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Slope Monitoring and Failure Prediction Techniques in Mines: A Review

Mohd. Maneeb Masood*, **Gunda Yuga Raju and Tarun Verma**

Department of Mining Engineering, Indian Institute of Technology (BHU), Varanasi – 221005, Uttar Pradesh, India; mohdmmasood.rs.min17@itbhu.ac.in

Abstract

The collapse of a mining slope can be predicted. Time is crucial, and forecasting slope failures has long been a major risk management concern for mining firms across the world. Forecasting the time of mine slopes collapse is a challenging but necessary job to control its impact on life and property. A good forecast of slope failure events allows mine management to analyse the situation and then implement an action response plan to minimise the effects of the failure on lives, machinery, and production. Predicting a slope failure starts with slope monitoring. Lately, numerous techniques based on monitoring and analysing displacement data have been used to anticipate the failure of mining slopes. Recent developments have opened new prospects for applying mine slope monitoring and failure prediction techniques. The main objective of this review article is to discuss and classify the slope monitoring and failure prediction techniques. This article has the potential to support mine management in understanding and applying these techniques better.

Keywords: *Creep Theory, Failure Prediction Techniques, Mine Slope Monitoring, Slope Failure*

1.0 Introduction

Potentially unstable mine slopes have a tendency to fail. In Indian surface mines, accidents and disasters due to slope failure are prevalent, resulting in damage to life and property. Between 1901 and 2016, there were 23 catastrophic incidents resulting in 143 fatalities caused solely by slope collapse. Recently, Rajmahal disaster killed 23 people[1]. These risks lead to concerns regarding the maintenance of balance between mine production and safety.

If the mine management monitors and correctly predicts the failure, either the slope can be stabilized or evacuation plans can be laid down. Significant works have been done in the slope failure prediction field[2-7] but majority are on landslides, that necessitates the knowledge of accurate slope monitoring and failure prediction techniques in mines.

So, the objective of this article is to help mine managers understand the available slope monitoring techniques and failure prediction methods better. We began this work with the literature review by searching the Web of Science, Scopus and Google Scholar database. This search provided us with articles, books and thesis. For basic knowledge, we referred Modern Technologies for Landslide Monitoring and Prediction[8], Doctoral Thesis of G.J. Dick[9] and Kayode S. Osasan[10]. This helped in figuring the terminology needed to understand and critically review the articles.

**Author for correspondence*

1.1 Basic Terminology

Instability: Deformation behaviour not involving collapse or failure[11].

Progressive deformation stage: Acceleration stage of the slope leading to failure[12].

Regressive deformation stage: Deceleration stage leading to a stability[12].

OOA or Onset-of Acceleration: Transition point from a deceleration to an acceleration stage of a slope.

TU or Trend Update point: Indicating a transformation in an accelerated deformation trend and/or a substantial decrease in noise[9].

Slope failure: Irreversible deformation of a slope, and the slope does not meet its function.

Predicted life expectancy: The difference between slope failure and the time predicted[13].

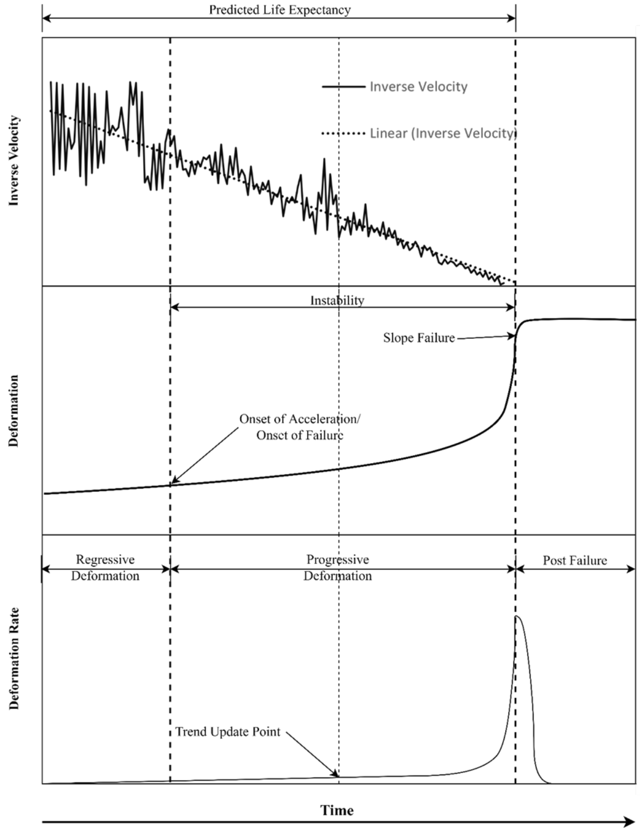

Figure 1. Basic terminologies related to slope failure are represented with graphs of inverse velocity, deformation and deformation rate versus time.

Inverse Velocity Trend Line: Straight line showing the best fit of the Inverse Velocity data.

Onset of Failure: This is the point that describes the transition from regressive deformation to progressive deformation[14].

All the above terminology is illustrated in Figure 1.

2.0 Literature Review

A literature review implies examining and evaluating the reported contributions in the area of interest. After exploring the available material, we learned about the existing knowledge, limitations, challenges, benefits, and disadvantages, which helped classify it[15].

Mining activities disturb the inherent stress conditions of the rock-mass which may lead to slope failure. To prevent any loss due to slope failure, potentially unstable slopes, dumps, or active mining sites should be continuously monitored. Also, with technological advancements, mine slope failures can be predicted with accurate results.

3.0 Slope Monitoring Techniques

For monitoring mine slopes there are various monitoring techniques from simple visual inspection to complex GPS and radar scanning. All these techniques can be classified into conventional and modern-day techniques, as presented in Figure 2.

3.1 Conventional Techniques

Conventional or traditional monitoring techniques involve physical examination and mapping of tension cracks along the slope face.

3.1.1 Visual Inspection

All mine personnel are involved in slope monitoring directly or indirectly. The initial stage in slope monitoring is a visual inspection, which is the foundation of any monitoring programme. Mine workers search for any evident signs of deformation and then report them for a more thorough examination and monitoring. Routine inspections of active mine slope and dumps slopes is done by mine management. Last visit observations are compared with the current data.

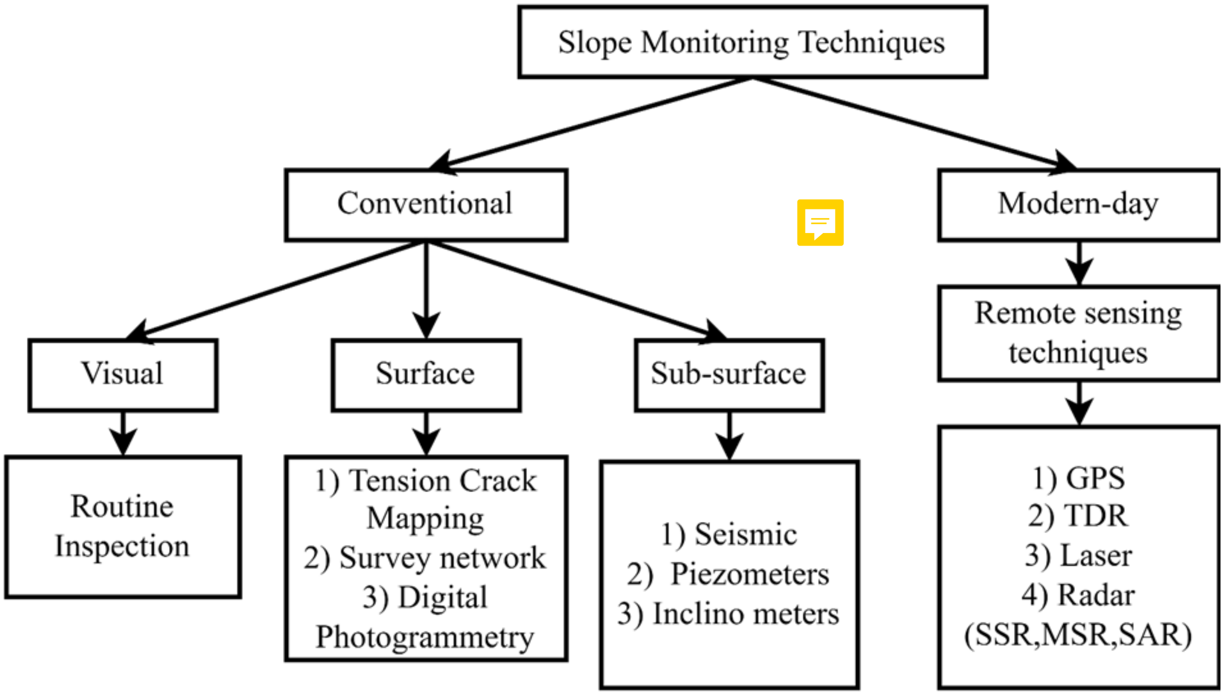

Figure 2. Slope monitoring techniques.

3.1.2 Surface Monitoring

Cracks at the surface are a strong indication of instability. Existing cracks are highlighted to distinguish them from the new cracks. The movement of points on the surface in relation to one another can be calculated by measuring the separations between two cracks with a survey tape or rod or extensometers.

Total stations require a survey network of several prisms or monitoring stations set on the slope at regular intervals. Using the movement of prisms, the relative motions of the target prism at the monitoring locations aid in identifying the deformation and key failure zones. Because they relieve humans from tedious, continuous work, surveying robots or robotic total stations are increasingly being used to monitor buildings and terrain. With the advent of long-range, high-accuracy total stations, slope monitoring with prisms has nearly become a real-time solution. Robotic total station networks include a built-in photogrammetric camera and GNSS receivers to provide automated, accurate, efficient, and cost-effective survey solutions.

Digital photogrammetry has been used to study slopes by comparing images for decades and has recently evolved to include 3D models from terrestrial images. The digital image processing tools available now allow for the automated collection of discontinuities and related information, eliminating the risk of human bias and enabling the survey of inaccessible locations and steep rock faces. Earlier, robotic total stations and now, with the introduction of Remote Sensing technologies, slope monitoring has become more accurate.

3.1.3 Subsurface Monitoring

Subsurface techniques like installing apparatus in long boreholes or transmitting signals into the rock mass are used. The movement along the weaker planes is collected as signals by sensors showing slope deformation status and even stress accumulation along the weaker zones. Extensometers map movement along a crack to distinguish an unstable rock mass from a stable segment of rock-mass. The weight linked to the wire moves as the earth accelerates along the fractures, and the displacement measurements are recorded in the monitoring device with digital outputs for downloading data. Inclinometers monitor subsurface motions and determine whether they are steady or accelerating, ensuring that deformations are within limits. Slope inclinometers measure the amount, depth, direction, velocity, and type of slope movement. Also, servo-accelerometers are used as sensors within inclinometers to measure proper acceleration. Both an extensometer and an inclinometer measure the slope's relative movement. Piezometers are also being used for monitoring slope instabilities with groundwater issues.

3.2 Modern-Day Techniques

Ground-based radar devices and GPS are increasingly integrated into most large open-pit mines' slope monitoring and management programmes.

3.2.1 Remote Sensing Techniques

The Global Positioning System (GPS) is a navigation and positioning system that follows GPS satellites' electromagnetic signals. It measures the movements of slopes, landslides, and subsidence on a continuous-periodical basis. The amount of deformation and slope movements are calculated by comparing the starting and ending positions of the GPS stations. An improvement to GPS called Differential GPS (DGPS) improves location precision in the range of operations of each system, from the nominal GPS accuracy of 15 m to roughly 1–3 cm. DGPS offers real-time information on slope stability and deformation rates. GPS is also being used as a control point for monitoring mine slope stability in conjunction with photogrammetry, total station networks, and remote sensing pictures. However, GPS has environmental limitations such as vegetation and mountains and is not suitable for fast deformation scenarios.

LiDAR (Light Detection and Ranging) directs a laser beam at the area of monitoring, which provides a graphical/digital depiction of slope and their relative motions based on the journey time of the reflected radiation. They produce virtual replicas of the slope in minutes, similar to photographic images emphasizing crucial regions. Modern LiDAR scanners can be placed on static and mobile surveying platforms and instantly give Digital Elevation Models (DEM).

Time Domain Reflectometry (TDR) can instantly and precisely identify the deformation zone's relative magnitude, displacement rate, and position. Since 2002, the micro-seismic technique has been used in opencast mining to anticipate slope movements and failures. Micro-seismic events caused by tiny rock movements are collected by data recorders and relayed to the processing system. The events are then analysed to identify the zone of weakness, stress conditions, deformation mechanics, and deformation rate within the rock mass. Significant advancements in mine seismology information effectively reduce risks far before they occur.

Selecting a proper monitoring system depends on several parameters, such as area coverage, mode of operation, cost, installation and maintenance concerns. Conventional methods are time-consuming and of low accuracy, and inclinometers, TDRs, extensometers, and LiDARs are not appropriate for real-time information and early failure prediction. The slope monitoring radar has radically revolutionised the evaluation of geotechnical risk in surface mines. In the last ten years, radar has developed into a cutting-edge technology for monitoring pit wall movements in surface mining with real-time slope monitoring. The radar beam emitted by the antenna scans the slope faces vertically and horizontally. The movements along the slope are tracked both quickly and constantly, in addition to broad area coverage in all-weather conditions. In recent years, 3D imaging of the damaged surface has also been made available by radar monitoring. Radar can be either space-borne or ground-based depending on the application. Recently, Slope Stability Radar (SSR) advances have included broad areal coverage, remote operation from greater distances, and better spatial resolution. Movement and Surveying Radar (MSR) and Synthetic Aperture Radar (SAR)/ Interferometric Synthetic Aperture Radar (InSAR) in open cast mines can detect both sizeable rapid slope failures and small slope deformation movements over time[10]. Radar systems provide long-range monitoring, broad aerial coverage, and customised aerial coverage with sub-millimetre precision and accuracy.

4.0 Slope Prediction Techniques

Techniques and recommendations for predicting the moment of failure or outlining the conditions of a predicted slope collapse abound in scientific literature. Therefore, getting an overview of the benefits and limitations of these different methods has become complex. Therefore, getting an overview of these methods has become complex. To simplify, we have classified the available works on slope monitoring techniques based on the input and output data, as represented in Figure 3. Some of these techniques have been used only in landslides, but

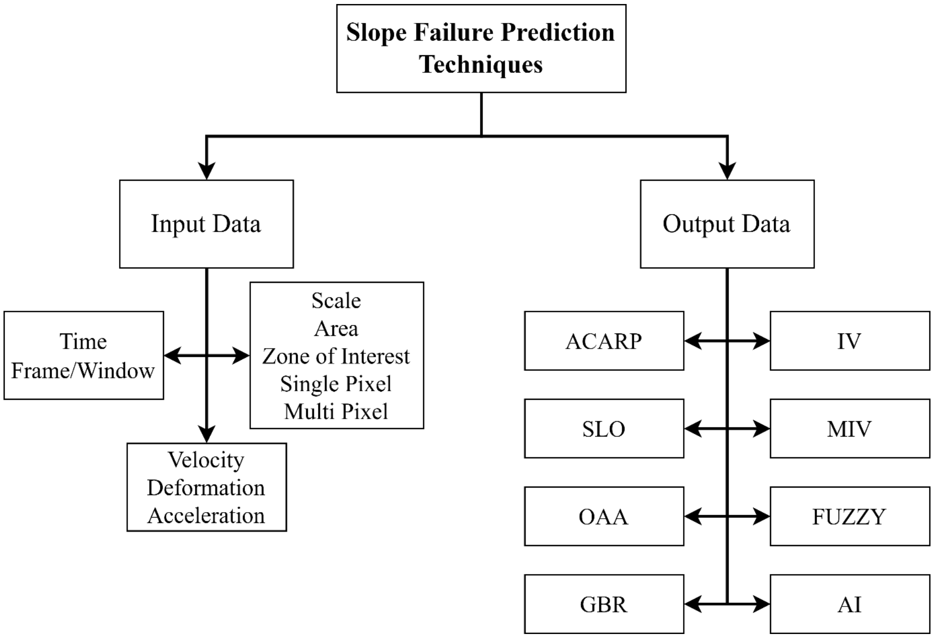

Figure 3. Slope failure prediction techniques.

we have included them because they show great potential in mine slope failure prediction.

4.1 Input Data for Prediction of Slope Failure

Most researchers have taken deformation/displacement data or some derivative of deformation/displacement data as the input. The input in some cases started varying with the advent of better technologies such as remote sensing techniques as per the operator's requirements in accordance to the area, pixel size, zone of interest for analysis, time frame, deformation rate, and acceleration. Moreover, the operator can also decide the size of the pixel depending on the needed clarity. It can also be decided whether to use multi-pixel selections or single-pixel selections to calculate deformation or displacement, which leads to velocity and acceleration. Despite its limitations and assumptions, multi-pixel selection gives better slope failure prediction than single-pixel selection analysis. The deformation or displacement values in slope monitoring systems using Radar are taken from the pixels updated every few minutes (~15 minutes in the case of SSR), leading to velocity and acceleration data. These inputs can be further divided into various time frames, for example, velocity of 60 minutes, over 480 minutes, over 1440 minutes. Similarly, acceleration or inverse velocity data can be collected as input over various time frames.

4.2 Output

Once reliable monitoring data is collected, the most challenging task for the mine personnel in charge of safety is to put up appropriate alerts that indicate when a slope collapse is imminent. Most of the majority of work in slope failure prediction uses graphs to find the time of failure of a slope and can also be integrated to achieve better results (Table 1).

4.2.1 Inverse Velocity Method (IVM)

The IVM is the most frequent approach for predicting the failure of accelerating(progressively) slopes. It is developed from the accelerating creep theory. The time to accelerating creep failure is inversely related to the deformation rate (velocity) under gravity loading[16]. The time of failure (TOF) can be estimated by drawing the inverse velocity(Y-axis) versus the time(X-axis) curve and extending the inverse velocity trend to the y=0. Rose effectively predicted the slope collapse in three hard-rock open-pit mines (2001-2005) using the IVM with geodetic prism data[17].

4.2.2 Minimum Inverse Velocity Method (MIV)

The MIV method basically takes into consideration the inverse velocity of any slope can't be zero. Therefore, a minimum inverse velocity ($\neq 0$) is calculated and is

Table 1. Slope prediction techniques with their basic formulae

Prediction Technique	Formulae
IV	$log_{10} t_L = 2.33 - 0.916\, log_{10} \dot{\varepsilon} \pm 0.59; where$ $t_f = t_L + ti, where\ ti\ is\ time\ of\ prediction$ $t_f = \frac{t_2^2 - t_1 t_3}{2t - (t_1 + t_3)}$ $t_L = C(\Delta t)^m;\ C\&m\ are\ empirical\ constants$
	$\Lambda = \frac{1}{v} = A(\alpha - 1)^{1/(\alpha-1)}(t_f - t)^{1/(\alpha-1)}$ $where\ t_f\ is\ failure\ time, \Lambda\ is\ inverse\ velocity$ $\alpha = 2$ *gives linear IV curve (most cases)* $\alpha > 2$ *gives convex IV curve* $1 < \alpha < 2$ *gives concave IV curve* $t_f = \frac{t_2(\Lambda_1) - t_1(\Lambda_2)}{\Lambda_1 - \Lambda_2}$
SLO	$\varepsilon = -B \log(t_f - t) + C$; ε *is strain, B & C are constants* $\frac{dD}{dt} = \frac{B}{t_f - t}$ $t_v = t_f v - B$ $t_f = t + \frac{B}{v}$
OAA	$\dot{\Omega}^{-\alpha}\bar{\Omega} - A = 0$; *Ω is displacement, dot refers to differentiation. A & α are dimensionless parameters*
	$\bar{v}_t = \frac{v_t + v_{t-1} + \square + v_{t(n-1)}}{n}$ n=3 (SMA) and n=7 (LMA)
	ESF = $\overline{v_t} = \beta \cdot v_t + (1 - \beta) \cdot \bar{v}_{t-1}$; $\beta = 0.5$ $v_i = \frac{d_i - d_{i-n}}{t_i - t_{i-n}}$; $T_{fw} = \left[T_{f(SMA)} - \frac{\Delta}{2};\ T_{f(LMA)} + \frac{\Delta}{2}\right]$
ACARP	$R_a = a_{3/24} = 7$ $R_b = a_{3/48} = 13$ $R_c = a_{24/48} = 12$

plotted on the Inverse Velocity (IV) vs Time graph. The Time axis value corresponding to the point of intersection of the IV and MIV lines is the predicted time of failure. The method showed a better accuracy than the IVM in some cases [6].

4.2.3 SLO

A technique was developed for calculating the time of geomechanical failure based on the slope of the t(du/dt)–du/dt plot, where 't' represents time and du/dt is the deformation rate[13]. Assuming strain divergence in the last stages of rock creep failure[18], "life expectancy" charts were created. This SLO approach was later used at the Tom Price Mine to investigate open-pit slope failures[19].

4.2.4 ACARP Method

In the context of 78 Australian case histories of slope failure in open cut mines, Australian Coal Association Research Program (ACARP) C17023 project, an extensive database of deformation/displacement data acquired by SSR. The authors investigated velocity and displacement data at various stages of the failure, but it did not lead to any realistic mathematical formulations capable of fully characterising the observed events. Cabrejo and Harries took the radar pixel with the greatest deformation[20]. They computed cumulative displacements and velocities at the failure moment, three hours before failure, twenty-four hours before failure, and forty-eight hours before failure. This technique emphasises the average acceleration experienced over numerous periods preceding the collapse. The ACARP database was examined, and linear correlations were found between many acceleration factors (0.99). It was discovered that the ratio of average acceleration in the final 3 hours to average acceleration in the final 24 hours was nearly constant, despite the vast range of fluctuation in slope velocity data[2].

4.2.5 Other Ground based radar systems (MSR, SAR, InSAR)

Ground-based radar is a type of remote sensing that uses phase-change interferometry to capture surface deformations and creates a cloud of deformation point (or pixel) data that is updated every few minutes[21]. When an accelerated slope deformation trend is observed, it is standard practise to examine a single or small cluster of pixels rather than the whole spatial range of the radar[22–25].

Ground-based slope stability radars use a fixed platform to remotely monitor the surface deformation without the need for reflectors or prisms[25]. Data is often accessible for interpretation within minutes[21] without detrimental impacts from rain, fog, dust, or smoke[26]. The use of MSR has specifically been extensive giving good prediction results[10].

4.2.6 Based on the Onset of Acceleration (OAA)

Many researchers interchangeably adopt distinctive nomenclatures when talking about slope instabilities. For example, nearly every phase of slope instability development that led to a collapse in the literature was used to characterise the term "failure"[11]. Dick introduces two new definitions: (i) Instead of the onset-of-failure, the Onset-Of-Acceleration (OOA) is employed (OOF) defined by author[12] and (ii) a trend update (TU) point[3]. This method is based on first finding the OOA, then doing the TOF analysis based on the time window selected post OOA, as the Inverse Velocity data becomes more linear after the progressive deformation of the slope starts. This improves the predicted TOF significantly.

4.2.7 Artificial Intelligence

Using Machine Learning and Artificial Intelligence to predict slope failure has been done in the past decade. With the technological advancements in the field, it has become an important technique, most recently with ANN[27].

4.2.8 Fuzzy Logic

The fuzzy set theory has recently gained popularity for slope stability research. Many effective forms of study for slope stability analysis have used the fuzzy neural network[28–30]. Several other research employ neural networks to measure slope instability. According to the research, this strategy aids in preparation for a probable slope failure, but it does not forecast the moment of slope failure.

5.0 Discussion and Conclusion

With technological developments, the integration of conventional and modern-day techniques for monitoring slopes and predicting their failures has been implemented in recent times. The Leinster Nickel Mine[22], Potgietersrust Platinum Mine[23], Tom Price Mine[24], Barrick Goldstrike Mine[31], Bingham Canyon Mine[32], Kemess South Mine[33], Grasberg Open Pit[34], Wallaby Mine[34] and Savage River Mine[35] are a few cases where conventional monitoring is used to assist modern-day techniques for improving the active monitoring of slopes.

GBRs have led significant progress in monitoring and predicting slope failures with periodic surveys of monitoring locations to look for accelerations and extrapolate them to anticipate approaching collapse. However, studying a single site or a sequence of locations might be risky due to uncertainty caused by rock mass heterogeneity and complicated failure mechanisms, which is also one of the qualities of rock-mass. This is also a research gap in is field. IVM is the most employed technique but it does not account specific physical characteristics, such as the geo-mechanical properties of the material and their impact on slope behaviour. Another disadvantage of the inverse velocity approach is that it implies infinite velocity when the IV is approaching zero at failure. As a result, failure-time projections should be seen as approximate estimates, and the inverse velocity technique and its derivations along with criteria for failure in general should be implemented with caution owing to the margin of error.

We have presented an overview of the slope monitoring techniques and failure prediction developments. The advent of Radar monitoring techniques has opened a new horizon in slope monitoring and failure prediction, providing an early warning of failure. It provides real-time, unmatched sub-millimetre accuracy data on wall motions through rainfall, dust, smog, and other environmental difficulties, allowing for continuous slope adjustment. The Radar data complements the failure predictions by some version of the IV or SLO methods with multiple assumptions, thus making these methods common.

The aim of this paper was to review the majorly used slope monitoring and failure prediction techniques. After reviewing, we find that currently, the most reliable way is to use multiple methods for monitoring and prediction, including the conventional techniques. This integrated approach will definitely lead to better results. While various data analysis techniques are being developed to improve the predictions, we attempt to develop a new technique that suits Indian mines and gets the desired results.

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