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Slope Monitoring Techniques in Opencast Mines: A Review of Recent Advances

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Abstract

The process of excavating rock mass induces changes in the stress distribution within the slope, rendering it prone to deformation over a specific duration. The potential consequence of movements along the weak planes is the ultimate breakdown of the slope. Various monitoring techniques, including visual inspection, laser scanning, Lidar scanning, total stations, Global Positioning Systems (GPS), state-of-the-art radar scanning, and micro-seismic monitoring, are currently employed in mining environments to forecast slope failure and deformation rate. This article will discuss the need to implement a continuous slope monitoring system, including categorizing such systems and an overview of the current state of existing slope monitoring technologies. The paper also discusses the applications of UAVs (Unmanned Aerial Vehicles) in slope monitoring. The research proposes implementing a consistent and continuous slope monitoring strategy grounded on empirical data when planning big and deep opencast mines. This approach is crucial for guaranteeing optimal safety measures and enhanced productivity levels.

Keywords: *Laser Scanning, Monitoring Advancements, Opencast Mines, Radar, Slope Monitoring, UAVs*

1.0 Introduction

The challenges linked with rock deformation, as well as their severity and frequency, all increase as the depth of the excavation increases. Even with the design of the most conservative slope, unpredicted movement of rock mass has become a significant concern. In developing deep surface mines, slope collapses have been highlighted as one of the primary concerns, as the Rajmahal coal mine disaster in 2016 claimed the lives of 23 people. Over 115 years, from 1901 to 2016, 23 accidents resulted in 143 deaths due to severe accidents, including disasters caused by unstable slopes[1]. Therefore, careful monitoring of slope deformation for early warning indications is necessary to ensure the safety of both personnel and equipment[2]. The occurrence of massive slope collapses within the mining environment, which often result in catastrophic losses of life and property, has enhanced the need for adequate slope monitoring. As a result, several slope monitoring devices have been developed to perform frequent checks on the rock movements. The development of such monitoring systems over the years is mainly responsible for the significant progress made in our knowledge of slope deformation and the prediction of instabilities.

The inclusion of slope monitoring programs in deep open pit mines has shown to be very valuable in predicting slope risks and implementing corrective actions against the inherent unpredictable behaviour of slopes[3]. Numerous geotechnical research show that slope collapse

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does not occur spontaneously but manifests specific indicators before the occurrence of a failure event. Hence, it is important to continually assess the pace of ground movement to predict impending collapse. Thorough documentation of failure symptoms include tension fractures, erratic water flows, and bulges or creep in the slope surface, and the presence of debris accumulation can enhance the likelihood of effectively rescuing individuals from operational areas and facilitating the evacuation of equipment. However, predicting the precise occurrence of collapse poses a difficult challenge due to its dependence on several elements, such as geological conditions, mine design, Hydrogeological conditions, and the structural characteristics of the rock mass. Nevertheless, by conducting a comprehensive geotechnical study and implementing regular monitoring systems, it becomes feasible to predict the occurrence of collapse based on scientific principles[4].

Furthermore, it should be noted that slope monitoring is highly site-specific. As a result, each hazardous slope may need a unique design for the monitoring system and research approach, i.e., the design of monitoring systems and research methodologies should be tailored to each slope's specific geological, environmental, and structural factors to ensure their effectiveness in accurately detecting and predicting instability. Therefore, it is essential to evaluate the requirements and nature of the issue before selecting the appropriate monitoring systems. Failure to do so may result in the whole project being rendered futile. This article provides an overview of the many slope monitoring approaches that are presently available and being used, along with their respective benefits and drawbacks.

The objective of this article is to emphasize the critical necessity for implementing continuous slope monitoring systems in mining environments, particularly in opencast mines. By emphasizing the increasing challenges of rock deformation with excavation depth, the article highlights the urgent need for effective slope monitoring techniques. Through a comprehensive examination of various monitoring technologies, including conventional and advanced methods, the article provides insights into the importance of proactive slope monitoring for ensuring the safety of personnel and equipment and optimizing productivity levels in mining operations.

2.0 Slope Monitoring Techniques

Various slope monitoring systems forecast potential instabilities and eventual rock failure. These systems encompass a range of technologies, from basic piezometers and extensometers to more advanced radars

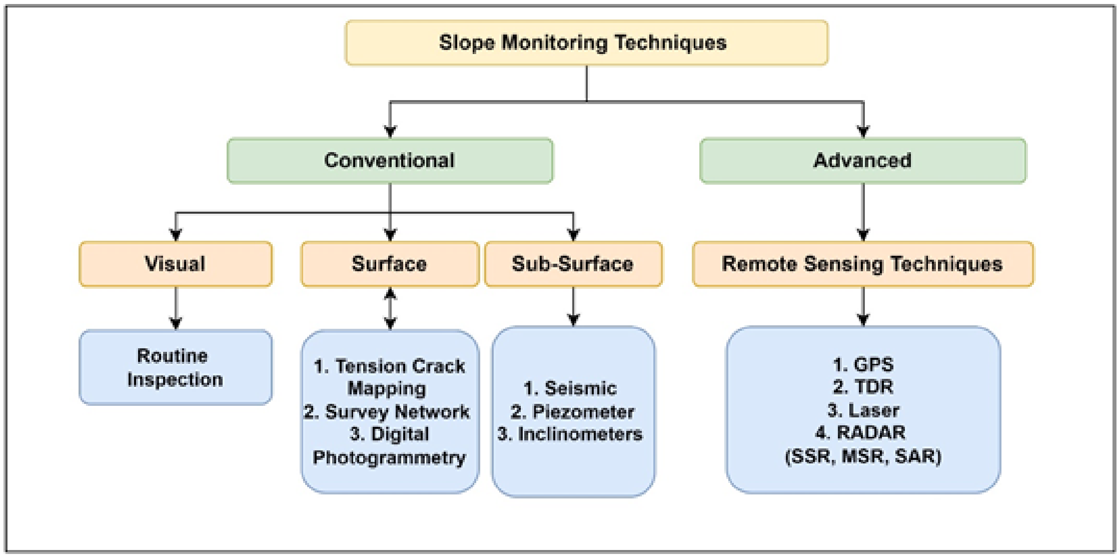

Figure 1. Classification of slope monitoring techniques.

and global navigation satellite systems. In addition, traditional methods like manual inspection and advanced micro-seismic monitoring are employed in opencast mines. Figure 1 categorizes the different slope monitoring techniques adapted from a previous study[5].

Further examination of the objectives and arrangements for monitoring programs may be found in the various research publications[6]. The essential characteristics of a proficient monitoring system encompass the timely identification of potential forthcoming threats, the provision of alerts when alarm thresholds are surpassed, the ability to conduct analytical assessments of current conditions and forecast future trends, and the verification that physical parameters such as deformation and pore pressure remain within acceptable tolerance limits. To provide a secure working environment and enhance ore recovery, it is essential to engage in prompt monitoring, data analysis, risk assessment, and response.

2.1 Conventional Slope Monitoring Techniques

Visual inspections are used as a means of monitoring slopes that are characterized by lower levels of danger. As the level of risk escalates, there is a corresponding augmentation in the magnitude and frequency of monitoring efforts to ensure precise data and enable real-time monitoring. Scientific principles underpin the occurrence of slope collapse, and with proper monitoring of the affected region, the failure may be anticipated and detected in advance. Anticipating the precise location of failure presents challenges due to the influence of several factors, such as the geological composition of the rock, the elevation of the slope, the presence of water, and the specific mode of failure. Based on the analysis of displacement monitoring data, the most reliable indicator of an impending failure is the observed acceleration in the rate of movement of any given slope. Historically, slopes were monitored by visual observation and basic instrumentation techniques. Several prominent warning markers of slope instability include tension fractures, erratic water flows, bulges or creep, and the presence of debris[7]. Visual inspections offer a direct method for assessing slope stability, providing immediate visual indications of potential instability. However, their subjective nature may lead to variability in observations, and they are limited to surface features, potentially missing subsurface deformations.

Historically, slope monitoring has primarily used wireline extensometers, inclinometers, borehole extensometers, and similar equipment. Wireline extensometers provide continuous displacement measurements, allowing for early detection of deformation and trend analysis. Nonetheless, their installation can be labour-intensive and prone to damage over time, requiring regular maintenance. They are also limited to specific monitoring points, potentially needing more overall slope behaviour. Inclinometers measure changes in slope inclination, offering insights into internal deformation and potential failure mechanisms. Yet, their installation can be complex, and various factors, such as groundwater levels or geological structures, may affect measurements. Borehole extensometers monitor deformations within boreholes, providing insights into rock mass behaviour and stress distribution. However, drilling boreholes can be costly and time-consuming, and data interpretation may require specialized expertise. Additionally, they are limited to monitoring specific locations along boreholes, potentially overlooking broader slope behaviour. The efficacy of these approaches is constrained to capturing changes within a 24-hour cycle, known as diurnal conditions, rendering them incapable of discerning the underlying failure mechanisms. Establishing slope monitoring programs to proactively avert failures, effectively execute corrective measures, and adopt remedies to address instability is crucial. The continuous identification and monitoring of deformations are necessary to implement suitable preventative actions.

2.2 Advanced Slope Monitoring Techniques

Advanced slope monitoring systems are advanced technological tools used to assess and analyse the stability of slopes in various environments. These systems employ a range of sensors and instruments to collect data on factors such as slope movement, deformation, and groundwater levels.

Digital photogrammetry compares slope pictures with three-dimensional (3D) models derived from land photographs. Diverse perspectives may be attained by capturing an area from many vantage points. Using the lines of sight unique to each place makes it possible to generate a three-dimensional representation. The three-dimensional image depicts many geological features, including faults, dykes, joints, and failure planes. The repetition of the procedure could unveil other failure planes and possible failure zones[8]. Digital photogrammetry has been shown to mitigate human error and minimize labour costs effectively. Additionally, it enables the scanning of steep rock walls and facilitates real-time measurements[7].

Monitoring all potential failure blocks on a mine slope via a survey network is fraught with risks and is not feasible. However, recent advancements in scanning laser rangefinders have made detecting movement over large areas possible. Laser scanners are capable of generating digital models of mine slopes in the absence of reflector prisms[9]. Laser scanners like the Site Monitor by 3D Laser Mapping Ltd. primarily aim to monitor and assess the stability of coal mine slopes. This innovative technology can accurately measure slope variations as small as 10mm over 1000m. A continuous, precise, and comprehensive slope profile may be generated by collecting data at a rate of up to 8,000 per second. The detection of slope deformation may be achieved by comparing slope scan data with base measurements. The use of point cloud data facilitates the estimation of volume. Laser scanners can efficiently monitor large slope faces without prisms, with a range extending up to 2,500 meters. Laser scanners, similar to radar devices, provide portability; yet, in terms of slope monitoring, they exhibit comparatively lower levels of accuracy when contrasted with radar. Laser scanning provides high-resolution data on slope geometry and deformation, allowing for real-time measurements and analysis, but it requires specialized equipment and maintenance, making it costly.

Prisms or slope-monitoring stations are necessary for use with total stations. Deformation and collapse zones are brought to light by prism movements. Prism monitoring is advantageous in providing accurate coordinates and continuous measurement regardless of the weather; nevertheless, it does not support satellite tracking and needs a clear view of the sky. Surveying robots and robotic total stations has become more common in recent years. Real-time, high-precision total station measurements are used in conjunction with prism-based slope monitoring systems. To conduct surveying that is both precise and efficient using robotic total station networks, photogrammetric cameras and Global Navigation Satellite System (GNSS) receivers are included. The number of robotic total stations required is determined by distance, climate, visibility, optics design, laser power, and mine camera resolution. Total stations are often situated towards the top of the pit in specialized shelters that protect them from blasts and weather and allow them to measure the most apparent items. At a minimum, one station stable point is required to adequately compensate for rotation orientation and temperature changes. Prisms are connected to total stations, and GPS integration ensures complete control over the system. On the slope, many prisms are set up to track the movement of the point. Prism installation is dangerous and time-consuming, and the performance of surrounding devices might affect the whole system. The software for wireless networks can monitor slope movements in the X, Y, and Z axes. The three movements, when combined, provide what is known as an absolute movement vector diagram. A few demerits are that installation and setup can be time-consuming, require clear sky for satellite tracking, and limit effectiveness in certain conditions. Prisms may require frequent recalibration and maintenance.

Time Domain Reflectometry (TDR) involves the application of an electrical pulse sent through a conductor to detect and evaluate any potential irregularities or interruptions in a given material. The polarity, amplitude, and frequency of a reflected pulse have the potential to serve as indicators of material breakdown. The primary use of TDR in the context of slope stability is the assessment of deformation in rock masses[10]. The coaxial wire is securely embedded inside a drilled hole, and a TDR system is used to propagate an electrical pulse along this cable. The coaxial cable is equipped with periodic crimps that serve the purpose of reflecting signals. The analysis of the reflected signals enables the assessment of rock mass deformation. The cable exhibits a characteristic response known as "spikes" when it encounters a disruption or distortion upon applying an electrical pulse. The spikes in the data may provide instantaneous and exact information on the relative size, rate of movement, and location. The quantity of movement via a computer linked to the tester is determined by the size of the spike increase[11]. Due to their many advantages, coaxial cables are deemed superior to inclinometers in detecting rock mass displacements. These advantages include reduced installation costs, increased capacity for hole depths, the ability to facilitate real-time remote monitoring, and expedited detection of deformations. TDRs are comparatively more cost-effective than probe inclinometers and data recording software. Probe inclinometers can identify changes in the rock mass that occur below the threshold of the TDR. There is a correlation ion between deformations and TDR cable energy; nevertheless, it is important to note that this connection is subject to variation over time and in different geographical locations. TDR has many advantages over traditional inclinometers, such as lower upfront costs (cable is around 20% less than the inclinometer case; deeper operation is feasible)[12]. The whole TDR equipment is situated on the surface, and the process of remote monitoring is characterized by its expeditiousness. The transmission of TDR data may be facilitated by telecommunications, using remote scanning and recording intervals to analyse specific areas of interest. This technique is limited to monitoring deformations along the cable's path, requires careful installation to ensure accuracy, and may require specialized expertise to interpret data.

Laser imaging systems, also known as three-dimensional scanners, provide the capability to rapidly and precisely identify slope stability, deformation, and many other geotechnical data using three-dimensional scanning technology. The ability to replicate pictures is accomplished within a matter of minutes. The battery-powered scanners lack levelling, characterized by many pan-and-tilt inconsistencies. This phenomenon leads to a decrease in operator error and an enhancement in accuracy. Using a streamlined scanner configuration has been shown to enhance overall efficiency. The devices above exhibit enhanced speed and modernity in comparison to traditional methods. Sensors simultaneously collect data from a wide area by using spinning mirrors and prisms, enabling the transmission and reception of multiple data beams. This process allows for acquiring substantial data, ranging from 6,000 to 10,000 data points per second. Office computers are equipped with Ethernet technology to receive scanned data efficiently. The scanning range of the target is contingent upon its reflection coefficient, having the ability to cover distances of up to 2500 meters while maintaining an accuracy of 1/25 mm. A few demerits are that battery-powered systems may have limited operational time, some inconsistencies in pan-and-tilt functions, and initial cost and complexity may be prohibitive for some applications.

Surface mines can use Global Positioning System (GPS) technology to monitor and track real-time slope movement. This approach demonstrates superior precision and cost-efficiency compared to inclinometers and extensometers. The monitoring area is equipped with GPS antennae. The positions of these antennas are determined by using GPS satellite data. Computing systems acquire spatial coordinates and then use data analysis techniques to ascertain slope displacement, enabling the prediction of potential problems. The accuracy of GPS is evaluated along the baseline, and its data necessitates processing to enhance accuracy. A few demerits are that accuracy may

Figure 2. Movement and Surveying Radar, MSR 300 [Reutech Newsletter].

be affected by environmental factors or signal interference, requires careful data processing and analysis, is limited to monitoring surface movements, and may not capture subsurface deformations.

Radio Detection and Ranging (RADAR) detects and determines the range, height, direction, and speed of both fixed and moving objects. Radar systems generate electromagnetic radiation to detect echoes from various targets. These echo signals provide valuable information about the targets[13]. The duration required for radiated energy to propagate to and from the target is a determining factor in establishing the range. The directional antenna uses the measurement of the arrival angle of the echo signal to ascertain the target's angle. Radar may be classified based on its primary characteristics: The list of radar systems includes meteorological observation radar, surveillance radar, high-resolution radar, pulse compression radar, pulse radar, Frequency-Modulated Continuous-Wave (FM-CW) radar, Moving Target Indication (MTI), pulse Doppler radar, continuous wave radar, imaging radar, Side-Looking Airborne Radar (SLAR), Synthetic Aperture Radar (SAR), inverse synthetic aperture radar (ISAR), weapon control radar, guidance radar, and tracking radar. Figure 2 depicts one of the two widely used radar systems for slope monitoring in mines. The other is Ground Probe's Slope Stability Radar (SSR) shown in Figure 5. This technique can be a costly initial investment and maintenance, requires specialized operation and data interpretation training, and is limited by line of sight and atmospheric conditions.

The advent of the latest technological inventions has led to the use of UAVs in the field of mining and geotechnical engineering for the monitoring of slopes and landslides.

3.0 Techniques for Monitoring Slopes with Unmanned Aerial Vehicles (UAVs)

Measurements and monitoring using geodetic equipment have traditionally been used to study the processes of slope displacement and landslides. In geodetic surveying, compliance is determined by whether or not the observed displacements of points surpass the measurement error of the device[14]. Specific sensors have grown more miniaturized and more intelligent as a direct result of the development and proliferation of unmanned aerial vehicles, often known as UAVs. UAVs with a wide variety of sensors are an important tool for gathering spatial information. Because of their low cost, ability to capture high-quality data according to the orientation, brief revisiting cycle, flexibility, and excessive precision, UAVs have become powerful equipment in geological, agricultural, ecological, and forestry growth monitoring and evaluation. The advantages of using UAVs include less influence on weather conditions, low cost, and the ability to capture high-quality data according to orientation. Studies using UAVs are ubiquitous nowadays because of the features mentioned above in the technique. In geotechnical engineering and mapping slope failure risks, the imaging capabilities of UAVs are currently widely used. Figure 3 shows one of the most commonly used UAV platforms.

Figure 3. UAVs DJI Phantom 4 platform.

The UAV survey is a technology for monitoring and surveying landslides that is both straightforward and efficient. Numerous research studies have shown that it is possible to generate precise Digital Surface Models (DSMs) of slopes using a UAV. The work uses UAV photogrammetry methods, notably SfM-MVS (Structure-from-Motion Multi-View Stereo), and tachymetric measures for accurate and reliable aerial photography[15]. UAV photogrammetry gives high-resolution pictures and tachymetric geodetic measurements for exact control of surface displacement analyses. Works using the multistep rocky slope stability analysis based on UAV photogrammetry have been implanted in the industry. This work generated a suitable and reliable 3D modelling approach for behaviour slope kinematic stability analysis.

Figure 4. 3D-view of the point cloud by digital camera[16].

An approach is being developed for multistep block identification using UAV photogrammetry to measure high and steep slopes. This approach is based on SfM (Structure from Motion), and with readily accessible software, a DEM (digital elevation model) of the rock mass is constructed for real-time monitoring. Figure 4 shows a representative result from UAVs.

To determine the structural planes included in the point cloud model, the RANSAC (random sample consensus) shape identification approach is being used[17]. An earlier investigation came to the conclusion that aerial photographs of landslides could be mapped and characterized with the use of UAVs, which were then analysed using SfM software. A Digital Surface Model (DSM), orthophotos, and accurate 3D representations of the surfaces were produced as a consequence of this process. This survey, using the UAV, was carried out several times throughout a variety of periods. Following the collection of many DTMs, or digital terrain models, the models are compared with one another to identify any morphological change and the characteristics of places on the slope that are prone to landslides[18]. This approach can be used for mining slopes as well. Combining multivariate data generated from UAV photogrammetry processing with Object-Based Image Analysis (OBIA) is one way that has been suggested for site-specific landslide assessment. The OBIA procedure is employed for landslide identification and classification[19].

The use of deep learning techniques in the field of landslide or mine slope monitoring

Only a few studies based on deep learning have been carried out to monitor slopes. Slope data and spectral information may be gathered with the use of remotely sensed pictures captured by UAVs. The slope can be initially detected from UAV images by combining spatial shape and spectral features, followed by extracting pre/post-failure/landslide change features using satellite sensing and UAV images[20]. Another study used back propagation neural networks with the help of feature fusion to detect failures from UAV images[21]. In the process of monitoring slopes and landslides using UAV data, other methods, such as an Adaptive Neuro Fuzzy Interference System (ANFIS) and a Logistic Regression methodology, are also used[22].

4.0 Comparisons between Conventional and Modern-Day Slope Monitoring Techniques

Conventional monitoring instruments, such as theodolites, total stations, inclinometers, extensometers,

Figure 5 SSR installed in Kusmunda Mines, SECL and India[23].

and piezometers, provide data for a limited number of locations, potentially resulting in undetected failures between distant monitoring sites. The use of classic mining procedures is sometimes harsh and unsafe in many mines due to the presence of steep, high walls and the absence of benches. The relocation of monitoring equipment incurs significant costs, requires a substantial investment of time, presents formidable challenges, and poses potential risks when conducted on unstable slopes. The presence of atmospheric anomalies in slope displacement data may be effectively addressed via the use of the atmospheric correction module inside advanced monitoring systems like radar.

Similarly, the system's disturbance detection module enables the identification of disturbances such as vehicle movement. When conducting radar-based monitoring of extensive territories, the user has the option to choose an area threshold and provide a description of the size of the region to identify modest slope failures. Modern techniques can continuously monitor expansive slope areas throughout the day, irrespective of prevailing weather conditions while being unaffected by the presence of haze or dust particles. Furthermore, radar exhibits a considerable range, enabling the monitoring of distant sites. Using various combined monitoring approaches is now regarded as the most dependable choice. Additionally, it offers improved data for comprehending the behaviour of slope deformation. Based on the findings of Bye's study, the success rates of different types of monitoring techniques for slope stability were evaluated and are as follows:

i. Visual monitoring only: This approach yielded a success rate of 32%. Visual monitoring involves visually inspecting the slope for any signs of instability or changes.
ii. Prism/Crack Meters only: The success rate for using prism and crack meters as monitoring tools was 45%. These devices measure the displacement of cracks or prisms to detect slope movement.
iii. Visual + Prism/Crack monitors: Combining visual monitoring with prism/crack meters increased the success rate to 63%.
iv. Visual + Prism/Crack + Laser: By adding laser monitoring to the visual and prism/crack methods, the success rate significantly improved to 86%.
v. Radar Only: The radar monitoring technique exhibited a high success rate of 93%. Radar systems can accurately detect displacement and movement in the slope.
vi. Visual + Prism/Crack + Radar: A combination of visual, prism/crack, and radar monitoring yielded a success rate of 97.5%.
vii. Visual + Prism/Crack + Laser + Radar: The most comprehensive approach, involving visual, prism/crack, laser, and radar monitoring, achieved the highest success rate of 99%.

5.0 Conclusion

The objective of this study was to conduct a comprehensive examination of slope monitoring approaches, with a particular focus on supporting a comparative study of these techniques within the mining industry. The study revealed that the current optimal methodology for monitoring slopes involves integrating various methodologies, including old and new methods. The success rates reflect the effectiveness of different monitoring techniques in assessing and predicting slope stability. The combination of multiple methods, particularly involving radar, laser, and comprehensive monitoring, proved to be highly successful in detecting and mitigating slope failures.

Conventional monitoring methods are employed in conjunction with contemporary techniques to enhance the effectiveness of slope monitoring at various mines. The advancement of slope monitoring has been led by the use of ground-based radar technology and UAVs, which give high-resolution outputs. The integrated approach in slope monitoring technology allows for performing real-time scans of monitoring stations and areas to detect accelerations and extrapolate this data to predict potential collapse events.

The use of modern monitoring methods like remote sensing techniques, including UAVs, enables the detection and tracking of failure progression and the identification of previously inconceivable processes, enabling a new avenue for the prediction of failures. These technologies provide instantaneous information on wall movements, even in the face of adverse environmental conditions like precipitation, dust, pollution, and other obstacles, thus giving accurate data on slope movements, further aiding in improving the safety standards of mines by forecasting slope deformation behaviour.

Advancements in technology are paving the way for future improvements in slope monitoring technologies. Remote sensing techniques like satellite imagery can provide high-resolution data for comprehensive monitoring of slope movements. Wireless sensor networks offer real-time monitoring without extensive cabling. Artificial Intelligence and machine learning can analyse large datasets, identifying early warning signs of instability. Advanced geotechnical sensors can enhance data accuracy and reliability. Innovative monitoring techniques like distributed fibre optic sensing and ground-based radar can provide new insights. Data fusion and integration can provide a comprehensive understanding of slope stability. Real-time monitoring systems can reduce the risk of catastrophic failures. Cost-effective solutions can facilitate widespread adoption.

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