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InSAR monitoring guidelines: using simple to use decision trees – an owner's perspective

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Abstract

Interferometric synthetic aperture radar (InSAR) application has recently benefited from an increased number of service providers (with more diverse satellite constellations), advances in algorithm processing methods and, with reductions in costs, is becoming a widely accepted method of surface deformation monitoring in the mining industry. InSAR monitoring is consequently being applied to a wide array of mine infrastructure and geotechnical risk management scenarios ranging from construction to operating and closed mines, including natural slopes traversed by mine access roads, rail and pipelines, to engineered open pits, waste dumps and tailings dams, as well as identification of subsidence and onset of potential collapse due to either active or legacy underground mining and/or karstic terrain sinkhole development. With this increased interest from a growing array of diverse technical disciplines, it has been shown that InSAR monitoring is complex and there are many variables to consider and levels of monitoring possible. Furthermore, making sense of vendors' claims on system deliverables versus demonstrated outcomes can be challenging. These aspects need to be considered and aligned with the anticipated mode of instability, size, magnitude and rate of movement, and the business risk. Using a premium InSAR product (as high resolution data with two look directions and high frequency reports) when budget is not a limiting factor or using a budget constrained product (such as low resolution freely available Sentinel data), unless appropriately matched to the business risk profile (and deformation characteristics), will likely lead to underwhelming and possibly misleading results.

This paper describes how decision trees were developed to assist in selecting the level of InSAR monitoring considering the asset infrastructure risk and the physical characteristics of the area of interest. The decision trees were built such that the user, without extensive technical knowledge of how InSAR functions, can make an independent evaluation of what InSAR product is adequate. A simple cost versus risk trade-off tool is discussed, outlining how the decision trees were developed to determine whether InSAR would be a viable solution at the site and what the appropriate resolution, acquisition frequency, report frequency, and orbit/s should be. This provides a consistent framework for firstly evaluating and matching monitoring rigour with geotechnical risk, secondly a process to facilitate alignment and ideally optimisation of monitoring outcomes between disciplines, and finally for communicating these to management to demonstrate an effective business case for monitoring.

Keywords: *InSAR, slope stability, tailings dams, displacement monitoring, risk management, decision tree*

1 Introduction

Interferometric synthetic aperture radar (InSAR) application has recently benefited from an increased number of service providers (with more diverse satellite constellations), advances in algorithm processing methods and with reductions in costs is becoming a widely accepted method of surface deformation monitoring in the mining industry. InSAR monitoring is consequently being applied to a wide array of mine infrastructure and geotechnical risk management scenarios ranging from construction to operating and closed mines, including natural slopes traversed by mine access roads, rail and pipelines, to engineered open pits, waste dumps and tailings dams, as well as identification of subsidence and onset of potential collapse due to either active or legacy underground mining and/or karstic terrain sinkhole development. With this increased interest from a growing array of diverse technical disciplines, it has been shown that InSAR monitoring is complex and there are many variables to consider and levels of monitoring possible. This paper describes how decision trees were developed to assist in selecting the level of InSAR monitoring considering the asset infrastructure risk and the physical characteristics of the area of interest. There is a school of thought that believes you should ‘buy the highest level of monitoring capability you can afford’. In principle, this makes sense, however, the challenge arises in demonstrating to management value or risk mitigation that can be achieved through monitoring. What is the effectiveness of the system to detect the early onset of the anticipated mode of instability, and how can this be integrated into the risk management plan? The decision trees were built such that the user, without extensive technical knowledge of how InSAR functions, can make an independent evaluation of what InSAR product is adequate. This provides a consistent framework for firstly evaluating and matching monitoring rigour with geotechnical risk, secondly a process to facilitate alignment and ideally optimisation of monitoring outcomes between disciplines, and finally for communicating these to management to demonstrate an effective business case for monitoring.

2 Applicability of the guidelines

An internal company guideline on InSAR monitoring is under development with the purpose of enhancing the understanding of InSAR and to ensure a common risk-based approach for selecting InSAR monitoring products across the operations. The specific objectives of the guidelines are to:

1. Describe at an introductory level how InSAR monitoring works (including benefits and limitations).
2. Describe the site-specific variables and deformation characteristics (footprint size, rate of movement, climate, man-made disturbance influences, etc.) that must be known to make informed decisions on what level of InSAR monitoring should be applied.
3. Provide guidance when the site-specific variables are known on what InSAR product level is reasonable with the use of simple to use decision trees.
4. Describe ways to moderate the budget when necessary.
5. Provide a consistent framework to evaluate the business case for monitoring to management.

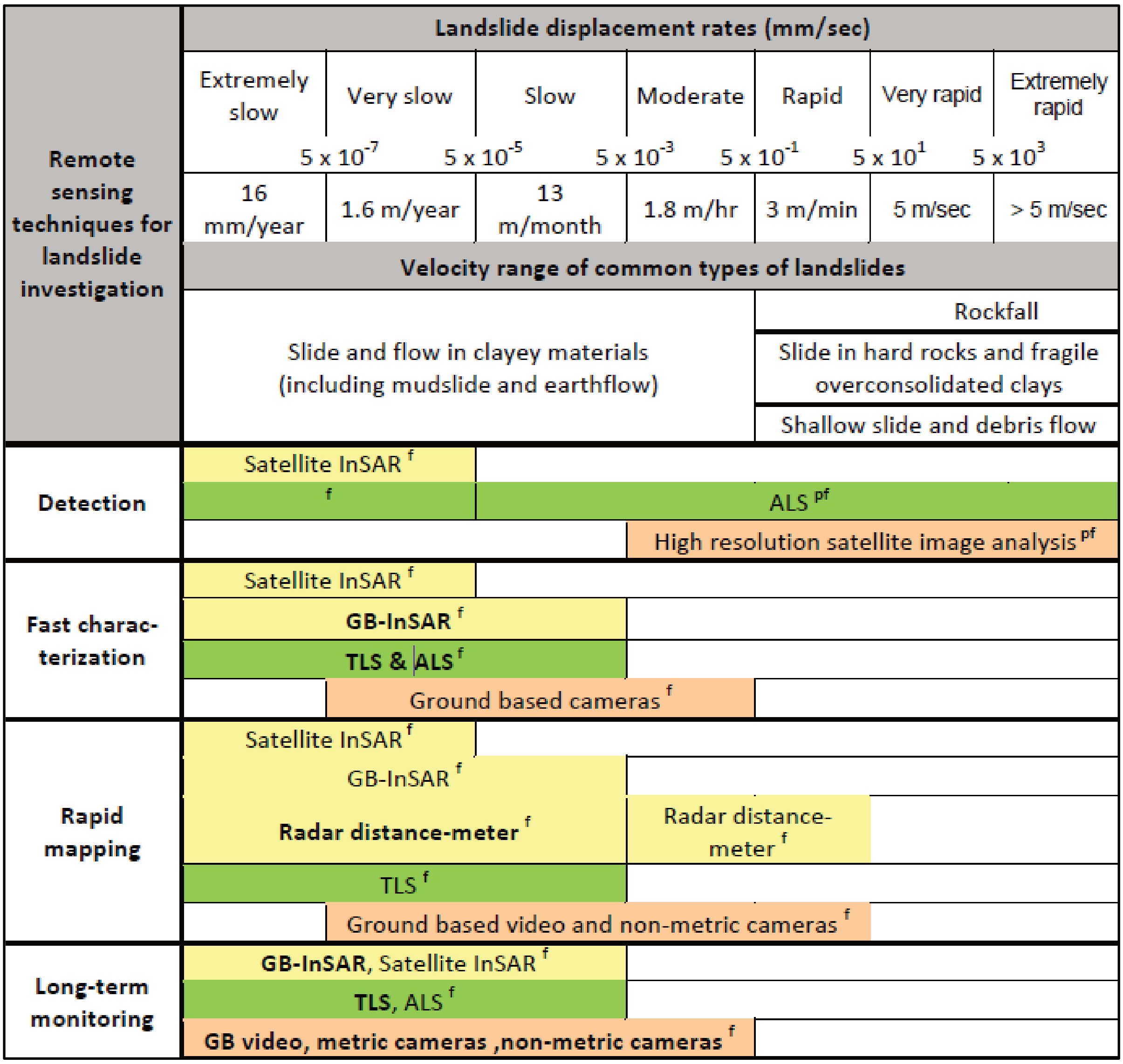
Sound asset management of various mine facilities and related infrastructure is predicated on the ability to detect the onset (and characteristics) of deformation. In some instances, fragile infrastructure cannot tolerate much differential subsidence (fixed plant, tanks, and rigid pipelines), whereas for others, deformation is expected and it is important to track the rate and extent of movement (mine slopes, waste dumps, and tailings dams). It is critical to understand the fragility of the infrastructure, the expected modes of instability (and associated deformation characteristics), such that relevant trigger action response plans can be developed.

InSAR is best adopted as a complimentary monitoring system (and validator) to ground-based systems. One reason simple to use guidelines are needed is that InSAR monitoring can be misunderstood as a silver bullet solution to monitoring, when in practice the complexities of the technology results in many constraints. The benefits and limitations of InSAR monitoring adapted from *Guidelines for Slope Performance Monitoring* (Sharon & Eberhardt 2020) are summarised in Table 1.

Table 1 Pros and cons of InSAR monitoring at mine sites

Pros	Cons
Safe, uninterrupted, continuous surveillance	Not real-time
Site-wide displacement monitoring	Not suitable for measuring volumetric changes
Low annual cost per measurement point	Not recommended as a replacement for ground-based instrumentation and inspections
Sub-centimetre precision is often achievable	Limited for detecting horizontal displacement in the north–south direction
Safety of life applications	Blind spots can occur due to terrain and slope orientation (e.g. geometric distortion)
Integration into existing geotechnical monitoring systems	Limited in vegetated areas, unless lower-precision/ longer-wavelength data are used (i.e. coherence)
Economical monitoring of closed sites	Limited on terrain with lingering ice and/or snow (i.e. coherence)
A decision-making tool for locating ground-based instrumentation	Varying sensitivity to displacement, depending on terrain
	Rapid displacement can go undetected if movement exceeds range thresholds (i.e. phase ambiguity)
	External surface influences (human and other) can obscure true surface deformations

The Norwegian Geotechnical Institute (NGI) (Norwegian Geotechnical Institute 2011) provides some useful guidance on selection of remote-sensing methods with details of their accuracy, data availability, costs, and technological limitations. As indicated in Figure 1, satellite InSAR monitoring is identified as a suitable monitoring method for slow ground movements which may help with early identification of failures at the mine site. At higher ground velocities, problems related to the period between scans and ambiguity of the signal wavelength are a limiting factor. It is noted that the industry is changing rapidly with innovative data processing techniques and with the increasing constellations being launched (some with daily revisit times). It is feasible in some cases to track faster ground displacement rates than what is indicated by NGI. Because of the satellite revisit time typically in the range of days to weeks, the objective of InSAR monitoring should not be for front-line safety where fast-moving instabilities need to be managed in near real-time.



Remote sensing techniques for landslide investigation	**Landslide displacement rates (mm/sec)**						
	Extremely slow	Very slow	Slow	Moderate	Rapid	Very rapid	Extremely rapid
	5×10^{-7}	5×10^{-5}	5×10^{-3}	5×10^{-1}	5×10^{1}	5×10^{3}	
	16 mm/year	1.6 m/year	13 m/month	1.8 m/hr	3 m/min	5 m/sec	> 5 m/sec
	Velocity range of common types of landslides						
	Slide and flow in clayey materials (including mudslide and earthflow)				Rockfall		
					Slide in hard rocks and fragile overconsolidated clays		
					Shallow slide and debris flow		
Detection	Satellite InSAR [f]						
	[f]		ALS [pf]				
				High resolution satellite image analysis [pf]			
Fast charac-terization	Satellite InSAR [f]						
	GB-InSAR [f]						
	TLS & ALS [f]						
		Ground based cameras [f]					
Rapid mapping	Satellite InSAR [f]						
	GB-InSAR [f]						
	Radar distance-meter [f]			Radar distance-meter [f]			
	TLS [f]						
		Ground based video and non-metric cameras [f]					
Long-term monitoring	**GB-InSAR**, Satellite InSAR [f]						
	TLS, ALS [f]						
	GB video, metric cameras ,non-metric cameras [f]						

Figure 1 Suitable ground velocities for InSAR monitoring as per Norwegian Geotechnical Institute (2011)

Predicting the time of failure of slope instabilities and tactical monitoring of surface deformations has become common practice in the mining industry thanks to technologies such as ground-based slope stability radars and robotic total stations. InSAR has now joined the portfolio of monitoring solutions thanks to its capabilities of extending the monitoring scale to the entire mine site facilitating strategic monitoring (Morgan et al. 2020).

Due to the aforementioned limitations, InSAR should be complemented with other terrestrial and/or subsurface monitoring solutions as applicable. Examples of mine-related infrastructure amenable for aerial surface deformation monitoring are listed in Table 2.

Table 2 Mine related infrastructure that can be monitored with InSAR

Mine infrastructure (active and closed facilities)	Natural hazards
Pit slopes (and interfaces with natural slopes)	Natural slopes above or below mine infrastructure
Waste dumps and stockpiles	Karstic terrain with sinkhole development (often exacerbated by mine dewatering/ reinjection programs)
Tailings dams	
Mine infrastructure (e.g. fixed plant or processing plants near pit crests)	
Access routes (road, rail, and pipelines)	
Undermined land planned versus unexpected subsidence (crown pillars, planned cave breakthrough etc.)	
Groundwater abstraction subsidence (mine dewatering)	

3 Decision trees: a tool for selecting the correct InSAR product

Decision trees were developed to guide the interested operation to a suitable InSAR product considering the asset infrastructure risk and the physical characteristics of the area of interest (AOI). The decision trees were built such that the user, without extensive technical knowledge of how InSAR functions, can make an independent evaluation of what InSAR products are adequate. To use the guideline decision trees, some basic information is required for each of the assets to be monitored onsite with the highest risk structure dictating the minimum requirement. An understanding of the following site-based information is required to navigate the decision trees:

- Detailed understanding of mode/s of instability:
  - Expected area of ground movement.
  - Rate of expected ground movement.
  - Whether horizontal movement is expected.
- Overall slope angles if the AOI is an open pit or dump and the aspect (direction) with respect to the satellite orbit.
- Structure or asset risk rating value from 1–5 (such as from a 5 × 5 risk matrix).
- Whether or not there is an extended period during the year with snow or ice cover.
- Degree of vegetation cover on the AOI/s.
- Frequency and extent of extraneous ground disturbance (e.g. grading or reshaping of slopes, etc.).

3.1 InSAR applicability

As discussed, InSAR monitoring can greatly enhance monitoring capabilities and improve asset management, however, there are several limitations that must be considered. The following site-specific variables are used to direct whether InSAR should be considered as a viable monitoring solution at the operation:

- Size and shape of expected movement area (m^2).
- Rate of expected movement (m/year).
- Vegetation cover on the AOI or regular surface disturbance (regrading, dragging pipelines, construction works, or blowing sand/erosion).

Figure 2 shows the decision tree for determining InSAR applicability for an asset.

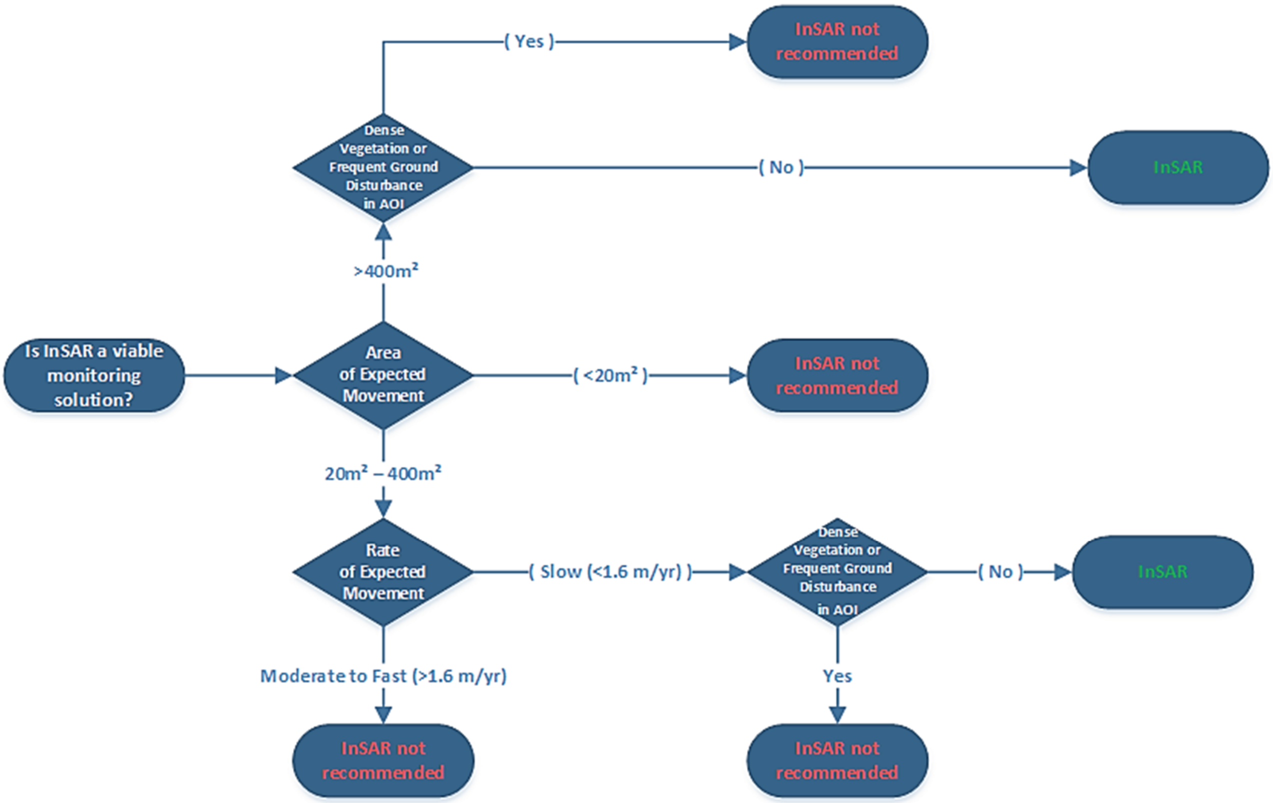


Figure 2 InSAR applicability

3.2 Resolution

Resolution is defined as the size of the area over which the satellite gathers one measurement value. A higher resolution results in an increase in the number of measurement points. Lower resolution does not mean poorer accuracy as both low and high resolution InSAR can achieve sub-centimetre vertical accuracy. The difference is the number of data points captured per unit area. It is important to understand the relative size of data point with respect to the mode of instability. "Higher spatial resolution offers the opportunity to distinguish comparatively smaller areas of significant movement" (Morgan et al. 2020). It should also be noted that satellite coverage is not equal across the globe and in certain locations either low or high resolution synthetic aperture radar (SAR) might not be available or may not be available from both look directions.

The Sentinel-1 satellite sensor resolution is 20 × 5 m (rectangular cells) and is considered the lowest practical resolution to use at a mining project. The data collected is publicly available and it is therefore categorised as 'standard' or 'low' resolution in the InSAR industry. Any pixel size of approximately 3 × 3 m or better (such as TerraSAR-X) is considered 'high resolution'. There are options for better resolutions described here as 'very high resolution' with approximately 1 × 1 m pixels using 'spotlight mode'. Although there are even finer resolutions available that are typically used for civil applications, they are not discussed in these guidelines because they are typically not practical in the mining industry. This is because, as resolution increases, the area coverage decreases (see dataframe in Table 3) and the cost to cover the entire mine site becomes prohibitive.

Table 3 InSAR reference table showing relationship between increasing resolution and decreasing area coverage (data frame)

Constellation	Agency	Tasking	Band	Wavelength (cm)	Satellites	Revisit (days)	Mode	Resolution (m)	Dataframe (km)
TerraSAR-X/PAZ	DLR / Airbus (Germany)	YES	X	3.11	2	11	Stripmap	3 × 3	30 × 50
							Spotlight	1.2 × 1.8	10 × 10
							Starring spotlight	0.6 × 0.25	4 × 3.5
COSMO-SkyMED	ASI (Italy)	YES	X	3.12	4	16	Stripmap	3 × 3	40 × 40
							Spotlight	1 × 1	10 × 10
SENTINEL-1	ESA	NO	C	5.93	2	12	Standard	5 × 20	250 × 250
RADARSAT-2	CSA (Canada)	YES	C	5.55	1	24	Standard	20 × 5	100 × 100
							Fine	8 × 5	50 × 50
							Wide fine	10 × 5	150 × 150
							Multi look fine	3 × 3	50 × 50
							Extra fine	5 × 5	150 × 150

Figure 3 depicts the decision tree for determining the resolution based on a budget-conscious solution. The reason high resolution is recommended in areas affected by snow cover is that it is necessary to take advantage of the faster return period to build the data stack in a shortened monitoring period. The following two variables dictate the resolution outcome:

- Size of expected movement area (m²/year).
- Whether there is a short monitoring season due to snow cover.

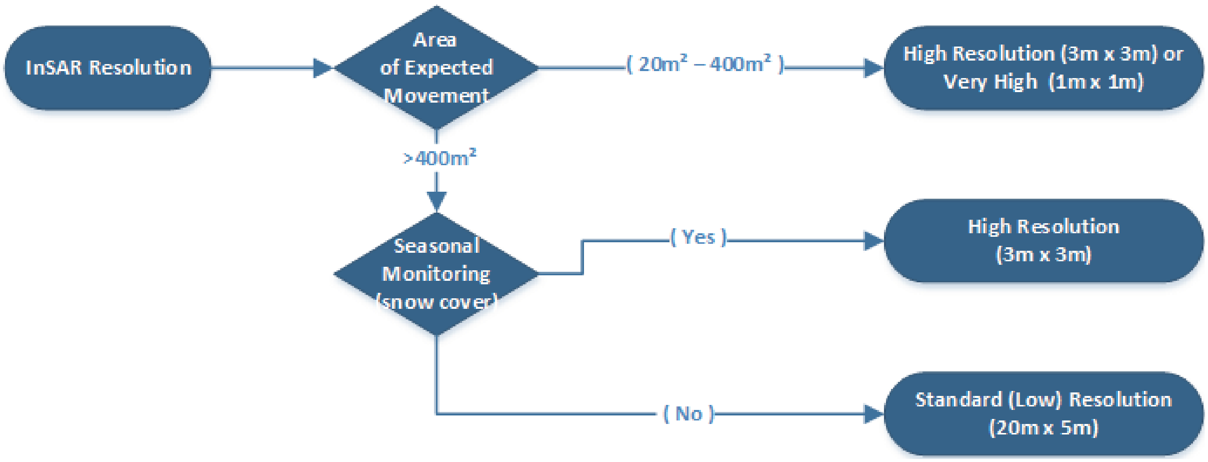


Figure 3 Recommended resolution

3.3 Report frequency

The suggested report frequency decision tree depicted in Figure 4 depends mostly on the asset risk level. Due to intensive data processing, reduced reporting can reduce annual monitoring costs significantly. The frequency varies from ‘frequent’ (as soon as possible based on satellite specific return time) to annual.

Seasonally affected sites are considered and the report frequency increased to benefit from the information during the shortened monitoring (and maintenance/inspection) window.

The following variables are used to determine the recommended report frequency:

- Whether there is a short monitoring season due to snow cover.
- The risk rating of the asset/s being monitored (1–5).

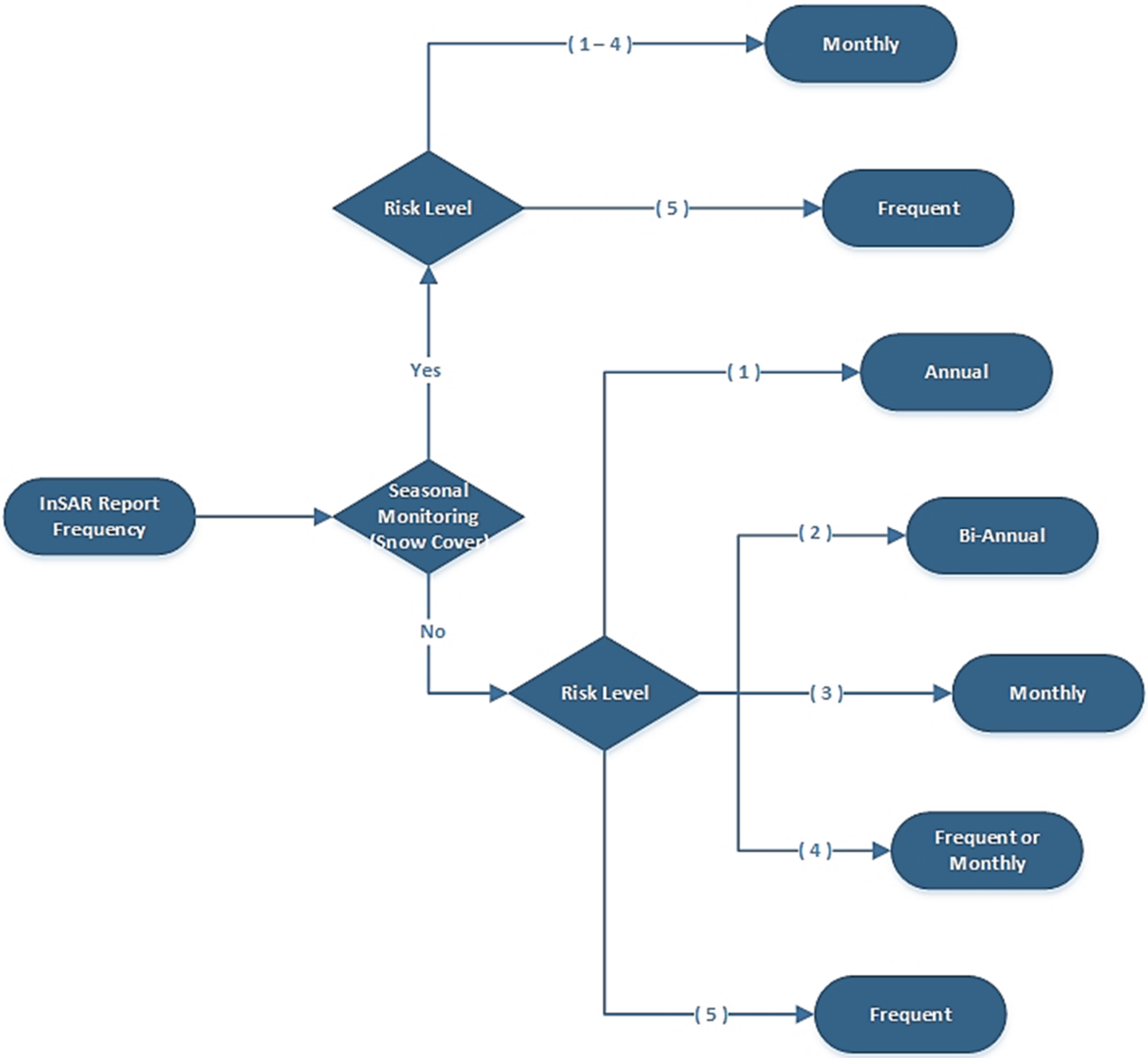


Figure 4 Report frequency

3.4 Orbit selection

SAR satellites travel in a near-polar orbit at an altitude ranging from 500–800 km above the Earth's surface, depending on the satellite platform (Ferretti et al. 2007). When satellites travel from north to south, it is referred to as the descending orbit. On its return, when the satellite travels from south toward the north, it is referred to as the ascending orbit (Figure 5).

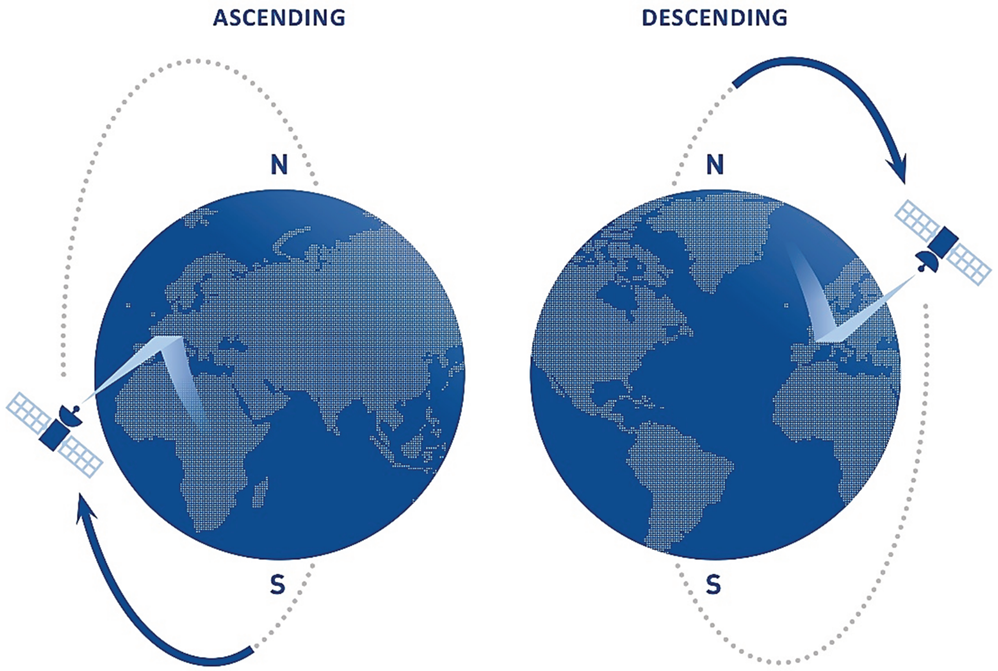


Figure 5 **Ascending and descending orbits**

Unlike other optical sensors that look straight down, SAR sensors transmit and receive the radiation with a side-looking perspective while the platform is moving, i.e. the antenna is aimed perpendicular to the direction of flight. The satellite's sensor transmits radar signals (active sensor type) to the surface along the radar beam's line of sight (LOS). Basic InSAR measurements are one-dimensional (1D) along the LOS (Figure 6). The benefit of having two orbit directions and the side-looking perspective is the potential to discriminate between true vertical and horizontal movement (in the east–west direction), referred to as 2D monitoring instead of simple LOS measurements (Figure 7).

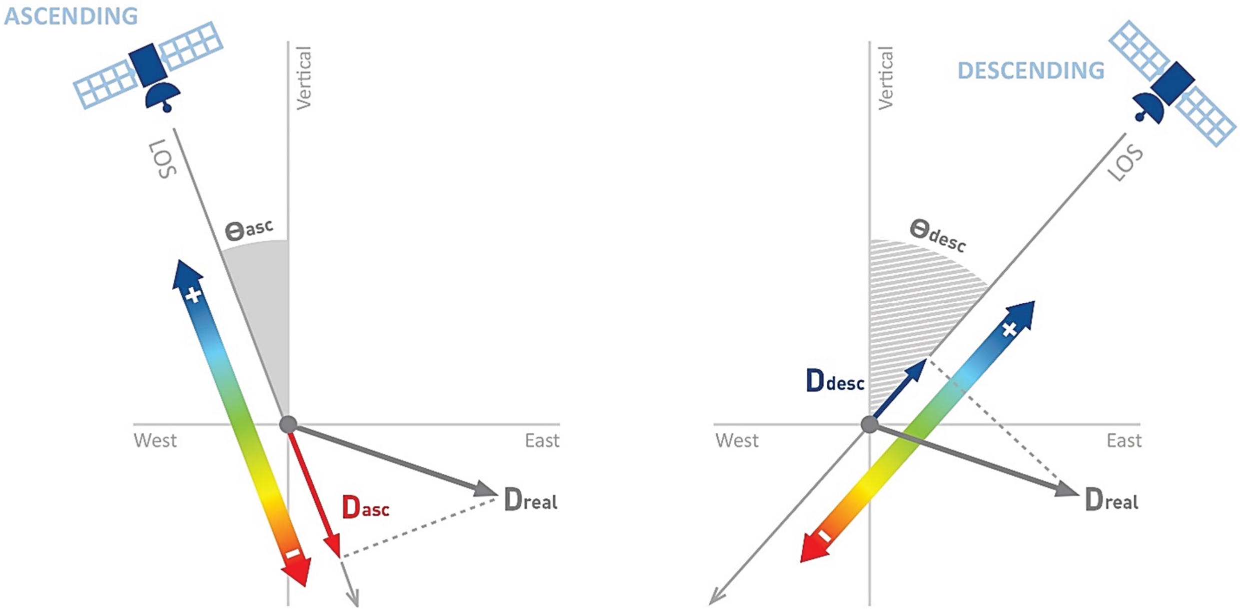


Figure 6 **Line of sight as the direction of measurement**

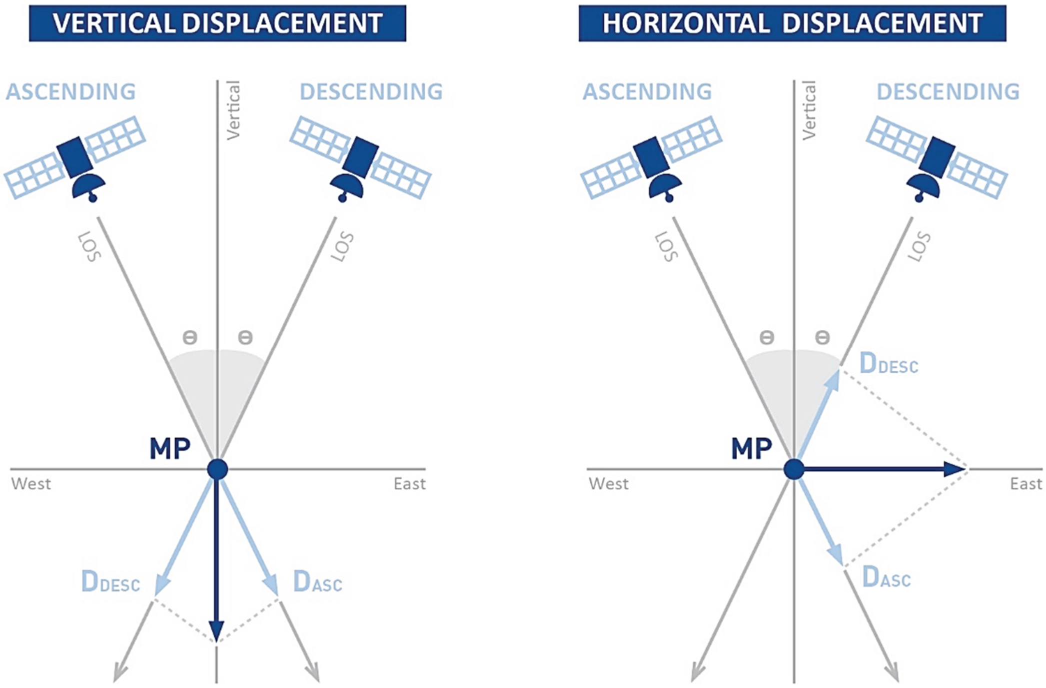


Figure 7 Vertical and horizontal displacement vectors with two InSAR look directions (2D)

> *"Given that SAR satellites look at the ground at an angle, and considering the slope geometry at a site, some areas may not be visible to the satellite's LOS. In areas with strong topography such as an open pit the use of a single orbit (ascending or descending) may miss steep portions on one side of the pit or a tailings dam."* (Morgan et al. 2020)

Viewing the area from two orbits allows more information to be captured within the pit. Due to the north–south travel path and the side-looking sensors, it is not possible to determine movement in the north–south horizontal direction using the 2D approach as this direction corresponds to the approximate direction the satellites are orbiting in (Morgan et al. 2019). In most cases, displacement contains both vertical and horizontal motion components but if the critical slopes have north–south aspects, the horizontal component limitation needs to be understood.

2D InSAR monitoring allows vector displacement information at an added cost due to doubling of the images being acquired and extra processing requirement. This is more of an impact with commercial tasking (high resolution) satellites than with Sentinel-1. The decision tree (Figure 8) developed to determine if 2D InSAR is required or necessary considers the following:

- Overall slope angles of AOI (degrees).
- Expected horizontal versus vertical displacement (high/low).

In some cases where it is determined that high resolution is needed in 1D, it is possible to combine this with standard resolution Sentinel-1 and is a way of obtaining a 2D product economically.

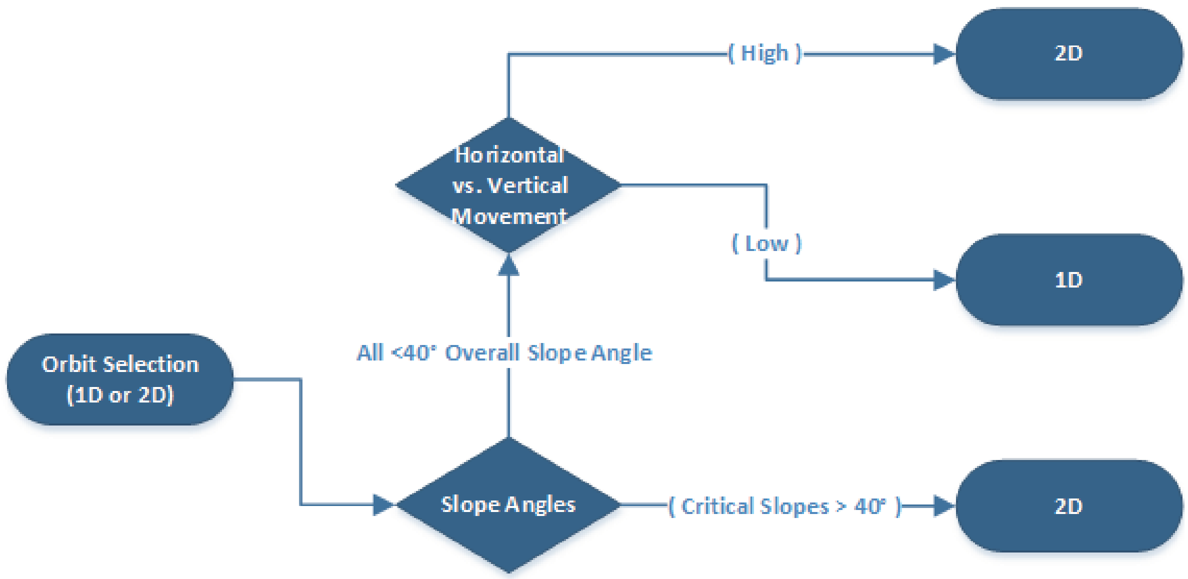


Figure 8 **Orbit selection**

4 Case studies

To benchmark and test the decision trees, six operations with existing InSAR monitoring programs were used to validate the outcomes. Figure 9 summarises the key inputs and outcomes of the InSAR decision tree process for these operations. These operations included active and closed mines, ranging from sub-arctic conditions with extensive snow coverage to semi-arid terrain and an extensive array of infrastructure and modes of instability. Not surprisingly, the outcomes were generally in alignment with the current monitoring activities, since each operation would have already had to match the monitoring resolution, reporting frequency and orbit selection to the mode of instability and the business risk. This validated that there were no outliers in the monitoring approach and provides assurance that there is consistency between the mines and various business units.

An additional benefit in compiling these data and integrating the monitoring requirements from the separate technical disciplines is that it makes the justification for mine-wide InSAR monitoring relatively easy. This is especially important in breaking down the silos between technical disciplines, often with divergent reporting frameworks and separate budgets.

Consolidating the procurement and administration of mine-wide InSAR services and reporting has several business benefits. However, it is imperative that efficient mechanisms are in place to ensure that reports and displacement alerts are communicated in a timely manner to the responsible individuals to appropriately investigate, act, and effectively manage the geotechnical risk.

By evaluating the deformation monitoring requirements for the different geographical areas and assets across the mine site in a systematic approach, this allows the primary monitoring requirements to be easily identified.

Clearly, the monitoring requirements will be dictated by the combination of the most stringent deformation conditions and the highest asset risk obligations. For example, if monitoring the open pit slopes is the highest risk facility, and/or requires the highest frequency of data analysis and reporting, then it makes sense that this will dictate the monitoring rigour for the mine site. While it is possible to analyse different areas to different reporting frequencies, it doesn’t make much practical sense. Rather, the whole scene is analysed every cycle but that area/facility specific deformation trigger action response plan criteria is applied to the outcomes. This provides a consistent site-wide surface deformation output, at negligible additional cost.

Mine and Asset		Decision Tree Inputs								Decision Tree Outputs			Current InSAR Monitoring	
Mine Site	Structure Name / Description	Expected Movement Area	Rate of Expected Movement	Risk level	Slope Angles	Critical Slope Aspects (NS vs EW)	Seasonality (Snow Cover)	Expected Lateral vs. Vertical Movement	Vegetation of AOI	Output Resolution	Output Report Frequency	Output Orbit Selection	Decision Tree vs. Actual Comparison	Comments
Mine A (Closed)	Fine Residue Deposit	Medium Scale (20m²-200m²)	Slow (<1.6m/year)	3 (Moderate)	All < 40° Overall Slope Angle	Both	Yes	Low	Arid/Sparse	High (3m x 3m)	Monthly	1D	Current InSAR product is same as the decision tree output	Trialing 1D high-res + 1D Sentinel = 2D
	Open Pit (Flooding)	Medium Scale (20m²-200m²)	Slow (<1.6m/year)	2 (Minor)	All < 40° Overall Slope Angle	Both	Yes	Low	Arid/Sparse	High (3m x 3m)	Monthly	1D		
	Coarse PK Dump	Medium Scale (20m²-200m²)	Slow (<1.6m/year)	1 (Insignificant)	All < 40° Overall Slope Angle	Both	Yes	Low	Arid/Sparse	High (3m x 3m)	Monthly	1D		
Mine B (Closed)	Open Pit (Flooding)	Large Scale (>400m² area)	Moderate to Fast (>1.6m/year)	4 (High)	Some Critical Slopes > 40°	Both	No	High	Arid/Sparse	Standard (5m x 20m)	Monthly	2D	Exception is resolution.	Purpose of monitoring is to moniotor the pit with 2D
	Coarse Residue Deposit	Medium Scale (20m²-200m²)	Slow (<1.6m/year)	2 (Minor)	All < 40° Overall Slope Angle	Both	No	Low	None	High (3m x 3m)	Bi-Annual	1D		
	Fine Residue Deposit	Medium Scale (20m²-200m²)	Slow (<1.6m/year)	3 (Moderate)	All < 40° Overall Slope Angle	Both	No	Low	None	High (3m x 3m)	Monthly	1D		
	Stormwater Management Dams	Medium Scale (20m²-200m²)	Slow (<1.6m/year)	2 (Minor)	All < 40° Overall Slope Angle	Both	No	Low	None	High (3m x 3m)	Bi-Annual	1D		
Mine C (Active)	Open Pit	Large Scale (>400m² area)	Slow (<1.6m/year)	3 (Moderate)	All < 40° Overall Slope Angle	Both	No	High	None	Standard (5m x 20m)	Monthly	2D	Current InSAR product is same as the decision tree output	
	Waste Dumps	Medium Scale (20m²-200m²)	Slow (<1.6m/year)	2 (Minor)	All < 40° Overall Slope Angle	Both	No	Low	None	High (3m x 3m)	Bi-Annual	1D		
	Plant/ Infrastructure	Medium Scale (20m²-200m²)	Slow (<1.6m/year)	2 (Minor)	All < 40° Overall Slope Angle	Both	No	Low	None	High (3m x 3m)	Bi-Annual	1D		
	Fine Residue Deposit	Medium Scale (20m²-200m²)	Slow (<1.6m/year)	2 (Minor)	All < 40° Overall Slope Angle	Both	No	Low	None	High (3m x 3m)	Bi-Annual	1D		
Mine D (Active)	Open Pit	Large Scale (>400m² area)	Slow (<1.6m/year)	3 (Moderate)	All < 40° Overall Slope Angle	Both	No	High	None	Standard (5m x 20m)	Monthly	2D	Current InSAR product is same as the decision tree output	
	Waste Dumps	Medium Scale (20m²-200m²)	Slow (<1.6m/year)	2 (Minor)	All < 40° Overall Slope Angle	Both	No	Low	None	High (3m x 3m)	Bi-Annual	1D		
	Plant/ Infrastructure	Medium Scale (20m²-200m²)	Slow (<1.6m/year)	2 (Minor)	All < 40° Overall Slope Angle	Both	No	Low	None	High (3m x 3m)	Bi-Annual	1D		
	Fine Residue Deposit	Medium Scale (20m²-200m²)	Slow (<1.6m/year)	2 (Minor)	All < 40° Overall Slope Angle	Both	No	Low	None	High (3m x 3m)	Bi-Annual	1D		
Mine E (Active)	Open Pit	Large Scale (>400m² area)	Slow (<1.6m/year)	3 (Moderate)	All < 40° Overall Slope Angle	Both	No	High	None		Monthly	2D	Exception is quarterly reports instead of monthly	
	Waste Dumps	Medium Scale (20m²-200m²)	Slow (<1.6m/year)	2 (Minor)	All < 40° Overall Slope Angle	Both	No	Low	None	High (3m x 3m)	Bi-Annual	1D		
	Sinkhole/Cavity Risk Management	Medium Scale (20m²-200m²)	Moderate to Fast (>1.6m/year)	2 (Minor)	All < 40° Overall Slope Angle	N/A	No	Low	Arid/Sparse	High (3m x 3m)	Bi-Annual	1D		
	Fine Residue Deposit	Medium Scale (20m²-200m²)	Slow (<1.6m/year)	2 (Minor)	All < 40° Overall Slope Angle	Both	No	Low	None	High (3m x 3m)	Bi-Annual	1D		
Mine F (Active)	Open Pit	Large Scale (>400m² area)	Slow (<1.6m/year)	3 (Moderate)	All < 40° Overall Slope Angle	Both	No	High	None		Monthly	2D	Exception is quarterly reports instead of monthly	
	Waste Dumps	Medium Scale (20m²-200m²)	Slow (<1.6m/year)	2 (Minor)	All < 40° Overall Slope Angle	Both	No	Low	None	High (3m x 3m)	Bi-Annual	1D		
	Sinkhole/Cavity Risk Management	Medium Scale (20m²-200m²)	Moderate to Fast (>1.6m/year)	3 (Moderate)	All < 40° Overall Slope Angle	N/A	No	Low	Arid/Sparse	High (3m x 3m)	Monthly	1D		
	Fine Residue Deposit	Medium Scale (20m²-200m²)	Slow (<1.6m/year)	2 (Minor)	All < 40° Overall Slope Angle	Both	No	Low	None	High (3m x 3m)	Bi-Annual	1D		

Figure 9 Case histories summary

5 Conclusion

The array of remote surface movement monitoring options can be overwhelming. The approach outlined in this paper provides a simple and consistent methodology to review the need and objectives for monitoring and presents three key outcomes:

1. Evaluate the suitability of InSAR methods to various surface monitoring mining scenarios, and matching monitoring rigour with geotechnical risk.
2. Provides a process to facilitate alignment and ideally optimisation of monitoring objectives and outcomes between separate technical disciplines (that collectively benefit from remote monitoring).
3. Communicating these requirements to management to demonstrate an effective business case for monitoring.

Furthermore, this approach is especially important to breaking down the intra-discipline silos, sometimes with divergent management reporting frameworks with separate budgets.

Consolidated evaluation of the mine site-wide deformation monitoring requirements (for the different assets) in a consistent approach facilitates quick identification of the primary monitoring requirements. These will be defined by the combination of the most stringent deformation conditions and the highest asset risk management obligations.

To date, relatively few case studies have been used to validate the decision tree approach presented, with none having critical slope angles greater than 40°. As InSAR use expands within the company at various operations with different physical characteristics, the decision trees will be tested. Further validation of the proposed approach is needed and the decision trees will likely evolve and be improved over time based on case study findings and changes to InSAR technology.

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All opinions and conclusions drawn in this paper are those of the authors alone and it should not be assumed that any views expressed herein are also necessarily those of De Beers or Anglo American.

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