TIME SERIES INSAR ANALYSIS FOR SLOPE STABILITY MONITORING USING SENTINEL-1 IN OPEN PIT MINING

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ABSTRACT:

Surface mining is an important economic activity in many regions where mineral resources are located close to the surface. The process of ore extraction is characterised by high pit walls with steep slopes. The mining process introduces significant stress and strain changes that could lead to movement on the slope face. Slope failure on the pit walls can occur without warning and can lead to loss of life and disruptions to the mining process. The monitoring of slopes remains the most reliable way to detect movement on unstable slopes. Therefore, slope monitoring programmes have been established to monitor and measure slope movement to help mine management with the stability status of open pit slopes. Conventional monitoring techniques include visual inspections and in situ instrumentation that are point-based, time-consuming, and costly. Open-source remote sensing techniques such as Synthetic Aperture Radar interferometry have been used to monitor slope movements on open-pit mine walls. Time series interferometric Synthetic Aperture Radar (InSAR) can be used to overcome limitations of in-situ monitoring for monitoring slope movements in open-pit mines.

1. INTRODUCTION

Slope failures can occur in open-pit mines without warning and with devastating consequences, including damage to mining equipment, environmental damage, and potentially fatal injuries. Common causes of slope failures include mining activities (such as blasting, loading, and hauling), rainfall fluctuations, and seismic vibrations. Due to the consequences of slope failure, slope stability monitoring remains a priority to ensure safe and sustainable mining operations. Slope stability monitoring programmes are designed to identify potential high-risk areas and monitor their long-term stability. Effective slope stability monitoring systems provide notice of slope movement through accurate and timely measurements using the appropriate monitoring techniques.

Conventional monitoring approaches include 1) geotechnical instrumentation such as piezometers, inclinometers, extensometers, and 2) surveying techniques consisting of global navigation satellite systems (GNSS), total stations, terrestrial laser scanners (TLS) and ground-based interferometric synthetic aperture radar (GB-InSAR). These techniques are well established and provide high-quality measurements. The main limitations of instrumentation and surveying techniques, except for TLS and GB-InSAR, is that they provide measurements only at targeted point locations. Obtaining coverage in larger areas would be resource and cost intensive (Amitrano et al., 2019). TLS and Gb-InSAR provide small-scale coverage of localised targeted slopes with a predetermined risk of failure. Gb-InSAR also provides a high frequency of monitoring (every few minutes) (Carla et al., 2018). However, unforeseen collapses have been known to occur on slopes not included in GB-InSAR and TLS monitoring (Carla et al., 2018).

To overcome these limitations, remote sensing technologies have been incorporated into slope stability monitoring. programmes to improve monitoring capabilities in terms of cost and accuracy. To make reliable time-to-failure projections and detect precursory movements, continuous monitoring that covers the entire slope at a high resolution is required. Differential Synthetic Aperture Radar Interferometry (dInSAR) from both ground and satellite platforms has been recognised as one of the most effective approaches to measure slope displacements, with many documented cases of catastrophic failures that could be predicted based on these observations (Carla et al., 2018; Lopez-Vinielles et al., 2020). DInSAR techniques use the measurement of the phase difference between pairs of SAR images acquired at different times or at slightly varying viewing angles to detect radar LOS of surface displacement (Pepe et al., 2016).

The use of open source software and tools in InSAR has become more prevalent in geospatial and remote sensing research. Currently, the use of satellite InSAR for operational monitoring of mine slopes stabilities has increased due to the growing availability of large archives and new SAR acquisitions that operate at different wavelengths (Pepe et al., 2016). There has also been the development of open-source software tools to analyse time-series InSAR measurements such as MintPy and Snaphu (Chen and Zebker, 2002; Yunjun et al., 2019). The use of open-source algorithms has several advantages. Mining engineers and stakeholders can use open-source dInSAR algorithms to conduct deformation analysis that can be cost-effective alternatives to propriety software (El Kamali et al., 2020) Free and open data also allows to conduct historical analysis of slope movements due to large archives of data that are available (Raventos et al., 2018).

In this paper, we extract deformation time series from Sentinel-1A/B scenes using open-source MintPy time series Small-Baseline Subset (SBAS) implementation (Yunjun et al., 2019). The objective is to observe instances of slope creep and potentially accelerating creep that may be indicative of imminent slope failure. The results will determine the suitability and operational limitations of this approach for operational slope stability monitoring and specifically early detection of accelerating creep that may lead to failure of this slope. This paper will also highlight the benefit of open-source tools and open data for deformation monitoring using time series InSAR.

2. OPEN REMOTE SENSING DATA

Open source data refers to data that is freely available for anyone to access, use and distribute, offering several benefits. The open access of Sentinel-1 data by the European Space Agency (ESA) through the Copernicus programme provides free and open access to Earth Observation data. Sentinel-1 offers global covers and provides SAR data at regular intervals. This has been used in various applications including slope failures and mining-related deformation (Carla et al., 2019; Tang et al., 2020; Wang et al., 2021). The role of open-access Sentinel-1 data enables collaboration between various users (Ramachandran et al., 2021). Furthermore, studies can replicate the results and verify the findings. This promotes the reliability and credibility of remote sensing research. By providing open data, stakeholders with limited resources can access remote sensing research and contribute to the field (Nelson et al., 2019). Furthermore, open data can facilitate innovation in geospatial applications. In addition to being open-source, open-source data and software can provide the flexibility to modify datasets if needed.

3. OVERVIEW OF TIME-SERIES INSAR FOR SLOPE STABILITY MONITORING

Synthetic Aperture Radar (SAR) are active imaging systems that exploits the microwave part of the electromagnetic spectrum (EM) to form images of the Earth's surface (Hanssen, 2005). A pulse is transmitted from the SAR sensor, and the backscattered signal consists of both amplitude and phase information. When two images are acquired at different times or at slightly different orbital positions, the phase information can be compared. The difference in the phase information shows an interference pattern known as an interferogram (Massonnet et al. 1993). If there was any surface movement between the two acquisitions the phase contributions can be isolated and measures. This is known as differential SAR interferometry. This can be used to detect movement that ranges between centimetre and millimetre (Bamler and Hartl, 1998). SAR systems measure displacement only the Line-of-Sight (LOS) which is defined between the satellite, the sensor, and the ground target (Herrera et al., 2010).

Although conventional dInSAR techniques have been used to monitor slope stability in mines, there are limitations to the technique. These include spatial and temporal decorrelation, signal due to atmospheric conditions, and orbital or topographic errors (Pawluszek-Filipiak and Borkowski., 2020). Time series InSAR techniques such as Small Baseline Subset (SBAS) have been proposed to overcome limitations of conventional dInSAR techniques. This technique was developed to study the temporal evolution of the deformation pattern where a combination of several SAR interferograms series generated by a proper selection of SAR image pairs, to provide a dense map of measurements (Berardino et al., 2002). The technique is based on the use of a network of SAR images that has small temporal and spatial baselines known as small baseline subsets (Berardino et al., 2002). The goal of this technique is to mitigate the effects of the atmospheric and tropospheric phase contributions to obtain an accurate detection of displacement (Ferretti et al., 2002). Open source tools and software have been developed to implement the SBAS technique, which provides accessible algorithms to measure deformation in mining environments.

Additionally, with free SAR data such as Sentinel-1 from the European Space Agency (ESA) Copernicus project, deformation monitoring can be implemented to complement ground surveys that are already employed for open pit mines. Sentinel-1 is a free and open SAR data source that provide frequent revisit intervals (every 12 days) and has wide coverage. This provides the potential to use free and open data for ground deformation monitoring campaigns (Karamvasis and Karathanassi, 2020). When combined with time series InSAR algorithms, the temporal evolution of surface deformation can be extracted from a sequence of repeated SAR images (Yunjun et al., 2019). Using this approach, high-precision measurements, below 1 mm/year in the best case, are obtainable due to the ability to reduce topographic residuals and atmospheric artefacts (Chen et al., 2020). The resulting InSAR measurement data have been found to be comparable to measurements from conventional geotechnical instrumentation and surveying techniques (Raventos et al., 2018).

4. DATA AND METHODS

4.1 Sentinel-1A data and overview of study area

The study area is an operational, undisclosed open pit iron mine in South Africa. For this research, Sentinel-1 SAR data was obtained through the Copernicus Programme of the European Space Agency (ESA) from Copernicus Open Access Hub. The data for the analysis of pit wall stability were captured in Interferometric-Wide-Swath (IW) mode providing roughly 14 m spatial resolution. The data was captured at 12-day intervals between January 2020 and May 2021. Both ascending and descending orbits were available which have look directions from the east and west of the open-pit mine in dual polarisation (VV and VH). The sensor characteristics are shown in Table 1.

	Sentinel-1A	Sentinel-1B
Acquisition mode	IW	IW
Wavelength	C-band (~5.3 cm)	C-band (~5.3 cm)
Spatial resolution	14 m	14 m
Temporal Revisit	12 days	12 days
Incidence Angle	39.3°	38.9°

Table 1. Sentinel-1A sensor characteristics

4.2 Small Baseline Subset (SBAS) Processing

4.2.1 Interferogram network generation

The workflow starts with conventional repeat-pass dInSAR techniques that generate a stack of unwrapped interferograms in ESA SNAP v.8.0. The processing chain is shown in Figure 1. Firstly, a reference scene known as the master scene and an image captured at the subsequent date are used to form an interferogram. The master and slave scenes are coregistered to sub-pixel accuracy prior to the interferogram generation. The phase contributions due topography, atmospheric artefacts and orbital errors are removed to form a differential interferogram. The SRTM 1sec HGT DEM was used for the removal of topographic phase and for terrain correction. The differential interferogram is filtered using a three-by-three Goldstein filter. Finally, the differential interferogram undergoes Phase unwrapping. This is the process of removing the 2π phase ambiguities. Phase unwrapping was undertaken using he Minimum Cost Flow (MCF) algorithm that is implemented in the open-source software SNAPHU (Chen and Zebker., 2002).

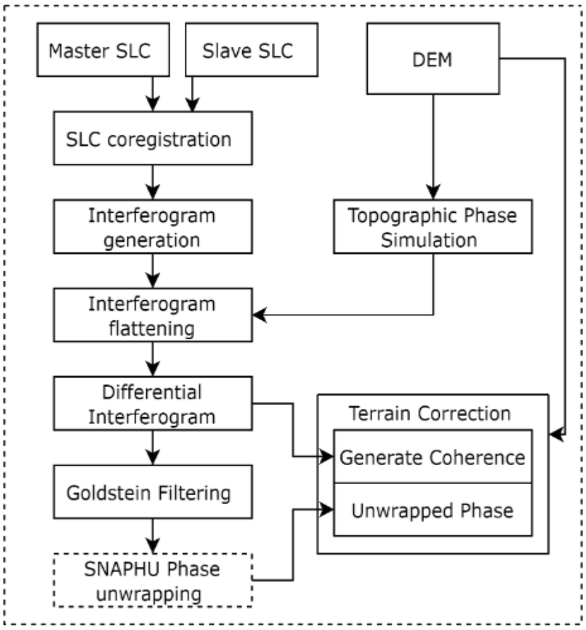

Figure 1. Conventional dInSAR processing workflow

4.2.2 MintPy processing

To obtain redundancy in the network, each image was processed as a master scene with four successive scenes as slaves, providing a total of 89 interferograms for the ascending orbit and 92 for the descending orbit. The resulting small-baseline interferogram stack was then processed using the Miami InSAR Time-series software in Python (MintPy) to produce a line-of-sight (LOS) displacement time series for every pixel in the dataset (Yunjun et al. 2019). This is an open source software package that is used for SBAS processing. This is based on a weighted least squares inversion (Yunjun et al. 2019). An example of a fully connected interferogram is shown in Figure 3.

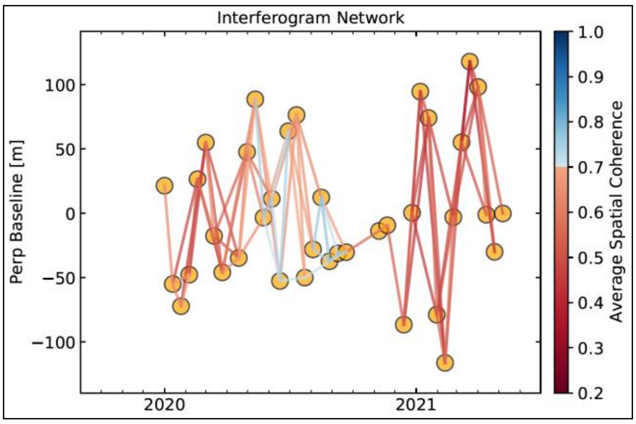

Figure 3. Interferogram network example from MintPy processing

For the MintPy processing workflow, the input is a stack of phase-unwrapped interferograms. The processing chain consists of two main parts 1) correcting the unwrapping errors and inversion from the raw phase time series and 2) correcting the phase contributions from different sources to obtain the displacement time series. The processing workflow is shown in Figure 2. In the first stage, the input stack of interferograms is inverted to acquire the interferometric phase for each date. Pixels with a temporal average coherence less than 0.7 were masked out in this process. The next stage corrects for deterministic phase components including 1) tropospheric delay correction using global atmospheric models, and 2) topographic residual correction based on the proportionality with the perpendicular baseline time series (Yunjun et al., 2019). In the final phase, the residual phase noise is estimated, and the average phase velocity is estimated as the slope of the bet fitting line to the displacement time series. The Line-of-sight (LOS) displacement was extracted as a point vector dataset for further analysis.

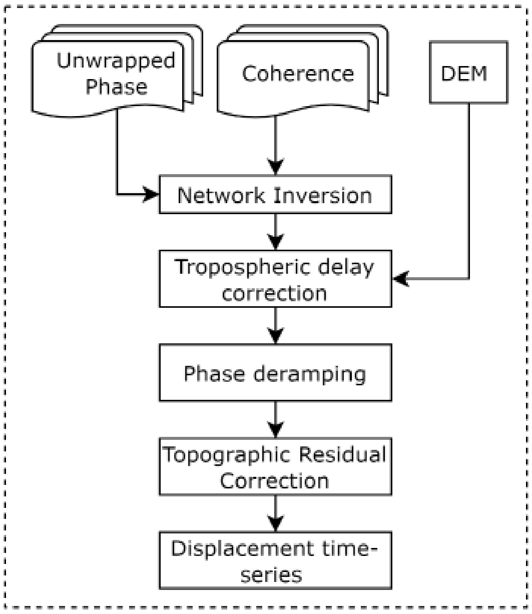

Figure 2. MintPy SBAS processing workflow

For the interpretation of the movement velocities, the orbital geometry of the sensor in relation to the ground needs to be considered. For the LOS measurements, positive values represent values movement towards the satellite and negative values represent movement away from the satellite. The LOS displacement points extracted from the time series with warmer colours indicating movement towards the LOS and colder colours indicating movement away from the LOS. In ascending Sentinel-1 geometry, movement towards the satellite is indicative of movement direction predominantly eastward or vertically downward (subsidence). In the descending geometry, movement towards the satellite suggests upward and/or in a westward direction. Any movement that occurs perpendicular to the LOS cannot be detected in InSAR.

5. TIME SERIES INSAR RESULTS

5.1 Observations in Zone 1

The displacement time series obtained from MintPy processing is the LOS displacement measurements over the time frame between January 2020 and May 2021. One of the open pits was used as a test case for the time series SAR technique and an area of interest was identified and illustrated in Figure 4. In Zone 1 the area to the east of the pit wall is exhibiting elevated velocities from the Sentinel-1 ascending line of sight. The time series was extracted and is shown in Figure 5.

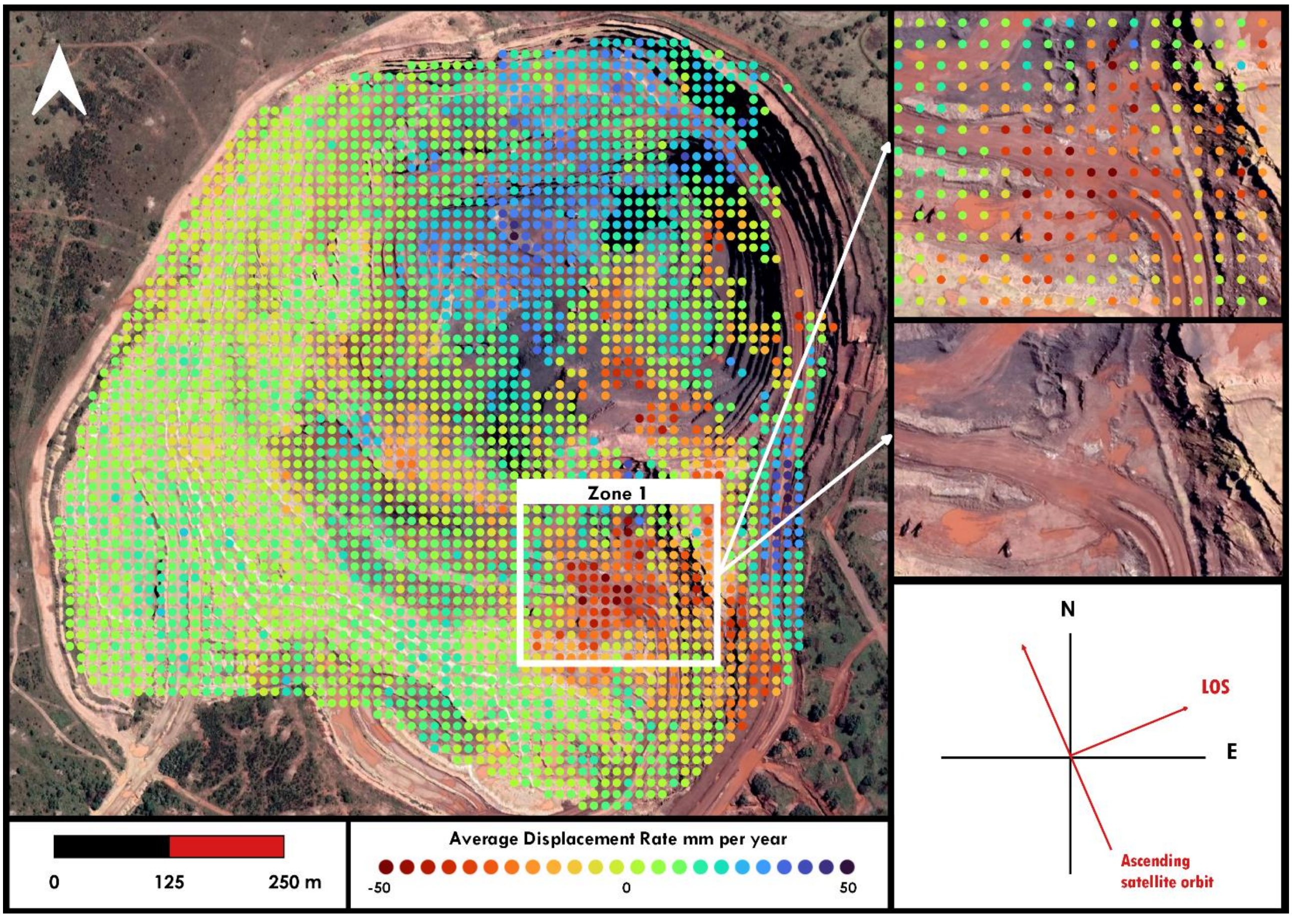

Figure 4. Deformation displacement values derived from Sentinel-1A data and Zone 1 which shows the area of interest.

In Zone 1 there are clear tension cracks that can be observed in the optical satellite images and there are scarps visible which is the crescent-shaped cliff on the upslope end of the open pit. The results indicate that for the south-east pit wall in the ascending orbital geometry, there was little movement between January 2020 and November 2020. However, from November 2020, there was an acceleration of movement until stabilisation in March 2021.The negative movement velocities are indicative of movement towards the east and/or vertical movement. The mean velocity was -23.25 mm per year.

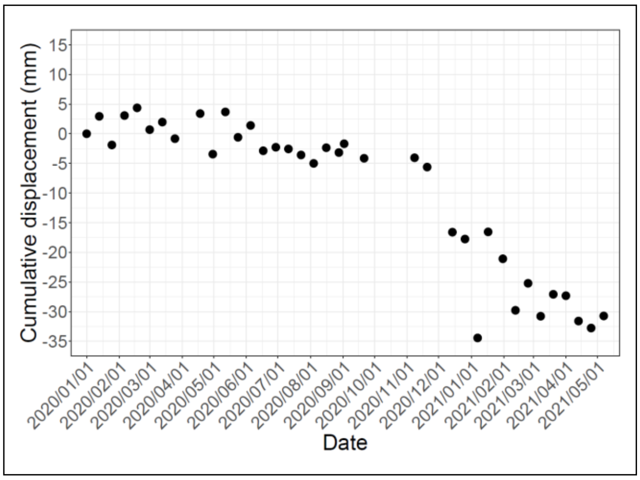

Figure 5. The cumulative displacement measurements derived Sentinel-1A data.

5.2 Observations in Zone 2

The results for the descending geometry extracted from the time series are shown in Figure 6. Positive movement velocities suggest that the movement is in an upward and or/westward direction.

However, when considering the results from the ascending orbit illustrated in Figure 5, the movement is predominantly in the eastward component.

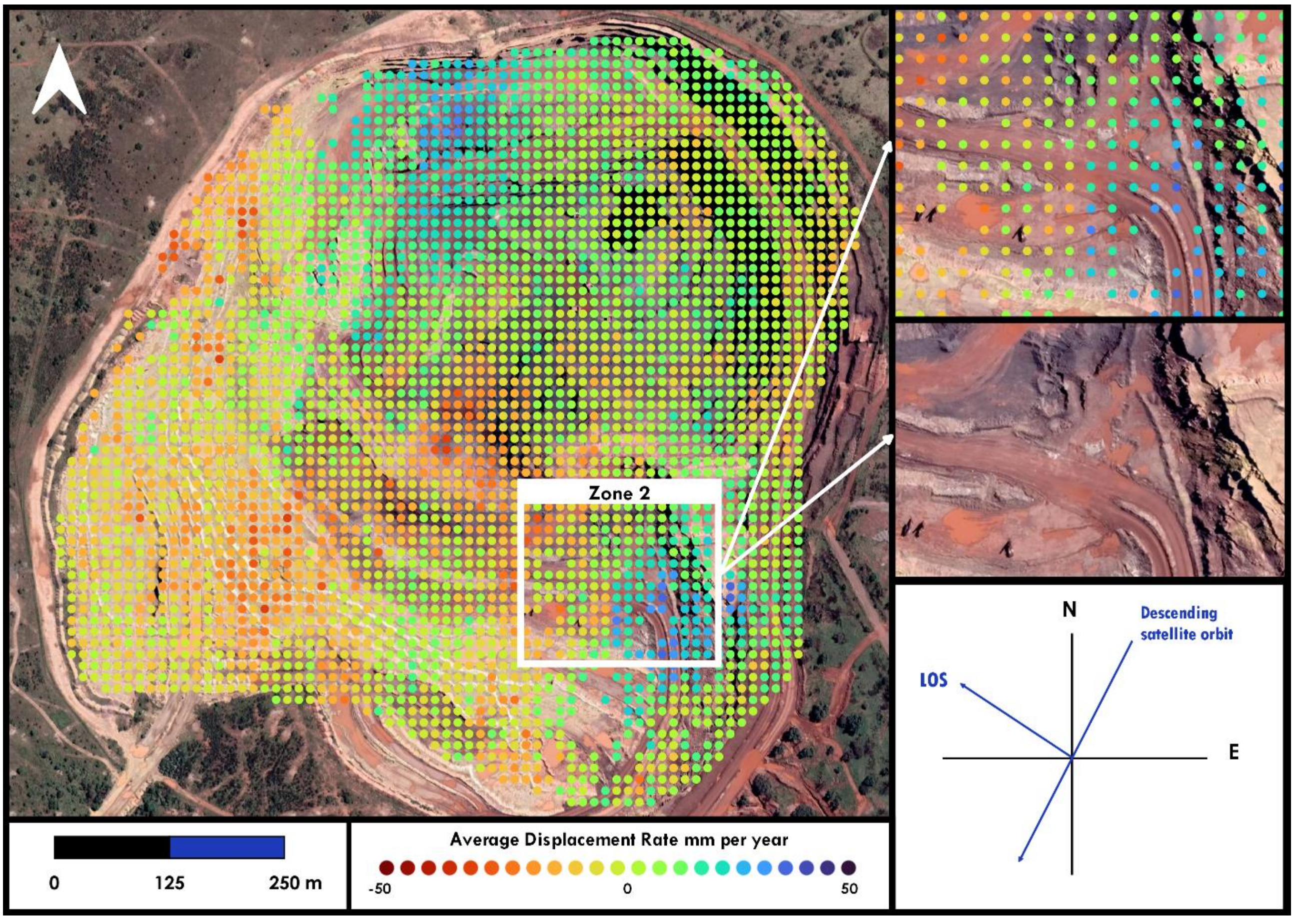

Figure 6. Deformation displacement values derived from Sentinel-1B data . Zone 2 shows the area of interest.

The time series was extracted from the 3 January 2020 and 10 March 2021 and is illustrated in Figure 7. There was little movement for the period. The total velocity was 7.9 mm per year. There is a slight upward trend however the time series evolution shows an irregular positive movement.

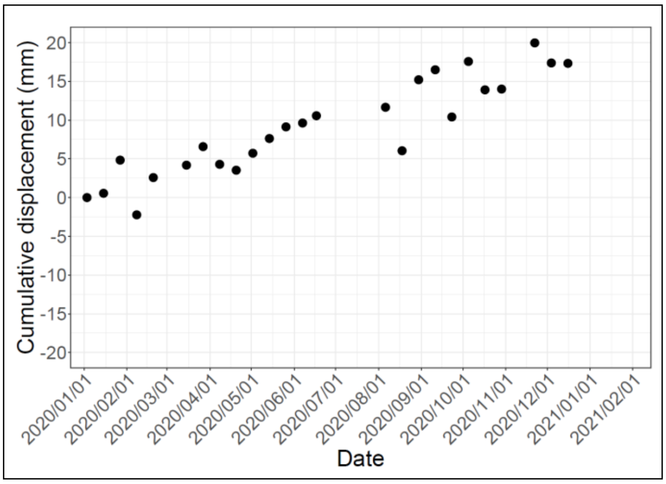

Figure 7. Cumulative displacement measurements derived from Sentinel-1B data.

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6. DISCUSSION

From these preliminary results, there is an indication that slope movement occurred on the south- east pit wall and could be extracted using open source time series SAR algorithms. The analysis of ground deformation revealed that there was distinct movement in the eastward direction in Zone 1 of the area of interest in the ascending Sentinel-1 data. The eastward movement could suggest that there was ongoing movement from November 2020 and until stabilisation in March 2021. The descending data indicates a positive trend which suggests that movement was still predominantly in the eastward component. It is important to note, however, that this study lacks in-situ data that could be used to validate the LOS displacement measurements.

The deformation observations derived from Sentinel-1 data could provide valuable information for mining companies about slope movement velocities. The availability of open-source tools enables mining organisations and interested stakeholders to generate their own SAR derived ground deformation surveys. Furthermore, open source time series InSAR methods could complement in situ ground survey measurements (Karamvassi et al., 2020). This will allow insight into existing methodologies, as well as support the evolution of remote sensing approaches that will make use of big data in terms of accuracy and computational cost (Karamvassi et al., 2020). The use of open data and open source software such as MintPy provides several advantages for deformation monitoring. Sentinel-1 frequent revisit and consistent data acquisition allow for long-term observations and historical analysis. This can be used to monitor slope stability remotely and in areas where in situ data are not accessible. Open source tools such as MintPy can offer cost-effective flexible solutions for data processing where algorithms can be tailored to specific needs of the mining company (Pawluszek-Filipiak and Borkowski., 2020).

Although these benefits are encouraging for monitoring mining-related deformation, there are limitations that need to be acknowledged. One of the limitations is the data processing and computation requirements of large data archives. The processing of large volumes of Sentinel-1 data and the execution of SBAS algorithms may require substantial computational resources and expertise. Time-series algorithms are often complex and may pose a challenge for uses with limited computation infrastructure or technical skills (Duan et al., 2020)

7. CONCLUSION

The time-series interferometric SAR method was evaluated for slope stability monitoring in an open-pit mine. This technique relies on a stack of SAR images which has been made possible with open and freely available SAR data such as Sentinel-1 C-band data. Furthermore, open source SBAS methods can be applied to provide ground displacement information that could be complementary to conventional techniques. There are benefits to using open remote sensing data and software for deformation monitoring. These include the promotion of collaboration and knowledge generation where stakeholders can replicate studies and validate findings. Future work will include X-band SAR data for the same area of interest.

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