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On the monitoring and early-warning of brittle slope failures in hard rock masses: Examples from an open-pit mine

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ABSTRACT

The management of unstable slopes is one of the most critical issues when dealing with safety in open-pit mines. Suitable notice of impending failure events must be provided, and at the same time the number of false alarms must be kept to a minimum to avoid financial losses deriving from unnecessary outages of the production works. Comprehensive slope monitoring programs and early warning systems are usually implemented to this aim. However, systematic procedures for their tuning are lacking and several key factors are often overlooked. Therefore the mitigation of slope failure risk is still a topic of great concern, especially in open-pit mines excavated through hard rock masses featuring markedly brittle behavior, which supposedly provide little or no measurable precursors to failure. In this paper, 9 instabilities occurred at an undisclosed open-pit mine, and monitored by ground-based radar devices, were reviewed with the goal of characterizing the typical slope deformation behavior and defining the appropriate strategy for the setup of alarms. The estimated mass of the case studies ranged from 1500 t to 750,000 t. 5 instabilities culminated to failure, whereas the other 4, although showing considerable amounts and rates of movement, ultimately did not fail. The analysis provided critical insights into the deformation of hard rock masses of high geomechanical quality, and allowed the identification of "signature" parameters of the failure events. General operative recommendations for effective slope monitoring and early warning were consequently derived.

1. Introduction

Detecting ongoing processes of rock slope deformation that may lead to failure is a critical aspect in the fields of geomechanics and engineering geology. Mitigation of slope failure risk requires knowledge of the structural geology, of the rock mass properties, and of the influence of water and other external forces in the monitored area. The topic is of particular concern in open-pit mines, where production works must proceed at high rate, and at the same time the safety of the personnel and the integrity of the mining equipment must be guaranteed.

Regardless of the driving factors, displacement and velocity are widely considered as the best indicators of slope stability conditions (Lacasse and Nadim, 2009; Intrieri et al., 2013). Several time-dependent relationships have been proposed to fit monitoring data of slopes approaching failure (Federico et al., 2012; Intrieri and Gigli, 2016). Most of these are based on the observation that slope velocity increases asymptotically towards failure ("tertiary" or "accelerating" creep, usually known as "progressive deformation" in the mining field), and are solved with the application of the inverse velocity method developed by Fukuzono (1985), (Voight, 1988; 1989). Accordingly, monitoring ground surface movements is one of the fundamental precautionary measures of open-pit mine operations, and a variety of instruments may be used to this aim (Read and Stacey, 2009; Vaziri et al., 2010). In particular, ground-based radar has become one of the leading-edge technologies, due to its ability to detect movements with high accuracy, spatial coverage and frequency of acquisition. Several successful applications of ground-based radar systems to identify large-scale failures in open-pit mines have been published in the literature (Armstrong and Rose, 2009; Doyle and Reese, 2011; Ginting et al., 2011; Farina et al., 2013; Macqueen et al., 2013; Farina et al., 2014; Atzeni et al., 2015; Dick et al., 2015).

Even though tertiary creep may be assumed as a precondition for failure occurrence, prediction and early warning are still difficult to obtain because of the variability of slope behaviors. Phases of progressive deformation may in fact develop rapidly or over very long periods of time, involve a wide range of possible rates, and show an alternation of acceleration-deceleration cycles (Zavodni and Broadbent,

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1980; Hutchinson, 2001; Crosta and Agliardi, 2002). While large-scale failures that are anticipated by extended periods of progressive deformation (i.e. ductile behavior) are relatively easy to predict, in other geological conditions failures can be brittle (even though brittleness is properly referred to a post-failure behavior consisting in an abrupt strength drop, here it is used to indicate failures characterized by little or negligible precursor deformation) (Eberhardt et al., 2004; Rose and Hungr, 2007; Paronuzzi et al., 2016). Markedly brittle failures in tension or shear on steep slopes, especially if related to small-scale slides and hard rock masses (e.g. high-grade metamorphic or volcanic rocks), usually are the most difficult to predict. Anticipated by seemingly step-like, nearly instantaneous displacements, it is common perception that these cannot be identified with sufficient advance (Rose and Hungr, 2007).

In this paper we present 9 cases of slope instability monitored by means of ground-based radar devices at an undisclosed open-pit mine. The pit is excavated through an ore body consisting of hard rock formations of high mechanical quality in terms of Rock Mass Rating (RMR). 5 of these movements reached failure, whereas the other 4, although showing intense phases of deformation, ultimately did not ("non-failures" in the rest of the paper). With the goal of supporting the tuning of an ad-hoc early warning system, the analysis of the monitoring data provided new insights into the precursory deformation in markedly brittle rock slope failures. Thanks to the high temporal resolution of ground-based radar data, it was observed that the pit slopes are subject to very rapid phases of tertiary creep, and that "signature" parameters differently described failures and non-failures. General operative recommendations for effective slope monitoring and early warning were consequently derived. Finally, methodologies to be used for the activation of alarms at the pit were defined.

2. Overview of the open-pit and of the instability case studies

Name and location of the open-pit operation object of the present study are confidential and therefore cannot be disclosed, as well as specific details concerning the mined ore body. The mine (which has been active for over 50 years) has a length of roughly 3 km, a width between 400 m and 600 m, and a current depth > 200 m (Fig. 1). Benches are either 15 or 30 m high (depending on the stage of production), and the overall slope angle of the pit is between 45° and 55°. According to the RMR classification, the rock mass quality in the pit mostly ranges between "fair" and "very good", with values that on average are included between 60 and 80 (thus falling in the "good" category). Instabilities are typically structurally controlled and relatively shallow. These include planar, wedge and toppling mechanisms, while there are no records of identified deep-seated movements. Extremely large-scale movements are also uncommon. The highest risk is posed by rockfall and by single or multiple bench scale failures of small to medium size. Specifically, the mass of the instabilities discussed in this paper ranges from 1000 to 750,000 t.

2.1. Geological and structural setting

From a geological point of view, the ore body consists of an intrusion through an enclosing anorthosite formation. Xenoliths of anorthosite are also present within the ore, along with two major cross-cutting diabase dikes of sub-vertical inclination. Both the ore body and the enclosing anorthosite are characterized by several areas of heavy alteration related to fractures and fault systems. In correspondence of their contact, movement indicators like S—C fabrics, secondary structures, and slickensides can be observed.

In the area of the pit 6 different joint sets, distributed in 8 different geological domains, were defined (Morales et al., 2017). The structural fabric derived by these domains leads to the formulation of wedges/tetrahedrals, which may be unstable when the required kinematic conditions are fulfilled. As a result planar, wedge, and toppling instabilities have taken place during the operational life of the mine. The geometrical relationship between slope faces and fracture planes, and the deterioration of the mechanical properties of the planes, are the main predisposing factors. In some cases, even if the kinematic conditions for the initiation of an instability were reached, the wedges prone to slide did not show any displacement for many years. Discontinuities are occasionally filled with clayey material, and free swell of up to 230% has been measured in some smectites. The joint wall compressive strength varies from 25 MPa to 100 MPa, depending on the degree of weathering and on the presence and type of clayey minerals. The residual friction angle can reach values as low as 24°, while the Joint Roughness Coefficient (JRC) can be of 4–6 or even lower.

2.2. Slope monitoring data

Nowadays, the use of ground-based radar in open-pit mines is a standard practice for active slope monitoring. Displacements are calculated by measuring the phase difference of the back-scattered microwave signal between two or more coherent acquisitions (Antonello et al., 2004; Luzi et al., 2006; Casagli et al., 2010; Di Traglia et al., 2014; Monserrat et al., 2014; Bardi et al., 2017; Casagli et al., 2017). The technology presents the advantages of high measurement accuracy, high spatial and temporal resolution, long-range capabilities, and limited impact of atmospheric noise (Farina et al., 2013). This is obtained without the need to install artificial reflectors on the slope.

The analyzed set of monitoring data is made of radar displacement time series from 5 cases of failure and from 4 cases of significant slope movements that did not evolve into failure. In every instance, a displacement time series was extracted by averaging data of all the pixels included in the unstable section of a single bench; meaning that one displacement time series was obtained for single bench instabilities (or smaller), whereas for multiple bench instabilities their number is equal to how many benches were involved in the detected movement. Pixel selection was based on a velocity cutoff that was in place at the mine as part of the safety strategies for slope failure risk reduction. Although measurement error varied with the level of disturbance induced by vibrations and blasting, this was generally below 0.5 mm/h. The distance between radar and monitored instability ranged from 200 m to 850 m (Fig. 1).

Depending on the radar model in use (two Real Aperture Radar and one Synthetic Aperture Radar were in operation at the mine), the frequency of acquisition was either 20 or 3 min. When dealing with high-frequency radar measurements, filtering is needed in order to remove noise and highlight the fundamental trends in the data (Dick et al., 2015; Macciotta et al., 2016; Carlà et al., 2016). Given the abrupt nature of the accelerations potentially affecting slopes in the pit, the interval over which smoothing must be performed is necessarily short, so that the detection of sudden trend changes is not crucially delayed. In this context, a better understanding of the main trends may be simply gained by reducing the number of plotted data points, grouping measurements relatively to the selected reference time window (e.g. by averaging all data acquired on the same hour, obtaining one representative value for every hour of monitoring). The analysis of the radar measurements was herein performed by considering thus calculated 1-h averaged data (Sections 3.1 and 3.3), with the exception of failure #5; a separate sub-section was dedicated to this case study due to its peculiar deformation behavior with respect to the other failures (Section 3.2).

Displacements measured by radar are relative to the direction between the target and the receiver (i.e. line-of-sight, or LOS), and therefore may not represent the full component of the actual movement. The latter aspect is often not taken in due consideration, which potentially leads either to the setup of too conservative thresholds owing to uncertainty (i.e. monitoring is affected by an excessive number of false alarms, resulting in a lack of credibility to the eyes of the production team) or, even worse, to a false sense of safety.