International Journal of Rock Mechanics & Mining Sciences 93 (2017) 76–81

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

A new method to identify impending failure in rock slopes

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ARTICLE INFO

Keywords:
Slope failure
Slope acceleration
Mining
Early warning
Ground-based radar

1. Introduction

Assessing when an unstable slope is at the point of critical equilibrium is one of the main points of research and discussion in the field of rock mechanics. The topic has great relevance especially in the mining industry, as significant economic benefits derive from the ability to safely prolong works in areas where rock deformation is underway. Mining near an unstable slope requires strong confidence that a failure of the excavated area will not happen in the relatively immediate future; achieving this goal determines a more efficient and profitable extraction of the mineral resources.[1] An effective monitoring program, able to provide notice of slope instability through the accurate and timely measurement of precursors to failure, clearly represents an essential benefit for the safety and productivity of the mine operation. Adequate anticipation of events of slope failure allows mine operators to plan and implement response actions with sufficient advance to minimize the effects of the failure on personnel safety and mine productivity. As a consequence, in most of the large surface mine operations around the world, extensive slope monitoring programs are undertaken nowadays as part of the mine performance monitoring system, by integrating various instruments such as slope stability radar, robotic total stations and geotechnical sensors.[2] Detailed datasets of surface and underground displacements are thus collected and their analysis can provide valuable information for the understanding of the behavior of rock slopes approaching failure. Once accurate monitoring data are acquired in near-real time, the most challenging task for the site staff in charge of risk management is the set-up of suitable alarms representing when slope failure is impending.[3]

Without entering into their details, a number of “phenomenological” failure criteria (i.e. based solely on datasets of displacement measurements versus time)[4] have been proposed in the past to forecast the time of slope failure[5–10]; among these the inverse velocity method, derived from the accelerating creep theory, is the most common tool used to predict the time of failure of progressively accelerating slopes. Failure criteria often provide very useful descriptions of the risk associated with the ongoing deformation, but are also characterized by several limitations. Most notably, universal laws used to describe the displacements of failing slopes do not take into account the specific physical aspects of the phenomenon under investigation, such as the mechanical properties of the material and the influence that these have on the development of the landslide.[4] With reference to the inverse velocity method another important limitation is that this assumes that velocity at failure is infinite, whereas the velocity of slopes is evidently never infinite. It follows that failure-time predictions must be regarded just as general estimations and that the inverse velocity method (and failure criteria in general) should be used with caution[9,11]; the margin of error (i.e. the time difference between actual and predicted failure) can in fact range from few hours up to several days.[12,13] In other cases predictions cannot be performed with adequate confidence. As a result, the issue of determining when slope failure may be impending is still of great concern.

According to a different approach, other methods are instead based on the review of databases of failure case histories in order to identify characteristic conditions for slope failure occurrence.[1,14,15] Rather than providing failure-time predictions, the aim is to define recurrent correlations between certain variables in close proximity to the instant of failure. In the framework of the ACARP (Australian Coal Association Research Program) C17023 project, Cabrejo and Harries[16] analyzed a large database of deformation data acquired by Slope Stability Radar

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http://dx.doi.org/10.1016/j.ijrmms.2017.01.015
Received 3 March 2016; Received in revised form 26 December 2016; Accepted 22 January 2017
Available online 30 January 2017

(SSR) devices in several undisclosed Australian open-cut coal mines and reviewed 78 case histories of mine slope failure, which were all anticipated by progressive accelerations. Parameters associated to both displacement and velocity at different stages of the failure process were considered by the authors, but reliable mathematical expressions able to comprehensively characterize the observed events could not be found. In this work further in-depth analysis of this database is presented. In particular, the average accelerations during different sub-sets of time prior to the instant of failure have been studied and highlighted the presence of a common behavior of the slope failures in the database.

2. Database of mine slope failures

SSR has emerged in the last 15 years as an effective tool for safety-critical monitoring of slope movements in surface mining, mainly thanks to its ability to rapidly measure displacements with sub-millimetric accuracy over wide areas and in almost all weather situations, obviating the need to install artificial reflectors. The successful implementation of ground-based radar in mining operations is well-known and has been demonstrated in several instances.[17–21] As part of the ACARP C17023 project, 78 sets of deformation data, corresponding to as many slope failure events, were acquired by a total of 20 SSR systems from October 2004 to March 2010 in several Australian open-cut coal mines.[16] The observed failures were all preceded by a general phase of progressive acceleration and were subdivided based on three slope configurations: high wall (HW, when the rock mass overlies the coal seam on the excavated slope), foot wall (FW, when the rock mass underlies the coal seam on the excavated slope) and low wall (LW, the accumulation of the granular waste products obtained from the excavation and blasting of the HW and FW). Diversely from the first two, LW consist of loose material.

For every event collected in the research study, Cabrejo and Harries[16] made reference to the radar pixel displaying the greatest amount of deformation and considered cumulative displacements and velocities at failure instant, 3 h before failure, 24 h before failure and 48 h before failure. However, because SSR can be rapidly moved and in most cases was deployed on site only when the progressive movement had already started, data relative to 48 h (or also 24 h) before failure are sometimes lacking. In mine operations it is in fact not unusual to deploy radar devices to monitor a slope only in consequence of the observation in the field of warning signs of potential failure (e.g. tension cracks) or following the detection of progressive displacements by means of other monitoring systems. On this topic Szwedzicki[22] provided a comprehensive list of slope failure indicators and precursors that are commonly observed in mining excavations when structural damage affects the behavior of the rock mass. It is therefore inferred that the failures at the ACARP coal mines were anticipated by relatively short phases of acceleration (i.e. few days).

When allowed by the length of the available historical record, velocities were calculated over time windows (Δt) of 1, 2 and 12 h. The database of velocities calculated over $\Delta t = 1$ h is the most comprehensive and therefore was selected for the analysis methodology described in Section 3. Values of velocity and acceleration display a significant degree of variation among the different events, up to two orders of magnitude; more specifically, velocities at failure instant range from < 1 mm/h to > 400 mm/h. This scattering makes virtually impossible to establish characteristic alarm thresholds merely based on slope velocity. Moreover, measurements performed by means of radar are influenced by the Line of Sight (LOS) between the sensor and the target. Depending on how the system is setup and on the direction of the observed slope movement, the recorded displacements can represent a significantly lower component of the actual total displacements. For this reason, setting pre-determined thresholds of velocity as the only discriminant for the alarm set-up process is definitely not recommended.

The reviewed database of failure case histories presents some limitations, among which the most notable are the lack of information regarding the geological and geomechanical background of the mine sites and the lack of complete time series data. The size and the mechanisms of the failure events are also unknown. Because of the mentioned deployment strategy of the SSR, historical record of the long-term deformation trends are not available as well. Cabrejo and Harries[16] attempted several approaches in order to identify recurrent correlations involving displacement or velocity values as measured by the SSR, including the analysis of maximum displacement vs. slope length, cumulative displacement 3 h, 24 h and 48 h before failure vs. cumulative displacement at failure and velocity 3 h, 24 h and 48 h before failure vs. velocity at failure. The results did not highlight the presence in the data of a relationship of statistical significance.

3. Analysis methodology and results

Our newly proposed approach focuses instead on the average acceleration occurred during different time intervals prior to the instant of failure. As described in Section 2, the dataset provides velocity measurements relatively to the time of failure (v_f) and to defined instants before failure (3, 24 and 48 h, respectively v_{f-3} , v_{f-24} and v_{f-48}). For each event the average acceleration between t_f and t_{f-3} (a_{3h}) was thus calculated, along with the average acceleration between t_f and t_{f-24} (a_{24h}) and between t_f and t_{f-48} (a_{48h}). Values of v_{f-3} and v_{f-24} are simultaneously available for 40 out of the 78 reported slope failures. Values of v_{f-3} and v_{f-48} are simultaneously available for 16 out of the 78 slope failures, while values of v_{f-24} and v_{f-48} characterize 13 case histories. The ratios between pairs of the quantities defined above (i.e. $R_a=a_{3h}/a_{24h}$, $R_b=a_{3h}/a_{48h}$ and $R_c=a_{24h}/a_{48h}$) were considered. Scatterplots of a_{3h} vs. a_{24h}, a_{3h} vs. a_{48h} and a_{24h} vs. a_{48h} for the ACARP failure case histories are shown in Figs. 1–3. Since the a_{3h} vs. a_{24h} scatterplot is characterized by the largest amount of points, in Fig. 1 the results are displayed both cumulatively and separately based on the slope classification; in Fig. 2 an enlargement of the chart area enclosed by the box in Fig. 1d is shown. A striking linear correlation can be observed in each of the presented scatterplots (R^2≈0.99). Linear regression lines are all calculated with a zero-y intercept. Concerning the a_{3h}/a_{24h} ratio, only a total of four points deviate from the dominant trend ("outliers", Fig. 1b–d) and are excluded from the computation of the linear regression lines. Equivalently, three points are excluded from the linear regression line of the a_3 vs. a_{48} scatterplot in Fig. 3a. No outliers are detected in the a_{24h} vs. a_{48h} scatterplot (Fig. 3b). Slope classification does not appear to affect data trends, despite the different mechanical properties between HW-FW and LW (hard rock masses and loose granular material, respectively). The plots of a_{3h} vs. a_{24h} show that most of the failures occurred at the point of progressive deformation where the average acceleration of the previous 3 h was approximately seven times the average acceleration of the previous 24 h; the order of magnitude of the deformation does not appear to have any influence. Among the outliers, one failure took place with R_a < 2 and three failures with negative values of a_{3h} (and consequently of R_a), i.e. during a phase of slope deceleration. Similarly Fig. 3 suggests that mostly constant values of R_b (~13) and R_c (~2) characterize the failures in the database; however it must be noted that these are evinced from a lower amount of points with respect to R_a.

Fig. 4 exemplifies how such scatterplots may be interpreted: the linear best-fit ("failure-line") represents the state of critical slope stability. Points near this line signal that the related failures complied with the identified correlation. Points located above the failure-line indicate that the progression of the acceleration persisted longer than expected. Remarkably, none of the events in the database is found in the upper section of any of the plots, thus suggesting that the failure-line actually represents a potential ultimate alarm threshold for this dataset. Conversely, points lying at a significant distance below the failure-line indicate that failure occurred earlier than expected in the