The paper was published in the proceedings of the 11th International Symposium on Field Monitoring in Geomechanics and was edited by Dr. Andrew M. Ridley. The symposium was held in London, United Kingdom, 4-7 September 2022.

11th INTERNATIONAL SYMPOSIUM FIELD MONITORING IN GEOMECHANICS

On the importance of proactive collaboration between mining operators and InSAR monitoring specialists

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Abstract

Following the recent high profile catastrophic failures of a number of tailings storage facilities (TSFs), the need for better management and governance of mine sites gained international momentum. This culminated in the release of the Global Industry Standard on Tailings Management (GISTM, 2020) which set out an ambitious agenda with the goal to reach “zero harm” from tailings facilities. TSF monitoring has been highlighted as one of the six key areas of the GISTM that would assist mining companies in reaching this goal. This has allowed monitoring technology providers and specialists to showcase their capabilities and enter a relatively new and challenging market.

Interferometric Synthetic Aperture Radar (InSAR) is one recently adopted technology. This powerful geodetic tool benefits from wide spatial coverage and fine resolution. The technology requires no ground instrumentation and SAR data acquired by the Sentinel-1 satellite is freely available, making it an increasingly popular solution for remote TSF monitoring.

TSFs located at operational mine sites represent 4D jigsaw puzzles of displacements. For the most part, the displacements result from operations occurring on a TSF, such as tailings deposition and consolidation, wall raises or excavations and ongoing construction activities. InSAR delivers complex data, and subsequent interpretation of this in isolation may result in a distorted picture of whether the TSF is stable or undergoing tolerable movements. In other words, uninformed use of InSAR data may produce misleading interpretations of field behaviour, leading to unnecessary anxiety.

This paper illustrates the added value that site intelligence (i.e. where expected displacements have occurred due to day-to-day operations) can have on interpreting InSAR results and the importance of collaboration between all parties. Contrary to some suggestions that InSAR can single-handedly predict displacements leading to the onset of catastrophic failures, InSAR should be considered as part of an overall monitoring approach that combines complementary technology and expertise.

Keywords: Tailings Facilities, InSAR, Displacements

1. Introduction

Tailings Storage Facilities (TSFs) are dynamic structures that expand over the life of the mine to accommodate increased tailings accumulation. TSFs, particularly upstream raised facilities (see types of dams below), often rely on the strength of hydraulically placed tailings that are variable in strength due to mine processing changes, operational practices on deposition and climate variations. TSFs are usually constructed from earth and rock waste materials from the mine and have variable design lives (continuously constructed).

TSFs evolve over their life cycle, from planning, design, construction, operation, through to closure and post-closure. There may also be periods of care and maintenance between operational phases.

Most TSFs start with a ‘starter dam’, and depending on various factors, they are raised using different raising techniques. The choice of design is based on factors such as dam location, geology, seismicity, climatic conditions, construction materials and the nature of the tailings. The techniques include:

- Upstream, where embankment raises progress towards and onto the impounded tailings. These raises are the most cost-effective. However, as a downside, this construction method relies on the strength of the impounded tailings for stability of each additional dam lift.
- Downstream, where the embankment raises progress towards the downstream side of the starter dam. These TSFs are the most stable, but they require large volumes of fill material and large construction areas or real estate.
- Centreline, where the embankment is raised vertically above the starter dam.

TSFs have an estimated likelihood of catastrophic failure of between 10 to 100 times greater than hydroelectric dams (Adam and Li, 2010). Between 1915 and 2016, over 290 TSF failures were reported (Bowker and Chambers, 2017). Two recent major catastrophic failures in Brazil, namely the Fundao and Brumadihno events in 2015 and 2019 respectively, have brought TSF failures into the global limelight. Following these recent high profile catastrophic failures, the need for better management and governance of TSFs gained international momentum. This culminated in the release of the Global Industry Standard on Tailings Management (GISTM, 2020) which set out an ambitious agenda with the goal to reach 'zero harm' from tailings storage facilities.

TSF monitoring has been highlighted as one of the six key areas of the GISTM that would enable mining companies to reach this goal. Interferometric Synthetic Aperture Radar (InSAR) is one recently adopted technology for TSF monitoring. This powerful geodetic tool benefits from wide spatial coverage and fine resolution. The technology requires no ground instrumentation and SAR data acquired by the Sentinel-1 satellite is freely available, making it an increasingly popular solution for TSF monitoring. The shorter the revisit time of the satellite over an area, the more complete picture of temporal progression of displacements over a particular feature of interest.

TSFs located at operational mine sites represent 4D jigsaw puzzles of displacements. For the most part, the displacements result from operations occurring on a TSF, such as tailings deposition and consolidation, wall raises or excavations and ongoing construction activities. InSAR can capture these displacements, but the subsequent interpretation of this data in isolation may result in a distorted picture of whether the TSF is stable or undergoing tolerable movements. In other words, uninformed use of InSAR data may produce misleading interpretations of field behaviour.

This paper considers over 1000 days of Sentinel-1 InSAR data collected for an active TSF and compares it with interpreted InSAR data available in the public domain from two other TSFs, namely the Zelazny Most TSF in Poland and Correjo do Feijao in Brazil (Sciortiono et al., 2021; Holden et al. 2020).

2. InSAR measurements and data processing

The radar sensors on SAR satellites operate in the microwave domain with wavelengths of several centimetres, allowing them to efficiently operate through various light and weather conditions with a sub-centimetre precision. InSAR measures the signal phase change between two images of the same area acquired at different times. An interferogram represents the post-processed image of the signal phase change. Combining multiple interferograms makes it possible to generate a time-series of ground movement and maps showing cumulative or average displacement.

The frequency of data acquisition is determined by the revisit period of the satellite, which for Sentinel-1 satellites is 12 days (ESA 2022). The two-satellite constellation can capture data every 6 days in some cases. The SAR satellites travel in the North-South and then the South-North direction. The satellites can capture 1D surface deformations in the line of sight (LOS) of the radar. The LOS depends on the orientation of the satellite in relation to the ground surface geometry, and as such, surface displacements perpendicular to the LOS (i.e. north or south) are much harder to detect. This means that InSAR can monitor for surface deformations along the vertical and east-west directions.

The Sentinel-1 constellation offers excellent coverage over the TSF investigated in this study, acquiring data every 12-days.

3. Active TSF

The active TSF investigated in this study underwent a number of activities that resulted in significant elevation changes. This is typical for any active TSF that may undergo embankment raises, tailings deposition, and road access constructions, which result in changing topography of the TSF. Therefore, updating the digital elevation model (DEM) of a TSF following such activities is essential for providing up to date topography of the area of interest. In addition, an up-to-date DEM is useful in InSAR data processing to remove errors associated with topographical changes.

4. Results

Displacements along an approximately 1 km long section of the wall of the TSF are interpreted. All temporal elevation changes in this study are provided as total displacements that occurred over that period. Two periods of interest are illustrated: a 1000-day period and a 72-day period. The active TSF from this current study is labelled as 'active TSF' in the figures and discussion below.

4.1 1000-days data processing

The displacement map showing the total cumulative displacement of a 1 km long section of the active TSF wall over approximately 1000 days is depicted in Figure 1. Given the length of time for which InSAR data was collected, and taking into account that a number of activities were undertaken on site which would have significantly impacted elevation changes, the displacement map could not incorporate total displacements over all parts of the active TSF infrastructure.

Figure 1 shows that a total settlement of more than 40mm has been detected in the various tailings impoundment areas over the investigated time period. Therefore, without having any additional information from the mine site operators and design team and without further segmentation of the time period of interest, it may be deduced that the tailings settled by more than 40mm and no additional tailings were deposited in the impoundment over the 1000-day period.

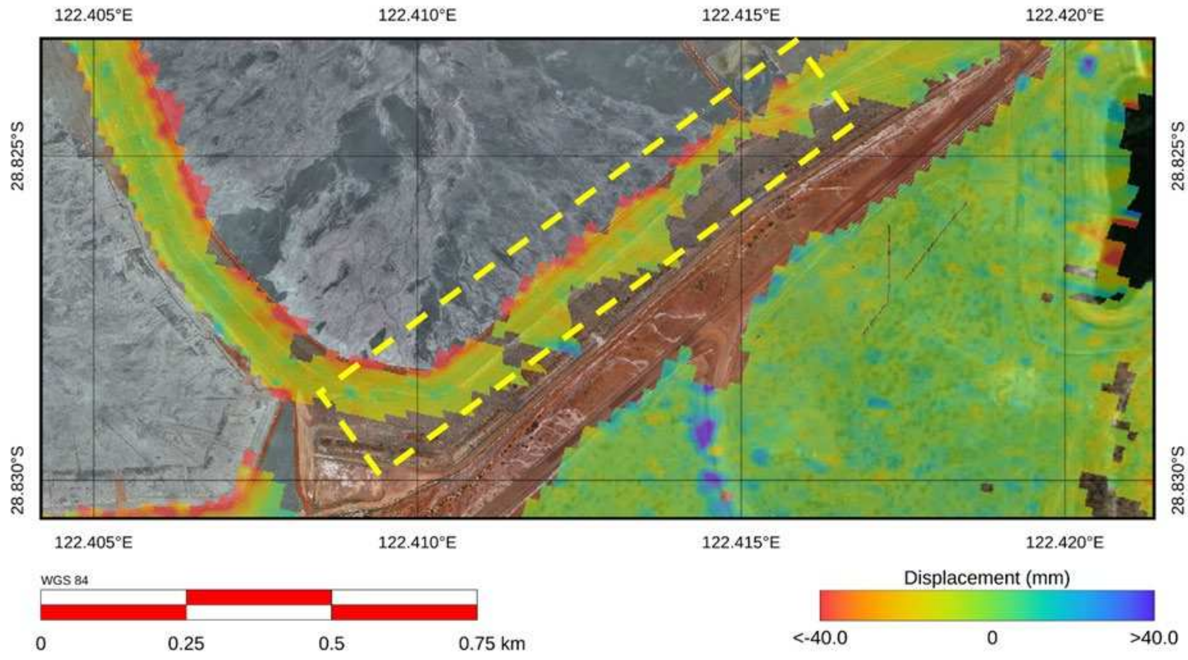

Figure 1: Three year (approximately 1000 days) line of sight total displacement over a section of the TSF wall

4.2 Shorter-term data processing

The cumulative displacement map in Figure 2 shows the total displacement observed with InSAR in the same section of the active TSF wall over a three-month period, taken within the previously interrogated 1000-day period of interest. In this case, several portions of the tailings impoundment (i.e., above the TSF wall section) exhibit positive elevation changes of more than 15 mm. Comparing the total displacements shown in Figure 1 and Figure 2, some areas of the active TSF impoundment show over 55 mm of total elevation change. Considering that the positive total displacement changes during the 3 months were achieved inside the 1000-day initial period of interest, several hypotheses based solely on the displacement maps may be formulated:

- The 3-month period captured swelling (or heave) of the deposited tailings following an increase in the water content of the tailings, which could have been the result of several factors (e.g., precipitation during the wet season; increase in the phreatic surface in the tailings).

- The +15mm displacement may be the result of tyre treads from machinery used when re-instating the pipework needed for the recomission of an adjacent cell.
- As the measurements are from a single LOS, the fraction of displacement in the vertical and horizontal directions is unknown. In this case, the satellite is in a descending orbit, and the satellite is right-looking. Therefore positive displacement could be uplift and/or eastward. Uplift caused by swelling seems the more likely cause.

Although displacement maps provide a wide area snapshot of total displacements, they do not provide a detailed step-by-step temporal history of displacements. As such, time series plots of specific areas of interest (AOIs) are employed to assess changes in surface displacements and potentially detect anomalous rates of change in displacement.

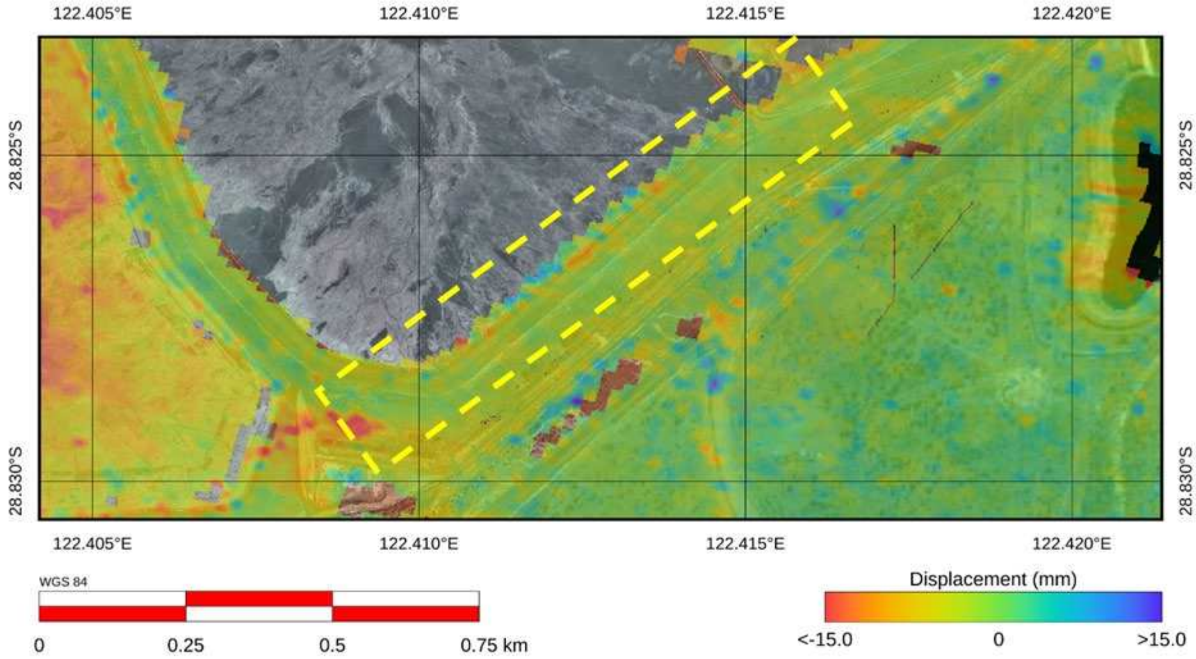

Figure 2: Three-month (approximately 72 days) line of sight total displacement over a section of the active TSF wall

3.3 Discussion

Detailed average time-displacement histories have been calculated for three AOIs located on the active TSF embankment. The three AOIs are graphically shown in Figure 3. The active TSF embankment shows minimal changes in displacement with time during the 1000-day period of interest.

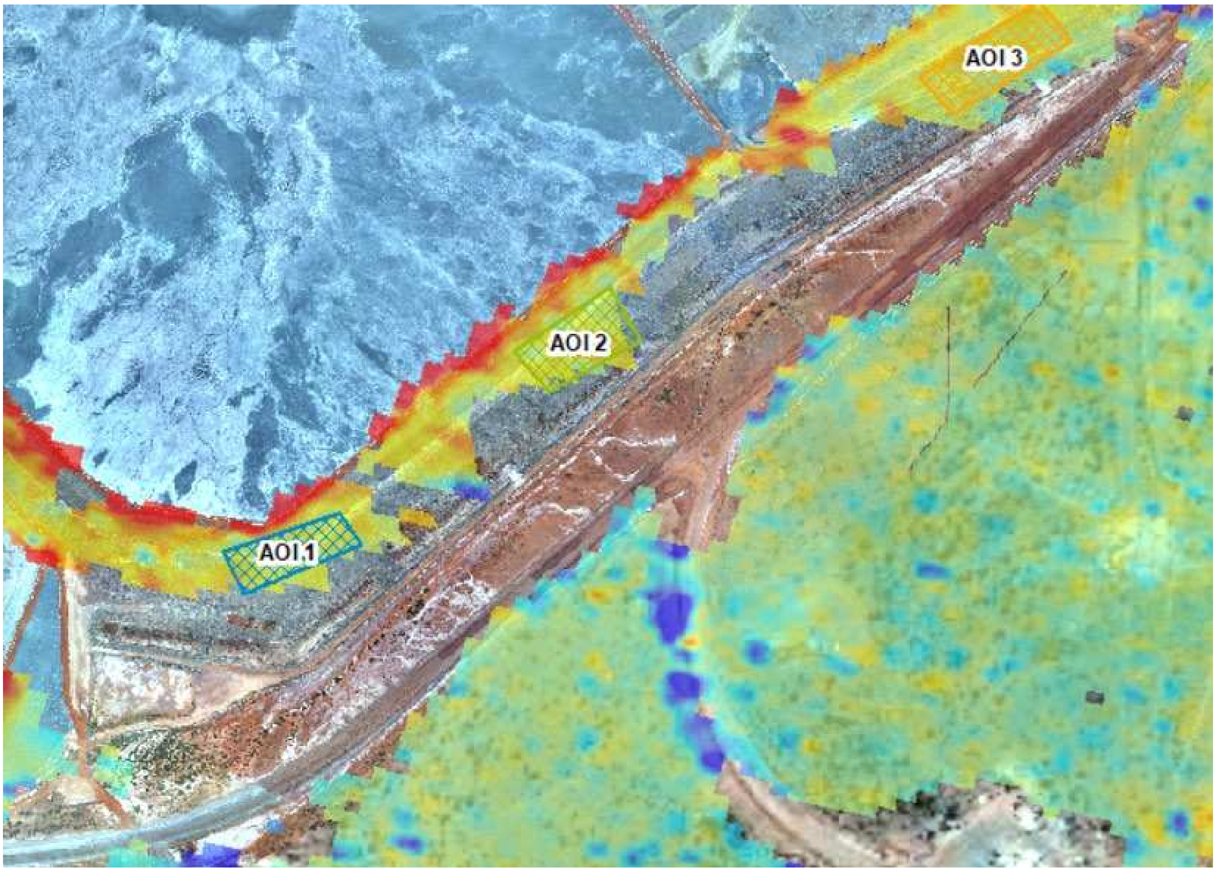

Figure 3: Location of areas of interest (AOI) on the active TSF wall for which averaged time-displacements were calculated

To compare the time-displacement histories from the active TSF, additional sets of time-displacement histories of two active TSFs available in the public domain have been included in the current study: the Zelanzy Most TSF in Poland (Sciortino et al. 2021) and Corrego do Feijao TSF before catastrophic failure (Holden et al. 2020).

Figure 4 illustrates the average time-displacement histories for the three AOIs of the active TSF in the current study, three AOIs located on the wall of the Zelanzy Most TSF, and two AOIs from the lower section of the wall of the Corrego do Feijao. The temporal history for all AOIs extends over approximately 1000 days, but the actual dates are not identical. It is also important to note that the three TSFs are located in three very different climatic regions.

Figure 4 shows very different time-displacement behaviours between the three TSFs, with accumulated average displacements ranging from less than 10mm for the active TSF in the current study to accumulated average displacements of close to 100 mm for the Zelanzy Most TSF. The Corrego do Feijao TSF, which ultimately catastrophically failed in 2019, displays average displacements between those observed at the other two active TSFs.

Figure 5 shows the time-displacement histories for the AOIs of the three TSFs illustrated in Figure 4, but for the intermediate period between 400 – 800 days, taking into account that the displacement at 400 days was set to zero. This period was selected because it exhibited the highest rates of change in displacement over the entire 1000 days for each of the three TSFs. The Zelanzy Most TSF shows the greatest accelerated changes in displacement rates of close to 2.4 cm/month compared to ~1 cm/month at the active TSF in the current study and the Corrego do Feijao TSF. Based on the InSAR data alone, the Zelazny Most TSF would exhibit the highest likelihood of failure, with Corrego do Feijao TSF undergoing relatively steady changes in displacements. As noted by Holden et al. (2020), InSAR would not have been able to provide actionable prior warning to a catastrophic collapse of the Corrego do Feijao dam.

Although the Zelazny Most TSF shows the highest surface average displacement accelerations, it is considered a stable dam since the dam has been under continuous monitoring over several decades, benefitting from a wide range of monitoring instrumentation (Jamiolkowski 2014; Stefaniak and Wrozynska 2018) and active collaboration between monitoring specialists, the design team and mine site operators.

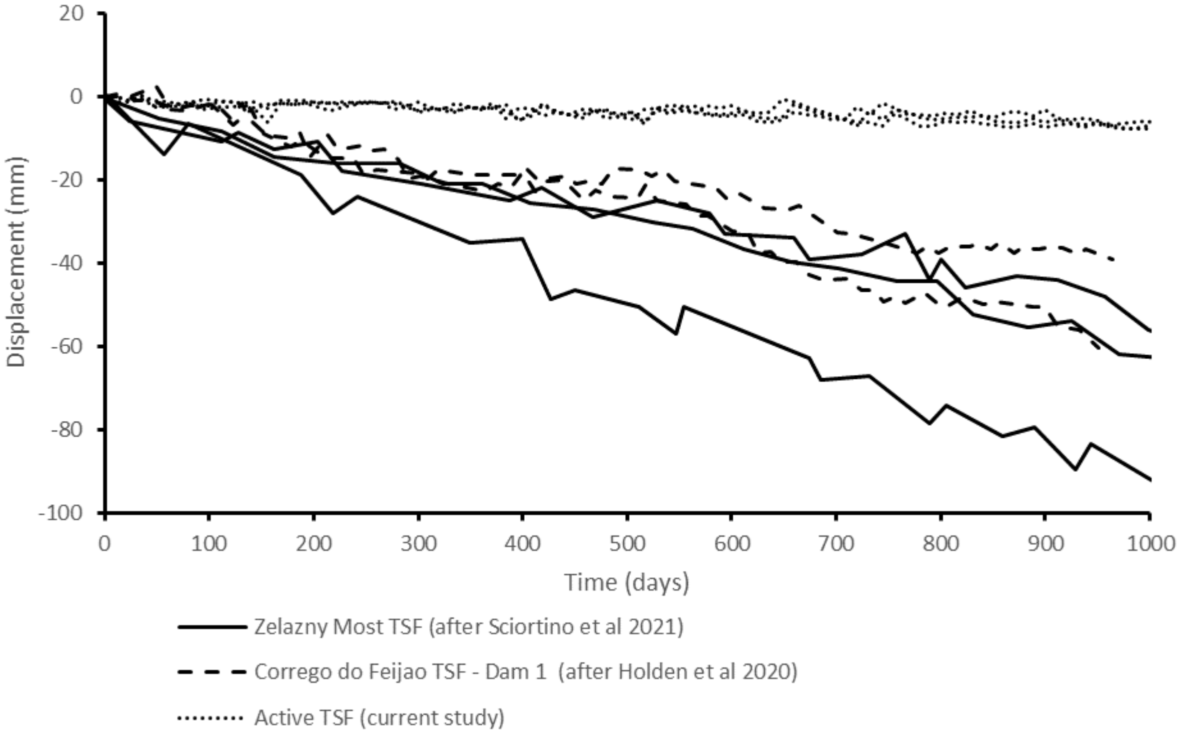

Figure 4: Average settlement history over 1000 days over a number of areas of interest at three active TSFs: Zelazny Most (after Sciortino et al. 2021), Corrego do Feijao (after Holden et al. 2020) and active TSF from the current study.

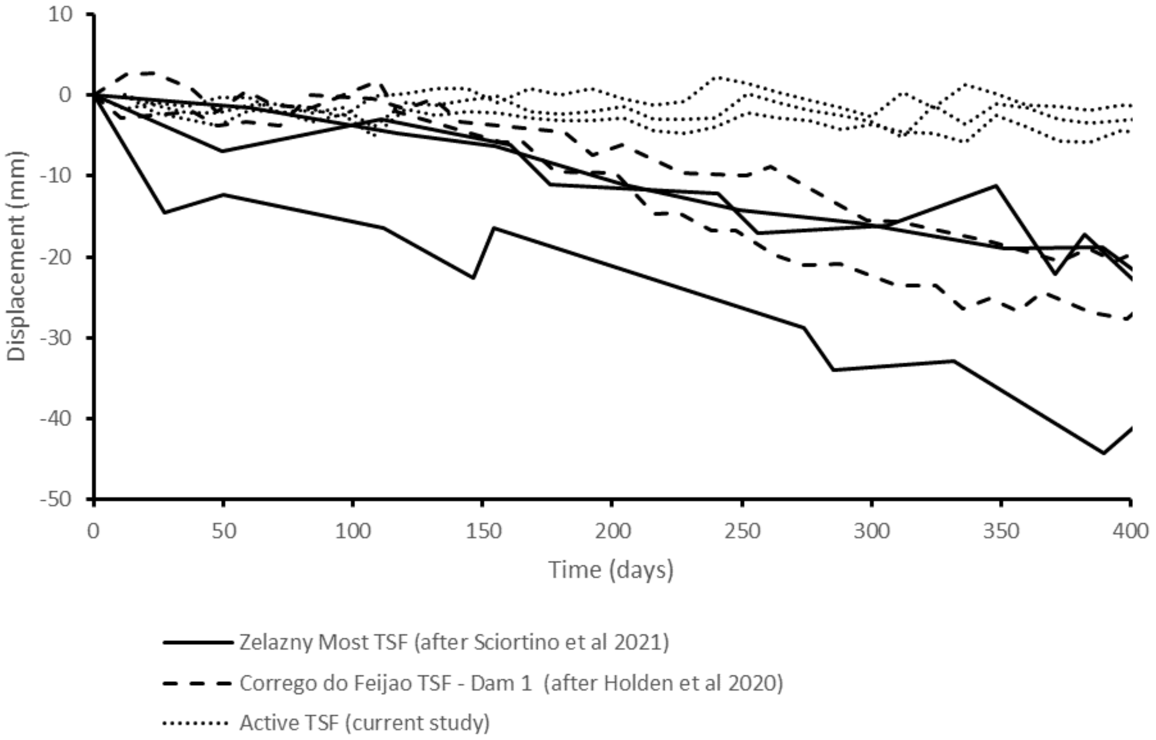

Figure 5: Average settlement history over 400 days over a number of areas of interest at three active TSFs: Zelazny Most (after Sciortino et al. 2021), Corrego do Feijao (after Holden et al. 2020) and active TSF from the current study.

4. Implications on effective monitoring

Figure 4 and Figure 5 highlight that active TSFs may undergo significantly varied surface average displacement accelerations. These surface average displacement accelerations alone do not necessarily provide early actionable warnings about impending failure. “Prior intelligence” offered by mine site operators is essential in understanding observed displacements and changes in acceleration of displacements. The wealth of activities undertaken at an active TSF may result in high but acceptable changes in average displacements. Thus, the analysis and interpretation of InSAR data needs to be strictly linked to and interrogated against the expected effects of specific operations at the mine site. After the InSAR data is post-processed and cumulative displacement maps and time-displacement series are generated, monitoring specialists should analyse and interpret the results taking into account previous activities on and around the TSF. This could mean that higher surface average displacement accelerations may represent acceptable and tolerable levels of movement.

Additionaly, effective monitoring is complete by also interrogating InSAR results against complementary monitoring data from other types of instrumentation and comparison to suitable, calibrated numerical models.

5. Conclusions

The current study evaluated over 1000 days of Sentinel-1 InSAR data collected for an active TSF and compared the observed displacements with interpreted InSAR data available in the public domain from two other active TSFs, namely the Zelazny Most TSF in Poland and Correjo do Feijao in Brazil (Sciortiono et al., 2021; Holden et al. 2020).

The data revealed how prior knowledge of activities on the mine site is essential for providing accurate and reliable information about the structural health of the structure of interest. In addition, changes in displacements may occur due to numerous activities that regularly occur on an active mine site, including changes in precipitation and temperature depending on the location of the TSF.

Prior knowledge of the construction/history of the TSF is of equal importance as this might inform monitoring specialists, the design team and mine site operators about acceptable and tolerable levels of movement. Displacements, taken as absolute values and without context, do not necessarily indicate impending failure.

Acceleration of displacement changes as observed by InSAR may provide helpful information about potential precursors to structural instability when interrogated against a number of complementary monitoring data and when compared with a suitable, calibrated numerical model. Still, InSAR alone should not be relied upon for determining the structural health of a TSF. A number of monitoring programs, such as DAMSAT (Lumbroso e al 2021) and the Zelazny Most TSF monitoring program, have illustrated the importance of best practices in TSF monitoring.

Acknowledgements

The authors would like to gratefully acknowledge funding awarded from the Amira P1217 Evaluation of Tailings Storage Facilities monitoring technologies Project, funded through Amira Global by Gold Fields, Agincourt Resources, Anglo American, Lundin Mining, Rio Tinto, Independence Group, CMOC, BHP, LKAB, 3vGeomatics, Ground Probe, Institute of Mine Seismology, CGG Services UK, Sercel, Canary Systems and Loupe Geophysics.

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