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A risk-based methodology for establishing landslide exclusion zones in operating open pit mines

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ABSTRACT

The high consequences of recent large open pit slope failures have increased industry and regulatory interest in establishing exclusion zones beneath an impending pit wall failure. This paper proposes a methodology to delineate an exclusion zone for an impending pit slope failure. The focus of this paper is a framework for the management of life loss risk to the most exposed individual. The probability of the landslide occurring and the probability of the resulting landslide being very or extremely rapid are described in this paper. Set in a probabilistic framework, empirical runout analysis tools are useful for estimating the spatial probability of impact throughout the open pit and establishing exclusion zones. Runout exceedance probability charts calibrated to a large dataset of pit slope failures are provided. The temporal probability that the most exposed individual is present and cannot be evacuated is also described. The resulting risk is mapped across the pit floor by dividing it into square grid cells and calculating the probability of death to the most exposed individual for each cell. The cells can be colour coded to indicate specific risk exposure ranges relative to the exclusion zone set. A conceptual case study is used to illustrate the proposed methods.

1. Introduction

The high consequences of recent large open pit slope failures demonstrate shortcomings in establishing exclusion zones beneath an impending slope failure. In several recent pit slope failures, geotechnical staff have effectively identified the impending failure but underestimated the resulting runout.[1,2] Damaged infrastructure, buried equipment and fatalities have resulted despite geotechnical staff effectively identifying the hazard and predicting its approximate time to failure. Creating exclusion zones (i.e., zones within the pit where equipment and personnel are prohibited to work) is an effective means to reduce risk in open pits; however, uncertainty remains as to how far they should extend.

Empirical runout models that can be used to predict the runout distance and zone of impact of natural landslides[3–6] and linear infrastructure[7,8] are well established. Whittall[9] compared established empirical runout relationships for natural landslides to a dataset of 105 pit slope failures and identified correlations between failure volume and Fahrböschung angle (the angle connecting the crest of the source and the toe of the deposit) specific for open pit slope failures and runout prediction. The objective of this paper is to present a clear procedure and tools to apply these runout relationships to open pit mining operations to estimate runout below impending landslides and delineate exclusion zones based on tolerable risk.

2. Landslide risk management in open pits

Risk-based decision-making has been widely applied to the management of natural landslides.[7,8,10,11] Landslide risk can be calculated based on the following general equation:

$$\text{Risk} = \sum_{i=1}^{n} P(H)_i x P(S \mid H)_i x P(T \mid S)_i x V_i x E_i \tag{1}$$

where: i is the landslide scenario number (i.e., representing a landslide within a specific volume range); $P(H)_i$ is the probability of the landslide occurring within a given time interval (note that annual probabilities are typically used in landslide risk calculations, but this approach may not be appropriate for impending open pit slope failures, as discussed in more detail below); $P(S|H)_i$ is the spatial probability that the landslide will reach the "element at risk" (i.e., a specific piece of equipment or person) if it occurs; $P(T|S)_i$ is the temporal probability that the element at risk will be present if the landslide reaches its location; V_i is the

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vulnerability (or probability of loss) if the element at risk is impacted; and E_i is the value of the element at risk (for economic risk calculations) or the number of people at risk (for life loss risk calculations). The calculated risks can be compared against established risk tolerance criteria to quantify the level of landslide safety and aid risk management decision-making in terms of land use planning and/or the design of mitigation measures.

Decision-making in operating open pits has moved towards this risk-based framework.[12–14] Geotechnical considerations are balanced with many other factors in the mining industry, and tolerating marginally lower factors of safety for economic advantages may be desirable in certain cases, although the same basic risk management principles apply. Several open pit practitioners[12,15] provide strategies for risk-based slope design. A similar framework can be used to manage risks when landslides develop in open pit slopes.

The focus of this paper is a framework for the management of life loss risk. Life loss risk can be expressed as either the risk to an individual (e.g., a single equipment operator) or a group (e.g., a number of equipment operators who may be present in the runout zone at the same time). Risk to individuals can be expressed as the probability of death of an individual within a given time interval, PDI, by setting the value of E_i to 1 in Eq. (1):

$$PDI = \sum_{i=1}^{n} P(H)_i x P(S \mid H)_i x P(T \mid S)_i x V_i \tag{2}$$

The runout analysis tools described in this paper are based on the observed behaviour of very rapid (3 m/min to 5 m/s) to extremely rapid (> 5 m/s) landslides (refer to[16] for landslide velocity class definitions). The first term on the right side of Eq. (2) can therefore be broken down into two components as follows:

$$P(H)_i = P(H)A_i x P(H)B_i \tag{3}$$

where $P(H)A_i$ is the probability of a landslide of any velocity occurring within a given time interval and $P(H)B_i$ is the probability that the resulting landslide is very rapid to extremely rapid. The third term on the right side of Eq. (2) can also be broken down to reflect the opportunity for early warning systems to reduce the risk:

$$P(T \mid S)_i = P(T \mid S)A_i x P(T \mid S)B_i \tag{4}$$

where $P(T|S)A_i$ is the temporal probability that the worker is on duty when the landslide occurs and $P(T|S)B_i$ is the probability that the worker is *not* evacuated before the landslide reaches their location. The full risk equation that forms the basis for the framework described in this paper is therefore:

$$PDI = \sum_{i=1}^{n} P(H)A_i x P(H)B_i x P(S \mid H)_i x P(T \mid S)A_i x P(T \mid S)B_i x V_i \tag{5}$$

3. Conceptual case study

A conceptual case study is used in this paper to clearly illustrate the proposed methods. The scenario, geological conditions, and geometries specified have been selected to be representative of those reported in the literature as compiled in.[17] The intent is that this relatively simple scenario can be used as a straightforward template by others, and expanded as needed to address more complex scenarios that may be encountered in practice.

Fig. 1 shows a hypothetical open pit configuration and landslide scenario. A shovel is working near the toe of the slope. The pit wall is composed of strong, fresh igneous rock with fault zones and is monitored with a robotic total station and network of prisms. Monitoring data are compiled in spreadsheets in-house by the mine geotechnical staff. As mining progresses, the movement of the prisms accelerate. Tension cracks at the headscarp form, roughly aligned with two gouge-infilled faults, creating a wedge-shaped rupture surface geometry.

The mine is a 24-h operation with equipment operators working 12-h shifts, one week on and one week off. Blasts are carried out daily during daylight hours. Breaks not related to blasting total 1.5 h per shift. The mine's geotechnical team works dayshift, Monday to Friday.

4. Estimating individual risk at a specific point

Referring to Eq. (5) and the conceptual case study described above, the individual risk calculation is based on the following six questions:

$P(H)A_i$: What is the probability of a landslide within volume range i occurring within a given time interval?

$P(H)B_i$: If a landslide occurs, what it the probability it will be very rapid to extremely rapid?

$P(S|H)_i$: If the landslide is very rapid to extremely rapid, what is the probability it will reach the equipment?

$P(T|S)A_i$: If the landslide reaches the equipment, what is the probability the operator is on duty?

$P(T|S)B_i$: If the operator is on duty, what is the probability they will

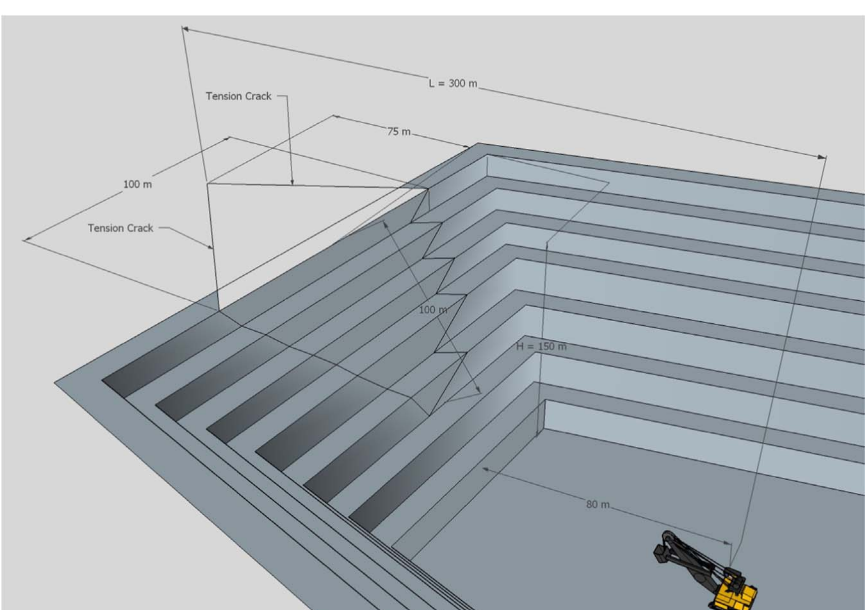

Fig. 1. Layout of conceptual case study.