Paste 2023 – GW Wilson, NA Beier, DC Sego, AB Fourie & D Reid (eds)

doi:10.36487/ACG_repo/2355_60

Assessing tailings consolidation and changes in supernatant pond area using InSAR and the normalised difference moisture index

A Koleshwar *TRE Altamira Inc, Canada*

R Tortini *TRE Altamira Inc, Canada*

G Falorni *TRE Altamira Inc, Canada*

Abstract

Monitoring of tailings storage facilities (TSF) is a critical component of sustainable mining practices. The primary goal of monitoring programmes is to ascertain the correct performance of the tailings facility, thus preventing impoundment failures that may lead to fatalities, severe environmental consequences, and substantial financial losses. Field geotechnical investigations and displacement analysis at tailings impoundments are usually spatially limited as their implementation over a large spatial extent would be cost-prohibitive. Interferometric Synthetic Aperture Radar (InSAR) is a widely used remote sensing monitoring tool that provides a synoptic view of displacement by utilising a high density, high frequency and high-precision network of measurement points.

Tailings undergo consolidation settlement as they desaturate over time. Although the movement is mainly vertical, the detection of lateral movement towards the east or west may indicate preferential desaturation pathways. The following study describes the use of an advanced multi-temporal InSAR algorithm to process both commercial high-resolution TerraSAR-X and publicly available lower-resolution Sentinel-1 satellite radar imagery to monitor tailings consolidation. To characterise saturation changes over the same period, optical images from the Sentinel-2 satellite are employed. The specific goals of the study are to: (i) monitor motion within TSFs, focusing on changes in rates of consolidation and any lateral movement over time, (ii) identify areas of higher magnitudes of settlement along with any lateral (east–west) movement, suggesting preferential desaturation pathways, and (iii) correlate changes in consolidation behaviour with the changes of the supernatant pond area. The conclusion of the study suggests that the combined use of both technologies over tailings facilities provides valuable insight into governing dynamics of tailings. The results indicate a probable correlation between the consolidation rates with the supernatant pond area changes. This information can be implemented with the operational plans for a better characterisation of the dynamics within TSF's.

Keywords: *InSAR, remote sensing, monitoring technology, tailings consolidation*

1 Introduction

Tailings impoundments store the waste by-products, such as fine rock particles with a variable range of particle size from a few microns to a few millimetres, from mining operations after the separation of the metals from the hard rock (Hudson-Edwards 2016). To accommodate the large volumes of waste generated from the mining processes, tailings impoundments generally cover spatial areas of several square kilometres (US EPA 1994). The monitoring of these vast tailings facilities helps build a risk management framework aimed at preventing impoundment failures. The understanding of the factors affecting the stability of the impoundments, along with their internal dynamics, including tailings consolidation behaviour, is a critical part of sustainable mining practices.

Tailings consolidation occurs as excess porewater pressure that is generated in a saturated soil matrix is dissipated when it is subjected to a vertical load, including self-weight. The gradual compression of the load is transferred from the porewater to the matrix as the volume of voids is reduced (Morrison 2022). However, as tailings properties are heterogeneous within an impoundment, there can be significant spatial variability on the locations with the highest magnitude of consolidation. Similarly, identifying the presence of a lateral displacement component (eastward or westward) can enhance understanding of any preferential desaturation pathways and/or any added stresses to the embankments of the impoundment, further assisting in the geotechnical assessment of tailings facilities (Caldwell & Charlebois 2010).

In general, the process of tailings consolidation is a function of material properties (such as compressibility and permeability), rate of rise (i.e. filling/production rate), and boundary conditions (Terzaghi et al. 1996). Similarly, monitoring for saturation changes (i.e. changes in saturated area and locations) over time provides further insights into the governing dynamics (Hu et al. 2017; Morrison 2022). For example, upon tailings deposition, process water can drain to the centre of the pond which can be adjacent to decant towers. Therefore, characterising the magnitude of consolidation response with any saturation changes to the supernatant pond location and the surrounding area can be applied to promote sustainable water management practices (Morrison 2022; Necsoiu 2015).

Interferometric Synthetic Aperture Radar (InSAR) uses data from radar satellites to remotely perform displacement monitoring (Ferretti 2014, 2000). Advanced InSAR techniques provide frequent (e.g. bi-weekly), spatially dense measurements of displacement to monitor ground movement with millimetric precision (Ferretti 2014). This technique is widely used in the mining sector, including for the monitoring of tailings facilities (Ferretti 2014, 2000). Here, we use it for tailings consolidation monitoring by quantifying the rate of settlement and identifying any lateral displacement of the tailings mass, which may indicate preferential desaturation pathways and/or displacement towards the embankments. The InSAR analysis was coupled with a normalised differential index (i.e. normalised difference moisture index, NDMI) (ESA 2015) generated from Sentinel-2 optical images to capture saturation changes. Historical archives of the NDMI can be analysed to monitor the saturation changes at a surface level of a tailings facility. These changes can be used to correlate with the operational activities related to tailings deposition and environmental changes (precipitation and/or evaporation).

2 Methodology

In the present case study InSAR was employed with NDMI data as monitoring tools for an active tailings facility. The impoundments store paste/coarse tailings within their facility and rely on the consolidation water release for re-use within their processing facilities. The name and the geographic location of the tailings facility are anonymous for the scope of this paper. The following section describes the two complementary remote sensing methodologies used for the analysis and validation of the research.

2.1 InSAR Technology

SqueeSAR® is a proprietary multi-interferogram technique that provides high-precision measurements of ground displacement by processing multi-temporal satellite SAR images acquired over the same area, with the same acquisition geometry. A statistical analysis of the returned radar signals allows the algorithm to identify measurement points, which can then be used to monitor surface deformation with millimetric precision (Ferretti 2014).

SAR satellites have polar orbits and image the ground to the east while they are travelling from south to north, and to the west when they travel from north to south. These are known as ascending and descending orbits, respectively. InSAR measures the projection of the real vector of displacement onto the satellite line-of-sight (LOS) as illustrated in the Figure 1. The decomposition of the separate 1-D (LOS) results obtained from ascending and descending orbits over the same area and overlapping time periods produces 2D (vertical and east–west) measurements. Current SAR satellite systems provide time series of displacement data over large areas with revisit frequencies that vary from 6 to 24 days, depending on the satellites used. Similarly, the spatial resolution of a satellite varies from sub-metric to 20 m × 5 m grid cells (Ferretti 2014).

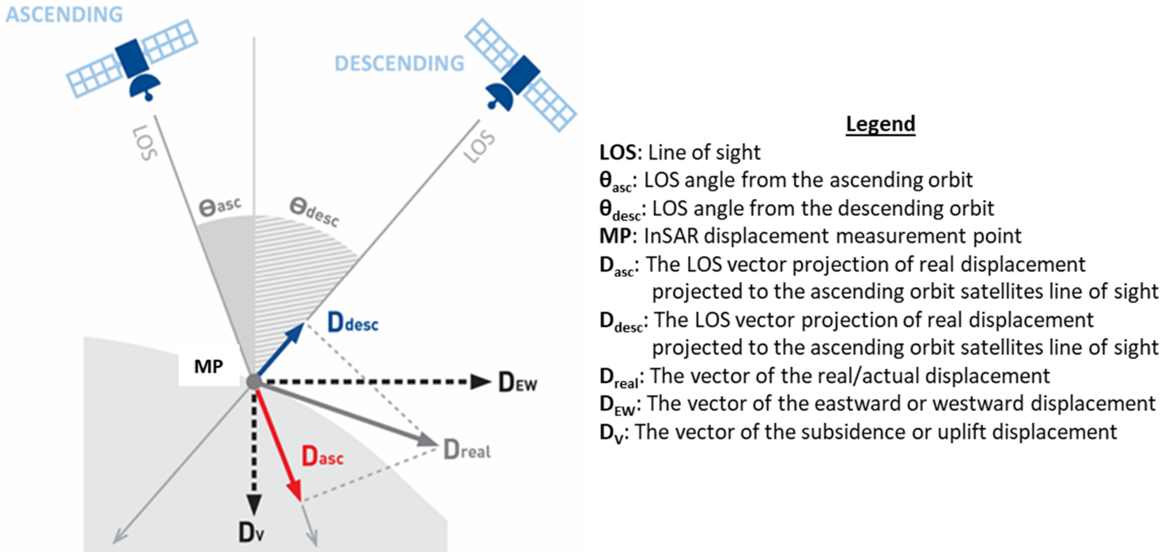

Figure 1 Decomposition of LOS (ascending and descending orbits) displacement into vertical (D_V) and horizontal (D_{EW}) components from images (Aslan et al. 2020)

For the scope of the study, two SAR satellite systems, with varying spatial resolution, were used to generate the 2D (i.e., vertical and E–W) displacement on a regular grid of 20 m × 20 m. The ascending orbit data was acquired by the TerraSAR-X (TSX) satellite (3 m × 3 m spatial resolution) and the descending orbit data by the Sentinel 1-A (SNT-1A) satellite (20 m × 5 m spatial resolution). The satellites have a similar image acquisition frequency (i.e. 11 days for TSX and 12 days for SNT). The time frame for the analyses conducted was a historical archive of SAR imagery from January 2021 to September 2022.

An overview of the InSAR measurement point coverage over the site location of the case study is presented in Figure 2. Each measurement point is based on a regular grid of 20 m × 20 m to provide true vertical (i.e. settlement and uplift) and lateral (i.e. east–west) displacement. An optical image of the tailings surface is used from the Sentinel-2 satellite. InSAR cannot capture displacement points within water, hence, there is an area of missing points on the supernatant pond (Figure 2).

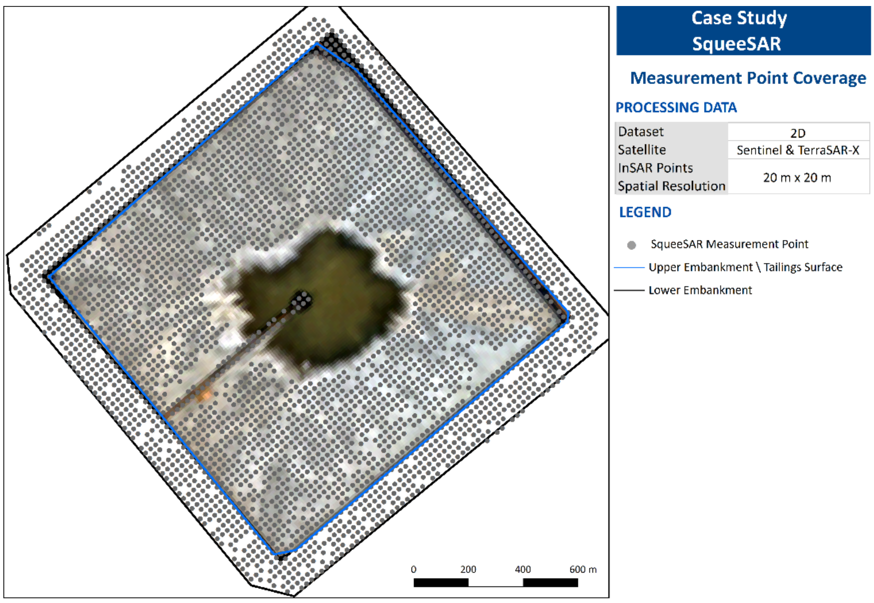

Figure 2 2D SqueeSAR measurement point coverage over the TSF included for the case study. Tailings surface is a true colour optical image from the Sentinel-2 satellite

2.2 Sentinel satellite missions

Sentinel-2 (SNT-2) is a constellation of polar-orbiting multispectral high-resolution imaging satellites. SNT-2 samples 13 spectral bands with a spatial resolution of 10 m in the visible light, 20 m in the near-infrared (NIR) and shortwave infrared (SWIR), and 60 m in the thermal infrared (TIR), with 290 km field of view and a 10-day revisit cycle. To achieve more frequent revisits (i.e. a 5-day revisit cycle) and high mission availability, SNT-2A and SNT-2B operate together. The SNT-2 images were acquired at Level-1C (Top-of-atmosphere reflectance) and were radiometrically and geometrically corrected (including orthorectification).

2.2.1 Normalised Difference Moisture Index

The Normalised Difference Moisture Index (NDMI) uses NIR and SWIR bands to display pixel moisture content (Gao 1996). Historically the NDMI has been used to monitor changes in the water content of vegetation by exploiting the amount of water available in the internal leaf structure. This behaviour largely controls the spectral reflectance in the SWIR interval of the electromagnetic spectrum (i.e. SWIR reflectance is negatively related to the leaf water content).

More recently, the NDMI was demonstrated to also represent an effective tool for monitoring TSF moisture (McJannet et al. 2022). In fact, the NDMI has close ties with the Normalised Difference Water Index (NDWI) first proposed by Gao (1996), and the two are often used synonymously. In general terms, NIR-SWIR highlight differences in the water content of leaves and green-NIR highlighting differences in the water content of water bodies. Specifically, for SNT-2 images the NDMI is computed using the NIR and the SWIR reflectance as follows (Equation 1):

$$NDMI = (Band\ 08A - Band\ 11)/(Band\ 08A + Band\ 11) \quad (1)$$

with B08a and B11 representing spectral reflectance in band 8a and band 11, respectively (cfr. Table 1).

Table 1 Sentinel-2 data characteristics

Band	Sentinel-2A		Sentinel-2B	
	Central wavelength (nm)	Bandwidth (nm)	Central wavelength (nm)	Bandwidth (nm)
Band 8A – Narrow NIR	864.7	21	864.0	22
Band 11 – SWIR	1,613.7	91	1,610.4	94

3 Results and discussion

The InSAR and the NDMI methodologies as discussed in Section 2 were utilised in conjunction to assess tailings consolidation and changes in supernatant pond area. The analysis period for the case study is from 10 January 2021 to 25 September 2022.

3.1 Assessing consolidation response with InSAR and NDMI

As a first step, the InSAR results in the vertical direction (settlement or uplift) was analysed to assess the magnitude of tailings consolidation over the TSF. The spatial distribution of the vertical InSAR results suggests that the settlement of the tailings varies based on the distance from the embankment, with the highest magnitude of consolidation (up to 280 mm/yr) are identified directly adjacent to the supernatant pond (Figure 3), while consolidation rates adjacent to the embankments decrease (up to 85 mm/yr), indicating a 3.5:1 ratio from the centre of the pond to the embankment. To identify shorter term variations, the vertical InSAR data was queried based on acceleration. A localised region of measurement points northwest (NW) of the supernatant pond displayed a deceleration of the displacement trend in the last three months of the analysis (July 2022 – September 2022) (refer to the points outlined in black in Figure 3).

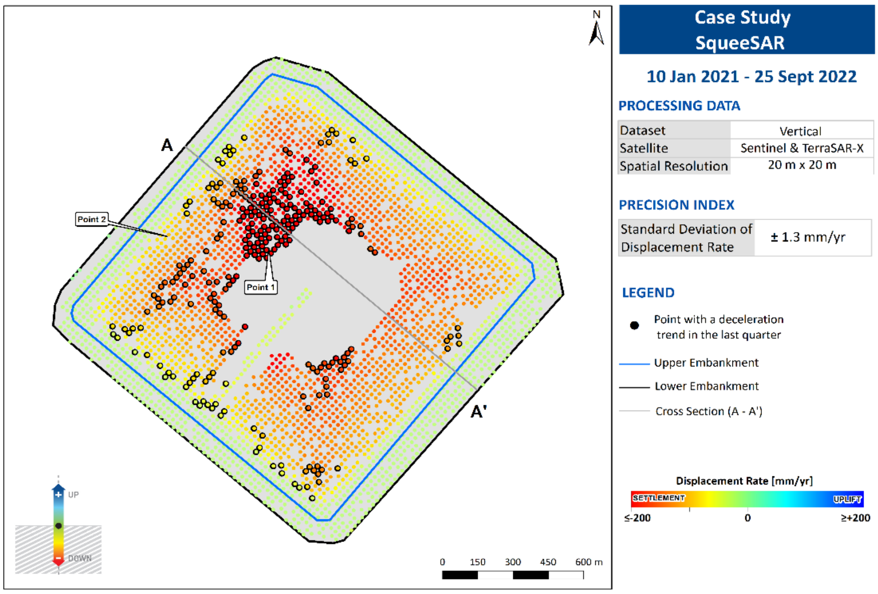

Figure 3 Overview of vertical InSAR measurement points over the TSF

Figure 4 plots time series of displacement from January 2021 to September 2022. Point 1 and Point 2 time series show two periods of acceleration from January 2021 to May 2021 and from September 2021 to May 2022. Similarly, between the periods of acceleration, two periods of deceleration are noted (June 2021 – August 2021 and June 2022 – September 2022). This behaviour suggests a cyclical nature of acceleration of the consolidation response within the tailings regardless of the position from the embankments.

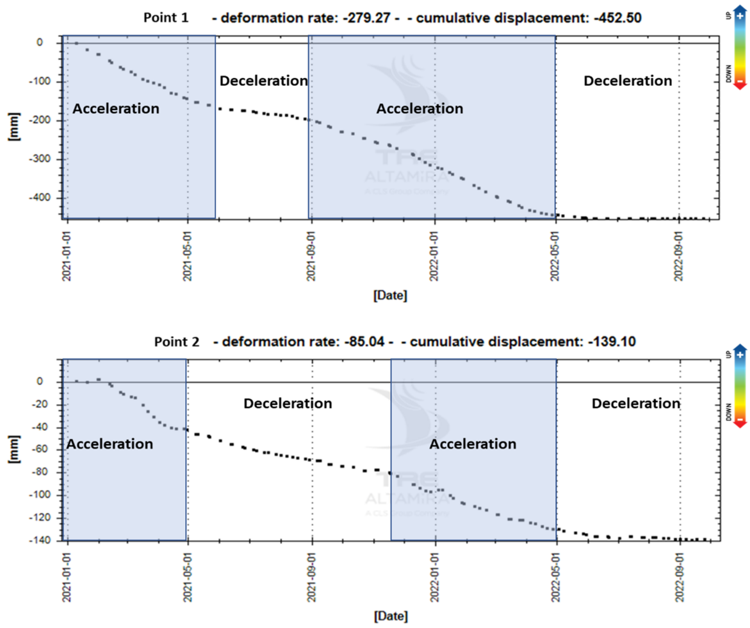

Figure 4 Time series of vertical displacement with InSAR points adjacent to the ponded surface (top) and adjacent to the embankment (bottom)

The saturation change results from the NDMI for the same time period (i.e. January 2021 – September 2022) covered by the InSAR analysis are analysed. The tailings surface area was calculated based on the 'True Colour' optical image from the Sentinel-2 satellite (as discussed in Section 2.2). The area of the tailings is 2.5 km^2 (Figure 5).

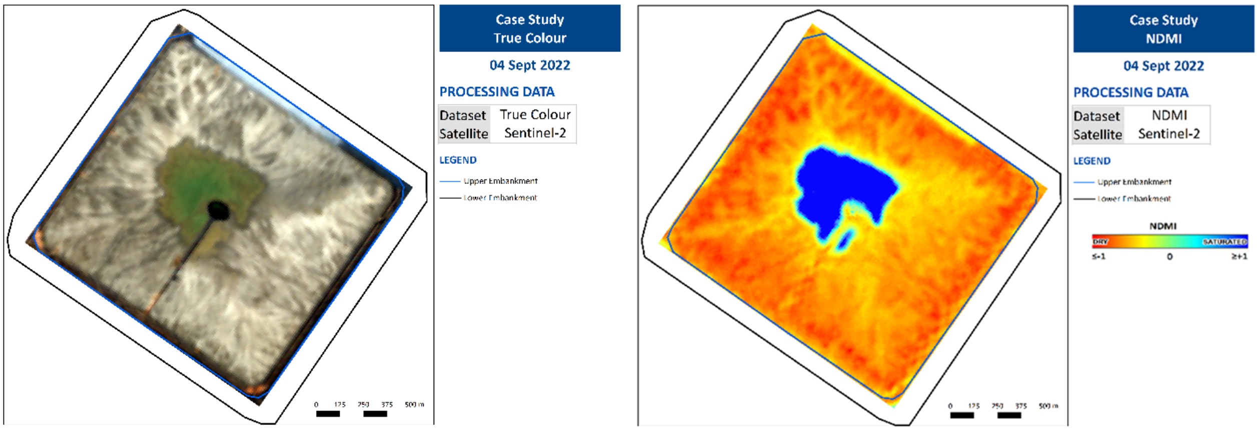

Figure 5 Sentinel-2 optical images output from the True Colour (left) and NDMI (right) from 4 September 2022

The NDMI was used with the true colour to validate the extent of the saturated pond area. Water stress is typically signalled by negative values approaching -1, while +1 may indicate waterlogging, with every value in-between corresponding to different saturations. The pixel value frequency distribution of each NDMI layer was analysed to establish three saturation classes: (i) dry, (ii) transition zone, and (iii) saturated. This sensitivity analysis suggests that, after ignoring anomalous profiles due, for example, to cloud cover, conservative estimates were used for this study. The lower and upper bound of the NDMI threshold are as follows; (i) values <0.0 are classified as dry, (ii) the transition zone values are 0.0 and 0.4, and (iii) values <0.4 are classified as saturated. The transition zone represents the range of the NDMI values observed directly adjacent to the saturated pond or other pockets of saturation on the tailings surface. These classes are in good agreement with O'Donovan et al. (2022), suggesting thresholds of 0.05 and 0.4. Values >0.4 are representative of saturated pond zone, whereas values <0.0 characterise the dry zone. Figure 5 illustrates an example from 4 September 2022, where all three NDMI classes are present. The largest proportion of the NDMI values are < 0.0 (up to 10% of the total tailings surface area). However, smaller peaks (up to 1% of the total tailings surface area) can be observed at values around or greater than 0.4, indicating the presence of wet material within the TSF (Figure 6).

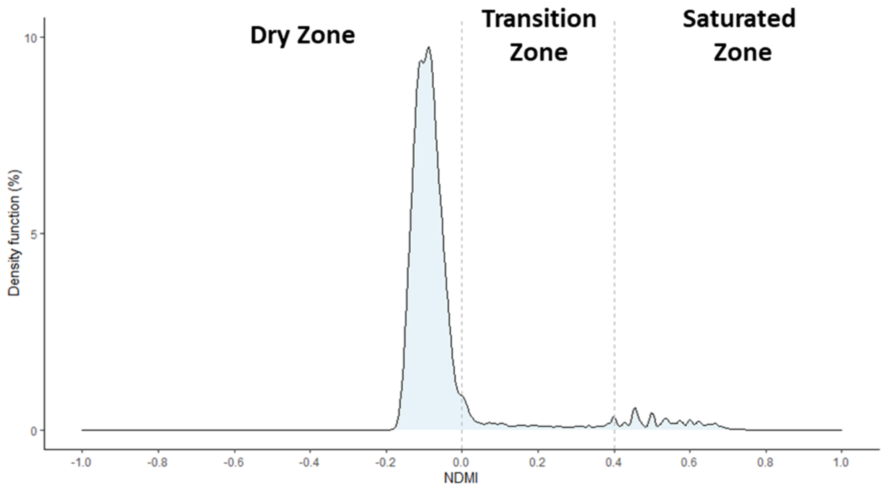

Figure 6 NDMI pixel value frequency distribution (%) at TSF (cfr. Figure 5) from 4 September 2022

A validation for the saturation classes for the same time period (i.e. January 2021 – September 2022) covered by the InSAR analysis was performed. The overview maps show visible changes in the supernatant pond surface area over the period considered (Figure 7). As the TSF is active, new tailings deposition, water captured adjacent to the decant towers and water loss due to consolidation to the underdrainage are some of the primary drivers of changes in water balance. Similarly, the TSF is an open to atmospheric components such as precipitation and evaporation, these are also suggested to be affecting the supernatant pond surface. However, they are not part of the scope of this study and can be included to enhance the analyses to better understand the phenomena contributing to the drying and the wetting of the supernatant pond area (Morrison 2022).

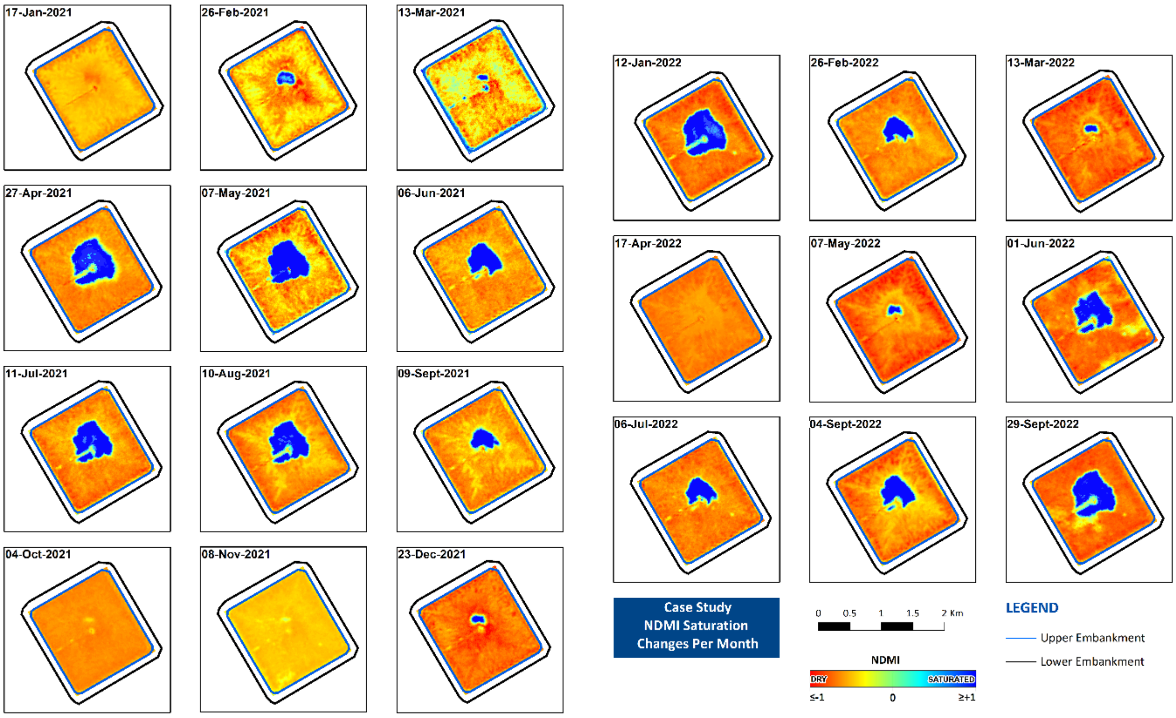

Figure 7 Overview of NDMI saturation outputs on a monthly basis over the TSF

Building on the overview maps from Figure 7, a time series of pond surface area changes were plotted to identify temporal trends of higher pond volume with respect to the total TSF area as shown in Figure 8. Four periods of changes to the supernatant pond area are observed over the time period of the analysis: (i) January 2021 to May 2021, less than 5% saturation of the total TSF area, (ii) May 2021 to September 2021, greater than 5% saturation of the total TSF area, (iii) September 2021 to May 2022, less than 5% saturation of total TSF area, and (iv) June 2022 to September 2022, greater than 5% saturation of the total TSF area. The NDMI results provide a similar cyclical patter as observed by the InSAR vertical displacement results as shown on Figure 4.

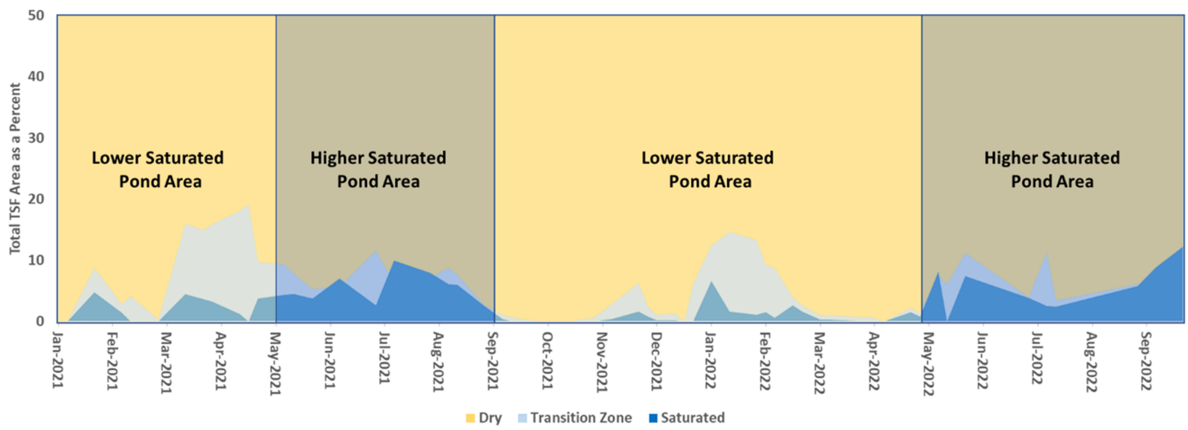

Figure 8 Time series of changes in pond saturated area as a percentage of the total area of the TSF

The temporal correlation identified between consolidation rates and volume changes in the supernatant pond could suggest a seasonal impact. During the dryer months (October to May) an acceleration of the consolidation of the tailings surface is suggested. This could also suggest an increase in the use of the supernatant pond water by the decant towers, lack of tailings deposition and including a greater rate of evaporation (Morrison 2022). Similarly, during the wetter months, (June to September), the inverse relationship is hypothesised. With a deceleration of the consolidation noted and could suggest a period of tailings deposition and a greater seasonal impact due to precipitation. To gain better insight into the discussed variables of seasonality, water usage by the decant towers and tailings deposition, in situ data is recommended to supplement the geospatial results.

3.1.1 Identifying higher magnitudes of consolidation settlement

To characterise the regions with highest magnitude of displacement over the tailings surface and the embankments, a cross-section over the vertical InSAR points was drawn across the facility (Figure 9). The location of the cross-section across the tailings surface is presented on Figure 3. Cross-section A-A' denotes a greater degree of consolidation on the NW region of the supernatant pond. This suggests a heterogeneous nature of the tailings with a localised region of greater settlement. The gap of measurements in the cross-section corresponds to the area of the supernatant pond, as InSAR does not yield results over water (as discussed in Section 2.1).

To further investigate the NW region of the tailings surface, the NDMI overview maps were referred to for a qualitative check. The pond surface adjacent to the NW region as observed on the NDMI overview maps is seen with a pond extent extending towards the NW as compared to the SE region (Figure 7) during the wetter months (June to September 2021). This observation could suggest that there is a higher consolidation response occurring during the dryer months or the pond volume within that region due to tailings deposition. Similarly, a localised cluster of vertical InSAR points on the NW region are shown with deceleration trend in the last three months (July 2022 – September 2022) of the analyses period (Figure 3).

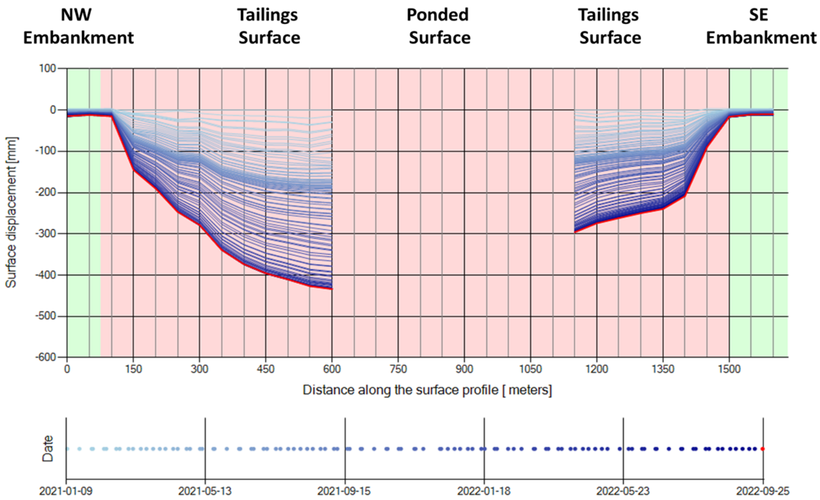

Figure 9 Surface displacement over the TSF along the Cross-section A-A' (cfr. Figure 3) during January 2021 to September 2022

3.2 Assessing lateral east–west direction on the tailings surface with InSAR

The lateral east–west InSAR results were used to further characterise displacement (Figure 10). Higher magnitudes of displacement are observed on the northeast (NE) and southwest (SW) sections of the tailings surface. The displacement rates suggest a preferential westward displacement (up to 45 mm/yr) on the NE section and an eastward displacement (up to 30 mm/yr) on the SW section of the tailings surface. This motion suggests a probable desaturation towards the supernatant pond. To supplement this Point 1 and Point 2 time series are checked (as shown on Figure 10). The time series of Point 1 on the NE region within the tailings surface highlights an initial, one-month period of westward displacement (toward the embankment) followed by a general eastward displacement towards the ponded surface as illustrated in Figure 11. Point 2 is observed with a similar behaviour in the SW region of the tailings (Figure 11). This displacement behaviour could be due to the heterogeneous nature of the tailings with a preferential desaturation pathway towards the supernatant pond. The behaviour can be further validated by in situ surveys using piezometers and other ground-based survey techniques (Morrison 2022).

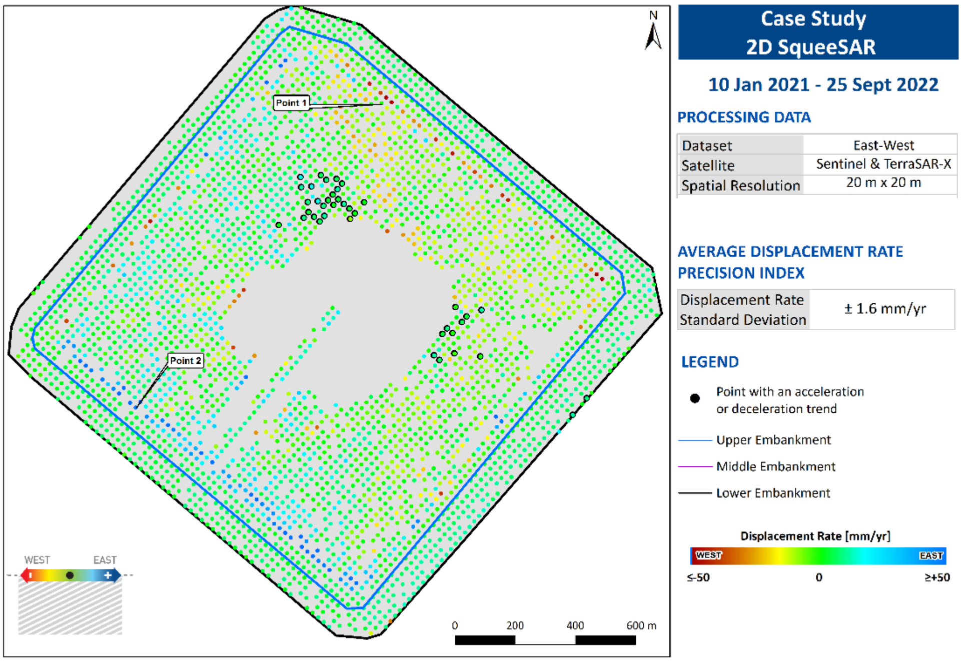

Figure 10 Overview of east–west InSAR measurement points over the TSF

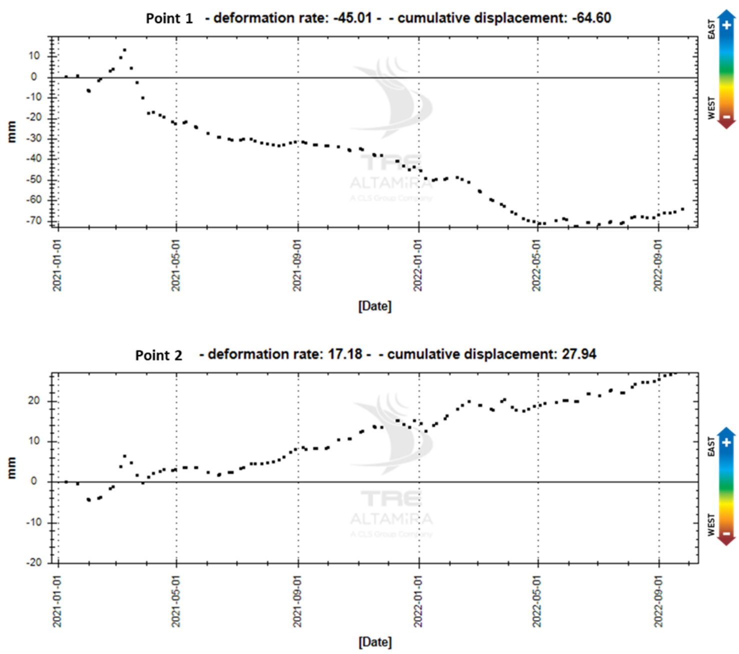

Figure 11 Time series of east–west displacement for InSAR points adjacent to the southwest embankment (top) and adjacent to the northeast embankment (bottom)

The InSAR results suggest a minor contribution of eastward and westward motion outside of the NE and SW regions of the tailings surface. Specifically, any contribution of the displacement in direction of the embankments is not present (Figure 10). Therefore, the InSAR results predominantly suggest settlement consolidation (as discussed in Section 3.1).

4 Conclusion

The 2D InSAR provides a spatially dense dataset of tailings consolidation measurements, including lateral east–west displacement. Similarly, NDMI output from the SNT-2 satellite provides insights into the changes in saturated pond location and areas over time. The combined use of both technologies over tailings facilities provides valuable insight into governing dynamics of tailings consolidation rates with the saturation changes over the supernatant pond area along with any preferential desaturation pathways. InSAR and the SNT-2 NDMI imagery can be acquired and processed at similar temporal frequencies, and these tools can assist in geotechnical and water management practices for tailings working groups. Therefore, this information can be used to supplement any operational plans.

The vertical InSAR and NDMI when assessed together provided probable correlation of the impact of the supernatant pond saturation changes with the acceleration and deceleration consolidation trends. Although, a minor contribution, the east–west displacement results indicate a possibility of preferential desaturation pathways in direction of the supernatant pond. However, this observation can be further validated with field investigations. Therefore, the two geospatial techniques when assessed together can provide frequent and precise results to enhance the understanding of tailings dynamics.

Future studies to supplement and validate the results of the present study could include the use of ground-based surveys and instrumentation such as piezometer and pore pressure data. The availability of precipitation rates and evaporation rates can assist in enhancing the analyses of better characterising seasonal impacts. To build on existing geotechnical analyses, the consolidation rates derived from the InSAR results can be used as an input for geotechnical models to better manage the raising of embankments as the consolidation response of tailings may limit construction rates (Morrison 2022). Similarly, mapping the area of the supernatant pond at a regular frequency can indicate the volume available adjacent to the decant tower to be re-used within the processing facilities and to ensure that water area does not spread laterally to cover a larger area of the tailings surface. This will allow to promote sustainable water management practices and avoid water related issues for geotechnical instabilities (Caldwell & Charlebois 2010; Morrison 2022).

References

Aslan, G, Foumelis, M, Raucoules, D, De Michele, M, Bernardie, S & Cakir, Z 2020, 'Landslide mapping and monitoring using persistent scatterer interferometry (PSI) technique in the French alps', *Remote Sens*, vol. 12, p. 1305, https://doi.org/10.3390/rs12081305.

Caldwell, J & Charlebois, L 2010, 'Chapter 3: Geotechnical Considerations – Tailings impoundment failures, black swans, incident avoidance and checklists', in *Tailings and Mine Waste 2010*, the Organizing Committee of the 14th International Conference on Tailings and Mine Waste, A.A. Balkema, Rotterdam, pp. 33–39.

ESA (European Space Agency) 2015, *Sentinel User Handbook and Exploitation Tools (SUHET): Sentinel-2 User Handbook*, European Commission, ESA Standard Document 24/07/2015, iss. 1, rev. 2.

Ferretti, A 2014, *Satellite InSAR Data: Reservoir Monitoring from Space,* EAGE.

Ferretti, A, Prati, C & Rocca, F 2000, Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry, *IEEE Trans. Geosci. Remote Sens*, vol. 38, no. 5, pp. 2202–2212.

Gao, BC 1996, 'NDWI – A normalized difference water index for remote sensing of vegetation liquid water from space', *Remote Sensing of Environment*, vol. 58, no. 3, pp. 257–266.

Hudson-Edwards, K 2016, 'Global collaboration is needed to mitigate the environmental impacts of mine wastes', *Science,* vol. 352, no. 6283, pp. 288–290.

Hu, X, Oommen, T, Lu, Z, Wang, T & Kim, JW 2017, Consolidation settlement of Salt Lake County tailings impoundment revealed by time-series InSAR observations from multiple radar satellites, *Journal of Remote Sensing of Environment*, vol. 202, pp. 199–209, https://doi.org/10.1016/j.rse.2017.05.023.

McJannet, D, Carlin, G, Ticehurst, C, Greve, A & Sardella, C 2022, 'Determination of Evaporation from a Tailings Storage Facility Using Field Measurements and Satellite Observations', *Mine Water Environ*, vol. 41, pp. 176–193, https://doi.org/10.1007/s10230–021–00832–9.

Morrison, K 2022, *Tailings Management Handbook: A Life-Cycle Approach*.

Necsoiu, M & Walter, GR 2015, 'Detection of uranium mill tailings settlement using satellite-based radar interferometry', *Eng Geol*, vol. 197, pp. 267–277.

O'Donovan, C, Adam, E & Torres-Cruz, LA 2022, 'Remote sensing of the decant pond of tailings dams: Insights from a South African case study', *The Journal of the Southern African Institute of Mining and Metallurgy*, vol. 122, no. 4, pp. 167–172, http://doi.org/10.17159/2411–9717/1766/2022.

Terzaghi, K, Peck, R & Mesri, G 1996, *Soil Mechanics in Engineering Practice*, 3rd ed, Wiley, Hoboken.

US EPA (United States Environmental Protection Agency) 1994, *Technical Report: Design and Evaluation of Tailing Dams*, EPA Report, EPA 530-R-94–038, 59 p.