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Qualitative evolving rockfall hazard assessment for highwalls

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ABSTRACT

This paper presents a new qualitative rockfall hazard assessment procedure primarily designed for the Australian open-pit coal mining environment. The methodology, named qualitative Evolving Rockfall Hazard Assessment (ERHA), intends to be a simple tool for a quick identification of the most hazardous sections of a highwall. The methodology mainly relies on in situ observations. The hazard levels (low, medium and high) are defined as a function of rockfall intensity and rockfall frequency. The former is described by means of the translational kinetic energy expected at the base of a highwall and the latter is introduced as state of activity of the highwall. The proposed methodology allows the quick identification of the sections with high hazard levels, where a strict quantitative hazard assessment is recommended. Besides the expected rockfall energy and rockfall activity, the methodology provides practitioners with key information regarding the standoff distance at the base of the highwall. The ERHA is therefore a useful tool for providing greater confidence in locating personnel, machineries, and infrastructures over the working areas at the toe of highwalls.

1. Introduction

Rockfalls consist of the detachment, fall, rolling, and bouncing of a single rock block or more rock fragments, which mainly interact with the substrate.[1] Generally, the dynamic interaction between discrete rock fragments remains minimal.[2] Rockfalls are extremely rapid processes and can travel long distances.[3] Due to their high motion velocities, rockfalls, although involving limited volumes, have the capacity to cause significant damage and even result in fatalities.[4] When a rockfall event occurs, a person is usually unable to take evasive action. Thus, the risk of injury and loss of life is extremely high.[5]

In open-pit mines, rockfalls threaten not only human lives, but also machinery and portal structures located at the toe of highwalls. Hence, rockfalls are one of the major hazards in open-pit mines. This hazard can have significant financial consequences should the production be temporarily stopped for safety issues. Despite the fact that a rigorous and effective approach to rockfall hazard management in open-pit mines could minimize risks in all the areas potentially affected, no standard methods exist so far to deal with such a hazard in open-pit coal mines.

Over the last three decades, several methodologies have been proposed for assessing the rockfall hazard along transportation corridors, such as roadways and highways[6–10] and along mountain slopes and alpine populated areas.[11–14] A small number of methods have been proposed to cope with rockfall risk in ornamental stone quarries.[15,16] In open-pit mines, a few methods have been recently developed for assessing the general slope stability,[17–19] but none of them focuses especially on rockfalls.

Generally speaking, the existing hazard assessment methodologies can be classified into qualitative and quantitative methods. The former describe the hazard by means of ranked attributes or classes. They are quick and easy to use and suitable for hazard mapping over large areas by allowing a fast identification of the most critical zones. The quantitative methods, instead, are more complex and laborious as they use numerical probability analyses to define the level of hazard and, therefore, they require a significant amount of data and time. As such, these methods are more suitable for hazard mapping of specific slope sections.

This paper presents a new qualitative rockfall hazard assessment methodology, named qualitative Evolving Rockfall Hazard Assessment (ERHA), which has been specifically developed for the Australian coal mining environment. The methodology provides the coal industry with a quick and rigorous tool for the identification of different hazard levels at the bottom of highwalls. Since the highwalls are subjected to changes in rockfall hazard over the time in response to mining activity, the hazard assessment of a given highwall can be easily updated and this is the evolving part of the methodology. The ERHA involves a first qualitative assessment for the identification of the most hazardous areas where a second more robust quantitative analysis is further required. The framework of the qualitative step is inspired by the Swiss

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guidelines,[20,21] being one of the most well established and widely accepted methods to assess the rockfall hazard. The Swiss guidelines define a matrix of three hazard levels (low, moderate and high) as a function of the probability of occurrence (i.e., frequency) and the intensity (i.e., energy) of rockfalls along mountain slopes. Within the ERHA, the boundaries of the matrix were adapted to the open-pit mining environment. The methodology, implemented into a numerical tool, generates hazard zoning maps based on in situ observations. The frequency is defined by the state of activity of the highwalls through a rating based approach. The estimate of the rockfall energies is based on an extensive sensitivity analysis carried out through two-dimensional (2D) rockfall simulations. The qualitative ERHA procedure, its validation and the definition of the hazard levels are described in the following. Finally, examples of the application of the proposed methodology to two highwalls located in Australian open-pit mines are presented.

2. State of the art

The detailed review of the existing methods to assess the rockfall hazard undertaken by Ferrari et al.[22] highlighted a severe lack of methodologies specifically designed for open-pit mines. Therefore, rockfall hazard and risk assessment methods commonly used in quarries are usually also applied to surface mining environments. In addition, methods for assessing the general slope stability of open-pit mines are more common than methods for assessing the rockfall hazard. The methods most relevant to this research are briefly discussed in the following. For a more detailed review the reader is referred to Ferrari et al.[22]

The Rockfall Risk Assessment for Quarries (ROFRAQ) method was the first method specifically designed to address rockfall risk in ornamental quarries located in temperate climate regions.[15] The ROFRAQ is a statistics-based empirical method that assesses the likelihood of rockfall-related accidents in mining environments. The method considers five ratings to describe the presence of blocks on the investigated slope, the potentially unstable conditions, the occurrence of triggering events, the potential path of the blocks, and the presence of workers or machinery at the toe of the slope. Each rating is scored between 0 and 10. The product of the scores plus a final corrective value based on the rockfall history of the quarry yields the final value of the ROFRAQ index. This value provides a yearly estimate of the likelihood of a rockfall-related accident occurring on any given quarry slope. While the ROFRAQ methodology explicitly considers the exposure of vulnerable elements, their vulnerability and economic values are not accounted for. Therefore, the final score represents neither the hazard nor the risk but rather the likelihood of the occurrence of an accident. The method requires both a detailed geo-mechanical survey of the rock mass and a historical database of rockfall events occurred at the site which is not always available. Moreover, the considered triggering effects depend on climatic parameters (i.e., maximum 24 h rainfall for a 50-year return period and average 0 °C frost-free period) relevant for to European countries. Therefore, the method is hardly applicable to Australian coal mines.

The ROFRAQ methodology was later modified by Peila et al.[16] to define the Quarri index, whereby ratings describing the presence of blocks on the slope, the potentially unstable conditions, the occurrence of triggering events, and the rockfall history of the quarry are defined as per the ROFRAQ methodology. The product of these scores subdivided by a factor of 1000 gives the expected number of rockfall events per year. The final risk assessment includes a more rigorous assessment of the probability of reach (calculated by site-specific 2D rockfall simulations) and a factor that accounts for the time spent in the quarry yard or at benches by workers and machinery. The Quarri index has the same limitations as the ROFRAQ methodology. In addition, it requires 2D simulations that are derived from detailed topographic profiles of slope sections. Therefore, it is not suitable for a quick hazard mapping of large areas.

The Slope Stability Assessment (SSA) is a rating classification system that assesses the general slope stability in open-pit coal mines.[18] This system was developed by analysing the failure mechanisms of six open-pit coal mines located in Central India. The system defines a Slope Failure Hazard class (very high, high, medium, low or very low) by assigning a rating to both rock mass parameters and slope conditions. The rock mass parameters include the intact rock strength and the volumetric joint count. The slope conditions consider the presence of strike faults, spoil dumps, localized instabilities, and general drainage conditions, as well as possible adjustment factors related to the presence of active fire, rainfall and any other parameter that may have an influence on the slope stability. The SSA does not focus on the rockfall hazard, but on general slope stability. The method does not consider the frequency of occurrence, which is a key parameter in most of the hazard assessments. Moreover, a description with the meaning of the different hazard classes with consequent restrictions/protection measures is missing.

The Risk Rating System (RRS) was initially developed in South Africa from Anglo Coal in order to provide an unbiased, standard and quantifiable assessment of the risk in open-pit mines.[23] Afterwards, the system was adapted to evaluate the risk of highwall and lowwall failures in Australian coal mines.[17] The system is a semi-quantitative risk rating approach that takes into account both geotechnical and performance risk rating parameters. The former includes 18 parameters related to the geology, the presence of water, spontaneous combustion and the use of a dragline. The latter uses 17 parameters that pertain to three categories: geometry, mining and blasting operations. Each parameter has associated a different weight, which ranges from 1 to 20, as a function of the potential severity of the consequence. The final risk level (low, medium or high) is defined by overlapping the ratings to a matrix based on a back analysis of failures and experienced gained from highwalls in South Africa and Australia. The RRS aims to assess the overall slope stability in mine sites and is not specifically designed for the rockfall hazard. In addition, by considering 35 different parameters it is not suitable for a quick hazard mapping approach.

The Mine Slope Instability Index (MSII) assesses the overall slope stability conditions in open-pit mines.[19] The MSII takes into account 18 parameters related to the rock mass properties, the presence of water, the tectonic regime, the pit-wall geometry, the blasting method and any previously occurred instability. A rating is assigned to each parameter and the weighted sum of the ratings gives the MSII value. The weights were calculated through the Rock Engineering System approach,[24] using an artificial neural network. The MSII value ranges from 0 to 100, the higher the value the higher the hazard. Three hazard levels (safe zone, failure in set of benches, and large scale or overall failures) were differentiated on the basis of 84 case histories of open-pit slope stability. The MSII also focuses on general slope stability. It uses numerous parameters which are not suitable for a quick assessment. Moreover, some parameters are significant for overall slope failure and failure in set of benches, but they can be neglected in assessing the rockfall hazard.

Finally, some recommendations developed for surface mining are provided by BMA.[25] Regarding the rockfall hazard, these recommendations cope with standoff distances (i.e., exclusion zones) at the toe of continuous highwall slopes. In particular, they report a criterion for the quick evaluation of primary standoff distances for different slope configurations. Specifically, a primary standoff distance of 10 m is required for less than 60 m high continuous slopes, and a 15 m primary standoff is required for continuous slopes with heights above 60 m. According to these recommendations, mine equipment can reach into the primary standoff distance as long as the operator's cab remains outside the required standoff distance. These recommendations are useful for a quick evaluation of the standoff distances, although they are quite general. No information about the expected energy and frequency of occurrence can be gathered from these recommendations.