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A new method to identify impending failure in rock slopes

Tommaso Carlà[a,b,*], Emanuele Intrieri[b], Paolo Farina[b], Nicola Casagli[b]

[a] Regional Doctoral School of Earth Sciences, Università degli Studi di Firenze, Via La Pira 4, 50121 Firenze, Italy
[b] Department of Earth Sciences, Università degli Studi di Firenze, Via La Pira 4, 50121 Firenze, Italy

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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

* Corresponding author.
E-mail address: tommaso.carla@unifi.it (T. Carlà).

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(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 ($R^2 \approx 0.99$). 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

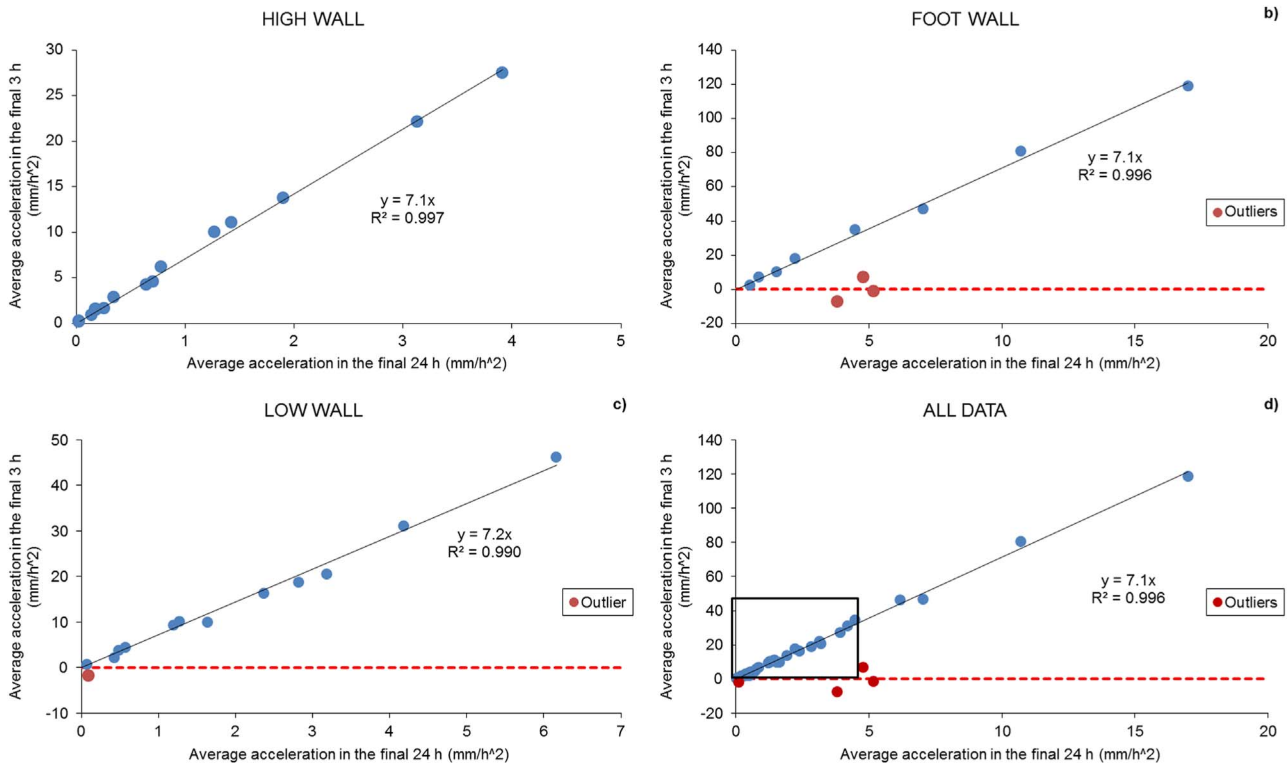

Fig. 1. Average acceleration during the final 3 h before failure vs. average acceleration during the final 24 h before failure. Results are classified according to: a) high wall b) foot wall c) low wall and d) all data. The red points represent the outliers, which are not included in the best-fit line calculation. The box in d) highlights the area that is enlarged in Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

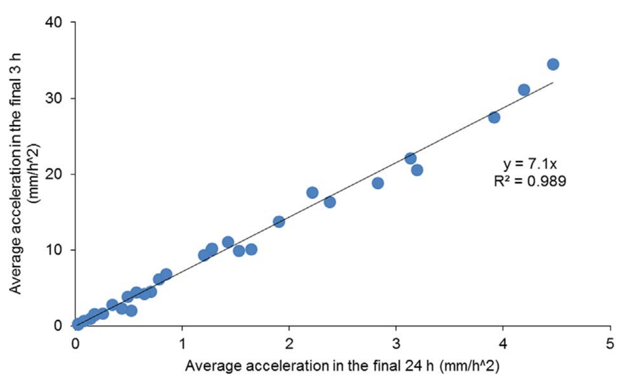

Fig. 2. Enlargement of Fig. 1d: excellent linear correlation (R^2≈0.99) between a_{3h} and a_{24h} is verified regardless of the slope classification and of the magnitude of the deformation.

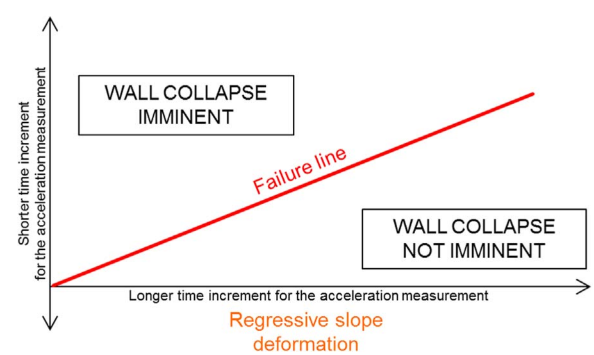

Fig. 4. Conceptual model for the interpretation of the scatterplots in Figs. 1–3.

acceleration phase. In Figs. 1d and 3a very few events (4 of 40 and 3 of 16, respectively) are found in the lower graph section; in at least some of these instances it appears that failure did not occur in good accordance with the accelerating creep theory. In fact, points below

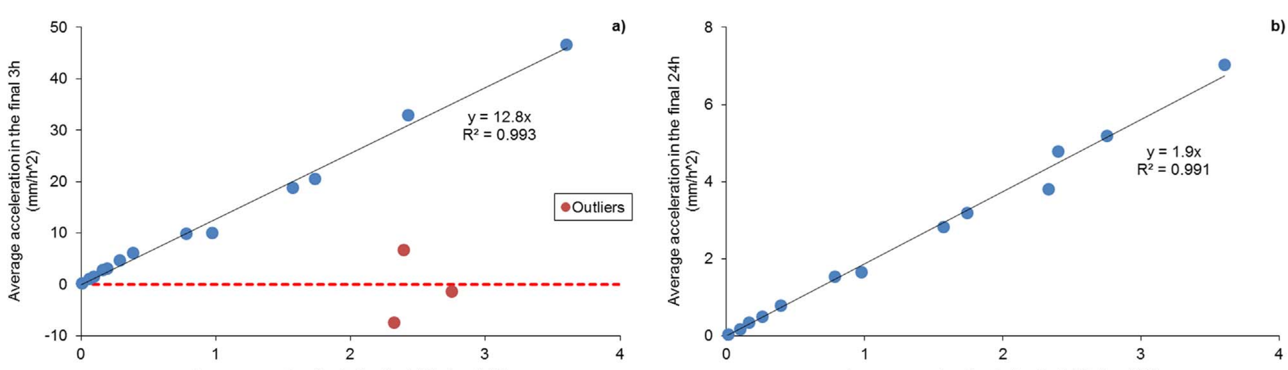

Fig. 3. (a) Average acceleration during the final 3 h before failure vs. average acceleration during the final 48 h before failure and (b) average acceleration during the final 24 h before failure vs. average acceleration during the final 48 h before failure.

the *x*-axis point out that the slope failed during a phase of regressive acceleration (i.e. negative values of acceleration for the shorter time increment). On this topic Mazzanti et al.,[23] after reviewing data from ten rock slides monitored by means of terrestrial SAR interferometry, reported that in some cases the slope acceleration indeed decreased in the latest hours prior to failure and argued that such behavior is rarely detected because of the need of very accurate, high-sampling rate monitoring data. As a result the case studies falling below the *x*-axis in Figs. 1d and 3a might actually have been consistent with the dominant "failure-line" if data were to be considered up to the onset of the final short-term deceleration. The underlying physical mechanism behind this pre-failure regressive behavior might be related to mechanical features of the landslide that deviate from the assumptions of the classical creep theory[23] and should be the subject of further investigation because of its potential influence on the reliability of failure predictions and on the management of slope instabilities.

4. Implications for the management of unstable slopes and future developments

In the field of slope failure prediction the accelerating creep theory, from which derives the well-known inverse velocity method,[6] is certainly a powerful tool for the analysis of materials approaching failure with increasing deformation rates. Attempts at identifying consistent trends and at extrapolating linear regression lines in inverse velocity plots are among the main points of emphasis for interpreting the displacements of unstable slopes. In several instances, this allowed to successfully anticipate the failure of rock slopes at mine sites.[24] However, the method provides approximate estimates of the time of failure[12] and, in near real-time monitoring scenarios, does not necessarily answer the question whether failure must be expected in the immediate future or not. Failure criterions are in fact "phenomenological" approaches and do not consider the heterogeneous nature of factors like the mechanical behavior of the failing material and its influence on the development of the slope failure.[4] Since there is no direct relation with the physics of the phenomenon, a universal law for describing the slope displacements leading up to an event of failure is necessarily an approximation[4,9,24] and consequently failure criterions must be applied with caution. Fell et al.[11] argued that failure-time predictions are clearly uncertain and that too great reliance should not be given to them. An example of such is given by Hutchinson,[25] who documented that the use of inverse-velocity for two important acceleration phases of the Vajont landslide (which did not evolve to failure) would have been misleading. Carlà et al.[12] also described that the accuracy of inverse-velocity predictions is extremely variable and relies significantly on the amount of measurement noise and on the type of data filtering applied. Other assumptions and simplifications affect the practical effectiveness of the inverse velocity method in mining operations, among which the fact that velocity at failure is supposed to be infinite. This is obviously not true and slopes will actually fail upon reaching a certain finite value of velocity and acceleration. However the range of velocities at which failure can take place is extremely large. The observations collected in the ACARP C17023 project on slopes of several Australian open-cut coal mines show that velocities ranging from mm/h to dm/h were detected in proximity of events of failure. Consequently, determining the point of the velocity curve which corresponds to the state of critical slope stability is still a major issue.

In order to fill this gap, databases of failure case histories can be reviewed in order to seek for recurrent correlations between monitored variables. With this approach, rather than providing failure-time predictions, the main purpose is to identify characteristic conditions for slope failure occurrence. Determining common slope behaviors at the instant of failure or in its proximity would in fact be of crucial support when evaluating the risk associated with ongoing events of slope deformation. This research field has not yet been explored comprehensively, mainly because of the difficulties implied in retrieving large databases of failure case histories. Following a review of monitoring data from 13 slope failures, Zavodni and Broadbent[15] proposed that the velocity at failure corresponds to $v_f = K^2 v_0$, with v_0 being the velocity at the onset of acceleration and K a constant that is deduced from a collection of past failure case histories where both v_0 and v_{mp} (velocity at the mid-point of the acceleration) are known. They also observed that a velocity of 5 cm/d signaled that failure would occur within 48 days. The strain-based method to failure prediction[1,26] proposes instead that the strain at failure (defined as the total surface movement divided by the height of the slope failure) is generally influenced by the quality of the rock mass (estimated from the Rock Mass Rating index); distinguishing for different failure mechanisms, the amount of strain that the slope can accommodate prior to failing is thus defined based on the deformability of the rock mass.[1]

Within this framework, the analysis of the ACARP database of mine slope failures[16] revealed the presence of a striking linear correlation between the average acceleration in the final 3 h before failure and the average acceleration in the final 24 h before failure ($R^2 \approx 0.99$, Figs. 1 and 2). The vast majority of the events, which involved both hard rock masses (HW-FW) and loose granular material (LW), occurred when a_{3h} was about seven times a_{24h}, regardless of the order of magnitude of the deformation. Analogue correlations were found to characterize also the a_{3h} vs. a_{48h} and the a_{24h} vs. a_{48h} plots (Fig. 3). Results appear to imply that most failures were anticipated by a phase of progressive deformation and that a significant percentage of the total slope displacements were concentrated in the last few hours of acceleration. Operatively the ratios R_a, R_b, and R_c are related to the gradient of the velocity curve and are not dependent on the acquisition geometry of the radar (i.e. LOS). The fact that values of R_a, R_b, and R_c were approximately constant across the different case histories (≈7, ≈13 and ≈2, respectively) suggests that the progression of the acceleration in proximity of each failure event had, in relative terms, mostly the same intensity. Moreover, it indicates that the condition of impending failure could be defined in advance for future cases of slope acceleration occurring at the studied mine sites. It is of great interest to note that these results are in accordance with previous preliminary observations made by Ryan and Call,[14] who reviewed a database of 14 slope failure case histories and hypothesized that, in the final 48 h before failure, the intensity of the slope acceleration is a more consistent failure indicator than the slope velocity.

Consequently, suitable alarm thresholds could be set-up by implementing an early warning system consisting of near real-time displacement monitoring, by means of which it would be possible to continuously calculate R_a (and/or R_b and/or R_c) and to follow its evolution on the relative scatterplot (Fig. 4). If the path approaches the failure-line, the deforming slope sector would be considered close to the point of critical equilibrium and the failure could be anticipated. In this way evacuation of the dangerous area could be declared with suitable notice. Conversely, production could safely continue (with the appropriate precautions) as long as R_a (and/or R_b and/or R_c) remains in the lower portion of the scatterplot and at a significant distance below the failure-line. Acceptable confidence may probably not be obtained for cases of extremely low acceleration, i.e. when points are located very close to the origin and thence assessing the distance of safety from the failure-line is not possible. Points well above the failure-line would represent slopes which sustained unexpectedly high accelerations before failing, thus causing the alarm to be issued prematurely; however such instances have not been observed in the reviewed database. Of the four outliers in Fig. 1d, three represent slopes which failed during a regressive phase of acceleration and therefore predictions by means of inverse velocity would have probably been likewise inaccurate. Only one outlier marks a slope which failed at a stage of the acceleration characterized by a substantially lower gradient of the velocity curve ($R_a < 2$).

Parameters of the acceleration of the like of R_a, R_b and R_c at failure are not expected to be universal constants and might vary depending on several different factors, including geology, mechanical properties of the rock mass, size and mechanism of failure. The slope failures presented in the ACARP database do not belong to a unique mine site[16] but, unfortunately, such background information have not been disclosed and thus no conclusion can be drawn in this regard. Another current limitation is that the analysis presented herein was restricted by the availability of slope velocities relatively to the failure instant and to 3 h, 24 h and 48 h before failure only.

For future development of this new method it is necessary that also the abovementioned data are provided and that it is verified if similar or equivalent correlations occur in other databases of slope failures. An appropriate number of case histories must be considered in order to obtain sufficient statistical reliability. If on one hand this appears to be a disadvantage, on the other it would permit to group the results and to determine data trends based on the characteristic properties of the failing material and to different types of failure mechanism, unlike the phenomenological approaches. In relation to this point it should be noted that the length of the pre-failure deformation phase tends to be influenced by the size of the instability, i.e. large-scale failures are usually anticipated by longer phases of precursor deformation and provide more advanced warning with respect to small-scale failures (e.g. bench scale wedge failures versus overall slope failures). It follows that also the size of the failures may need to be considered in the calibration of the method and therefore in the definition of appropriate alarm thresholds and trigger action response plans (TARP). Testing should be performed using measurements acquired by the same type of monitoring device and processed with the same technique, with particular reference to the data filtering applied to remove the influence of error and noise. The latter aspect may be essential in order to avoid excessive short-term variation of the parameters of the acceleration (i.e. R_a, R_b and R_c). Assuming the availability of complete time series data, the analysis should be extended in order to also consider velocities at other instants of the failure process. Different parameters of the acceleration may in fact be more suitable in different contexts, depending on the amount of filtering that is required to remove the effects of measurement error and noise, and on the specific demands of the TARP. Finally a definitive assessment of the efficiency of the method should be made through the retroactive back-analysis of such time series data in order to determine the frequency of eventual false alarms.

5. Conclusions

Assessing the impending failure of natural and engineered slopes is a topic of enormous importance. Mining companies usually invest significant resources for the deployment of extensive slope monitoring programs in order to calibrate and define efficient TARPs. Production works of the mineral resources must be kept active for as long as possible, while at the same time the safety of the personnel and of the equipment must be guaranteed. An alarm threshold that is too conservative may lead to false alarms and economic losses, whereas an alarm threshold that is set excessively high could put workers at risk in the case of a missed alarm.[27] Identifying recurrent correlations of slope monitoring data in close proximity of events of failure is therefore a research field of major interest.

Linear correlations between different parameters of acceleration were identified in the reviewed ACARP database ($R^2 \approx 0.99$). In almost each of the presented failure case histories the ratio of the average acceleration in the final 3 h before failure and the average acceleration in the final 24 h before failure was found to be approximately constant ($R_a \approx 7$), despite the wide range of variability displayed by the measurements of slope velocity. Similar results were obtained by plotting data relative to 3/48 and 24/48 h before failure ($R_b \approx 13$ and $R_c \approx 2$, respectively). In each scatterplot a clear linear trend is observed and the best-fit regression line can be traced with confidence. The method permitted to assess, in relative terms, the intensity of the acceleration that progressively deforming slopes at the studied mine sites sustained before failing and therefore to define characteristic conditions for slope failure occurrence.

Despite some partial limitations that are due to deficiencies in the reviewed database, the analysis produced extremely promising results and revealed a potential new area of research in the topic of slope failure prediction and management. Decisive support could be provided to establish ultimate alarm thresholds of impending slope failure risk at mine operations. Further investigation on other databases of failure case histories is needed in order to further corroborate the results presented herein.

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