Advancing mine closure safety with InSAR: monitoring an inactive tailings storage facility

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Abstract

Engineers managing legacy assets such as tailings storage facilities (TSFs) that have been inactive for decades, face many geotechnical challenges such as lack of archived data, uncertainty of past instabilities, remote locations, and inaccessibility.

We highlight the application of satellite-based interferometric synthetic aperture radar (InSAR) as an effective complementary tool for geotechnical risk assessment after mine closure to proactively manage risk at a TSF that has been inactive for over 30 years. Previous ground-based investigations identified minor, localised zones of subsidence. Consequently, an independent investigation employing InSAR was undertaken to evaluate the presence of any indicators of instability based on patterns of ground deformation.

A five-year period (2019–2024) of SAR images was selected to demonstrate feasibility. Persistent scatterer interferometry (PSI) was used to account for challenging site conditions, including vegetation and water presence. The InSAR specialists optimised a processing methodology to specifically deal with an annual 5-month snow season interrupting the continuity of the radar scatterers on the dam. This study demonstrates that this annual gap can be bridged effectively, to generate a high confidence statement about risk-related patterns of motion.

Close collaboration between the owner´s team governing the legacy mine sites, the surveyors and the InSAR specialists ensured the validation of InSAR monitoring results. Combined with the site context, deformation patterns detected were ultimately assessed as non-substantial for overall stability. The partnership between InSAR specialists and site teams was integral to getting meaningful geotechnical insights and supporting decision-making. These important decisions would be more difficult to make without the use of a monitoring system that can retrospectively analyse ground movement.

This practice provides an example of how InSAR monitoring coupled with careful diagnostics and onsite information and validation can act as a catalyst in choosing the right approach to managing geotechnical risk, and is now being expanded in other legacy sites

Keywords: *inactive legacy TSF, tailings storage facility, InSAR monitoring, geotechnical risk assessment, mine closure management, snow season data gap, mine closure*

1 Introduction

This study is concentrated on an abandoned TSF facility located in central Sweden. The facility has been inactive since closure and remediation activities concluded over 30 years ago. As part of a broader strategy to enhance long-term safety at legacy sites (Geological Survey of Sweden 2022), three tailings storage facilities (TSFs) were selected for InSAR-based monitoring to analyse ground movements potentially

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indicating areas of critical concern and to assess their geotechnical condition. This study focuses on one of these three sites, indicative of the process that was followed for the other two.

The TSF comprises three containment structures: the north dam, southwest (SW) dam, and southeast (SE) dam, which collectively enclose a decant pond for water management, critical infrastructure for erosion control and sediment retention. The facility primarily contains fine and coarse-grained tailings mainly derived from historic mining operations, exhibiting limited vegetation cover.

The selected site (Figure 1) is representative of the challenges commonly faced when conducting InSAR analysis of legacy mine environments (Bennett 2016): limited historical documentation and instrumentation data, evolving vegetation cover, and seasonal snow cover. The primary geotechnical risk was associated with the historical deposition of materials across a broad area situated to the north of the main dam structure, where multiple layers of material in the subsurface play a role theoretically to the development of instability mechanisms on the north dam wall. The long-term behaviour of these layered deposits has remained uncertain after several decades of closure. Other related stability risks were associated with two additional dams located to the southeast and southwest, respectively. Conventional site inspections in 2022 and 2024 revealed minor surface alterations, such as small subsidence features. These observations were inconclusive in identifying any broader deformation pattern potentially affecting the dam's stability.

Satellite-based InSAR was chosen as a tool to generate an InSAR historical baseline study for the site. The aim was to identify subtle deformation patterns and assess whether any specific sections of the TSF embankments required reclassification in terms of geotechnical risk.
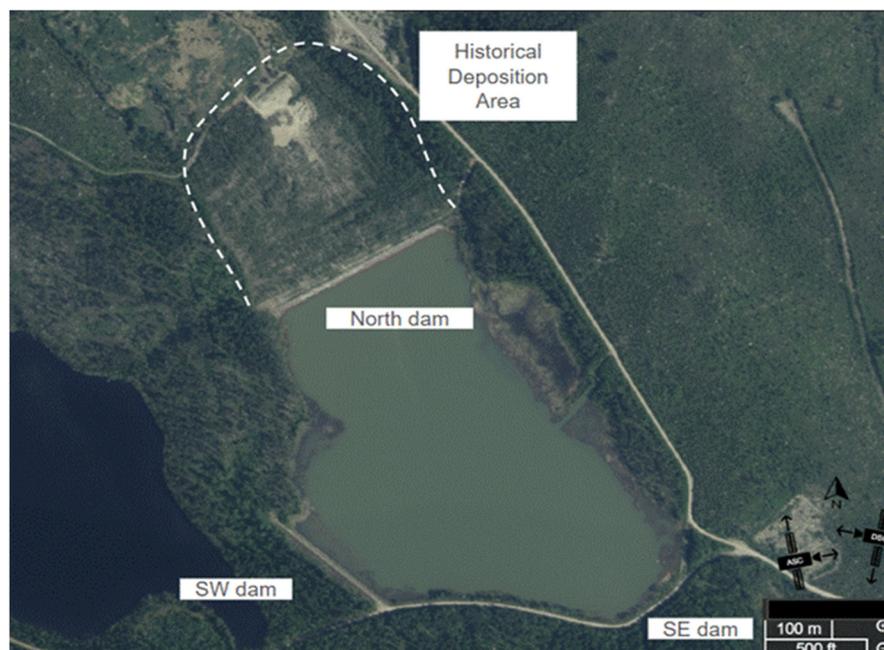

Figure 1   The tailings storage facility

2   Methodology

Ground deformation was quantified with persistent scatterer interferometry (PSI) applied to Sentinel-1 data from the European Space Agency. The satellite's C-band imagery, with an effective ground-range resolution of ~5 × 20 m, is freely available (Copernicus - ESA), so no additional data-acquisition cost was incurred. All ascending and descending scenes acquired between 2019 and 2024 were processed with SkyGeo's proprietary PSI processing chain. This processing chain resulted in amplitude imagery and line-of-sight (LoS) time-series from that period at a 12-day frequency for each track covering the full TSF. The time-series consisted of three different datasets depending on ground reflectivity: persistent scatterers (PS), weak scatterers (WS), and distributed scatterers (DS) methods to improve coverage over vegetated or decorrelated areas (Ferretti et al. 2002; Van Leijen 2014).

A critical factor taken into consideration was the snow cover period that expands from approximately November to April each year. To mitigate this snow cover interference, this period (November–April) was excluded from the time-series. This seasonal gap required checks to ensure continuity in the data as well as the absence of unwrapping errors or sudden, unexplainable changes. Any discontinuity between pre-winter and post-winter periods could indicate ground deformation or unwrapping errors, but no consistent discontinuities were found in the data sets. Displacement measurements are indicated in orange dots, while grey dots represent ambiguity band calculations on the same measurements. This feature in time-series data is key in uncovering unwrapping errors or large-scale displacements (Figure 2).
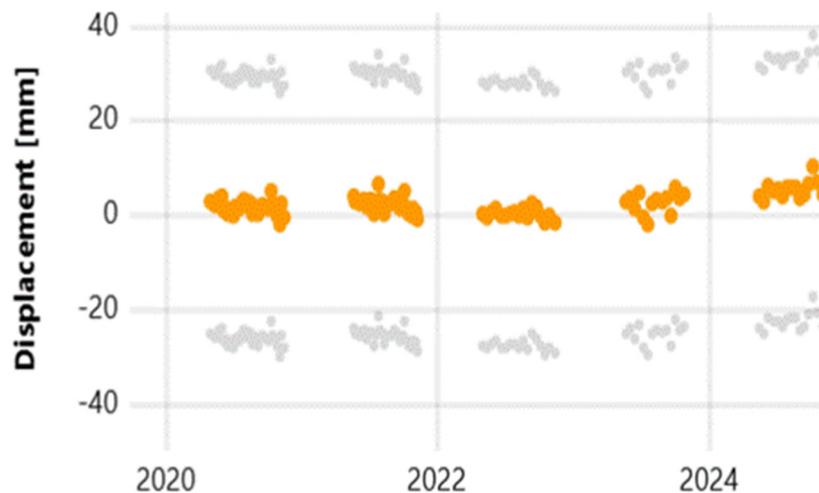

Figure 2   Example of inspected time-series of one of the persistent scatterers over the north dam showing no consistent discontinuities between the pre-winter and post-winter periods

The PSI approach allowed for millimetric precision over long time intervals, enabling both whole-site ground deformation assessments and detailed analysis of localised anomalies. Instead of relying on a preset PS-density threshold each point scatterer was examined individually using expert judgement to confirm signal coherence and to exclude points affected by phase unwrapping.

The approach included not only InSAR processing but also interpretation of the InSAR data, in this case, based solely on the PSI time-series by analysing data from the whole time-period (2019–2024) and each individual year.

The scope of this approach is to distinguish real displacement from noise in the data and decipher patterns of movement that might relate to instabilities, such as sudden acceleration in the displacement rate or spatial differences in displacement rate for localised zones with respect to their surrounding areas.

3   Data

Figures 3 and 4 present maps of the LoS displacement results for the TSF and its surroundings, derived from Sentinel-1 data acquired from the ascending and descending orbits, respectively. While data coverage varies across the study area, most regions with available observations exhibit displacement rates of less than 10 mm/year, indicating relatively low levels of ground deformation.
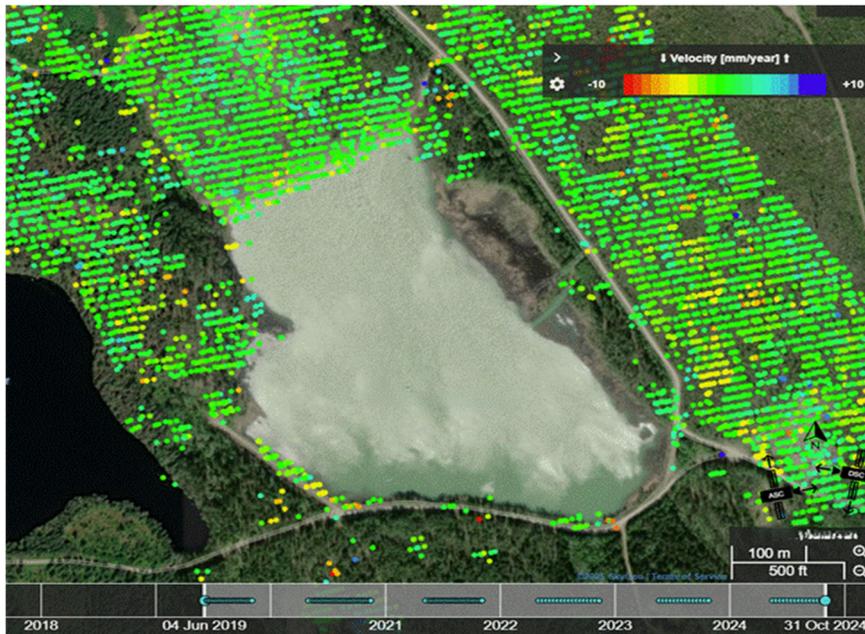
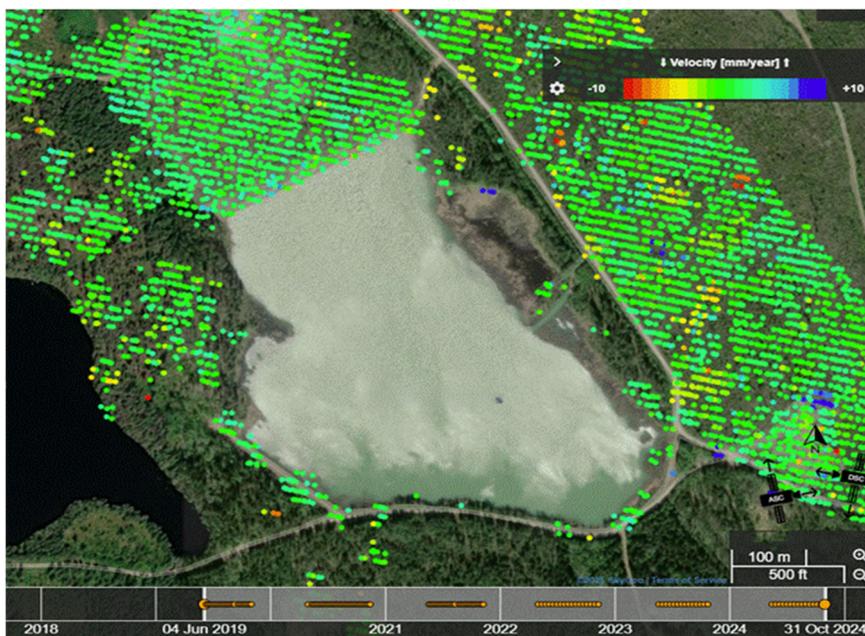**Figure 3   InSAR results from Sentinel-1 ascending (ASC) satellite track**

Figure 4   InSAR results from Sentinel-1 descending (DSC) satellite track

3.1   Individual asset approach

A dam-by-dam review was performed to determine whether any of the localised anomalies detected in the InSAR data were of geotechnical significance. Two small zones one on the north dam and one on the southwest dam wall (Figures 5 and 8) displayed slightly higher settlement rates than their surroundings. The analysis detailed in the proceeding sections show that these movements can be assumed to be shallow, surface-confined and well within tolerable limits for an inactive TSF embankment.

3.1.1   North dam

The northwest corner (white circle area) of the north dam exhibits cumulative subsidence of approximately 40 mm between 2019 and 2024 (Figures 5 and 6). This displacement signal is detected in the DS and in the WS datasets (Figures 5 and 6) but is notably absent in the PS layer (Figure 7). The presence of displacement

in the DS/WS points, which represent averaged returns from rough, lightly vegetated surfaces, indicates motion occurring within the thin cover soil and tailings beach. In contrast, the PS targets – typically located on rock armour, monitoring monuments, and other rigid infrastructure elements – remain essentially stationary, with displacement rates not exceeding -5 mm/year. This rate lies at the lower threshold typically considered when assessing potential indicators of ground instability, providing additional evidence of limited ground movement within the study area. This distinction suggests that the observed deformation is most likely associated with superficial, unconsolidated materials rather than the dam structure itself.
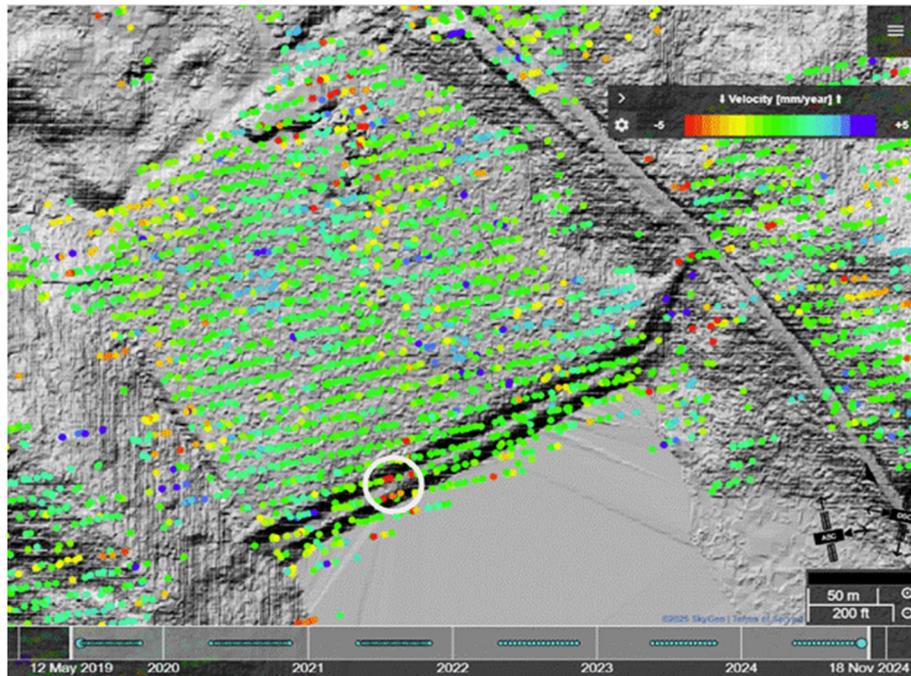

Figure 5   Persistent, weak and distributed scatterers points in the area of increased displacement rate
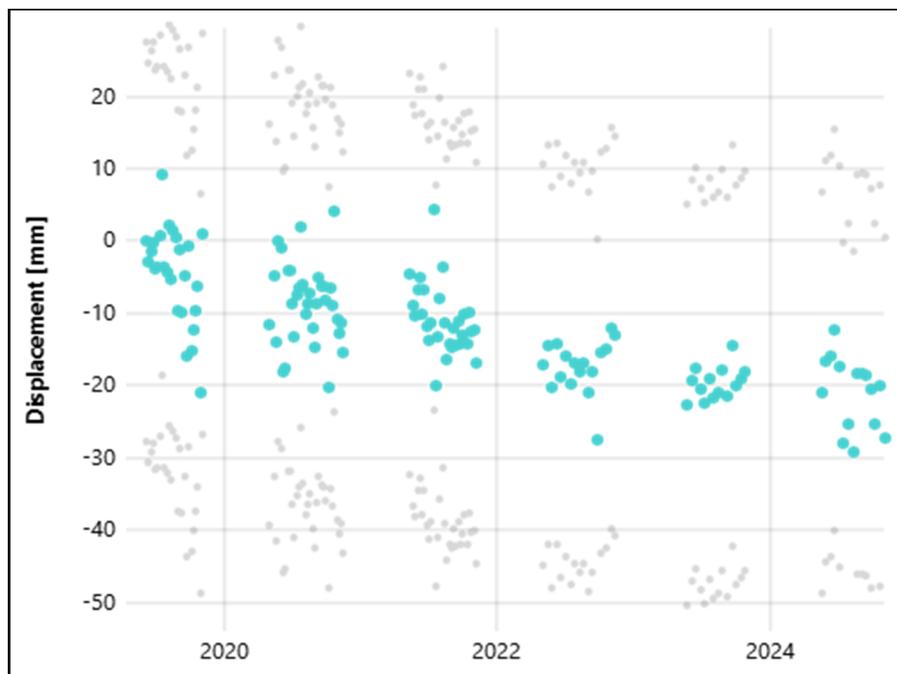

Figure 6   Time-series graph showing progressive displacement pattern from 2021 to 2024 for area of subsidence in the north dam (cyan dots represent displacement estimations while grey points indicate ambiguity band calculations)
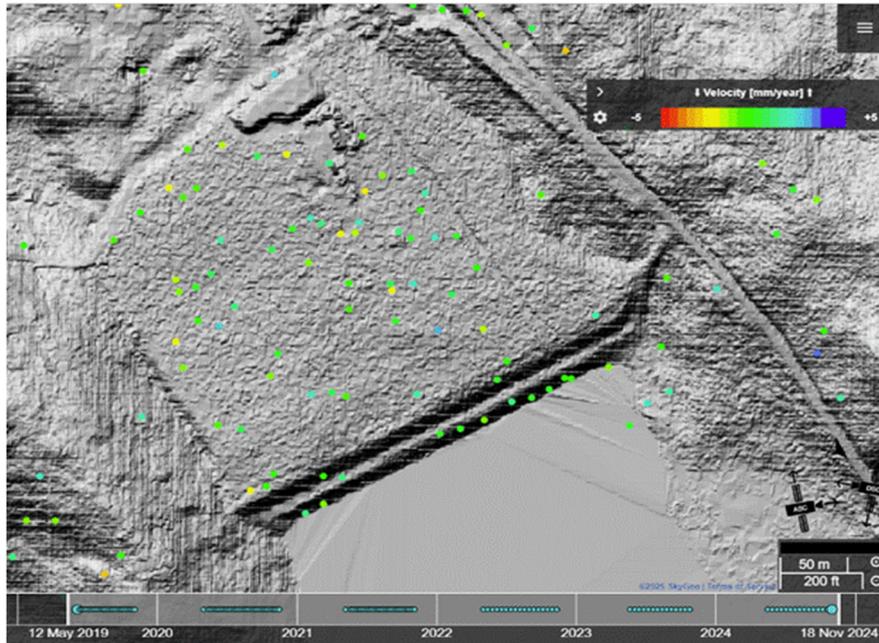
Figure 7   Persistent scatterers do not show instabilities on the dam wall, crest or area behind the dam

3.1.2   Southwest dam wall

A similar displacement trend to the north dam was detected along a specific section of the southwest wall (Figure 8), particularly at its southeast corner (white circle are), where a subsidence pattern emerged in 2022 (Figure 9). The DS data capture this displacement in greater detail; however, the sparse distribution of PS points (Figure 10) prevents any definitive conclusions regarding the overall structural stability of the dam wall. On their own, the DS results suggest that this trend is likely attributable to superficial or localised surface changes that have occurred within this area over the past five years.
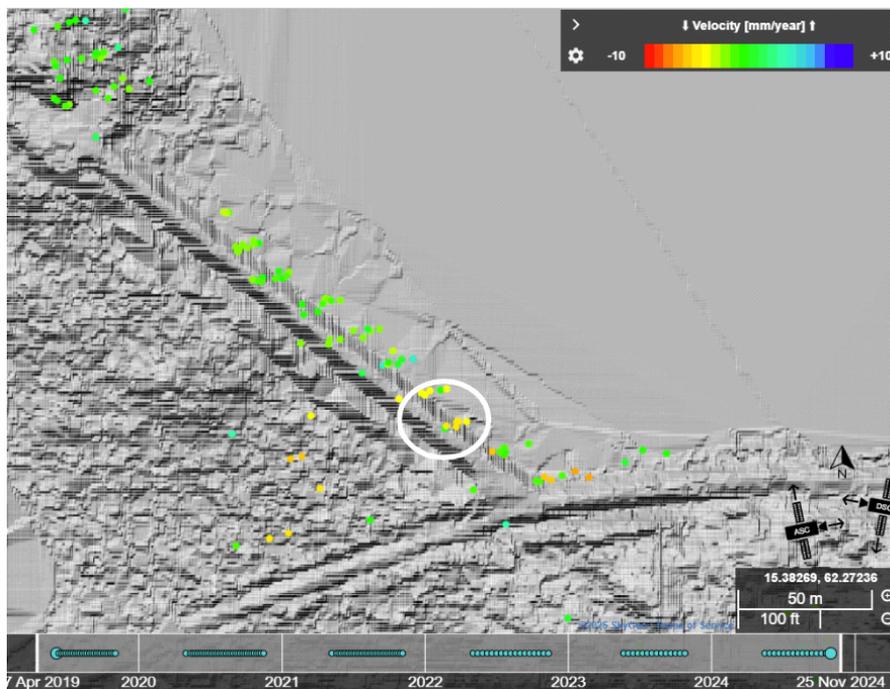

Figure 8   Southwest dam wall with persistent scatterer interferometry ASC distributed scatterer data coverage
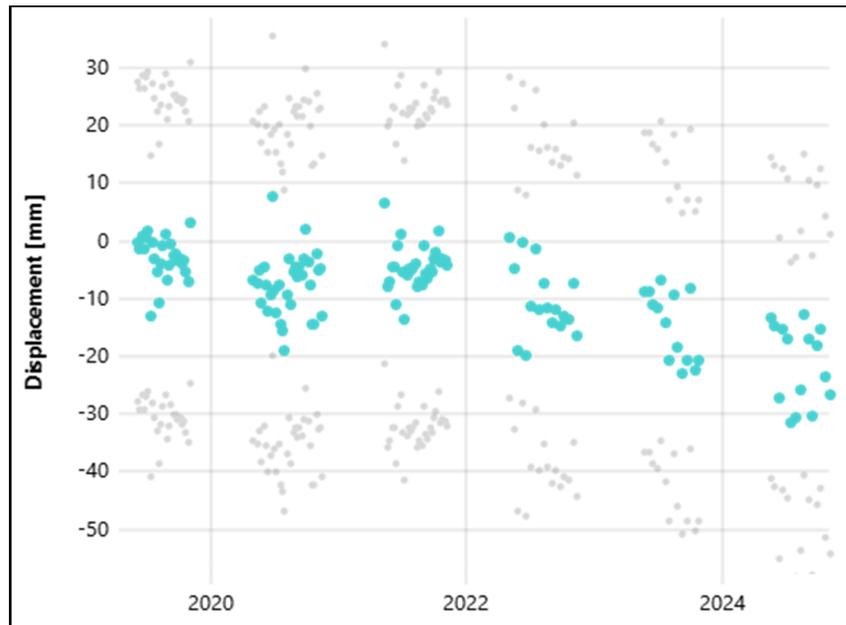
Figure 9 Time-series graph showing progressive displacement pattern from 2022 to 2024 for area of subsidence in the southwest dam (cyan dots represent displacement estimations while grey points indicate ambiguity band calculations)
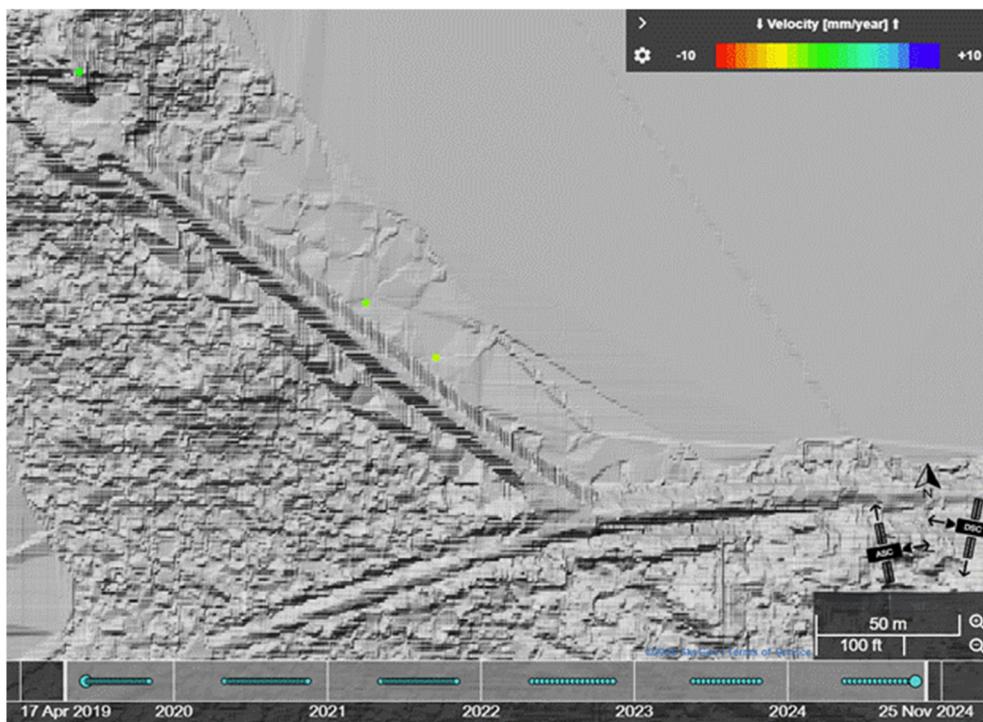

Figure 10 Southwest dam wall with persistent scatterer interferometry ASC distributed scatterer (DS) data coverage

3.2 Site investigation

Two field investigations were conducted in 2022 and 2024 to assess localised subsidence along a dam wall access road (Figures 11 and 12). The images show results from both campaigns where small, uneven depressions were identified in vegetated zones adjacent to the road and lake indicating isolated subsidence activity and damage caused by passing work vehicles. The findings from the site inspections were used to verify that the assessment based on the InSAR results did not indicate any alarming ground movements.

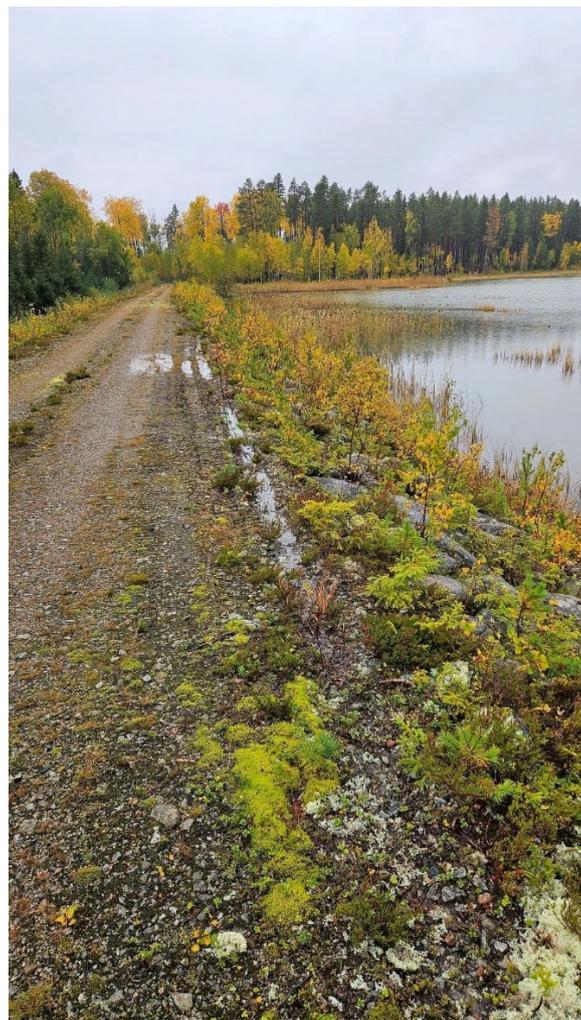**Figure 11   North dam as seen from west to east. Vegetation, as well as fine and coarse material, present**

Figure 12   Image captured on 29 September 2022 on southwest dam showing local damage caused by passing work vehicles

4 Discussion

During evaluation of the deformation data, two areas were highlighted because of a relatively high displacement rate with respect to their surrounding areas. These localised movements suggest that minor shifts could occur, although the team assessed that they do not currently pose an immediate threat to the overall stability and structure of the dam. Datasets showing increased deformation values in both highlighted areas (north dam and southwest dam) were observed in the DS points only, while the highly coherent PS points showed no such increase.

The PSI dataset is classified into PS, WS, and DS, each derived through specific processing approaches. PS points typically correspond to highly reflective targets such as infrastructure, enabling precise point-based displacement analysis. DS points, in contrast, are clusters of statistically similar pixels whose collective behaviour provides spatially averaged deformation estimates, capturing broader surface movements where discrete reflectors are absent. This combined approach improves the detection of both localised and distributed ground deformation.

5 Conclusion

After aggregating and reviewing all the data in a multidisciplinary team of geotechnical engineers, InSAR specialists and TSF closure specialists, and after site inspection findings provided by the owner as presented in Section 3.2, it was concluded that the InSAR analysis of ground movements from 2019 to 2024 was consistent with what was expected based on earlier investigations onsite. No additional concerns were identified about stability using this approach.

The seasonal limitations posed by snow cover were effectively addressed through iterative and locally optimised InSAR processing strategies, validating the utility of InSAR even in subarctic environments. Upon careful expert judgement of all individual time-series data, the optimal phase unwrapping was established. Thus, there is high confidence that no major deformation appears as a result of an incorrect unwrapping procedure.

The integration of remote sensing data with site-specific knowledge, visual inspections, and historical documentation enabled meaningful and appropriately contextualised interpretations, minimising the risk of false positives and unwarranted escalation. InSAR is demonstrating real value as a relatively low-cost tool for proactive, site-wide evidence-based risk management. When deployed with the right intent, InSAR is an effective complementary tool to assess geotechnical stability of mine infrastructure, for the long-term after mine closure.

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