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Combined monitoring remote sensing systems: Ground-based SSR and satellite-based SAR

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ABSTRACT

A combined ground-based slope stability radar (SSR) and satellite-based (InSAR) monitoring system was trialled at a remote mine site in the Northern Hemisphere in order to investigate relative changes in displacement experienced by a mine waste storage facility. The relative changes in displacements along the InSAR line-of-sight (LoS) were compared to the relative changes in displacement provided by the ground-based SSR LoS. Although the two LoS are different, this study showed good agreement between the magnitude of relative displacements observed by both remote sensing technologies on the slope of the facility. Additionally, the study looked at the effectiveness of InSAR and SSR on capturing relatively shallow operational works undertaken on the tailings storage facility slope. Results showed that SSR is able to provide near real-time information about progressive trends in displacements and alert mine site personnel of potential areas that might need attention. InSAR could detect anomalies in surface deformations during the period when SSR did, but the radar signal was sufficiently low to not unequivocally attribute these responses to real surface deformations.

Keywords: InSAR; SSR; remote sensing; deformations

1. Introduction

Satellite-based Interferometric Synthetic Aperture Radar (InSAR) and ground-based Slope Stability Radar (SSR) are types of remote sensing instrumentation that use the microwave region of the electromagnetic spectrum. Both transmit a series of radar pulses towards natural and man-made landscapes and record the returned signal along the line of sight (LoS) which contains an amplitude and phase. By interpreting the phase difference between consecutively returned signals, interferograms showing spatio-temporal changes in displacements are produced. Both ground-based SSR and satellite-based SAR monitoring systems are available and each type presents a series of advantages and disadvantages.

Wider spatial coverage is produced by satellite monitoring while near real-time monitoring is achieved by ground-based monitoring. Also, the LoS view for satellite-based is different than for ground-based, which provides an advantage to combine the information from both (Lumbroso et al 2021, Yan et al 2024).

With the release of the Global Industry Standard on Tailings Management (GISTM, 2020) and the requirement for its implementation at 'extreme' and 'very high' consequence risk tailings storage facilities (TSFs) by August 2023, structural health monitoring of mining infrastructure by means of various types of instrumentation has seen a significant uptake in the recent years. Measuring and tracking changes in surface deformations that could provide insight on potential impending failures has been a key component of structural health monitoring. Both InSAR and SSR, independently or in combination, are widely used monitoring tools nowadays.

A combined InSAR and SSR monitoring system has been trialled at a remote mine site to investigate relative changes in displacement experienced by a TSF. Two InSAR monitoring providers, denoted as InSAR provider 1 and InSAR provider 2, participated in this study. The relative changes in displacements along the InSAR LoS were compared to the relative changes in displacement provided by the ground-based SSR LoS. Although the two LoS are different, the aim of this study is to investigate whether the trends in relative changes in displacement are similar between the two remote sensing technologies. Additionally, the study looks at the effectiveness of InSAR on capturing relatively shallow operational works undertaken on the TSF slope.

2. Tailings storage facility location and implications for monitoring

The remote mine site analyzed in the current study is located in a cold climate zone and is covered by snow approximately 6 months a year. Thus, monitoring surface displacements by means of remote sensing offers a number of challenges given that the area to be monitored is physically obstructed for long periods of time.

The area of interest for this case study is the North face of the TSF.

The current study presents deformation results for the period between 1st June – 15th August 2023. Since the TSF in this case study is located in the Northern hemisphere, the area of interest was not obstructed by snow coverage.

2.1. Monitoring by InSAR

SAR satellites (e.g., the Sentinel constellation of satellites) travel in the North-South and then the South-North direction, capturing 1D surface deformations in the LoS of the radar. The LoS depends on the orientation of the satellite in relation to the ground surface geometry. This means that surface displacements perpendicular to the LoS (i.e. North or South) are much harder to detect. As such, satellites such as the Sentinel-1 satellite lack sensitivity to any North-South displacements we may anticipate in the area of the TSF investigated by this study, however it is possible to capture vertical components of such deformation.

2.2. Monitoring by ground-based SSR

The location of the ground-based SSR instrumentation can be chosen specifically to maximize the best possible coverage of the area of interest. SSR also captures the 1D surface deformations in the LoS of the radar, but this LoS is evidently different from that of the InSAR.

Table 1 summarizes the LoS for the ascending and descending satellites, and the SSR. The table also provides additional information about the measurement accuracy and type of processing technique.

Table 1. General details about InSAR and SSR

	InSAR ascending	**InSAR descending**	**SSR**
LoS	-22.3° (heading) 34.8° (incidence)	202.3° (heading) 31.8 (incidence)	Yes -Radial deformation from radar location
Accuracy	±15 mm (InSAR provider 2)	±12 mm (InSAR provider 2)	0.1 mm
Resolution	20 m	20 m	2.5x0.68 m
Processing technique	DifSAR	DifSAR	PA

DifSAR refers to the InSAR processing technique which uses Distributed Scatterers (DS) to capture surface deformations. The DS are comprised of multiple low to moderate responses within a SAR image pixel, which typically corresponds to natural targets such as the ground surface or rocky outcrops.

PA refers to Precision Atmospherics processing technique for ground-based SSR to remove slow and fast atmospheric variations.

3. Monitored areas

Figure 1 shows the area of interest on the TSF to be monitored by the two InSAR monitoring providers and one ground-based SSR provider. The SSR provider can monitor the North face of the TSF as shown in **Figure 2**.

The two InSAR providers could also monitor much larger areas including the TSF beach. The two InSAR providers are shown **Figure 1** as desired area of interest. Given that it is impossible to identify the 'exact' same area, the two InSAR providers reported monitoring data for areas as shown in **Figure 3** and **Figure 4**, respectively. Upon request, InSAR provider 1 divided the area of interest in a 'large' and 'small' areas. The 'small' area of interest was used to directly compare displacements on the slope between SSR and InSAR.

Figure 1. Intended area to be monitored is the slope of the TSF located between the two red lines (North direction is up).

Figure 2. Area monitored by the ground based SSR. The location of the radar is shown as an orange dot (North direction is down).

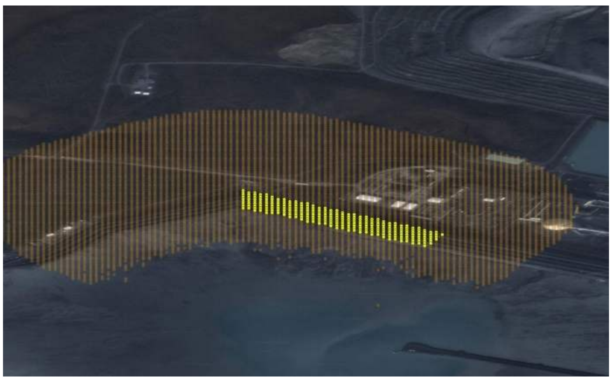

Figure 3. Area monitored by the InSAR provider 1: brown area is the 'large' area of interest; yellow area is the 'small' area of interest (North direction is up).

4. Availability of data

4.1. InSAR

The data acquisition frequency is dictated by the revisit period of the satellite. The revisit period for the Sentinel-1 satellites is 12 days (ESA 2022), alternating between the ascending and descending passes.

Figure 4. Area monitored by the InSAR provider 2 (North direction is up).

4.2. Ground-based SSR

The frequency of data collection for the ground-based SSR is dictated by the user. Data collection can be set to extremely small time intervals, up to the order of minutes. Depending on the monitoring location and internet connectivity, a compromise can be made between frequency of data collection (which dictates the size of the generated data file) and maintaining near real-time monitoring capabilities. For the current study, the frequency of data collection was set to 2 minute intervals.

5. Results

5.1. Detection of sudden changes in displacement

The mine operators conducted beach tailings sampling on the North face of the TSF on the morning of 20th June. The deformations resulting from this small excavation exercise were recorded by the SSR and a warning was raised about accelerated changes in displacement shortly after the excavation. The SSR identified a 27 m^2 area of an unsatisfactory progressive deformation trend which was soon identified as the beach sampling area by the mine operators.

The Sentinel-1 satellite passed this area on the 17th and 29th June, respectively, thus between the short interval period when beach sampling took place. As can be seen from **Figure 6**, although InSAR provider 2 picked up some small signals between 17th June and 29th June from the descending satellite, these signals were deemed very small and could be reasonably attributed to atmospheric anomalies.

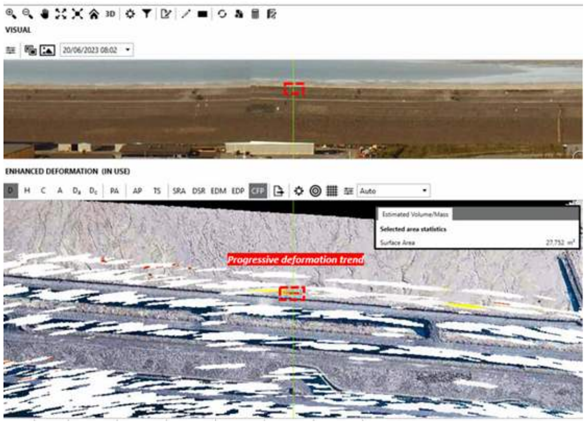

Figure 5. Aerial - deformation image overlay from SSR on June 20th.

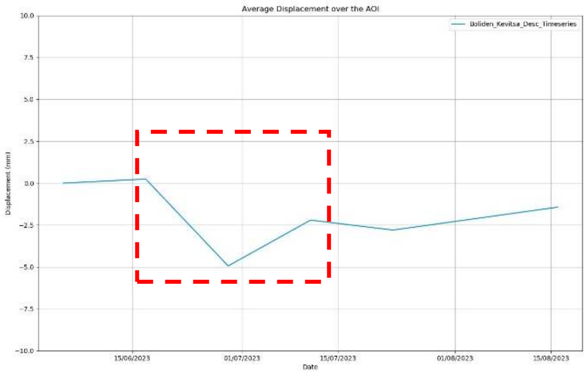

Figure 6. Time series from the descending satellite for the period of interest and area of interest (i.e., please see hatched area in **Figure 4**).

Figure 7 shows the relative displacements on the TSF slope as interpreted by SSR and InSAR provider 1. For the SSR, the relative displacements are computed from midnight of 1st June. For the InSAR data, relative displacements are computed from 4th June, when the ascending satellite passed this area. The InSAR displacements shown in **Figure 7** are for the 'small' area identified previously in **Figure 3**.

Although the LoS for each instrumentation is different, the resulting displacements are very similar both in absolute values and in trend of movement.

Figure 8 summarises the measured relative displacements for the area of interest. For reference, the area of interest is not identical for the three providers, including for the two InSAR monitoring specialists. The area of reference for the SSR is the slope of the TSF, as identified previously. The area of interest for InSAR provider 1 is shown by the brown dots in **Figure 3**, and for provider 2 is shown in **Figure 4**, respectively. Again, for the SSR, the relative displacements are computed from midnight of 1st June and for InSAR, relative displacements are computed from 4th June. For this reasons, apart from the difference in LoS, the relative displacement trends between the three observations are not very similar. Nonetheless, when taken as absolute values, the relative displacements reported by each provider are very similar, with cumulative relative displacements below 1 cm over the 1th June – 15th August time period.

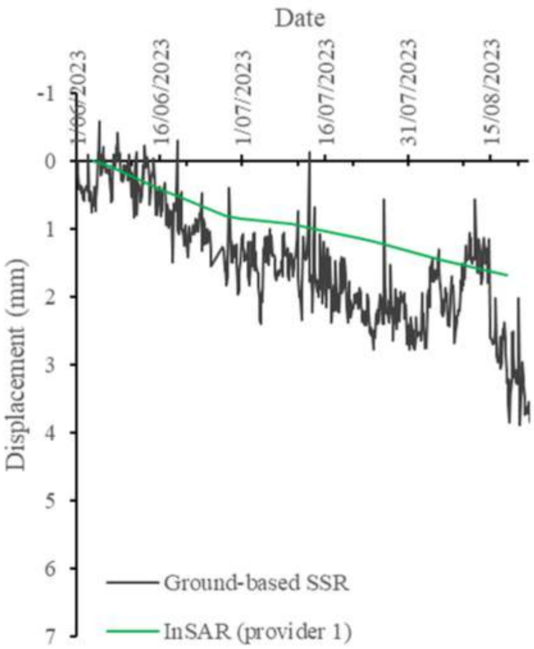

Figure 7. Comparison between SSR and InSAR displacement for the TSF slope.

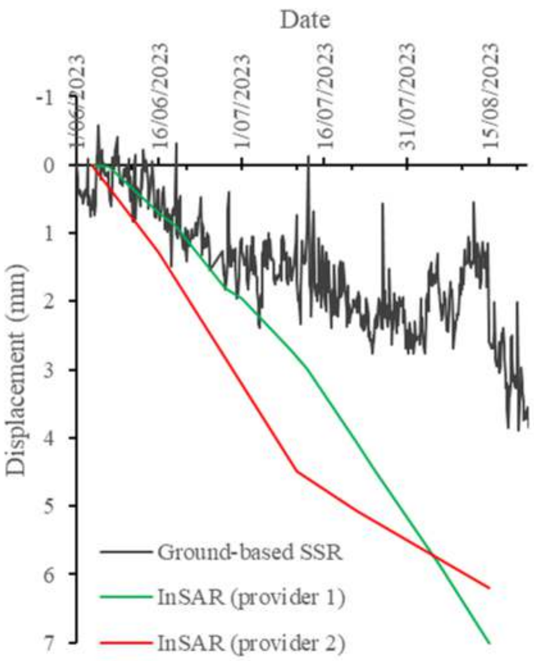

Figure 8. Comparison between SSR and InSAR displacements for the area of interest.

6. Conclusions

The Global Industry Standard on Tailings Management requires that mine site operators implement a monitoring system at their 'extreme' and 'very high' consequence risk tailings storage facilities in order to track the evolving structural health of mining infrastructure over its lifetime. As such, monitoring systems have seen a significant uptake in recent years. One important aspect that is regularly monitored is the change in surface displacements and both InSAR and SSR are widely nowadays.

The current study has trialled a combined InSAR and SSR monitoring system on the Northern slope and adjacent area of a TSF located in a cold climate area. The period of study was during the summer time between 1st June – 15th August. One SSR and two InSAR providers provided data for the current study. Although the three providers monitored the same area of interest, there were some differences in the extent of area they could measure. Additional difference between the technologies were given by the different LoS between SSR and InSAR.

All three providers reported very similar cumulative relative displacements over the area of interest, irrespective of LoS and reference zero deformation time. Nonetheless, when confined to a much stricter area of interest, both InSAR and SSR returned very similar absolute relative displacements as well as trends in changes in displacements, namely sub-centimeter displacements.

The ground-based SSR could detect almost in real-time relatively shallow operational works undertook on the TSF slope, alerting the mine site operators of a progressive deformation trend in the area where beach tailings sampling operations were taking place. InSAR detected some signals, but these were very small and could have been attributed to atmospheric anomalies.

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