# The Use of Radar in the Assessment of the Stability of Mine Slopes in Open Cast Mines

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**Abstract.** Many mines currently use radar for slope stability monitoring to monitor slopes and dumps in opencast mines in real-time and to send out early warning signals. In India, opencast mines make up about 4 out of 5 mines. Therefore, slope monitoring is essential to the design of any surface mine, mainly as the mine grows deeper and steeper due to production demands and technological advancements. Slope monitoring is the first step in failure prevention and prediction on a slope. In recent years, several methods have been developed to predict the collapse of mining slopes by monitoring and analysing movement data. Slope monitoring systems have developed over time, and when choosing a system, factors including coverage, mode of operation, cost, installation, and maintenance are crucial. This paper focuses on modern day contemporary slope monitoring methods, especially the radar system.

**Keywords:** radar · mine slope stability · slope monitoring · slope stability radar (SSR)

## 1 Introduction

We do not wholly comprehend geotechnical conditions, slope collapse, or slope stability investigations. Rapid opencast mining and improved automation have led to deeper opencast mines with better stripping rates. The amount of waste mined and dumped will increase the risk of highwall slope and dump collapses. With stricter environmental rules and a lack of alternative land for forestation, the threats are multifaceted, with deep excavations and rising dumps impacting stress concentration. These situations endanger employees and machinery. Several opencast mining accidents have been caused by slope and dump failures. Flatter slopes are stable but lock up tremendous mineral resources, whereas steeper slopes are riskier. Maintaining scientific equilibrium ensures the benches' longevity. Monitoring mine slopes for signs of imminent collapse is the most effective way to protect miners. Lack of proper pit and dump slope design and monitoring impedes mining accidents. In mining, monitoring is used to control residual


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design risk. Unknown constructions, unexpected weather patterns, or seismic stress may cause slope collapse [1].

Mining affects the surrounding rockmass, and excavation instability is when stress exceeds rock strength. A slope monitoring program is the most critical slope stability system. Keeping track of the stability of the rocks that make up a slope is defined as slope stability monitoring [2]. Monitoring uses reference points to identify deformation. Bench design may avoid slope collapses and increase geotechnical safety, but geology, weather, and earthquakes may collapse even conservatively designed slopes. Rock movement may interrupt mining operations, raise safety risks, cause serious injuries, and cost lives and money [3].

The primary goals of a slope monitoring programme are safe operations, offer prior notification of instability, slope behaviour related to geotechnical details and evaluate a slope remediation design [4]. These objectives can be achieved by verifying mine design, providing technical confirmation of stability for production and management personnel, serving as a warning system for unstable areas, monitoring and measuring unstable zone movements, and providing a crucial technique for minimising the danger of slope instability [2].

Monitoring mine slopes may range from visual examination to GPS and radar scanning. These procedures can be classified as traditional or modern-day, as shown in Fig. 1. Traditional slope monitoring includes reporting stress cracks. All mine personnel monitor slopes. Every slope monitoring scheme relies on visual inspections. Face and dump slopes are frequently inspected. The displacement can be calculated by comparing the last and current deformation data. Marking new cracks to differentiate them from old ones and measuring surface movement with a survey tape, rod, or extensometer is common to identify movements or instability. Many mines use radar devices to monitor opencast mines for dump or slope collapses. A radar system with submillimetre precision and wide coverage can detect alarm wall movements accurately. Radar can function 24 h a day without reflectors, providing data in minutes by comparing site movements in real-time. Cyclic monitoring of the target zone helps find failing spots. An auditory and visual warning system may be initiated when ground movements exceed a pre-set value. SAR, a ground-mapping radar for aircraft and satellites, can construct elevation maps and find surface movements.

## 2 Mine Slope Monitoring

A more in-depth analysis of the goals and preparations for monitoring programmes may be found in the works of Barla, Chiappone and Vai [5]. Key features of a well-designed monitoring system include; early detection of potential impending failure; notification of alarm exceedance; analytical capabilities in analysing present circumstances and estimating future projections; and, confirming physical parameters are within acceptable tolerance range (deformation, pore pressures, etc.).

Maintaining a safe working environment and maximizing ore recovery requires quick monitoring data analysis, and reaction. Rio Tinto made GRAHAMS, or Geotechnical Risk and Hazard Assessment Management System, to analyse and record the concerns

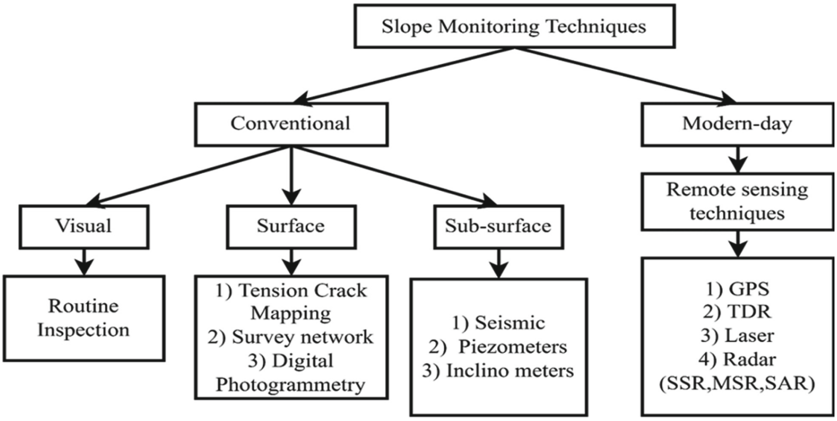


**Fig. 1:** Classification of slope monitoring techniques

of economics and safety of the slopes. Each risk evaluation addressed instability mechanisms, slope geometry, design recommendations, and personnel and equipment exposures. Visual inspections are used to monitor lower-risk slopes. As the risk rises, the intensity and frequency of monitoring increase to provide accurate data and real-time monitoring. This monitoring system is part of the geotechnical division of the Rio Tinto's Trigger Action Response Plan (TARP).

Slope failure has a scientific basis, and if the failed area is monitored correctly, the failure will not occur without notice. Predicting the exact point of failure is difficult because the eventual collapse depends on various elements, including the kind of rock, the height of the slope, the presence of water, and the manner of failure itself. Using displacement monitoring results, the best-proven sign of approaching failure is an increase in any slope's movement rate. Visual observation and simple instrumentation were formerly used to monitor slopes. Tension cracks, irregular water flows, bulges or creep, and rubble at the top are some of the most common warning indicators of slope instability [3]. Slope monitoring has traditionally relied on wireline extensometers, inclinometers, borehole extensometers, and other similar instruments. These methods are limited to working in the daylight; they cannot identify the failure processes involved. Slope monitoring programs should be in place to prevent failures, and implement remedial actions, and solutions to instability. Continuous detection and monitoring of deformations are required to take appropriate preventive measures.

## 3 Modern-Day Slope Monitoring Systems

### 3.1 Digital Photogrammetry

Digital photogrammetry compares slope photos and 3D models from land photographs. Working with robotic total stations improves slope monitoring. Different viewpoints are achieved when a subject is photographed from different angles and using each location's lines of sight, a 3D image can be produced. These photos build a three-dimensional face. The 3D graphic shows faults, dykes, joints, and failure planes. Repeating the technique may reveal additional failure planes and probable failure zones [6]. Digital photogrammetry reduces human error and labour expenses and permits scanning steep rock faces while enabling real-time measurements [7].

### 3.2 Laser Scanner

Monitoring every possible failure block on a mine slope with a survey network is risky and impracticable, but new scanning laser rangefinders can detect movement over broad regions. Laser scanners create digital mine slope models without reflector prisms [8]. SiteMonitor was created by 3D Laser Mapping Ltd., United Kingdom, to keep tabs on the safety of coal mine slopes in South Wales [9] and can capture 10mm slope movements at 1000m. Up to 8,000 measurements/second may be taken to construct an uninterrupted, accurate, and detailed slope profile. Anglo Platinum has deployed Site Monitor for slope monitoring for automated and manual long-range surface profiling up to 2,500 m with 50 mm precision. Site-Monitor software automatically analyses laser scanner point cloud data [10]. Comparing slope scan data to base measurements detects slope deformation. New laser scanning technology improves slope monitoring at De Beers Kimberley and Kumba Iron Ore. Point cloud data helps estimate volume. Laser scanners quickly monitor big slope faces without prisms up to 2,500m. Laser scanners are portable like radar systems, but compared to radar, they are less accurate for slope monitoring.

### 3.3 Robotic Total Stations

Total stations require prisms or slope-monitoring stations. Prism motions reveal deformation and collapse zones. Prism monitoring offers precise coordinates and continuous measurement in any weather but lacks satellite tracking and requires an open sky view. Surveying robots or robotic total stations have been used recently. Prism-based slope monitoring is real-time with long-range, high-accuracy total stations. Robotic total station networks include photogrammetric cameras and GNSS receivers for accurate, efficient surveying. Distance, weather, visibility, optics design, laser power, and mine camera resolution dictate the number of robotic total stations. Customised shelters protect total stations from blasts and weather and are generally placed near the pit's apex to measure the most visible things. At least one station stable point is needed for rotation orientation and heating/cooling compensation. Total stations are linked to a prism, and complete control is attained by integrating GPS. Several prisms are positioned on the slope to monitor point movement. Prism installation is risky and time-consuming, and nearby machines might affect system performance [11, 12]. Wireless network software can measure X, Y, and Z axis slope movements. Merging the three motions creates an absolute movement vector diagram.

### 3.4 Time Domain Reflectometry (TDR)

TDR uses an electrical pulse delivered through a conductor to check for material discontinuities. A reflected pulse's polarisation, amplitude, and frequency can indicate material failure. The most typical use of TDR in slope stability is measuring rock mass deformation [13]. A coaxial cable is grouted into a drill hole, and TDR transmits an electrical pulse down this cable. The coaxial cable has crimps at regular intervals to reflect signals. Examining the reflected signals determines rock mass deformation. The cable signature "spikes" when an electrical pulse contacts a break or distortion. Relative magnitude, rate of displacement, and location can be evaluated instantly and precisely by reading these spikes. The size of spike rise determines movement magnitude through a computer attached to the tester [14].

As coaxial cables are better than inclinometers for sensing rock mass displacements, they provide lower installation costs, higher hole depths, real-time remote monitoring, and fast deformation detection. TDRs are cheaper than probe inclinometers and data recording software. Probe inclinometers can detect rock mass changes below the TDR threshold. Deformations and TDR cable energy seem connected—however, this relationship shifts across time and place. Kane [15] explains TDR's benefits over regular inclinometers, cable costs roughly 20% less than inclinometer casing; possible deeper operation. All TDR equipment is surface-based, and the remote monitoring is quick. TDR data may be supplied over telecommunications with remote scanning and recording intervals to analyse zones of interest [16]. TDR locates deformations instantaneously, and TDR cables have been installed in slanted boreholes to monitor deep zones underneath moving upper zones in complex monitoring situations [13]. Typically, no further data reduction is required, and the cables may be used to monitor rock movement as well as determine shear and stress. In neither installation could traditional inclinometers be employed.

### 3.5 Light Detection and Ranging (LiDAR)

Laser imaging devices or three-dimensional scanners can detect slope stability, deformation, and other geotechnical data quickly and accurately with 3-D scanners. They can copy images in minutes. The battery-powered scanners are not levelled having many pan-and-tilt entries. This reduces operator error and improves accuracy. A simpler scanner setup increases productivity. These units are speedier and more contemporary than conventional total stations. Sensors gather data from a vast area concurrently by rotating mirrors and prisms broadcast and receive several beams of data acquiring 6,000 to 10,000 data points every second. Survey office computers utilise Ethernet to receive scanned data quickly. Depending on the target's reflection coefficient, they can scan up to 2500 m with 1/25-mm precision. Customised software lets users choose data gathering places and frequency. Most programmes employ ASCII formats. Contour plots show the investigated strata. The ground-penetrating radar identifies and monitors high regions. GPS may monitor instrument control points when accurate locations are unavailable. Laser monitoring, like prism monitoring, cannot discover flaws early [6].

### 3.6 Global Positioning System (GPS)

Surface mines may employ GPS to monitor real-time slope movement. This method is more accurate and cost-effective than equipment like inclinometers and extensometers.

The monitoring zone has GPS antennas. These antennas determine their locations using GPS satellite data. Computers get these locations and data analysis determines slope displacement, which is used to anticipate failures. GPS accuracy is measured throughout the baseline, and its data must be processed to increase accuracy.

## 3.7 Radar Systems

Radio Detection and Ranging (RADAR) detects and locates moving and stationary targets' range, height, direction, and speed. Radar emits electromagnetic radiation and detects echoes from targets, and echo signals offer target information [17]. The time taken by radiated energy to travel to and from the target determines the range. A directional antenna measures the echo signal's arrival angle to determine the target's angle. Radar can anticipate the course of moving objects. The scanning pattern of the SSR is shown in Fig. 2.

### RADAR Types

Radar may be categorised depending on its main properties: Meteorological observation radar, Surveillance Radar, High-resolution radar, Pulse compression radar, Pulse radar, 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, Tracking radar [17]. Few of these relevant to the mine slope monitoring are discussed below.

*Slope Stability Radar (SSR)*

In 2002, Australian researchers from the University of Queensland created a scanning radar system for monitoring mine slopes using differential interferometry. The SSR scans a slope in both horizontal and vertical directions. The device measures slope deformations at 10° per second across 60° vertically and 340° horizontally. Phase unwrapping eliminates $2\pi$ ambiguity from each point in the resultant picture [18]. The SSR has a 0.92m scanning parabolic dish antenna, computer, remote area power supply, warning siren and lights, CCD camera, communication lines, and internet compatibility. 15-min scan repeats are typical [8]. SSR-X can operate 2800m from the target slope without reflectors, and line-of-sight displacement is 0.1 mm. The SSR can scan 270 horizontally and 100 degrees vertically without vibration or mining equipment. SSR systems have

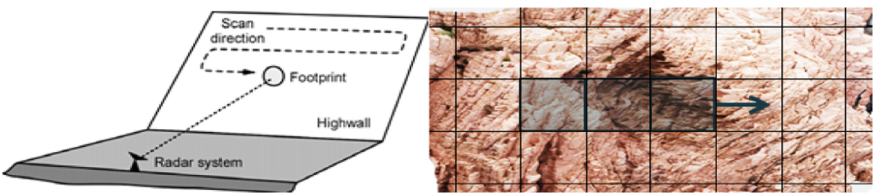


**Fig. 2:** Slope Stability Radar (SSR) scanning pattern (Source: GroundProbe SSR)


**Fig. 3:** SSR installed in Kusmunda Mines, SECL, India

functioned in −600 to +500 °C temperatures and 120mm/hour rain [19]. SSR georeferences deformation and picture overlays with mine coordinates and exports them to mine planning and design tools. The device scans a wall section and compares the phase measurement to the previous scan to estimate slope movement. Slope monitoring using SSR has been recently implemented in Indian mines. Figure 3 show SSR installed in Kusmunda Mines, SECL, India.

It creates an image exhibiting slope deformation compared to a reference image plotting each image point's displacement history. The SSR depicts the entire displacement on the slope face as rainbow plots, allowing the user to rapidly evaluate the failure's extent and the location with the most movement. The SSR sees the world as 3-D voxels and converts a 3-D wall surface to a 2-D pixel image Time vs displacement plots are presented at any location to analyse displacement/deformation rates. Software allows data to be examined and analysed remotely, such as at geotechnical offices. Figure 4 shows the deformation heatmaps of a slope/wall.

SSR systems are used worldwide in metal and coal mines [20] and has documented antecedent warning motions for over 500 rock slope and trash dump disasters [20, 21]. Cahill and Lee [22] claimed that the Radar had been used at Leinster nickel mine since 2002 to monitor slope walls with poor trust in prisms and eye examination. Small movements preceding slope collapse are regularly studied. SSR remotely scans rock slopes and

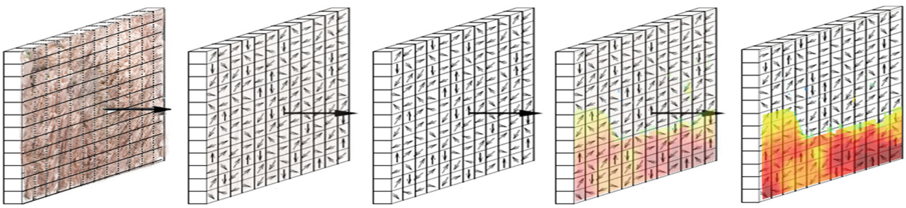

**Fig. 4:** 2D deformation images of the wall generating deformation heatmaps (Source: GroundProbe SSR)

monitors deformation. Differential radar interferometry can detect rough wall deformation with sub-millimetre spatial and temporal resolution. Signal processing may reduce atmospheric and false signals. Unlike conventional monitoring systems, the SSR does not need reflectors or other equipment on a wall, as radar waves penetrate rain, dust, and smoke to give 24-7 readings. An umbilical connection links the scanning antenna and radar electronics box. The scanning antenna is placed on a tripod and operated by azimuth and elevation gears. This system accuracy criterion influenced mechanical pointing accuracy and tripod stability requirements. A computer in the radar electronics box may adjust the parabolic dish's elevation from –15° to 165° and azimuth from –170° to 170°. Using drag-and-drop, the 2D scan zone may be customised. The scan takes 25 min for a 4000-pixel wall. 1° increment defines 2D picture pixel size. A 100-m-away rock slope has 2m × 2m pixels. The radar electronics box's intermediate frequency signal is up-converted to X-band (9.4–9.5 GHz) at the scanning antenna's feed.

GroundProbe debuted Work Area Monitoring (WAM) in 2010. WAM combines a high-resolution camera and radar technology to scan an area swiftly. If mine slope movement is detected, the equipment warns mining people through wireless Personal Alerts (PALS) via text messaging, audio, vibration, and local sirens and lights [19]. The machine can easily be put up with remote-controlled stabiliser legs and may be installed on a vehicle. WAM monitors risky work areas when slope displacement is expected [20]. The 100 MHz waveform provides a 1.5-m range resolution. The feed antenna sends 30 mW. The radar electronics box captures intermediate frequency signals from the receiver's umbilical connection. The signal-to-noise ratio (SNR) must be 1.0 or above to satisfy 0.1 mm system accuracy. Radar data automatically compensates for variations in temperature, pressure, and humidity. Because of the system's high repetition rate, phase unwrapping may be done pixel-by-pixel.

A spatial filter reduces phase errors caused by signal fades to pixels with a poor signal-to-noise ratio. Because there is no sky reflection target, interferometric phase fluctuation is unpredictable. The slope's shifting vegetation hides phase signals. Moving cars sometimes conceal a tiny region of radar pixels. These localized impacts can be overcome in the following scans. Combining interferograms reveals the wall's temporal and spatial mobility. A colour change shows pixel displacement relative to the radar location. Comparing an unstable area against a stable reference area shows the displacement history of chosen regions. Polynomial regression may be used to estimate the rock's outward acceleration. An interactive graphical user interface (GUI) displays and compares co-registered interferogram images. Select regions for continuous tracking and change picture reconstruction settings. More rock face covering improves geodynamics and increases warning time. This technique improves on traditional monitoring. Lower coal recovery risk enhances productivity. Under standard surveillance, the region would be isolated for high risk.

*Synthetic Aperture Radar (SAR)*

SAR is a ground-mapping radar for satellites and crafts, constructing terrain maps, providing high-quality DEMs, and identifying surface disturbances or moisture changes. SAR operates all day and produces high-resolution photographs. IFSAR or INSAR combines two or more SAR photos of the same location to create elevation and surface change maps [23]. Glacial movement, ground subsidence, landslides, and building stability are some of the areas that have benefited from IFSAR's utilisation of space-based radars (Peltzer, 2010). IFSAR is used to monitor unstable mining slopes. Singhroy and Molch [24] used INSAR photos of the Frank Slide from August 1995 to August 1997 to reveal a near circular fringe matching a maximum displacement of -1.3cm, indicating a probable rock motion before the 6000-tonne rock fall of 2001. They discovered that IFSAR works well in all-weather situations. IFSAR can function day and night in fog, mist, rain, haze, or clouds. The capacity to monitor a vast region for ground displacement provides an edge over traditional methods.

*Movement and Surveying Radar (MSR)*

South Africa's Reutech Radar Mining developed the MSR (MSR-200) in January 2006. It offers geo-referenced surveying information, enabling inaccessible surveying places [25]. The system's fully integrated total station enables precise geo-referencing of the MSR. The MSR survey can measure 3-D slope information and material removal. Figure 5 shows two types of MSRs by Reutech.

Each point's data and displacement may be seen independently. With radar monitoring, the displacement information of numerous slope sites may be analysed to identify high displacement and its magnitude indicating regressive or progressive deformation. This information may be used to predict the failure's size and timing.

The MSR is useful for controlling and monitoring sub-millimetre slope movements worldwide, like the SSR. Many mines in Africa, South America, the U.S., Europe, Indonesia, Papa New Guinea, and Australia use MSRs. Anglo Gold Ashanti uses it in its Namibian, Malian, and Australian mines. Anglo Coal's South African mines are using six MSRs. The latest MSR-060V is truck-mounted and can be deployed quickly in important work locations. The equipment has the MSR-300's slope monitoring capabilities but a 600m range [26]. IDS' IBIS-M can measure sub-millimetre mine wall motions constantly. It offers the highest spatial resolution at 1km (0.5m $\times$ 4.4m) and the maximum working distance at 4,000m [27]. The IBIS-M runs on solar panels, batteries, and a diesel generator as a backup. It can be controlled remotely through radio. The IBIS-M is completely geo-referenced and has automated atmospheric adjustments like the SSR. IBIS-M monitors Calgary's Turtle Mountain. According to Bye research (Table 1) [28], compared to other technologies, radar has a 93% success rate in detecting


**Fig. 5:** MSR-060 V (Reutech, 2011) and MSR-300 (Reutech, 2008)

**Table 1:** Success rate of various slope monitoring techniques (Source: Bye research [28])

| Monitoring Type | Success Rate |
|---|---|
| *Visual Monitoring only* | *32%* |
| *Prism/Crack Meters only* | *45%* |
| *Visual + Prism/Crack monitors* | *63%* |
| *Visual + Prism/Crack + Laser* | *86%* |
| *Radar Only* | *93%* |
| *Visual + Prism/Crack + Radar* | *97.5%* |
| *Visual + prism/crack + laser + radar* | *99%* |

slope problems. When radar is used in conjunction with other methods, the success rate rises to about 100%.

**Managing risks using radar technology**

Slope stability radar is a warning system. Generally, monitoring, which entails data collecting, is one of the primary functions of an early warning system with transmission, equipment maintenance; prediction and analysis, which thresholds can do, engineer's expertise, prediction methods, and others.

Harris et al. [21] created a risk management approach for slope stability. Step 1 is to choose a context—for example, monitoring a quick, bench-size failure. Next, identify the danger. A rock mechanics engineer can view a rock's deformation on a computer screen. A mine picture shows deformation. To obtain this information, the SSR system's staff checks the failure area's size, kind, and deformation rate. Data concerning slope damage may then be analysed using organisation criteria. If required, address a danger after evaluating it.

Two risk-reduction alternatives exist. Depressurising water or buttressing a failing section may reduce the chance of collapse. Commonly, failure consequences are reduced. Alarm evacuation of mine workers and machinery is best. Mines use four alarms:

- Green - a slight system problem that requires restarting the SSR application.
- Yellow-a failure of radar system that notifies a supervisor and a geotechnical department to assist in pinpointing the issue.
- Orange-a "Geotech alarm" that alerts geologists to prospective threats from ground movement.
- Red-a pit supervisor must evacuate a problem area or the whole pit.

Alarms may be sent by SMS to staff mobile phones, e-mail to responsible parties to halt equipment from entering a harmful area.

The real-time display of radar data in a computer room enables a rock-mechanics engineer to watch slope behaviour. Deformation, velocity rate, and failure size are used to construct a slope monitoring threshold. A increasing linear deformation trend signals growing risk in an alarm application. After a linear deformation trend has been identified, the velocity of the deformation may be a comment and the occurrence of a new velocity can trigger an alarm. Progressive deformation increases danger. At this point, failure may be predicted and alarms set to alert a rock mechanics engineer when a slope deforms sufficiently.

## 4 Conclusion

The paper aimed to review the slope monitoring methodologies, with special emphasis on the use of radar in the mining sector. The research found that the best reliable strategy for monitoring slope at the moment is to use multiple techniques, including traditional ones as an integrated approach. Conventional monitoring is used to complement modern techniques for improving active monitoring of slopes at a number of mines, such as the Leinster Mine, Tom Price Mine, Bingham Canyon Mine, Potgietersrust Mine, Kemess South Mine, Grasberg Open Pit, Wallaby Mine, Barrick Goldstrike Mine and Savage River Mine. Progress in slope monitoring has been spearheaded by ground-based radar, which conducts periodic scans of monitoring stations to search for accelerations and extrapolate them to anticipate impending collapse. Monitoring slope movement is the best way to identify and anticipate slope instability. Radar monitoring can trace failure development and identify processes not previously conceivable. Radar monitoring methods have also opened up a new frontier in failure prediction by giving real-time data on wall movements even in the presence of precipitation, dust, pollution, and other environmental challenges, enabling continuous slope modification. Real-time identification and failure prediction rely on monitoring equipment and human understanding. Typical monitoring equipment, like a theodolite, total station, inclinometers, extensometers and piezometers, offers information only for a few sites; thus, failure between monitoring sites may be possible go unreported if they are far apart. In many mines, the steep highwalls and lack of benches make it challenging and risky to implement traditional mining methods. Moving monitoring equipment is expensive, time-consuming, challenging, and hazardous on unstable slopes.

Atmospheric anomalies can be accounted for in slope displacement data owing to the radar monitoring system's atmospheric correction module, and disturbances like vehicle movement can be identified according to the system's disturbance detection module. When monitoring vast territories using radar, the user may select an area threshold and describe the area's size for small slope failure detection. Radar can monitor vast slope regions all day in practically any weather without being impacted by hazy or dusty conditions and also has great range to monitor far away points. Using multiple monitoring techniques is the most reliable option today, as seen by the Table 1. It also provides better data for understanding slope deformation behavior.

## References

1. Girard JM, Mchugh EL (2000) Detecting Problem with Mine Slope Stability
2. Kayesa G (2006) Prediction of slope failure at Letlhakane Mine with the Geomos Slope Monitoring System. In: Proceedings of the International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering Situations, Series S44. South Africa

3. Girard JM (2001) Assessing and Monitoring Open Pit Mine Highwalls. In: Proceedings of the 32nd Annual Institute on Mining Health, Safety and Research. Salt Lake City, Utah, pp 159–171
4. Sjoberg J (1996) Large Scale Stability in Open Pit Mining - A Review.
5. Barla G, Chiappone A, Vai L (2006) Instability of Slopes - Interactions with man-made structures, inhabited areas and the environment. Patron Editore, Bologna, Italy
6. Little MJ (2006) Slope monitoring strategy at PPRust open pit operations. In: Proceedings of the International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering. pp 211–230
7. Girard JM (2001) Assessing and monitoring open pit mine highwalls. In: Proceedings of the 32nd Annual Institute of Mining Health, Safety and Research. Roanoke
8. Mchugh EL, Long DG, Sabine C (2006) Application of Ground-Based Radar to Mine Slope Monitoring
9. Hunter G (2007) Mapping with 3D lasers. In: EE Publ. https://www.ee.co.za/wp-content/uploads/legacy/PositionIT%20Sept-Oct%2007%20-%20p54,-57.pdf
10. Little MJ (2006) The Benefit to Open Pit Rock Slope Design of Geotechnical Databases. In: The South African Institute of Mining and Metallurgy International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering. pp 97–116
11. Hoek E, Rippere KH, Stacey PF (2000) Large-scale slope designs – a review of the state of the art. In: Slope Stability in Surface Mining. McCarter & Van Zyl, SME, Hustrulid, Colorado, pp 3–10
12. Mufundirwa A, Fujii Y, Kodama J (2010) A new practical method for prediction of geomechanical failure-time. Int J Rock Mech Min Sci 47:1079–1090
13. O'Connor KM, Downing CH (1999) Geomeasurements by Pulsing Time Domain Reflectometry Cables and Probes. CRC Press
14. Dowding CH, Su MB, O'Connor K (1989) Measurement of rock mass deformation with grouted coaxial antenna cables. Rock Mech Rock Eng 22:1–23
15. Kane WF, Beck TJ (1998) Instrumentation Practice for Slope Monitoring. J Eng Geol Pract North Calif 1–20
16. Inc. CS (1998) Campbell Scientific Inc., Time Domain Reflectometry for Measurement of Rock Deformation, Product Brochure. https://s.campbellsci.com/documents/us/product-brochures/b_geotdr.pdf
17. Skolnik M (1990) Radar Handbook, 2nd Editio. McGraw-Hill Inc., New York
18. Reeves B, Noon D, Stickley G, Longstaff D (1997) Monitoring rock slope deformation by radar interferometry. In: A. Kulessa Edition AA of S (ed) Proceedings of the Workshop on Applications of Radio Science WARS'97
19. (2003) The Use of Slope Stability Radar (SSR) for Managing Slope Instability Hazards, Product Brochure
20. Noon D, Bellett P, Campbell L (2011) A New and Easy-to-Use Slope Radar Tool for Mine Production Crews. In: International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering. Vancouver, Canada, pp 1–6
21. Harries N, Noon D, Rowley K (2006) Case Studies of Slope Stability Radar in Open Cut Mines. In: International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering, The South African Institute of Mining and Metallurgy, Symposium Series 44. pp 335–342
22. Calhill J, Lee M (2006) Ground control at Leinster Nickel Operations. In: Proceedings of the International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering, The South African Institute of Mining and Metallurgy, Symposium Series 44
23. Peltzer G, Rosen P, Rogez F, et al (1996) Crustal Deformation Studies Using Synthetic Aperture Radar (SAR) Interferometry. In: ERS SAR Interferom. Proc. Fringe 96 Work. https://adsabs.harvard.edu/full/1997ESASP.406...17P

24. Singhroy V, Molch K (2004) Characterizing and Monitoring Rockslides from SAR Techniques. Adv Sp Res 33: 290–295
25. Reutech (2006) Slope Monitoring, New Radar System Provides Accurate Slope Survey. Reutech Newsl.
26. Reutech (2008) Movement and Surveying Radar Newsletter. Reutech Newsl.
27. Sistemi ID IDS – Radar for Mining Applications. www.mining-technology.com/contractors/exploration/idsingegneria
28. Osasan KS (2012) Open-cast mine slope deformation and failure mechanism interpreted from slope radar monitoring, PhD Thesis. Johannesburg: s.n.