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Automatic prediction of time to failure of open pit mine slopes based on radar monitoring and inverse velocity method

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ABSTRACT

Radar slope monitoring is now widely used across the world, for example, the slope stability radar (SSR) and the movement and surveying radar (MSR) are currently in use in many mines around the world. However, to fully realize the effectiveness of this radar in notifying mine personnel of an impending slope failure, a method that can confidently predict the time of failure is necessary. The model developed in this study is based on the inverse velocity method pioneered by Fukuzono in 1985. The model named the slope failure prediction model (SFPM) was validated with the displacement data from two slope failures monitored with the MSR. The model was found to be very effective in predicting the time to failure while providing adequate evacuation time once the progressive displacement stage is reached.

1. Introduction

Open pit mine slope failures can have devastating consequences on mine production, safety of mine personnel and the mining company. However, with the availability and capacity of modern slope radar monitoring equipment to completely scan the slope face within a few minutes and detect sub-millimeter displacements of the slope face, the consequences of slope failure can be managed. For such management to be achieved, a method is required that can detect location on slopes where failure is initiating and confidently predict the time to failure of mine slopes from the measured rates of displacement. A classic example of the importance of slope failure prediction is the accurate prediction of the 18th February, 1969 slope failure at Chuquicamata mine in Chile. Slope monitoring was conducted using conventional survey methods, quadrilateral tension crack stakes, tape and transit lines, crack extensometers and a seismograph [1]. On 13th of January, 1969, when the slope deformation became fully progressive, it was necessary to predict the time to failure in order to minimize stoppage of mine operations. The fastest moving point, Point 5 on F-2 bench, was used for extrapolating the displacement–time graph, and the prediction gave the earliest date of failure as 18th February, 1969. As stated by, the mine was closed temporarily at 15.00 on 16th February, 1969 [1]. At 18:58 on 18th February, 1969, the slope failure occurred [1]. Full production resumed on 19th February, 1969, as displacement measurements showed that the slope had stabilized [1]. As a result of successful prediction of the time to failure, the loss of production time was only 65 h, and there was no damage to equipment, or injury to mine personnel. This is classic example of management of a large slope failure.

In the last four decades, several attempts have been made by researchers to develop acceptable methods of predicting the time to failure of open-cast mine slopes. However, no single method has been found to be universally acceptable for mine slope failure prediction. The difference in the models used for predicting the time to failure of mine slopes depends on the adopted function, with the most commonly used functions being the linear, exponential and power law functions [2]. Variables describing the slope behavior before failure such as the strain or displacement or rate of displacement are used in the models [2]. An example of such a model developed by using Eq. (1), claimed that the logarithm of the time to failure (t_f) is proportional to the logarithm of the rate of displacement (Ω^i) [3].

$$Log(t_f) = c - m\log(\Omega^i) \quad (1)$$

where c and m are the empirical constants; t_f the time to failure, day; and Ω^i the rate of displacement, cm/day.

Reference [4] developed the inverse-velocity method of time to failure prediction, as shown in Fig. 1. The method is based on linearity of the slope deformation before failure. The displacement data used for the study were obtained from simulated rain-induced landslides in soil under laboratory conditions [4]. The conditions simulated were considered to be characteristic of accelerating

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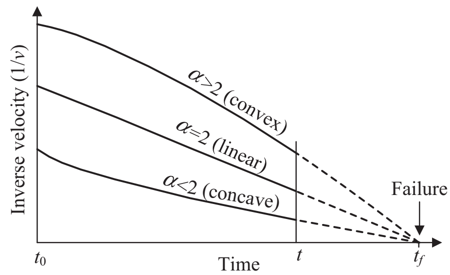

Fig. 1. Inverse velocity versus time relationships preceding slope failure [4].

displacement under gravity loading. Reference [5] successfully used the inverse velocity method to predict failure time at Betze-Post open-pit mine in Nevada. The time to failure is estimated by projecting a trend line through values of inverse velocity versus time to intersect the zero value on the x-axis [5]. Reference [4] fitted concave, convex and linear plots, defined by Eq. (2), to the laboratory data obtained and concluded that a linear trend through the inverse-velocity data usually provided a reliable estimate of failure time, shortly before failure [5].

$$V^{-1} = [A(\alpha - 1)]^{\frac{1}{\alpha-1}}(t_f - t)^{\frac{1}{\alpha-1}} \quad (2)$$

where t is the time; t_f the time to failure; A and α the constants derived from relationship$\Omega^i = A\Omega^{i\alpha}$, which describes the accelerating creep of materials by relating rates of displacement, Ω^i to changes in rate of displacement, Ω^{ii} [6].

Reference [6] established a failure relation, $\Omega^{ii} = A\Omega^{i\alpha}$, which relates acceleration (Ω^{ii}) to velocity (Ω^i), where A and α are rate coefficients under time invariant external conditions of load and temperature.

2. Slope failure prediction model (SFPM)

The following steps are adopted in developing a computer model termed SFPM based on the inverse rates of displacement of open-cast mine slopes. In this case a MSR were used for monitoring of the slopes.

2.1. Step 1: inverse rate of displacement (RD) calculation

When the progressive displacement stage is reached, the displacement data and time are extracted from the MSR, and the time interval between each scan is determined.

Using the cumulative time (min) and the corresponding displacement values (mm), the rate of displacement, (mm/min) is calculated over a given time interval using Eq. (3). The method results in the filtering of the displacement data, with the degree of filtering increasing with the increase in the length of the time interval. As observed by, no general rule regarding filtering can be given, since it depends on the measurement time interval as well as the type and quality of measurements [5]. Therefore, optimal filtering is determined by trial and error to remove variation, without concealing displacement trends. At a data interval of 1, 2, 5 and 10, corresponding with time intervals of 4, 8, 20 and 40 min respectively, the trend plots of inverse rates of displacement remain full of serious deviations with negative inverse rates of displacement and no clear trends. Note that slope failure prediction cannot be made when the trend is unclear and the inverse rate of displacement is negative. The degree of filtering is increased as the data interval is increased.

$$\frac{du}{dt} = \frac{u_i - u_{i-n}}{t_i - t_{i-n}} \quad (i = n+1, n+2, \ldots, m) \quad (3)$$

where du/dt is the rate of displacement, RD, mm/min; t_i the recent time; u_i the recent displacement; and n the nth observation.

Convert the obtained rate of displacement to the inverse rate. Note that since displacements are measured as negative in the MSR, the rates of displacement will be negative. Therefore, multiply by negative to obtain a positive inverse rate of displacement values. Conventionally, mine slope displacement is measured as positive, and hence, this particular step may not be necessary with other monitoring instruments.

2.2. Step 2: simple linear regression

Linear regression analysis is a statistical technique of determining the relationship that exists between two variables. The inverse rate of displacement method of predicting failure time is based on the degree of linearity between time variable (min) and the inverse rate of displacement variable (min/mm). To fit a linear trend to predict the time to failure from the values of time versus inverse rate of displacement, the linear equation to fit the trend is obtained using Eq. (4):

$$y = a + bx \quad (4)$$

The mean value of y is assumed to follow a linear relation $a + bx$ that is $E(y) = a + bx$

The slope and the intercept of the line $E(y) = a + bx$ are called regression coefficients. The slope is the change in the mean value of y for a unit change in x.

2.3. Step 3: regression line

To fit a regression line, which is step 3 of the SFPM process, b and a are determined using Eqs. (5) and (6) respectively:

$$b = \frac{n\sum_{i=1}^{n} x_i y_i - \left(\sum_{i=1}^{n} x_i \left(\sum_{i=1}^{n} y_i\right)\right)}{n\left(\sum_{i=1}^{n} x_i^2\right) - \left(\sum_{i=1}^{n} y_i\right)^2} \quad (5)$$

$$a = \frac{\sum_{i=1}^{n} y_i - b\left(\sum_{i=1}^{n} x_i\right)}{n} \quad (6)$$

With b and a known, the fitted regression line can then be written as Eq. (7)

$$\hat{y} = a + bx \quad (7)$$

The fitted value, y_i or a given value of the predictor variable, x_i may be different from the corresponding observed value y_i. The difference between the two values is called the residual, e_i given in Eq. (8) as:

$$e_i = y_i - \hat{y}_i \quad (8)$$

2.4. Step 4: coefficient of regression

The coefficient of regression provides a measure of how well future outcomes such as time to failure, are likely to be predicted by this model [7]. An R^2 of 1.0 means that the regression line perfectly fits the data. It is calculated using Eq. (9) and this corresponds with step 4 of the SFPM process.

$$R^2 = 1 - \frac{SS_{err}}{SS_{tot}} \quad (9)$$

where