large rockfalls (Figure 8), greater than 50 tonnes, where the majority occurred in the oredrives, representing 50%. If we consider the data on proximity to the stope brow, which is also located in the oredrive, the value reaches 61% of occurrences.

An important information is related to the origin of the rockfall (Figure 9). The vast majority originate from the back, 75%, with only 1% originating from the excavation face. The year 2018 shows a higher number of rockfalls originating from the back compared to other years.

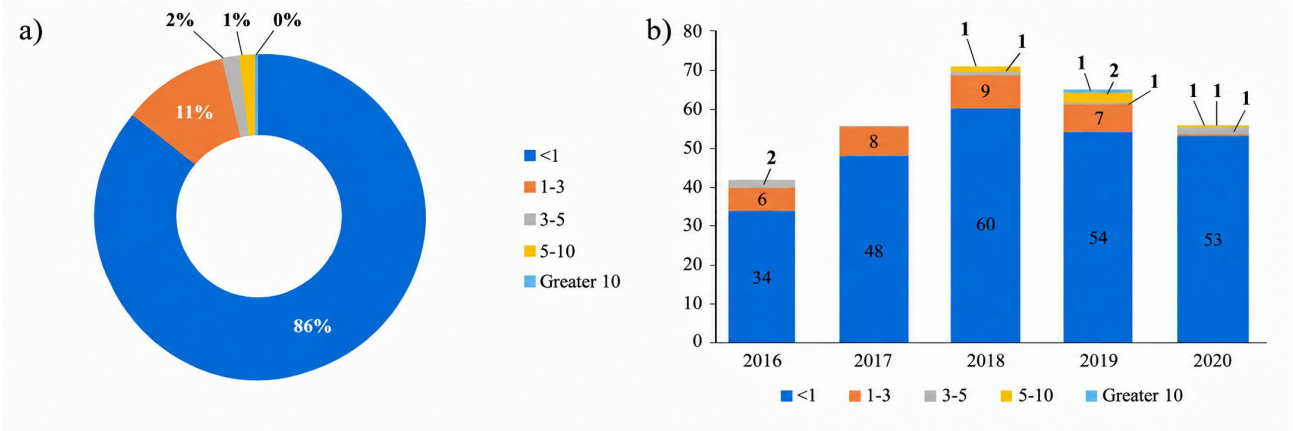


Figure 5. (a) Rockfall failure height (total: 290) and (b) distribution by year, with data from 2020 up to September (the years 2016 and 2017 with recovered data, with restricted reliability).

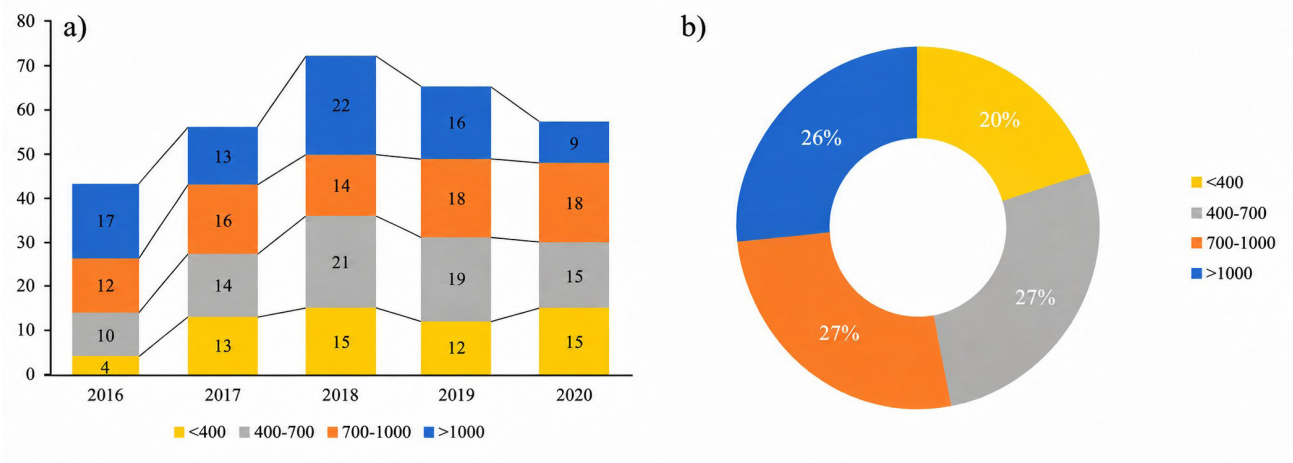


Figure 6. (a) Rockfall occurrence depth by year (total: 293) and (b) total distribution by depth, with 2020 data collected up to September (2016 and 2017 data were retrieved with limited reliability).

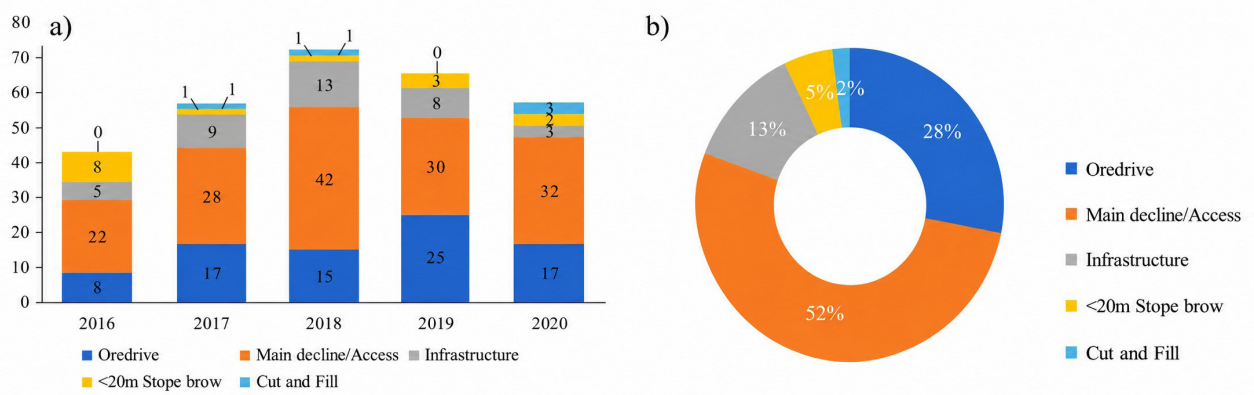


Figure 7. (a) Excavation type (total: 294) and (b) distribution by year, with 2020 data collected up to September (2016 and 2017 data were retrieved with limited reliability).

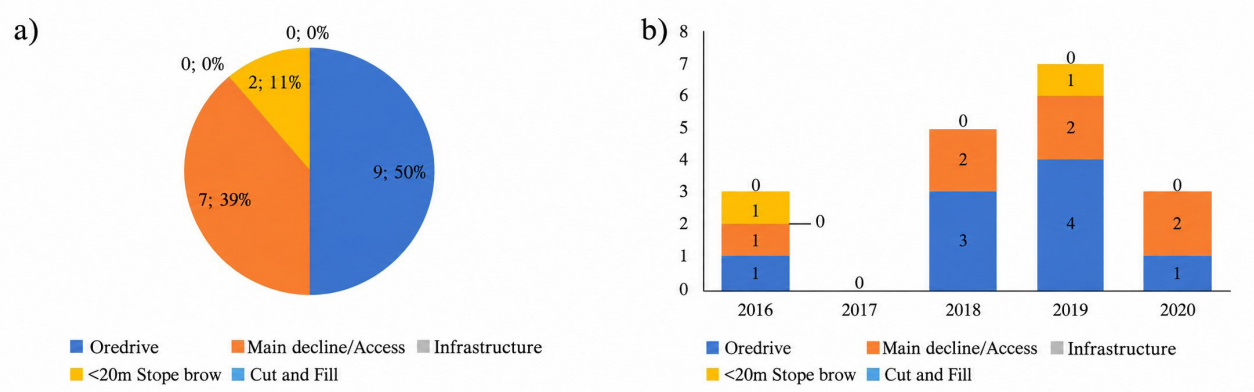


Figure 8. (a) Rockfall greater than 50 t (total: 18) and (b) distribution by year, with 2020 data collected up to September (2016 and 2017 data were retrieved with limited reliability).

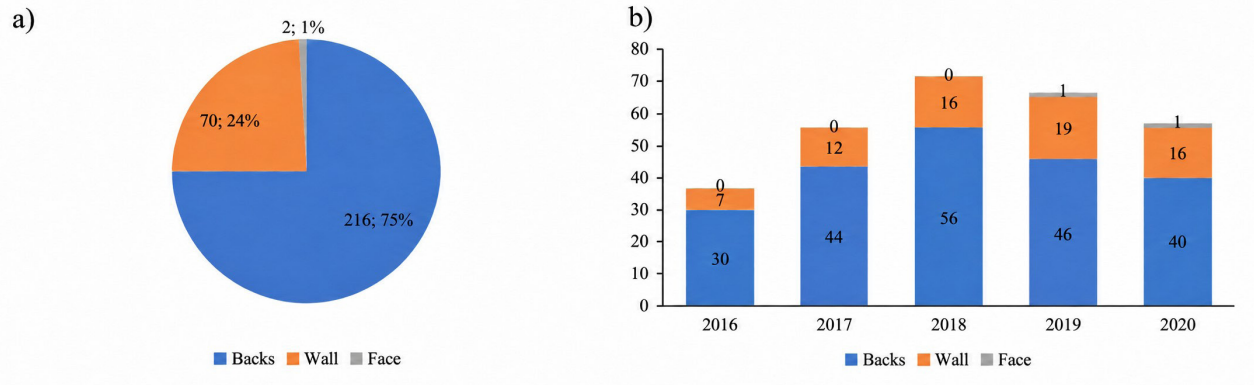


Figure 9. (a) Rockfall origin (total: 288) and (b) distribution by year, with 2020 data collected up to September (2016 and 2017 data were retrieved with limited reliability).

Another factor that may contribute to the occurrence of rockfalls is nearby blasting, which can induce vibration and/or stress redistribution. In Figure 10, it is possible to verify that 47% of rockfalls occurred within 30 m of the blasted face. Another point to highlight is the increase in rockfalls at greater distances, above 50 m, since 2017.

For the Rockfall Location and Personal Exposure group, we can draw some important conclusions:

- The majority of rockfalls, 52%, occurred in the main declines and access drives;
- A significant quantity, 61%, of large rockfalls, above 50 tonnes, occurred in the oredrives;
- The majority of rockfalls originate from the back;
- A considerable number, 47%, appear to be associated with nearby blasting within 30 m, considering the previous 3 shifts.

Another very important group when analyzing the occurrence of a rockfall is the Ground Support Practices and Performance, as in theory the support/reinforcement system should be designed to minimize/eliminate this risk. *"The primary objective of reinforcement and surface support is to arrest the loss of rock mass radial confinement along the excavation boundary"* (Potvin & Hadjigeorgiou, 2020). *"Support is the application of a reactive force at the face of the excavation"* (Windsor & Thompson, 1993). As can be seen in Figure 11, the majority of rockfalls occurred where no surface support existed, 80%. Considering that the majority of rockfalls weigh less than 1 tonne, 61%, this may be a determining factor. There was an increase in areas where surface support existed and rockfalls occurred in the last 3 years analyzed.

In addition to surface support, another factor that must be considered is the reinforcement element. *"Reinforcement is considered to be an improvement of the overall rock mass properties from within the rock mass and will therefore include all devices installed in boreholes"* (Windsor & Thompson, 1993). It can be seen in Figure 12 that the majority of reinforcement elements used in the mines at rockfall locations are resin bolts, 66%, followed by expandable bolts (Swellex) at 16%. Over the last 3 years, it is possible to identify a decrease in rockfall occurrences at locations with expandable bolts (Swellex), which is also associated with the declining use of these elements in the 4 mines studied. It is interesting to note some cases where no reinforcement element existed,

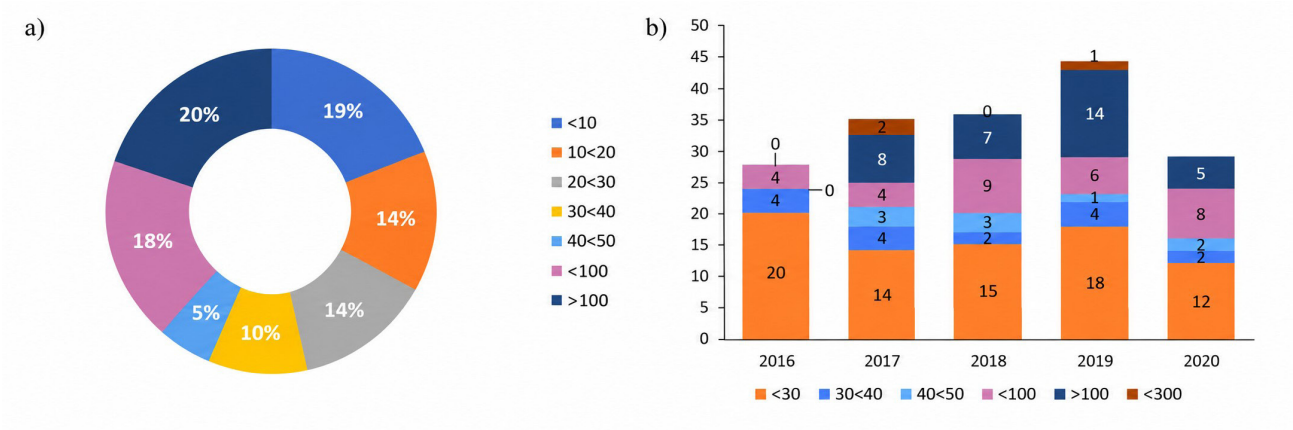


Figure 10. (a) Distance to nearest blast (total: 169) and (b) distribution by year, with 2020 data collected up to September (2016 and 2017 data were retrieved with limited reliability).

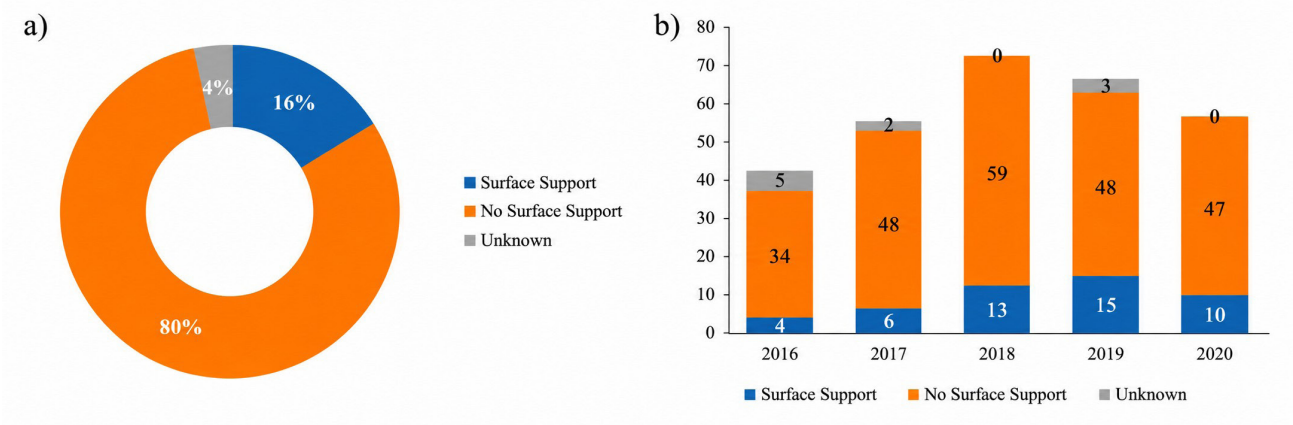


Figure 11. (a) Presence of surface support (total: 294) and (b) distribution by year, with 2020 data collected up to September (2016 and 2017 data were retrieved with limited reliability).

which is associated with areas that were developed at a time when there was no support/reinforcement recommendation for certain rock masses, a situation that no longer reflects the reality at the time of data collection.

Considering that the support/reinforcement system is designed to minimize/eliminate the risk of rockfall, it is extremely important to understand how this system performed at the rockfall location. In Figure 13, we can see that in 75% of rockfalls the reinforcement system did not fail, and only 21% of rockfall occurrences presented a failure in the reinforcement system, with no significant variations over the years. This data indicates that the majority of rockfalls, 75%, occurred between the reinforcement pattern, without pushing the reinforcement system to its maximum capacity.

Better understanding the reinforcement system that presented failure, we can see from Figure 14 that the majority is related to resin bolts, 46%, but with a significant number related to expandable bolts (Swellex), 28%. It is important to highlight the decrease in failures related to expandable bolts (Swellex) over the last 3 years, which, as already reported, is associated with the reduction in their application across the 4 mines.

When further detailing the reinforcement elements that failed during rockfall occurrences, it is possible to identify that only 40% of the reinforcement system was compliant with the recommendation (Figure 15). A significant number, 60%, presented some compliance issue, either due to damage (17%), corrosion (17%), low bond strength (8%),

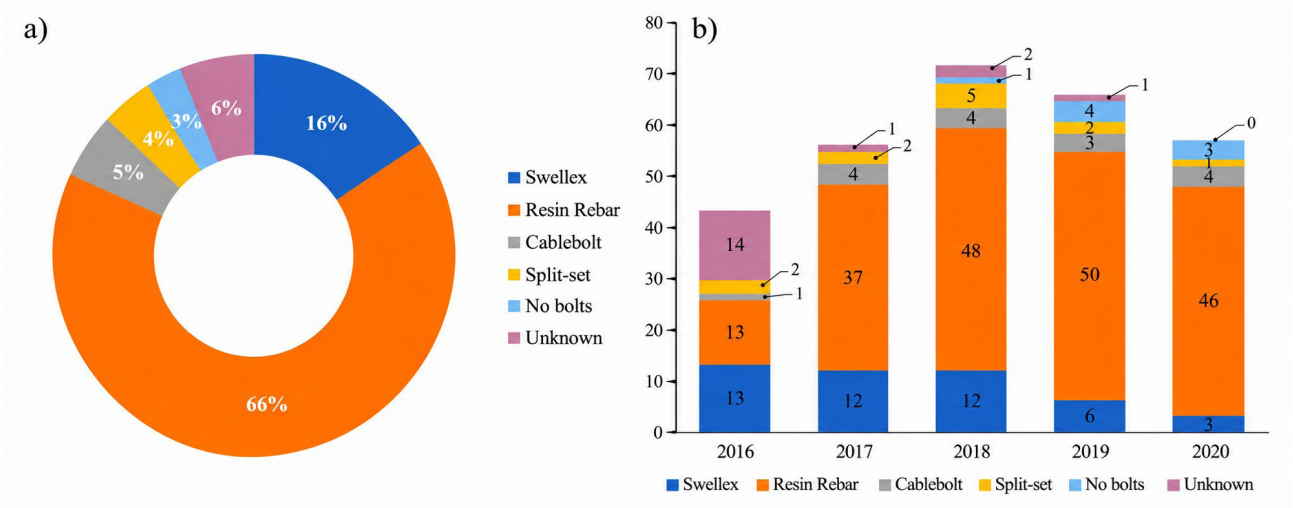


Figure 12. (a) Reinforcement element (total: 294) and (b) distribution by year, with 2020 data collected up to September (2016 and 2017 data were retrieved with limited reliability).

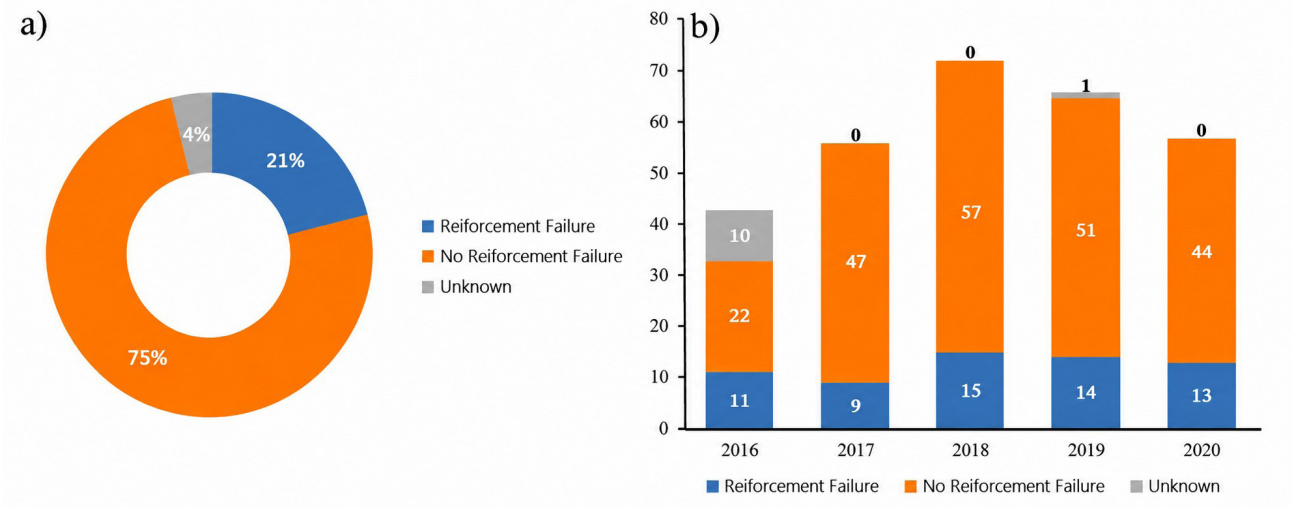


Figure 13. (a) Reinforcement failure (total: 294) and (b) distribution by year, with 2020 data collected up to September (2016 and 2017 data were retrieved with limited reliability).

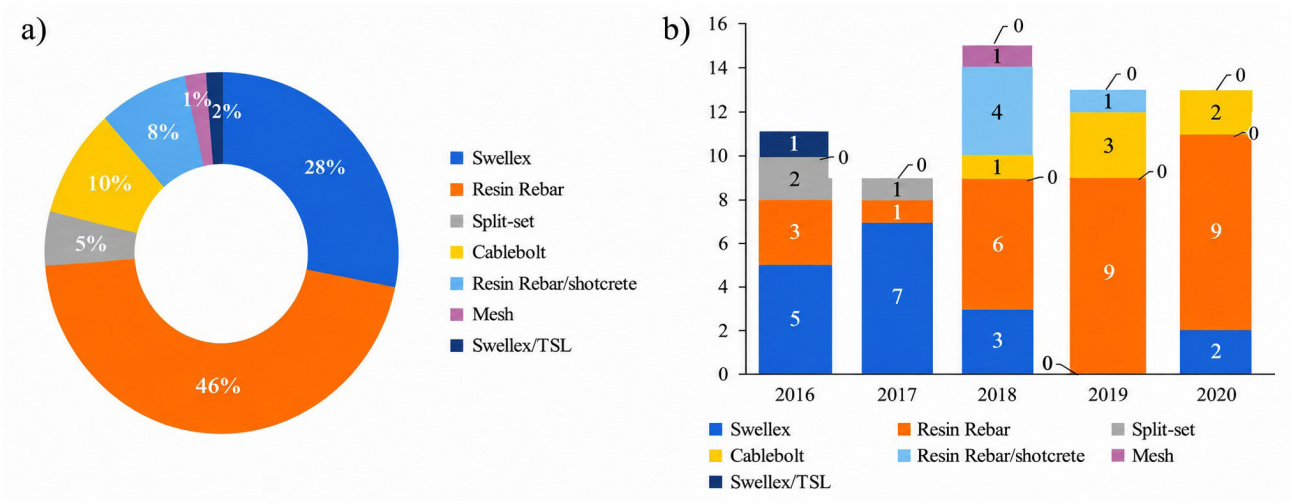


Figure 14. (a) Reinforcement failure type (total: 61) and (b) distribution by year, with 2020 data collected up to September (2016 and 2017 data were retrieved with limited reliability).

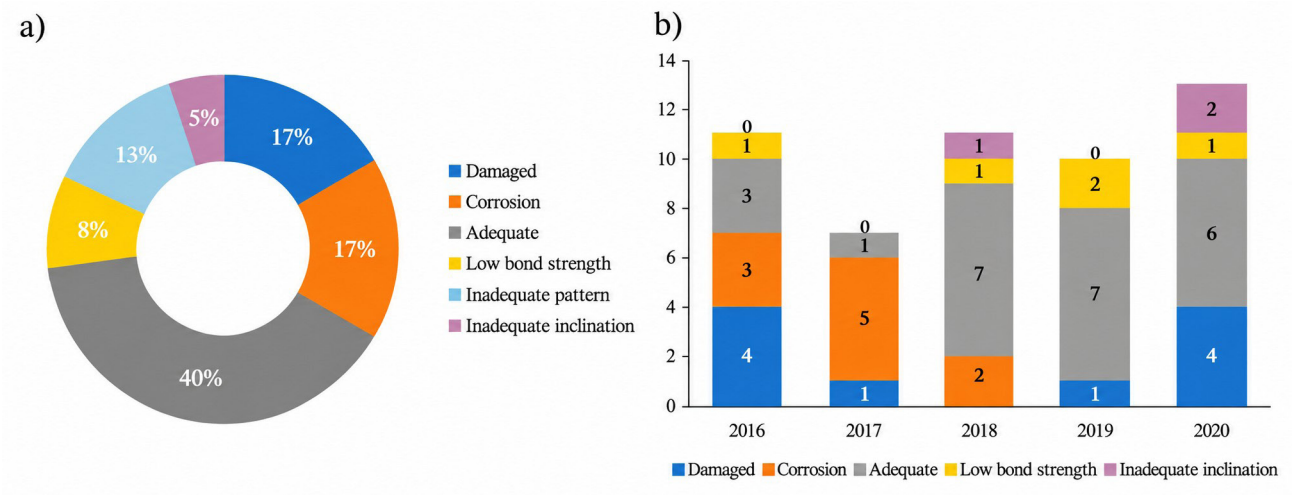


Figure 15. (a) Reinforcement condition (total: 60) and (b) distribution by year, with 2020 data collected up to September (2016 and 2017 data were retrieved with limited reliability).

or installation design problems (18%). It is also interesting to note the decrease in failures associated with corrosion in recent years, which may be mainly due to the reduced use of expandable bolts (Swellex), as previously reported. Another noteworthy factor is the increase in rockfalls associated with a reinforcement system considered adequate, in accordance with the recommended technical specification, which may indicate that a review of the support/reinforcement design may be necessary to prevent further events in the future. The reinforcement elements identified as damaged are generally related to the mechanized scaling system, which invariably damages these elements. In some mines, the replacement of damaged elements does occur, but there are failures in this process.

4. Conclusion

Considering the data collected and analyzed from rockfalls in the four underground mines in Brazil, some key points can be highlighted that may help in minimizing/eliminating the risk of rockfall:

- Use of surface support (mesh or shotcrete), which can eliminate from 61% to approximately 80% of rockfall occurrences, depending on the type of surface support and its resistance. With priority given to the back and to depths greater than 700 m in the main declines and access drives;
- A review of the support/reinforcement should be carried out for the system recommended for the oredrives, since 50% of rockfalls greater than 50 tonnes occur at this location;

- Verification or creation of a quality process for the application of support, as well as for the installation of reinforcement, establishing and managing compliance indices with respect to the recommended design, considering that 36 rockfalls presented some quality problem;
- Inspection for area entry within a radius of 30 m from the blasted face, given that 47% of all rockfall occurred in this area;
- Capacity testing for temporary reinforcement elements installed and subject to corrosion, 10 cases of rockfall were identified issue with corrosion;
- Creation of a unified database for Brazilian mines with regard to rockfall, with just one definition.

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The authors would like to thank all those who contributed to the collection and proper interpretation of each rockfall event in the four underground mines in Brazil, as well as the entire team of NUGEO (Geotechnics Research Centre) at the Federal University of Ouro Preto.

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

Reuber Ferreira Cota: Conceptualization, Methodology, Investigation, Validation, Data curation, Writing – original draft. Rodrigo Peluci de Figueiredo: Conceptualization, Validation, and Writing – review & editing.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

Declaration of use of generative artificial intelligence

This work was prepared without the assistance of any generative artificial intelligence (GenAI) tools or services. All aspects of the manuscript were developed solely by the authors, who take full responsibility for the content of this publication.

List of symbols and abbreviations

MOSHAB	Mines Occupational Safety and Health Advisory Board
NUGEO	Núcleo de Geotecnia – Federal University of Ouro Preto
UFOP	Federal University of Ouro Preto

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