Review of Radar Technologies for Slope Stability in Open-Pit Mines

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Open-pit mining operations are inseparable from the risk of slope failures. These slope failures do not only cause extensive production downtime and damage to assets, but the biggest risk is the loss of human life. Engineering the open-pit design to mitigate the risk of slope failures is only part of the solution, as the risk can never be totally mitigated. The risk of slope failure must be managed daily during the operation of the open pit. Although there are various technologies and systems available to monitor the slope stability of final pit walls, this review focusses on the radar technologies currently available on the market. This paper compares the available technologies and discusses the critical factors to consider when deciding on a suitable slope stability radar.

INTRODUCTION

There are difficulties in predicting potential instabilities in vertically high pit slopes. This is evident especially during the design phase of the pit where limited geological data are normally available. The result is that a lot of emphasis is placed on slope-management systems to control the slopes during mining. A comprehensive slope-monitoring strategy forms a crucial part of any slope-management system. Monitoring is an invaluable tool for assessing design performance and failure risk. It plays a role in minimising risk associated with slope failure. In the mining industry today, mining companies have the financial and moral obligation to eliminate the potential for accidents and ultimately fatalities. Thus, the failure to identify potential slope hazards and manage the associated risk could result in fines, mine closures or both.

MONITORING STRATEGY

A comprehensive slope-monitoring strategy aids in the identification of the hazard and or risk. It introduces a level of comfort to the workforce by creating the expectation that the ground conditions are being monitored by experienced and competent personnel. The main objectives of a slope monitoring strategy can be noted as follows:

- by identifying high risk areas and limiting exposure, safe operating conditions can be maintained to protect the workforce and equipment;
- providing advanced notice of unstable zones with the potential for slope failures, which enable pro-active mine design changes;
- providing geotechnical data for analysis into slope instability mechanisms and designing appropriate remedial action plans;
- assessing the performance of the implemented slope design.

A comprehensive monitoring system will generally include instruments for both surface and sub-surface measurements, as mentioned by Read and Stacey (2009). Typical instruments are: visual inspection; cross-crack measurements; survey monitoring; global positioning systems (GPS); photogrammetry; laser scanning; radar.

Radar has recently been adopted as a tool for monitoring slope movement for both man-made and natural slopes. In recent years, slope stability radar has become an integral part of slope hazard and risk identification tools. This can ultimately lead to hazard and risk mitigation. Emphasis is placed on radar systems in this paper; looking at the different types, limitations and how to choose the system best suited to the posed problem.

RADAR

The term radar is an acronym for radio detection and ranging. A radar operates by radiating electromagnetic energy and detecting the echo returned from reflecting objects or targets in the scan area, as noted by Bellett *et al*. (2015). The nature of the echo signal provides information about the target. The range, or distance, to the target is found from the time it takes for the radiated energy to travel to the target and back. Deformation is determined by the phase change between two returning signals. The amplitude of the returning signal gives an indication of the strength of reflection of the signal. Understanding the variants and the limitations of each radar system will assist in the selection process when choosing the right radar.

Real Aperture Radar Versus Synthetic Aperture Radar

There are currently two generic types of slope monitoring radar available. These are similar in the way that interferometry is used to measure small changes in range. The significant difference is the way data are located and mapped. In other words, the technology forming the spatial distribution of the reflections from the surfaces to be monitored differs.

Real aperture radar (RAR) traditionally uses a "real" conventional dish antenna to mechanically scan an emitted pencil radar beam in raster fashion over the scanning area. The data collected with a pencil-beam radar are three-dimensional, representing the signal strength and phase angle in each elevation, azimuth, and range cell. Repeated scans allow the change in phase at each position to be measured and converted to the displacement in range from the initial position. RAR can now also produce a fine vertical fan beam that results in two-dimensional (2D) data representation. Figure shows the current RAR systems on the market: that on the left is from Reutech and the other two are from Groundprobe.

Figure : Real aperture radars.

Synthetic aperture radar (SAR) uses a synthetic or "virtual" antenna. SAR is based on the generation of an effective long antenna by signal-processing means, rather than by the actual use of a long physical antenna. This type of radar does not form a narrow transmitter beam like the RAR: rather it

transmits and receives a wide beam pattern as the antenna traverses a horizontal rail. Figure 1 illustrates the current variants of SAR on the market today, where that in the top-right corner is manufactured by Groundprobe and the others by IDS.

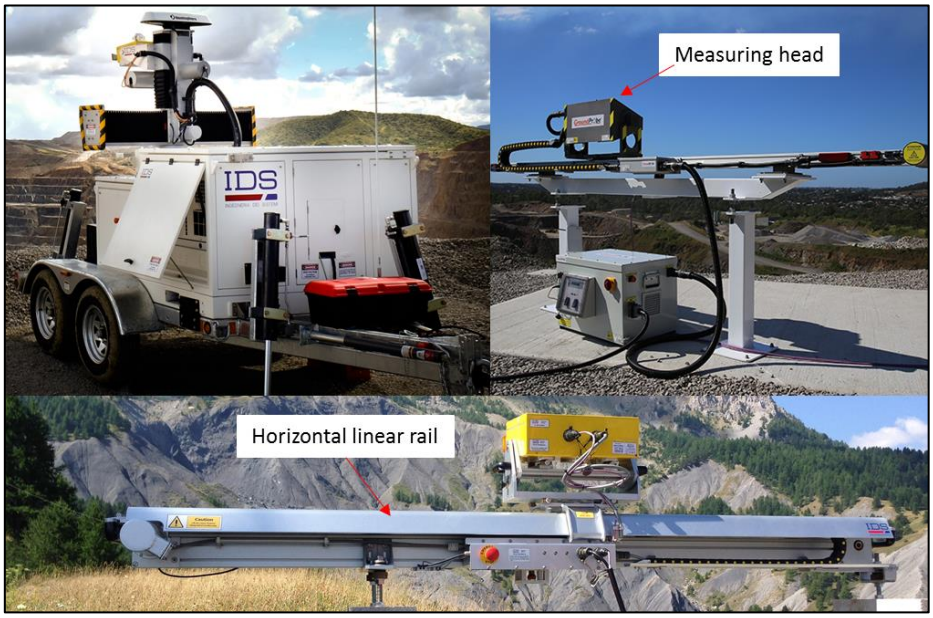

Figure 1: Synthetic aperture radars.

According to Longstaff (n.d.), the fact that vertical resolution is variable and dependent on the slope indicates the accuracy of measured displacements may not correspond well to the actual displacements. Hence, SAR-type of slope monitoring radar is not a precision instrument compared with real-beam radar; however, the SAR system is better suited for long-range and long-term monitoring.

Three-Dimensional versus Two-Dimensional Radar

Three-dimensional RAR creates a pencil radar beam that moves in a raster pattern across a selected scan area. Figure 3 illustrates how the 3D data is created by the radar. Each scan position has a distinctive horizontal (*Y*) and vertical (*Z*) position in the data set and a range (*X*) component, as demonstrated in Figure 3. The ability of the radar dish to move horizontally and vertically, combined with the range from the radar to the scan area, enables the 3D data generation.

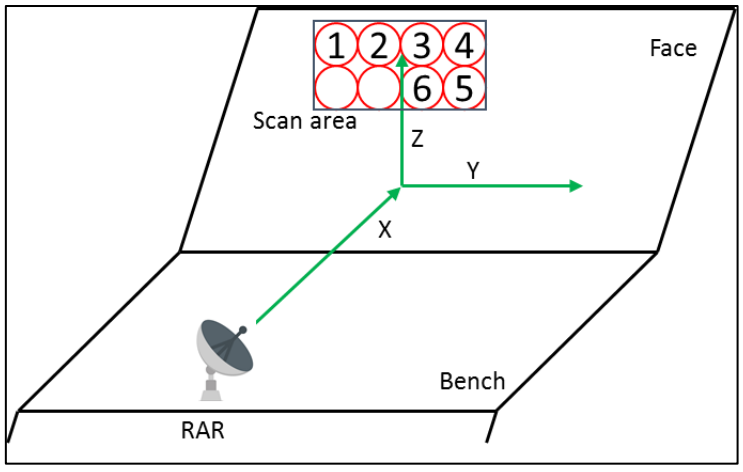

Figure 2: Real aperture radar creating three-dimensional data.

The pixel generation or resolution of the 3D RAR is dependent on the range (distance from the radar to the scan area), as schematically represented in Figure 4. For example, scanning a highwall 1000 m away might create 10 m × 10 m pixels; scanning the same size highwall at 2000 m might create 17 m × 17 m pixel. If the bench height is 10 m, scanning from 1000 m will vertically divide the bench into one pixel. Scanning the same highwall from 2000 m will have 1.75 bench in a pixel.

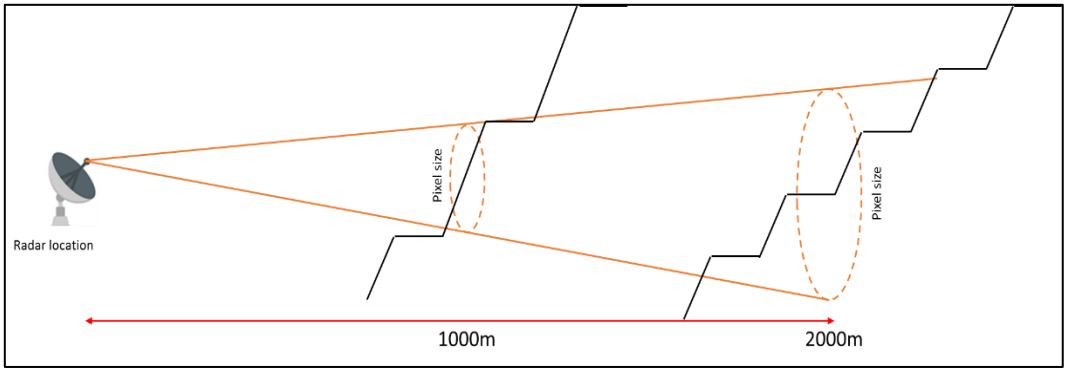

Figure 3: Resolution of real aperture radar.

Two-dimensional RAR uses large antenna that move horizontally to create the 2D data, as can be seen in Figure 5, which illustrates the horizontal (*Y*) movement across the scan area combined with the range (*X*), which relates to the 2D data representation. Although a point cloud of the data can be draped on a 3D surface of the scan area to represent the data in 3D, the data received from the radar is still only in 2D.

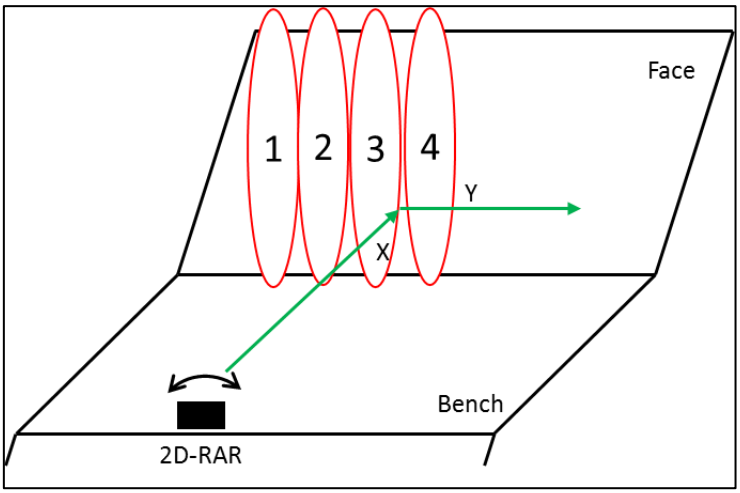

Figure 4: Two-dimensional real aperture radar creating two-dimensional data.

Two-dimensional RAR and SAR pixel size are influenced by the angle at which the radar signal intercepts the scan area. Figure 6 illustrates this concept, where the number of pixels into which the bench is vertically divided is dependent on the angle at which the radar signal intersects the bench. The pixel sizes and angles are for explanation only and are not according to scale.

SAR creates a balloon-shaped beam with small broad-beam horn antennas that only move in a vertical direction over the scan area. The measuring head moves on a horizontal linear rail in small steps, which then covers the entire scan area in these balloon-shaped beams. This horizontal (*Y*) movement across the scan area, combined with the range (*X*), relates to the 2D data representation in the same way as 2D RAR.

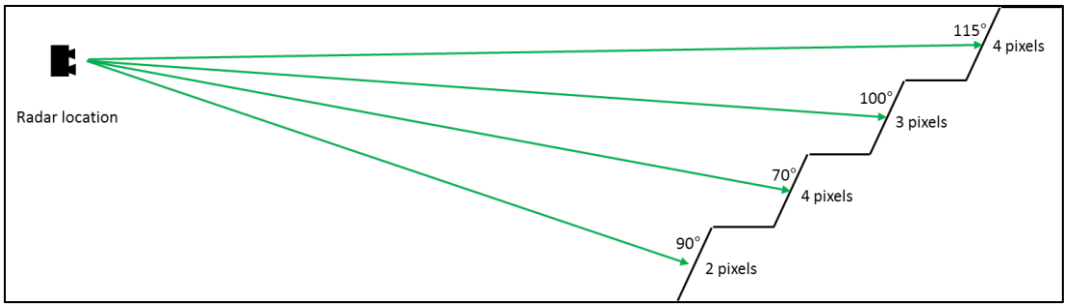

Figure 5: Synthetic aperture radar resolution.

Limitations of Radars

External factors play to the practical limitations of slope stability radars. Such factors include the movement of vegetation, interfering reflections, moving machinery and, most important, atmospheric changes. With the first two factors mentioned, both types of radar will be affected in a similar way, but with the last two the data are affected very differently.

Deformation measurement

Radar uses interferometry to determine deformation. The maximum deformation that can be measured in a direction, either towards or away from the radar, is limited by the wavelength of the radar signal. The RAR wavelength is around 16 mm, which means that maximum measurable deformation towards and away from the radar will be 8 mm. SAR has a shorter wavelength, which allows for about 4.2 mm measurable deformation towards and away from the radar. Figure 7 illustrates the wavelength and amplitude of the radar signal transmitted to the scan area.

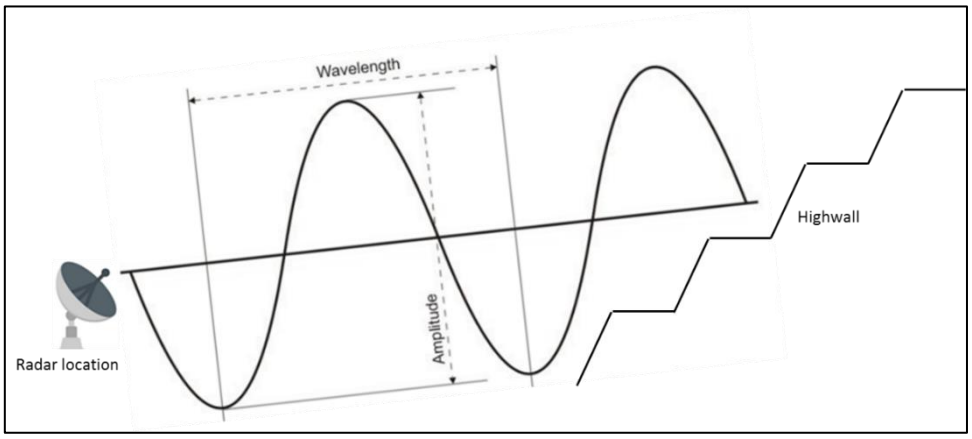

Figure 6. Radar has limited deformation, depending on the wavelength of the radar signal.

Atmospheric influence

All radar signals travels through the atmosphere and will therefore be affected by changes in the atmospheric conditions. Changes in temperature, humidity and pressure influence the refractive index of the atmosphere. The refractive index influences the rate at which the radar signal travels through the atmosphere and could be incorrectly illustrated as deformation.

Figure *7* shows radar signals traveling through various weather conditions. These could be incorrectly interpreted as deformation. For example, as the signal travels through rainy or overcast conditions, the time it takes for the signal to return is influenced by the change in humidity. As previously mentioned, deformation is determined by the time it takes for a signal to travel over the range between the radar and the scan area; therefore, a change in range or deformation can be incorrectly represented due to the change in travel time of the signal.

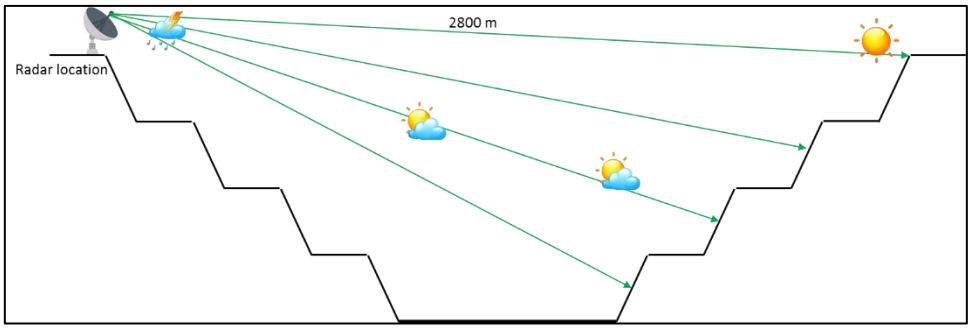

Figure 7: Atmospheric influences the returning radar signal and can be seen as deformation measured.

Vector loss

All radar systems can only measure deformation in one of two directions: towards the radar and away from the radar. The positioning of the radar with regards to the direction of movement will influence the accuracy of the deformation measurement. Figure 8 illustrates a concept called vector loss. It represents the percentage real deformation that is lost based on the angle between the direction of deformation movement and the radar signal. For example, if the radar signal is parallel to the movement direction, 100% deformation will be measured. If the radar signal is at 45° to the movement direction, only 50% of the deformation might be measured.

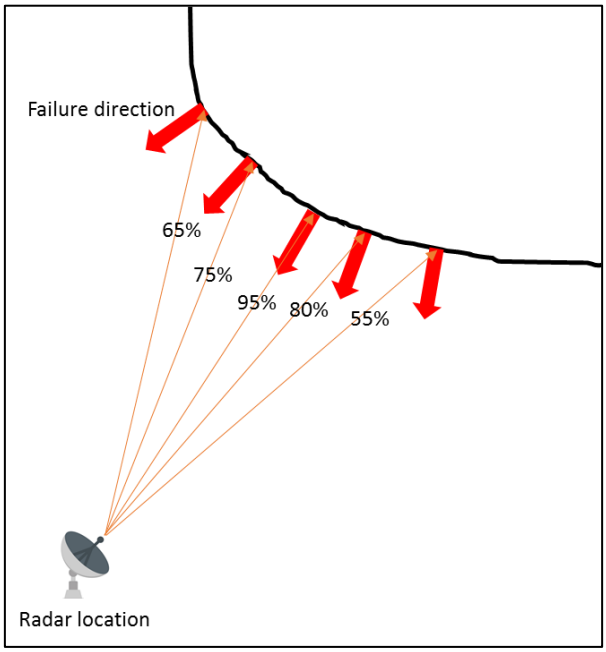

Figure 8: Vector loss influencing the deformation measured.

Rock type and failure mechanism

The failure mechanism plays a very important role in the selection of a radar type. The rate of movement is dependent on the failure mechanism and rock type. Circular-type failures usually occur in softer rock types, which tend to move more slowly than wedge or plane failures. These types of failures usually occur in hard rock types. RAR would be more suitable for slower-moving failures because the scan time is dependent on the size of the scan area and a faster-moving failure might occur between two scans. The failure mechanism and rock type impact the velocity or deformation/mm rate of the moving material. The main types of failure mechanisms are shown in Figures 10 and 11.

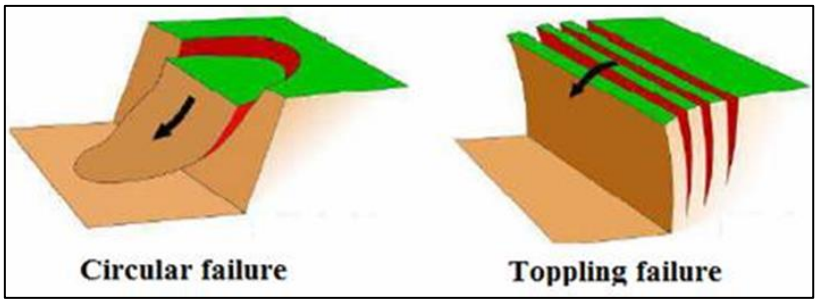

Figure 9: Circular and toppling slope failure mechanisms.

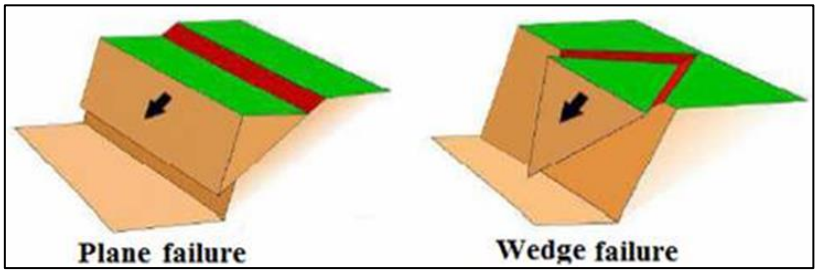

Figure 10: Plane and wedge slope failure mechanisms.

CONCLUSION

With respect to conventional monitoring systems, radar technology presents the advantages of high accuracy of the measurements, long-range capabilities, limited impact of atmosphere on the measurement performances and the possibility to simultaneously acquire the response over a large number of points.

Table I shows recommended radars to be used for various scenarios. These are based on the advantages of each type of radar as well as the limitations associated with each.

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Table I. Best suited radars.

	RAR vs SAR	Comments
Critical (target) monitoring	3D RAR	Focus monitoring on a known high-risk area
Broad area monitoring	2D RAR & SAR	Covers larger mine area to identify new risk and hazards (monitoring an area as big as possible).
Short range	RAR	Max. 2800 m
Long range	2D RAR & SAR	Max. 4500 m
Single or partial bench failure	RAR	Depends on resolution and distance to the slope
Multi-bench failure	2D RAR & SAR	Depends on resolution and distance to the slope
Dry climate	RAR	Less atmospheric influence
Wet climate	2D RAR & SAR	More atmospheric influence
Circular failure	RAR & SAR	Slower-moving failures, can use both SAR or RAR
Wedge failure	2D RAR & SAR	Fast-moving failure, but if wedge is known and being critical, monitoring with 3D RAR which would reduce the scan area
Plane failure	2D RAR & SAR	Fast-moving failure, but if plane is known and being critical, monitoring with 3D RAR would reduce the scan area
Complex pit design	2D RAR & SAR	SAR gives bigger scan area
Vegetation	RAR	RAR pixel size makes it possible to identify vegetation
Groundwater	RAR	RAR pixel size makes it possible to identify water
Scan size	2D RAR & SAR	Faster scan time