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Line-of-sight and total vector displacement discussion in slope monitoring: a case study at an open pit mine

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Abstract

Slope monitoring programs must be designed with the primary purpose of providing safety to personnel and equipment. The failure mechanisms and risk, in terms of the likelihood and consequences of slope movement types, inform the selection of suitable equipment for a reliable monitoring system.

The use of ground-based radar (GBR) in open pit mining has affirmed its efficiency in detecting movement and predicting failures with warning, near real-time acquisition and high precision – proving its need in critical cases. GBR is very important to indicate change of behaviour of a geotechnical structure and displacement trends, especially when a prompt response is mandatory, but is limited in interpreting the total vector displacement (direction and magnitude) and support failure mechanism investigation. In addition, the calibration of radar sensitivity to the real movement is necessary to evaluate its efficiency. If a particular area is moving orthogonal to the line-of-sight, the radar will not detect the full magnitude of the movement; consequently, it is not sufficient on its own to ensure adequate data collection for alarming purposes.

The total station combines measurements of the horizontal and vertical angles, and distances of the equipment to the monitored targets (prisms), to track displacement in 3D space. Collection of data over time provides the change in the position of the prisms, which is used to calculate and understand the displacement vector at slope walls and interpret failure mechanisms. Other than providing a vector of movement, robotic total stations (RTS) operating on a 24/7 mode validate the measurement data of other systems such as GBRs, and tracks wall displacement trends efficiently.

This article presents a real slope movement situation that was monitored with an RTS and a GBR installed at the same location and monitoring the same target. Interpretation and discussion of the output data, sensitivity calculation to the real movement, particularities and benefits of both technologies is provided, as well as the application in this case study.

Keywords: *slope monitoring, line-of-sight, total vector displacement, ground-based radar, robotic total station*

1 Introduction

This case study involves one of Vale´s legacy mines, located at the Iron Quadrangle in Brazil. Its monitoring system includes piezometers, water level indicators, weather stations, inclinometers, crack meters, InSAR (satellite-based radar), ground-based radar (GBR) real aperture radar (RAR), and a robotic total station (RTS). In 2023, after a heavy rainfall event, it was noticed that an area of approximately 4,300 m^2 indicated reactivation of movement. It was first detected by two prism targets inside the moving mass that set off a long-term alarm. Full instrumentation was then evaluated individually, and cross-correlated to support the assessment of the failure mechanism and interpretation of triggers and responses.

This article focuses on the data collected by the surface monitoring equipment – GBR and RTS – and it raises the importance of having total vector displacement data available for assessment. This work used a GroundProbe (GP) RAR and a Leica TM-50 RTS.

Four active prism targets were evaluated in this analysis: two inside the unstable area and two outside of it. Figure 1 illustrates the location of the moving mass detected by the radar, prism positions and the tension crack mapped in the field. Figure 2 shows the 3D view of the radar area projected on the pit surface, RTS and radar positions, and the two prisms inside the moving mass.

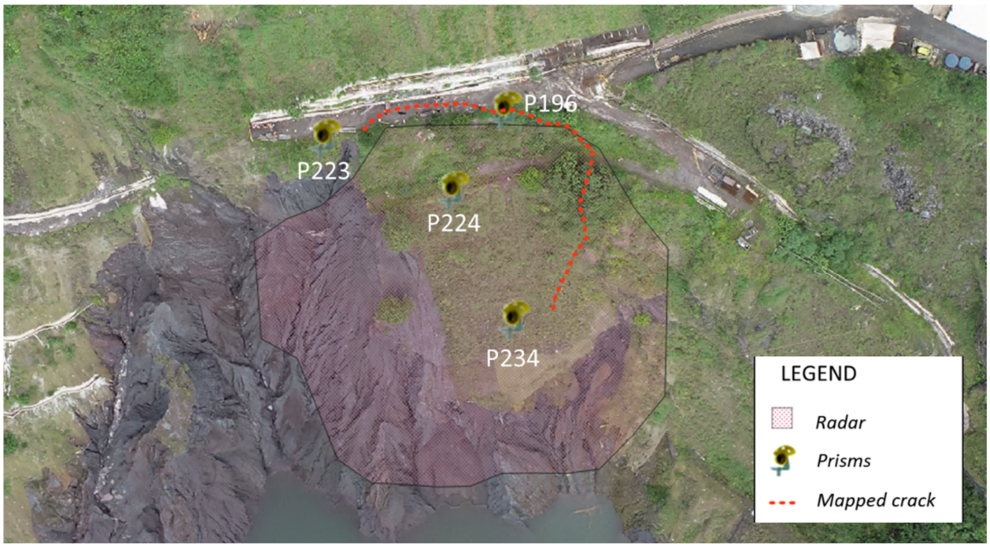


Figure 1 Plan view of moving mass detected by GBR, prism locations and mapped crack

Figure 2 3D view of the area detected by GBR, prisms inside the moving mass and the location of equipment (RTS and GBR)

2 Data and methods

2.1 RTS data

As mentioned previously, RTS combines measurements of the horizontal and vertical angles, and the distance of the equipment to the monitored targets. Based on survey calculations it is possible to combine these measurements to track displacement vectors of the target (3D, 2D and 1D displacements in the north–south, east–west and height).

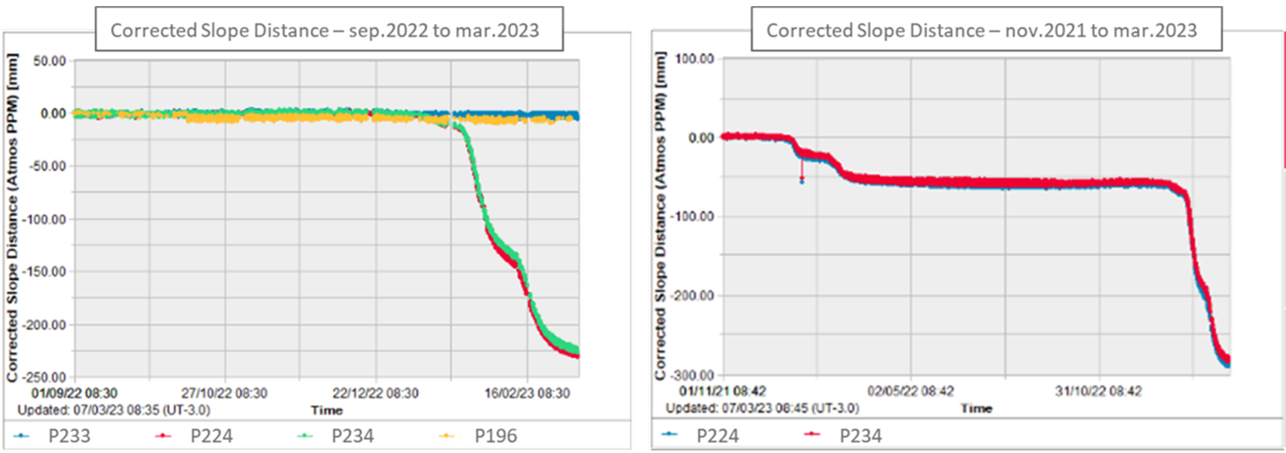
Reactivation of movement was first indicated by a long-term alarm set off by two target points (P224 and P234, inside the moving mass) as shown Figure 2. The alarm was defined on the slope distance parameter, which is analogous to RTS (line-of-sight) LOS. All alarms on the RTS were set using slope distance, mainly due to its lesser susceptibility to noise and system orientation. Klappstein et al. (2014) pointed out when investigating the accuracy of their RTS monitoring system that:

- Horizontal movements had the greatest error with distance, likely due to errors in calibration of the horizontal angle.
- Vertical movement had slightly less variance error with distance.
- The slope distance measurement was the most predictable (precise) of the three outputs'.

That being said, the investigation raised the following questions:

1. What is the extent of the moving mass? Was the movement propagated above towards other prisms near the triggered ones? This is important as the main access to the pit´s north wall is immediately above the moving area. (This is possible to evaluate with LOS.)
2. What is the magnitude of displacement compared to the historical data? Is the movement faster than seen in previous years? What is the displacement ratio of the current event to the historical data? (This is possible to evaluate with LOS but must be compared in true vector displacement.)
3. What is the direction of movement and has it changed over time (specify months or years)? If so, is there an indication to its cause? (Use true vector displacement.)
4. What is the percentage of true movement seen on slope distance? (Use the comparison of LOS to true vector displacement.)

According to the Figure 3a plot, it was observed that the movement was not propagated above to the access road, as prisms P233 and P196 remained stable; and to the Figure 3b plot, the magnitude of displacement experienced in the previous rainy season was much smaller compared to the current year (which was close to three times bigger in LOS). The graphs below indicate a negative trend which implies movement approaching the RTS.



(a) (b)

Figure 3 **(a) Corrected slope distance data of four analysed target points (2022–2023 rainy season); (b) Corrected slope distance data of the two unstable target points (2021–2022–2023 rainy seasons)**

Figures 4 and 5 show LOS magnitude, the true height vector magnitude, and the plan view direction of prisms P224 and P234 for the 2021–2022 rainy season and 2022–2023 rainy season, respectively. The analyses indicate corrected slope distance (negative approaching the RTS), height displacement (negative subsidence) and a 2D plan view of both targets. It was important to also evaluate the vertical cross-section of movement (profile) to understand the dip angle of movement for each prism. The values were manually calculated with basic trigonometry and the raw data was exported through a spreadsheet. The information collected is summarised in Table 1.

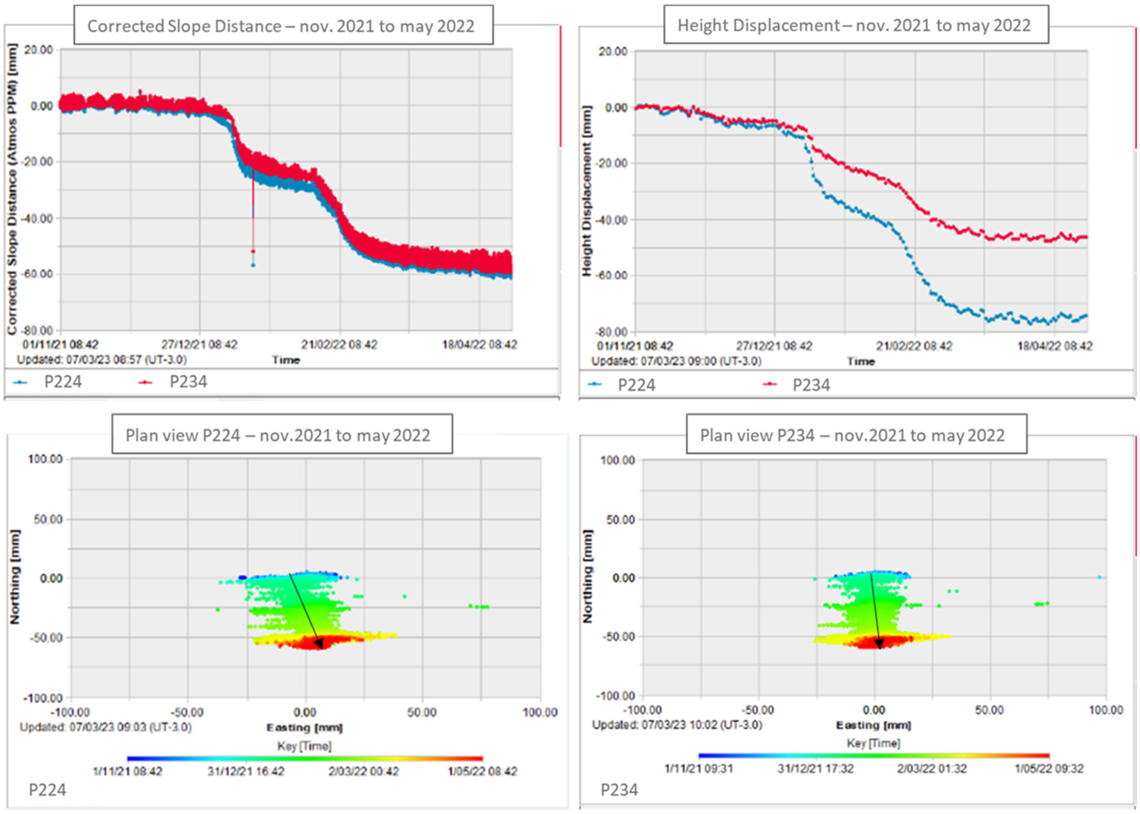


Figure 4 Prisms P224 and P234 true displacement vector evaluations of the 2021–2022 rainy season

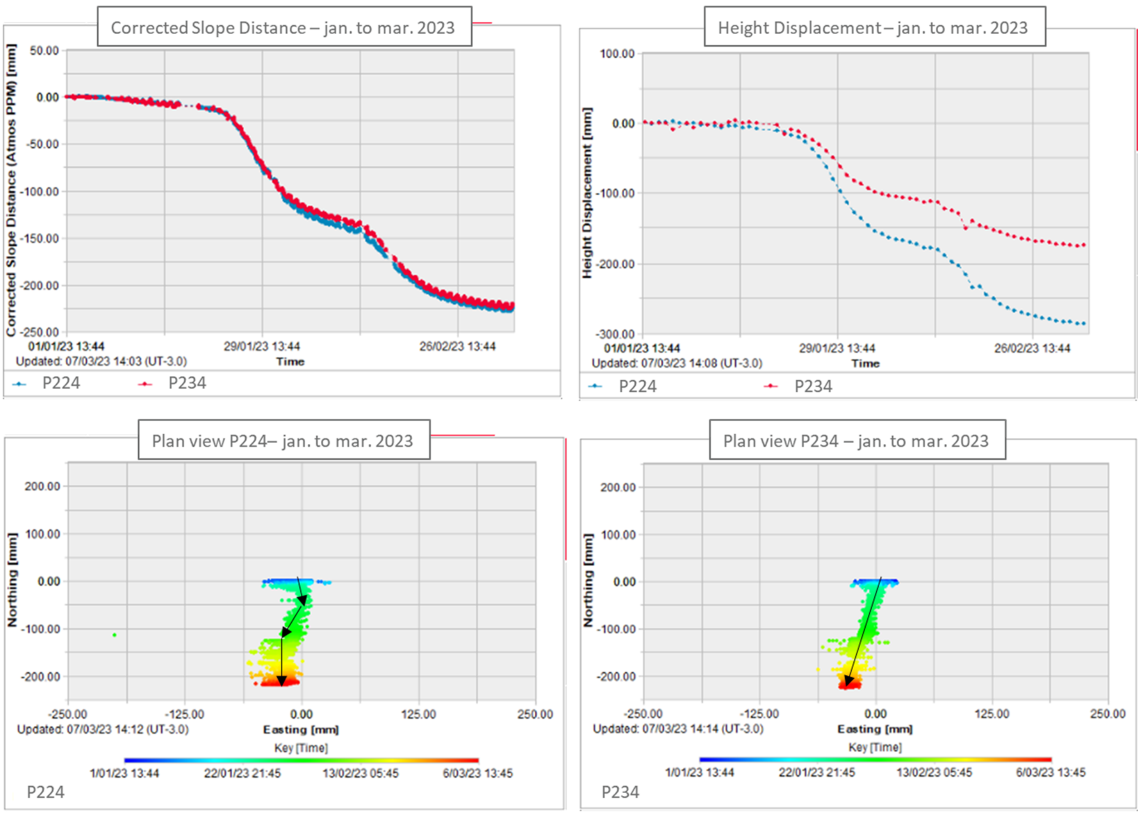


Figure 5 Prisms P224 and P234 true displacement vector evaluations of the 2022–2023 rainy season

Table 1 Summary of RTS data interpretation

Rain season	Target point	2D plan view (mm)	1D height (mm)	2D profile (mm)	Direction of movement	Dip (°)
2021–2022	P224	50	80	90	Southeast	58
2022–2023		220	300	370	South (variable)	54
2021–2022	P234	50	50	70	South	45
2022–2023		220	180	280	South-southwest	39

2.2 GBR data

The GBR installed on this open pit is a 2D RAR (GP SSR-FX). There are two types of radar, real and synthetic aperture. Real aperture radars differ from synthetic aperture radars in that the signal footprint sent to the wall is formed naturally by the physical antenna, and the aperture of the signal is what the antenna can deliver. Synthetic aperture radars generate the aperture of the signal through a synthetic process, mathematically. In both cases the resolution of the radars depends on the antenna and linear positioner size, in combination with the frequency used in the signal transmitted.

The smaller the pixel size the better, as it provides a higher resolution of pixels projected at the slope wall. In this case, the GBR is relatively close to the slope wall and the advantage is that the SSR-FX can scan up to 210° x 60° (azimuth and elevation), covering the entire north wall in usually less than two minutes. The distance between the radar and the slope is approximately 700 m, producing a pixel size varying from 3.9 x 0.68 to 7.7 x 0.68 m, which is equivalent to an average 4 m^2 pixel size. Besides having a good resolution and determining the equipment fit to the monitoring scenario, it is important to mention that this pit, as a legacy mine, has developed a significant amount of dense vegetation which is a major drawback to radar capability. Areas covered with dense vegetation prevent the electromagnetic wave penetrating them and reaching the surface ground, increasing data noise and reducing its reliability. Figure 6 exemplifies the interpretation of noise caused by vegetation and the real slope movement detected by the radar.

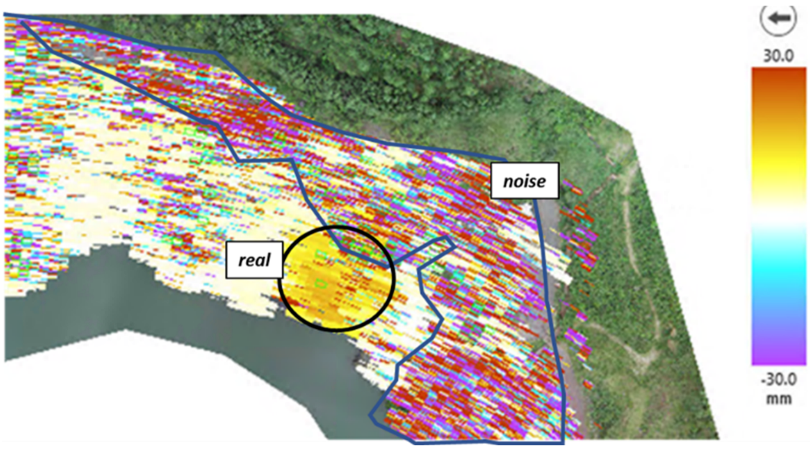


Figure 6 Example of noise caused by dense vegetation at the slope wall and real movement detected by the GBR in this case study

Following the RTS triggers, an extensive investigation was carried out on the RAR GBR. Data was analysed as 24-hour cumulative displacement on the map to identify the moving area. These maps were evaluated as sets of figures for the two progressions, and likewise noticed in the prism data. Figure 7 exemplifies these displacement maps, from 23 January to 1 February 2023 as an example. Positive displacement in this equipment indicates movement towards the radar, and negative displacement shows movement away from the radar.

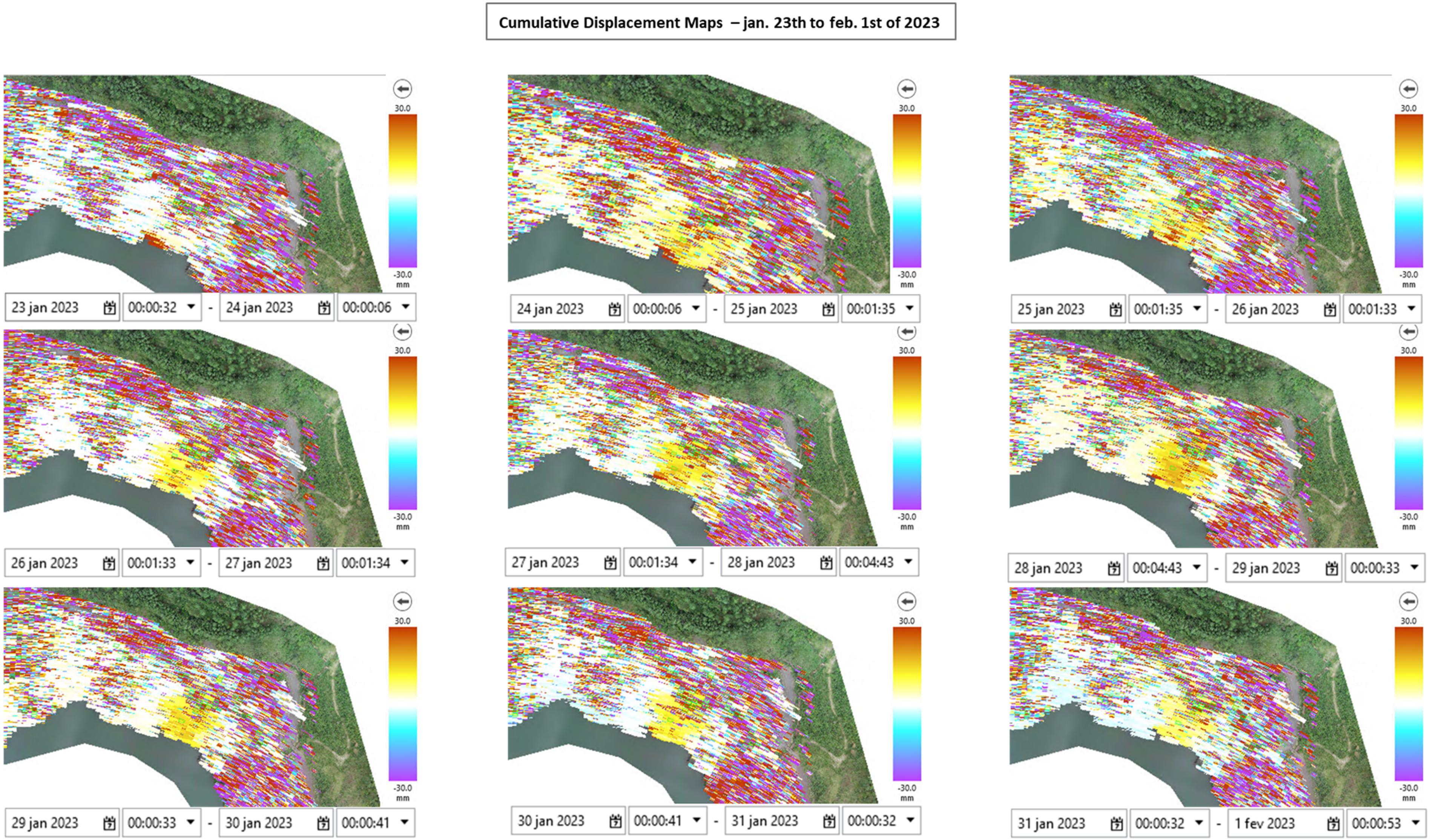


Figure 7 24-hour RAR cumulative displacement maps from 23 January to 1 February 2023 (with a 30 mm scale), when the first displacement progression was noticed

The cumulative displacement maps indicate another concern related to radar monitoring: the influence of atmospheric effect on data. Note the information given on 24 and 31 January, whereby the maps are considerably coloured in yellow or blue. According to Sharon & Eberhardt (2020):

> *'The propagation of the electromagnetic waves through the atmosphere is affected by variations of temperature, humidity, and pressure. Changes in atmospheric refractivity present slope monitoring radars with their most difficult challenge. This disturbance causes a shift in the phase of the backscattered signal and can be significant, requiring a correction of the data. Standard correction algorithms assume stability in the atmospheric conditions over the monitored area of interest, which are assumed as reference points for the calculation of the atmospheric correction'.*

After identifying the area on the radar cumulative displacement map, the analysis raised these questions:

1. What is the extent of the moving mass?
2. Was the mechanism noticed before radar data became available?
3. What is the velocity of the moving area?
4. Is the velocity of the first and second trends similar (velocity ratio)?
5. Is the velocity of the total area alike if smaller areas are to be sampled inside its perimeter? This information is important as larger areas tend to underestimate displacement over smaller areas. Areas average the displacement and velocity of radar pixels.

At first the total area (4,300 m^2) was analysed individually. Figure 8 shows the plot of displacement over time in January 2023. The first week of January, however, indicated a trend not implied by the RTS data. To evaluate it, the cumulative displacement map was analysed for this period (6–8 January) as shown in Figure 9. It was found that the deformation was concentrated at the toe of the total area, contributing significantly to its average displacement. Visual evaluation using the radar camera indicated that there was a significant loss of material at the toe following the rain event of the first week of January. To contribute, images over the years were compared to understand the erosion development (Figure 10). It was possible to conclude that the material that was washed away at the toe/lateral to the area of interest reduced its stability and reactivated the movement of the bigger mass (total area).

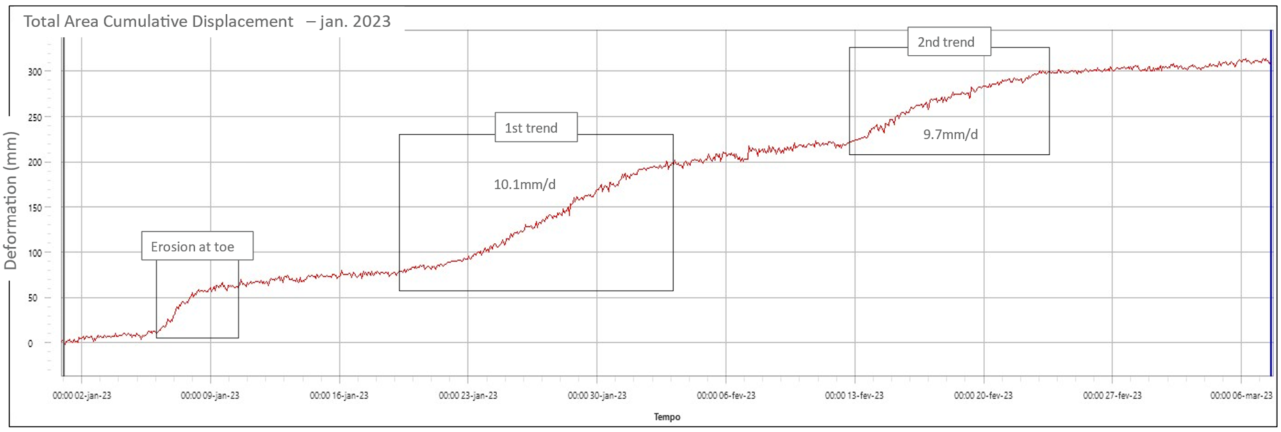


Figure 8 Total area displacement trend from January to March

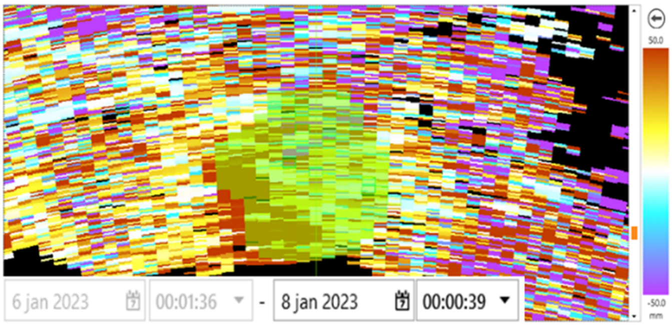


Figure 9 Total area cumulative displacement map for the first week of January 2023, indicating movement at the slope toe

Figure 10 Images over the years indicating the erosion development at the toe, lateral to the moving mass

Following this, smaller areas with good quality data (coherence above 0.95) inside the perimeter of the total area were sampled. It was observed that behaviour in the macro scale was mirrored in medium and smaller scales (700 m^2 down to 30 m^2), pointing out that the full mass was moving together. Both progressions indicated the same linear trend and velocity of approximately 10 mm/day in LOS vector.

2.3 RTS slope distance and radar LOS vector sensitivity

Displacement sensitivity is the percentage of the total displacement vector that the equipment is capable of measuring. Radar, analogous to RTS slope distance, is a 1D measurement along the LOS vector from sensor to target. If the total displacement vector happens to overlap the LOS vector, then 100% of the movement is measured. However, these two vectors will typically differ, and radar/RTS slope distance will underestimate the true magnitude of displacement.

Having both RTS and GBR in the monitoring system of this pit made it possible to calibrate the radar LOS to the total displacement vector. For the sensitivity calculation and calibration, the applied method used basic algebra, the directional cosine of the LOS versor and the movement versor (Carlà et al. 2017).

The sensitivity calculation was based on movement given by prisms P224 and P234, inside the perimeter of the moving mass and considering the versors of the 2022–2023 rainy season. The sensitivity to the movement was 55% in the upper prism (P224) and 78% in the lower prism (P234), which are equivalent to a 1.8 and 1.3 correction factor, respectively. This means that, for example: if the radar detects a deformation of 1 cm in LOS at the upper part of the total area, the true vector magnitude of movement is 1.8 cm; and, analogous to a 1 cm movement in P224 slope distance parameter, the true vector magnitude of movement is 1.8 cm. One needs to understand that if the direction of movement changes, the sensitivity analysis must be recalculated.

Coincidentally, the two pieces of equipment are installed side by side, making it possible to compare the slope distance parameter from RTS to GBR LOS. Figure 11 shows the magnitude and trends of the displacement of the total area and the two prisms (LOS). It was observed that they were very similar when compared to one another, validating the concept analogy of slope distance and LOS.

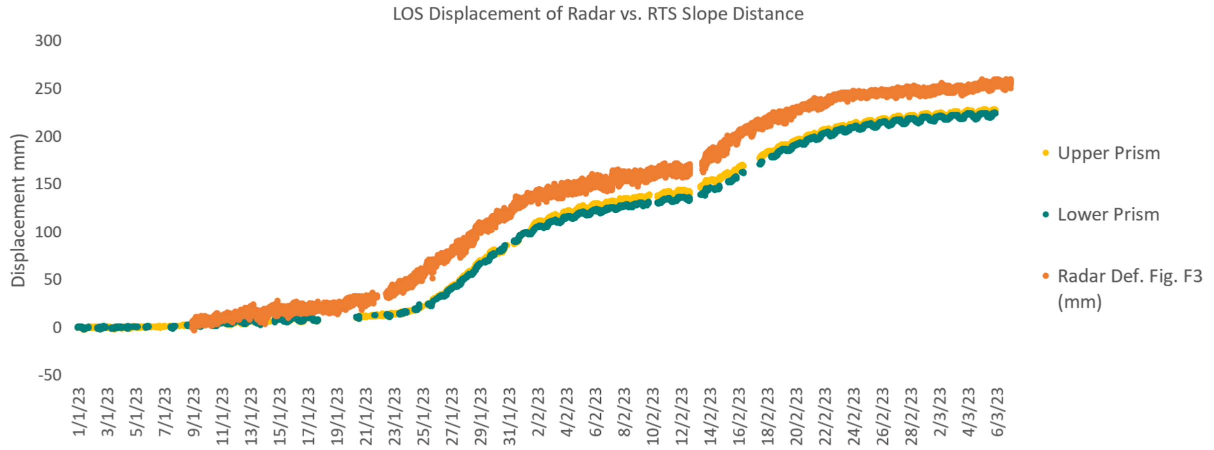


Figure 11 The LOS displacement trend and magnitude of the radar total area and the two prisms inside its perimeter

3 Results and discussion

In this study, RTS and GBR data, evaluated separately and cross-correlated, were critical to develop an understanding of the monitored area.

Thorough conventional surveying with RTS, it was possible to identify:

- No propagation of movement to the north wall access road (somewhat determines the extension of the moving mass).
- The same instability in the past year, however, with three times less deformation compared to the current year.
- Movement shifted its direction from 2022 to 2023, basically from south-southeast to south-southwest.
- Movement is bigger at the upper part of the mass, where the tension crack was also mapped in the field.
- The correction factor of LOS to the total vector displacement.
- Track displacement with long- and short-term alarm trends, progression, linear and regression.

Based on the GBR, it was possible to identify the:

- Extent of the moving mass.
- Macro and micro scales of deformation trend and velocity.
- Movement trigger, loss of material at the slope toe and, consequently, the unconfinement of the mass of interest, changing the direction of movement seen in the RTS data.
- Track displacement with long- and short-term alarm trends, progression, linear, and regression.

It is important to mention that the monitoring system of this open pit includes many other instruments that were also evaluated and cross-correlated. During the evaluation of datasets, access to the unstable area and other areas of interference were isolated. The monitoring output was key to understanding the failure mechanism of the slope, and to support slope stability analysis and the trigger action response plan calibration. It was found that the soft hematite was sliding on a hard itabirite contact when the mass of the toe was washed away after a heavy rainfall event. The mass was unconfined and shifted its sliding direction. Movement stabilised after March 2023 and has remained stable to date.

To summarise, the presented case study aligns with the information provided by Sharon & Eberhardt (2020) regarding radar and total station capabilities and limitations (Table 2).

Table 2 Summary of capabilities and limitations of GBR and total station for slope monitoring (adapted from Sharon & Eberhardt 2020)

Monitoring method	Capabilities	Limitations
Total station with prisms	Measures and tracks total vector movement	Angular error in repeatability proportional to distance from target – creates short-term noise
	Strategic or investigative and performance monitoring	Safety-critical monitoring
	Validated measurements from other systems	Monitoring limited to points where prisms are installed, must physically access area of interest
	Interpretation of failure modes	Measurement frequency limited to cycle time of the total station
	Monitors moderate to large block sizes	Measurability deteriorates over time with pitting, dust and loss of prisms
	Addresses operational and financial applications (e.g. slope design)	Changing atmospheric conditions
GBR	Measurement precision is at a very high level	Measures movement only along the LOS
	Monitoring frequency can be in near real-time	Unit cost
	Monitors small to large block sizes	Typically requires external support and associated costs
	Can see through dust and moisture	Unable to see though mesh installed on the slope or vegetation
	Monitors speed of failure from slow to rapid	Increased rate of movement can lead to phase ambiguity
	Differentiates stable limits of moving ground over large areas	Complexity of vendor-derived algorithms that could limit system performance
		Sensitive to changing atmospheric conditions

4 Conclusion

As with every technology, monitoring equipment has its limitations. One of the most considerable limitations, if not the most, that must be evaluated when applying GBR and an RTS slope distance parameter is the LOS, as these can only measure displacement in one dimension, indicating that the real movement of a slope will always be underestimated. If a particular area is moving orthogonal to the LOS, the radar will not detect the movement at all; consequently it is not sufficient to ensure safety on its own. Another scenario that must be considered is having dense vegetation at the slope wall, which reduces a radar's capability to track ground movement.

For areas associated with geotechnical risks and which must be safety-critical monitored, the application of both GBR and RTS is recommended. In this case study the combination of this equipment was crucial to the analysis and interpretation of the instability identified at the north wall. LOS calibration and interpretation of the sliding mechanism was only possible using: the conventional surveying method (RTS); movement in north, east and height; the 2D horizontal plane and the 2D profile.

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