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RESEARCH ARTICLE

MONITORING GROUND SURFACE DEFORMATION IN MINING AREAS: INSAR ANALYSIS OF THE MIDROC LEGA DEMBI GOLD MINE IN SHAKISO, ETHIOPIA

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ABSTRACT

When assessing the safety of a slope and the environmental impact resulting from open-pit and underground mining activities, it is imperative to consider the ground surface deformation induced by mining operations. Such deformations pose a significant risk to the environment, slope stability, and man-made structures within the mining activity region. Therefore, the monitoring of mining-induced ground surface deformations is crucial, and this study employs C- band Synthetic Aperture Radar (SAR) data to demonstrate the efficacy of the Persistent Scatterer Interferometric SAR (PS-InSAR) method. Specifically, the PS-InSAR method is applied to monitor ground surface deformation in the Midroc Gold Mine Company. The findings reveal that the PS-InSAR technique is capable of effectively tracking ground subsidence time-series, even in areas characterized by dense vegetation and rural landscapes. In the Midroc Lega Dembi open- pit mining region, the highest rate of ground surface deformation is observed at -90 mm per year, with cumulative subsidence values of -200 mm and -100 mm detected for ascending and descending geometries, respectively, through InSAR techniques. Additionally, ground survey data records cumulative subsidence values of -3.99866 m and -0.000122 m for ascending and descending geometries.The discrepancy between datasets is attributed to the thick vegetation cover in the study area. Integration of PS-InSAR results with ground survey data from the Midroc Lega Dembi open-pit mining zone reveals a correlation coefficient of 0.98, validating the accuracy of the PS-InSAR approach in identifying, tracking, and mapping ground surface deformation in the gold mine. This comprehensive methodology utilizes both ground survey data and C-band SAR data for a robust assessment of mining-induced ground surface deformations.

KEYWORDS

Ground Subsidence, Open pit mining, Persistent Scatters (PS), Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR)

1. INTRODUCTION

Among the prevalent challenges in the mining sector, subsidence on islands stands out as a common yet profound issue, leading to ground surface deformations with substantial environmental implications. Deformations induced by mining activities have the potential to wreak havoc on adjacent infrastructure and buildings (Henschel et al., 2014; Pawluszek and Borkowski, 2020a). Even when employing safe mining practices, ground surface deformation remains unavoidable, invariably posing a threat to nearby infrastructure (Tang et al., 2020). Consequently, the vigilant monitoring of ground deformation becomes paramount in every mining operation to ensure its effectiveness and reliability.

The integrated model captures a comprehensive deformation field by consolidating data from various sources, including differential interference contrast Synthetic Aperture Radar (D-InSAR), sub-band InSAR, and offset tracking. The proposed method's accuracy is validated using field survey data obtained from the Global Positioning System (Wang et al., 2020). Mining-induced land subsidence often gives rise to ecological, environmental, and safety concerns, impacting both life and property. Such subsidence can result in damages to buildings, soil, vegetation, and water resources, with the potential for triggering earthquakes. Real-time monitoring of ground movements in mining areas serves as a crucial tool for early detection, effectively mitigating or minimizing the impact of geoenvironmental hazards (Ge et al., 2007; Ng et al., 2009).

Interferometric Synthetic Aperture Radar (InSAR) emerges as an environmentally friendly, contactless surveillance technology, offering continuous monitoring capabilities in all weather conditions. It boasts consistent spatial coverage, automation, and high accuracy, positioning itself as a rapidly advancing technology for Earth observation and mapping. A group researcher pioneered the application of D-InSAR in soil deformation monitoring within mining areas, demonstrating its feasibility (Carnec et al., 1996). Subsequently, the use of InSAR for monitoring ground deformation in mining areas has expanded, yielding significant research outcomes (Carnec and Delacourt, 2000; Li et al., 2005; Haghighi et al., 2017; Hooper et al., 2012).

To enhance the effective wavelength and reduce interference fringes, some

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researchers have proposed the sub-band InSAR principle, which entails decreasing imaging bandwidth. This approach, introduced by most of researcher which contributes to improved data interpretation and unwrapping method simplicity (Madsen and Zebker, 1992; Bamler and Eineder, 2005). Mining companies commonly employ traditional techniques, including inclinometers, surveying level techniques, total stations, and GPS stations, for monitoring surface movement (Tang et al., 2020). While these methods enable precise observations in specific areas, their application can be both time-consuming and expensive.

Nevertheless, their preference over less accurate alternatives is evident (Pawluszek and Borkowski 2020b). Given the dynamic and ever-changing nature of mining operations, identifying optimal locations for monitoring equipment placement can be challenging, leading to the impermanence of such installations. In contrast, remote sensing techniques offer a valuable means of measuring changes on a large scale, providing crucial insights for addressing observed challenges (Ji et al., 2016; Lazecky et al., 2010).

Traditional Differential Interferometric Synthetic Aperture Radar (DInSAR) relies on a single interferometric measurement to estimate ground surface deformations (Carnec and Delacourt, 2000). However, this approach can be prone to inaccuracies stemming from topography, orbital mechanics, spatial and temporal decorrelation, as well as signal delays caused by atmospheric aberrations and data errors from the Digital Elevation Model (DEM) (Lillsand et al., 2009; Gupta, 2005; Ferretti et al., 2007). Previously, D-InSAR utilized the time difference between two consecutive radar readings to identify ground deformation at a sub-centimeter scale. To overcome these limitations, advanced multi-temporal DInSAR methods now leverage more than two repeat passes of the radar, offering enhanced accuracy and reliability (Wajs and Milczarek 2018; Yue et al., 2011).

Linear methods for calculating deformation velocity are unsuitable for assessing mining subsidence due to the unique characteristics of land subsidence. In this context, SAR interferometry stands out as a crucial technique for studying crustal dynamics and monitoring surface movements. Deformations can arise from various geophysical phenomena, and InSAR proves effective in tracking temporal modifications and changes in ground deformation over time. The Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) technique has demonstrated remarkable efficacy in detecting ground deformation at the millimeter level, surpassing the limitations identified in the D-InSAR technique (Liu et al. 2020; Gueguen and Rr 2009; Hongdong et al., 2018; Ge et al., 2007; Abdikan et al. 2014; Azeriansyah et al., 2019). The primary objective of this thesis is to systematically monitor ground surface deformation rates and cumulative displacements within the context of the Midroc Lega Dembi Gold Mine. To achieve this, the study leveraged 52 Sentinel-1 SAR images in C-band, acquired in both ascending and descending geometries, alongside 106 ground survey measurements. The assessment also involved an in-depth evaluation of the PS-InSAR techniques, aiming to monitor ground surface deformation in the vicinity of the Midroc Lega Dembi Goldfields situated in Shakiso, Ethiopia a location distinguished as the largest open-pit mine in the country.

2. MATERIALS AND METHODS

2.1 Description of the study area

The southern region of Ethiopia, particularly the Adola and Magado belt, has been a focal point for gold and base metal exploration over numerous years. In this strategic area, Midroc Lega Dembi and Sakaro stand out as significant contributors, with Midroc Lega Dembi currently operating as one of the most extensively explored and operational gold mines. Positioned between 5° 42' 00"–5° 44' 00"N latitudes and 38° 52' 30"–38° 54' 30"E longitudes (Figure 1), the Midroc Lega Dembi gold mine spans an expansive area of 144 km^2. Recognized as the primary gold deposit in the country, the Midroc Lega Dembi open-pit mine plays a pivotal role, set against a moderately seasonal climate characterized by notable diurnal temperature fluctuations.

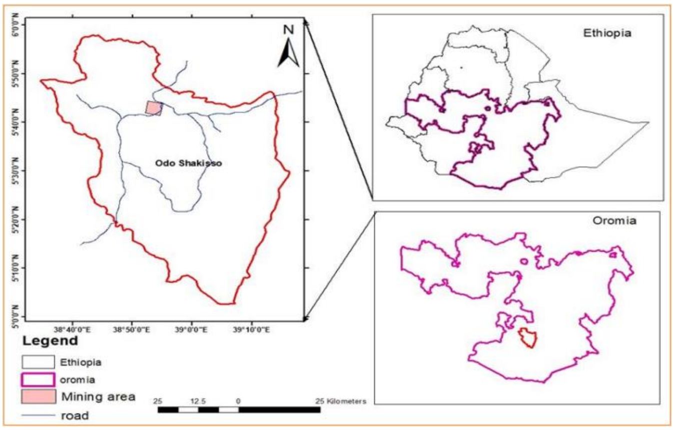

Figure 1: Location map of the study area

2.2 Datasets used for this study

This study employed a diverse range of data sources to facilitate a thorough and efficient analysis. Predominantly, InSAR data and Ground Survey data were the primary types of information utilized.

2.2.1 SENTINEL- 1A

The SENTINEL radar data, provided by ESA as part of a comprehensive data collection package, were obtained from the ESA virtual archive website (https://search.asf.alaska.edu) in both SAR level zero and SLC data set formats. Two stacks of Sentinel-1 images, acquired in 2014 and 2016, were utilized to evaluate the effectiveness of InSAR (Infrared Satellite Radar) time-series algorithms and to estimate land deformation. The dataset comprises 27 ascending geometry images for the period 2014-2016 and 25 descending geometry images for the same duration, with a brief explanation provided below.

2.2.2 Ground survey data

In this study, ground survey data from 106 points were collected for both years—2014 (68 points) and 2016 (38 points). However, to facilitate the streamlined monitoring of ground surface deformation, the analysis focused on 38 points of ground survey data from the same years. The time series data were acquired using a local coordinate system and subsequently projected to WGS1984 or UTM for comprehensive analysis.

3. METHODOLOGY

In this study, the PS-InSAR technique was employed, with a detailed explanation of its principles provided in the concluding part of this section. SARPROZ software was utilized for processing extensive time series data. The advantage of SARPROZ lies in its capability to detect deformation even in areas with low coherence due to decorrelation in the study area. The subsequent sections elaborate on the comprehensive methodology, outlining each step in detail.

3.1 Stack formation

The initial step in the processing involves importing raw Sentinel-1A data (Table 1). An additional advantage is gained by downloading orbit data, which includes the satellite's instantaneous location and velocity. Subsequently, automatically retrieving a Digital Elevation Model (DEM) becomes the next procedural step. It is noteworthy that the DEM plays a crucial role in co-registration and interferogram generation. Achieving high-quality and accurate co- registration of Sentinel-1 SLC data pairs is essential for interferometry, particularly with S1 TOPS SLC. Therefore, a well-defined processing strategy for co-registering these pairs is emphasized (Prats-Iraola et al., 2015).

Table 1: Satellite information of sentinel -1A used for this study.

No.	Parameters	Description	No	Parameters	Description
1	Image type	Sentinel -1A	1	Image type	Sentinel -1A
2	Acquisition pass	Ascending	2	Acquisition pass	Descending
3	Image in number	27	3	Image in number	25
4	Product type	SLC	4	Product type	SLC
5	Acquisition mode	IW	5	Acquisition mode	IW
6	Polarization	VV	6	Polarization	VV
7	Sub-swath	2	7	Sub-swath	2
8	Wavelength	5.6cm	8	Wavelength	5.6cm
9	Acquisition time	October 2014 – December 2016	9	Acquisition time	October 2014 – September 2016

3.2 Co-registration process of the images

In SARPROZ software, the chosen image (master) serves as the basis for co-registering the remaining images, acting as the slave image in both ascending and descending datasets. The pixel offsets resulting from the co-registration process between the master and slave images are determined for both the ascending and descending datasets. Additionally, coherence generation for each interferometric pair is a noteworthy outcome of this step. The topography phase parameter is excluded from the differential interferograms using the imported DEM, following the methodology proposed by (Goldstein et al., 1988). Following this, the optimal master image is selected. The reference master image is chosen to minimize spatial (m) and temporal (days) baselines, enhancing the interferometric stack's predicted coherence. This selection is made strategically to improve visual interpretation and ensure the production of high-quality findings. A single-reference stack is then formed using the specified reference image, with all secondary images co-registered to this chosen reference image.

3.3 Atmospheric Phase Screen (APS) Estimation

After co-registration, subsequent steps involve reflectivity and amplitude stability index computation, ground control point (GCP) selection, external Digital Elevation Model (DEM) integration, Atmospheric Phase Screen (APS) processing, Permanent Scattering Point (PS) identification, and APS estimation. The elimination of Atmospheric Phase Delay (APS) from the differential interferograms reduces signal delays between observations. It is defined as:

$$\text{Amp.Stab.Index} = 1 - \sigma/\mu = 1 - \text{DA} \quad (1)$$

where DA is the amplitude dispersion based on the concept introduced by (Ferretti et al., 2001).

In this study, PS candidates were identified by creating a mask using both the Amplitude Stability Index threshold (0.6) and temporal coherence set to 0.6. Reflectivity thresholds of 2 were applied for both descending and ascending datasets. These values were chosen to ensure a sufficient number of points, especially in the open-pit mining area with vegetation. A higher ASI threshold would have yielded no points for analysis (Figure 5).

While Persistent Scatterer Interferometry (PSI) has proven effective in urban areas, it faces challenges in open spaces due to low PS target density.

To estimate the preliminary height and velocity parameters (APS) and obtain the atmospheric phase screen, a network of PS candidates was utilized, as illustrated in Figure 1. The Reflectivity threshold varies between datasets, accommodating the distinct reflectivity range in the open-pit mining area for ascending and descending modes. The final phase of processing involves generating a cumulative displacement map for the PS network, aiding in monitoring ground surface deformation in mining areas, as depicted in Figure 2.

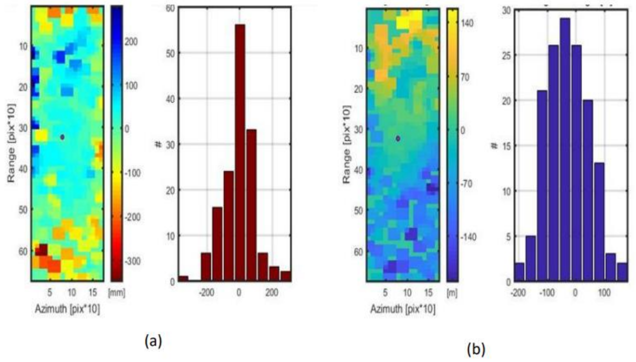

Figure 2: ASP Graph for Reference Point (a) Integrated cumulative displacement (b) Integrated heigh

Furthermore, the amplitude establishes an index indicating the scatter plot value, providing latitude and longitude information for the region, as indicated by SARPROZ software. The scatter plots of PS candidates for both ascending and descending images are shown in Figures 3 and 4, respectively. The main distinction between ascending and descending information lies in the angle of inclination of the area coverage.

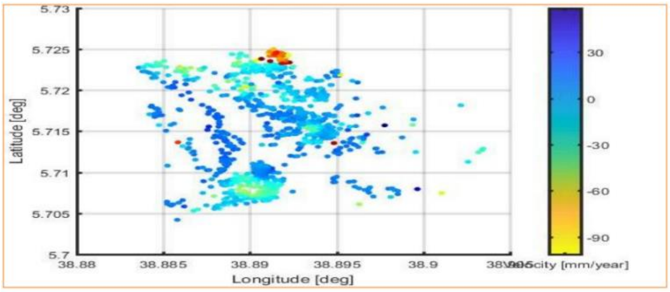

Figure 3: Scatter Plots of PS candidate for ascending images

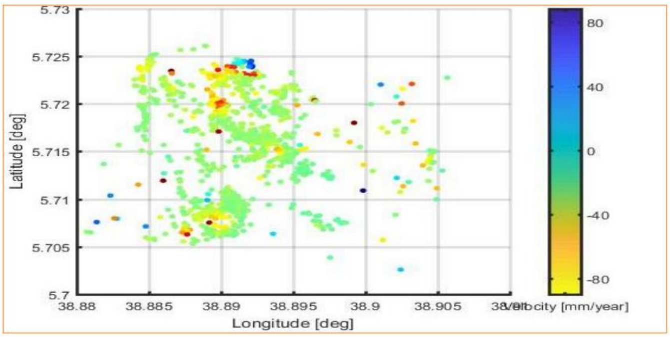

Figure 4: Scatter plots of PS candidate for descending images

4. RESULTS AND DISCUSSION

The ground surface displacement and velocity map are derived from the interferogram and InSAR time-series results, illuminating the predominant deformation patterns along the line of sight (LOS). This map provides insights into the subsidence rate along the LOS direction, employing C-band Sentinel dataset with a single-band SAR data. A comprehensive dataset of C-band Sentinel data, comprising 52 datasets collected between 2014 and 2016, was utilized in this study. The assessment involved the application of Persistent Scatterers and single interferogram methods, specifically developed to probe ground surface deformation within the open-pit mining area and its environs.

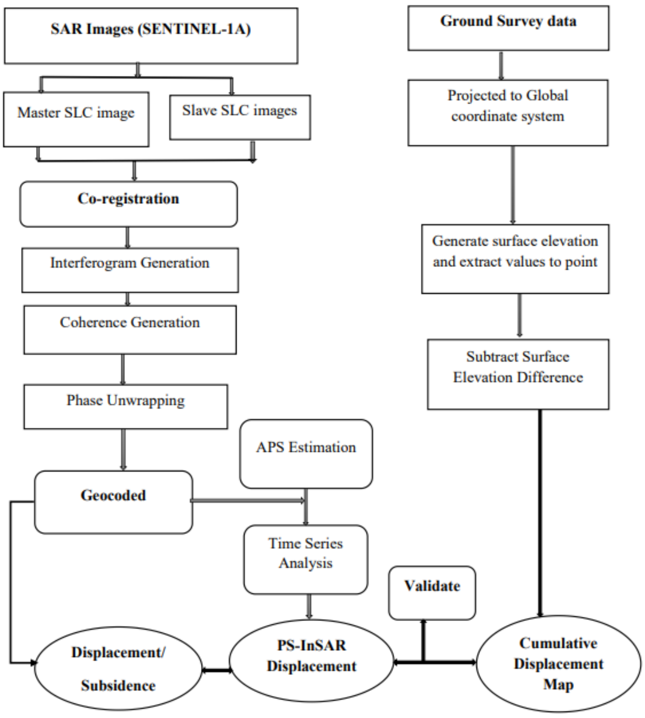

Figure 5: General workflow of the study

4.1 Resampled displacement

The subsidence pattern in the Midroc Lega Dembi Gold Mine, determined by Sentinel-1A data in the Ascending Geometry, reveals a resampled displacement range from 160mm to -160 mm, as illustrated in Figure 6. Similarly, the Descending Geometry data exhibits a resampled subsidence pattern in the study area towards the satellite, with rates ranging from 140 to −140 mm, as depicted in Figure 7. A zero rate of displacement indicates an almost stable area, where significant deformation is minimal.

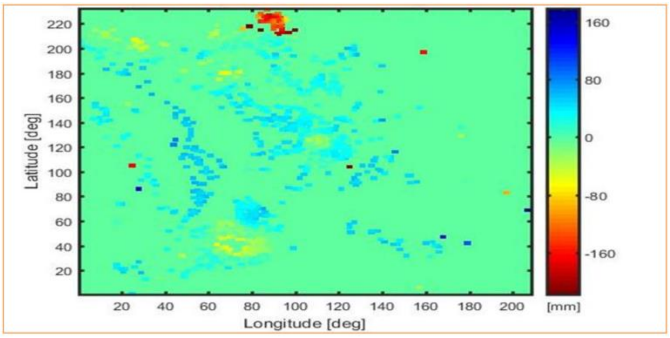

Figure 6: Resampled Displacement of Ascending images

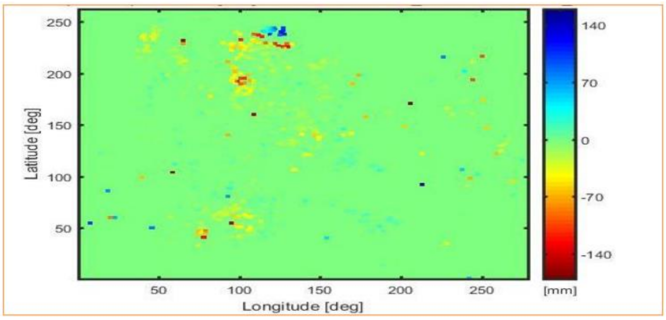

Figure 7: Resampled Displacement of descending images

4.2 Cumulative displacement of PS-InSAR

The PS values extracted from Sentinel-1A data comprehensively cover the central, northern, and southern regions of the Midroc Lega Dembi Gold Mine, revealing widespread ground surface deformation and, in some instances, uplift. The rate of deformation, relative to the resampled displacement in the Sentinel-1A data, exhibits uniformity across the entire study area. Within the Sentinel dataset, PS values encompass all mining activities and, to some extent, extend to infrastructure areas. The relatively lower number of PS values derived from the Sentinel-1A dataset suggests non-linear ground surface deformation in the Midroc Lega Dembi gold mining area, particularly in regions densely covered by vegetation. The PS rate is visually depicted by varying shades, with light blue indicating zero or minimal deformation in the central and western parts of the Midroc Lega Dembi Gold Mine. The red color in the northern part signifies maximum deformation, while light red values represent minimal deformation in the southern and some areas in the northwest mining region.

The InSAR-derived ground surface deformation rates and displacements are cross-validated using an independent estimate derived from ground survey data at the Midroc Lega Dembi Gold Mine. Instances of zero-level displacement in both InSAR-based PS ground surface displacements and time series ground survey measurements correspond to stable areas, confirming the reliability of the ground survey data. The cumulative displacement of ground surfaces resulting from the InSAR technique analysis is visually presented in Figure 8 below.

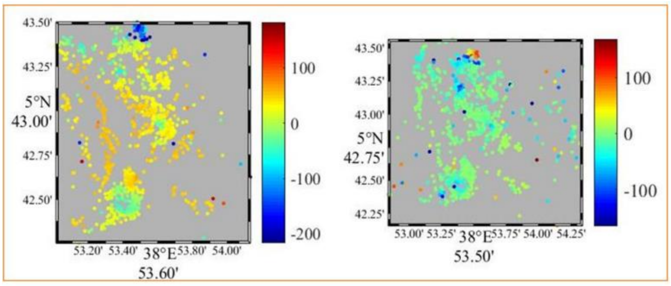

Figure 8: Cumulative Displacement of InSAR Data

4.3 Cumulative displacement for the ground survey data

The ground survey data utilized in this study were collected by the survey section of the mining company. Specifically, we employed ground survey data spanning the years 2014 to 2016, gathered by the mining company's survey section, to ascertain the cumulative displacement of the ground surface. Importantly, the observational periods for both the ground survey data and InSAR measurements aligned.

To integrate the surface elevation values from the ground survey data, we extracted point values for all Persistent Scatterer (PS) points generated by InSAR techniques within the study area for the years 2014 and 2016, respectively. The calculation of ground surface displacement from the ground survey data involved determining the difference between the measured data for 2014 and 2016. The results of this calculation are visualized in Figure 9 below, alongside surface elevation information.

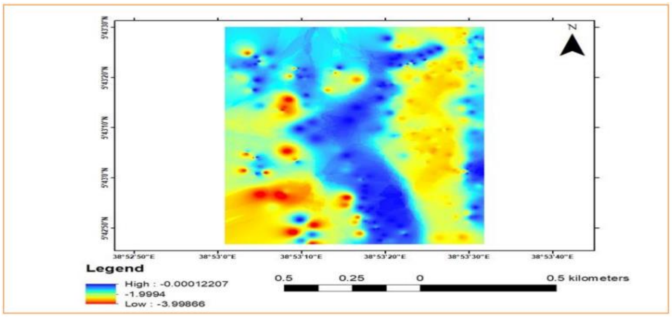

Figure 9: Cumulative Displacement of Ground survey data

4.4 Validation

The x-axis illustrates the displacement derived from ground survey data, while the y-axis depicts the displacement estimated by InSAR. The red line signifies the outcome of linear regression analysis. The calculated linear correlation coefficient (r) of 0.98 indicates a strong positive correlation, approaching the ideal value of 1. This high correlation implies a close alignment between InSAR measurements and ground survey data, closely mirroring the monitoring results at the selected point.However, upon analyzing the Root Mean Square Error (RMSE), a value of 3.24 emerges, significantly exceeding 1. This larger RMSE value signifies a considerable difference between InSAR measurements and ground survey data, indicating substantial ground surface deformation. The cumulative displacement of satellite Sentinel data, alongside the ground survey cumulative displacement, is presented as x, y data, with the RMSE and correlation coefficient displayed in Figure 10.

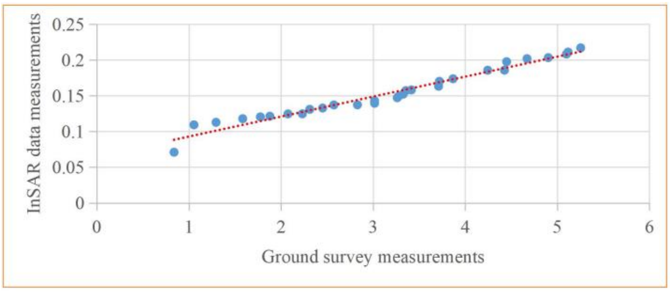

Figure 10: Validation of Ground survey data with InSAR measurements

5. DISCUSSION

The primary objective of this study was to assess the feasibility of utilizing InSAR (Interferometric Synthetic Aperture Radar) for monitoring ground surface deformation in the study area. Deformation patterns were effectively measured using Persistent Scatterer Interferometry (PSI) techniques and ground survey data spanning the period from 2014 to 2016. Notably, observable deformations manifested in the northern, southern, and central sections of the mining operations area, with active mining concentrated in the western portions of the pits, particularly in the extraction of gold. Despite the active excavation, surface deformation rates have induced substantial movement, especially in densely vegetated areas, where SAR techniques capture nuanced changes in the surface. Adjacent built-up regions near the mines are also experiencing subsidence due to this surface deformation.

There exists a divergence in the perceived direction of deformation when comparing radar or ground survey measurements to in-situ data, a phenomenon observed in similar studies, such as those conducted in Canada (Fydrych 2021). The directional disparities in surface movement near open pit mines compared to other rural areas are evident. While PS-InSAR techniques align well with measurements from Open Pit ground surveys, this concurrence is notable primarily in the northern part of the site (Simons et al., 2002; Nassir 2019). Unlike other regions worldwide where InSAR techniques have been employed to monitor ground subsidence in mining areas, such as in India, New York, Sweden, China, Iraq, and Germany, the current study area lacks comprehensive InSAR and ground survey data-based practices for monitoring ground surface deformation during mining activities (Ng et al., 2009).

Comparative studies in India and New York have identified subsidence rates, reaching up to 29 mm per year with a total subsidence value of 90 mm, and 8 cm/year respectively (Kumar et al., 2020; Valentino 2016). Both studies validate the accuracy of PS-InSAR-derived subsidence data through comparisons with previously published reports and independent observational data. A parallel study in Germany, focused on coal mining-induced subsidence south of Leipzig, utilized Sentinel-1A data analyzed through the Small Baseline Subset (SBAS) approach. This investigation revealed rapid subsidence of up to 4 cm/year between October 2014 and April 2017 in active open pit mining areas.

Additionally, a study in the Tianshan Mountains, China, employed SBAS-InSAR to compare three years of subsidence information derived from Sentinel-1A SLC products with field GNSS observations. The cumulative subsidence over the study region for a three-year period was significant, reaching a maximum of -129.39 mm (Du et al., 2017). In summary, this study adds valuable insights into ground surface deformation due to mining activities, contributing to the broader body of knowledge on this subject.

6. CONCLUSION

When assessing the safety and environmental impacts of both open-pit and underground mining operations, it is crucial to consider potential ground surface deformation (GSD). This study focused on measuring ground surface deformation in the Dembi Goldmine in Shakiso, utilizing data from Sentinel-1A sensors spanning the period from 2014 to 2016, along with ground survey data. The application of InSAR techniques played a pivotal role in detecting ground surface deformation in the Midroc Lega Dembi region, where sinking is attributed to mining activities.

Surrounded by vegetation and forest, the study area presented challenges for InSAR techniques, particularly in capturing the center of the open pit, which represents the most significant mine- induced surface deformation. Noteworthy nonlinear changes in the ground surface were observed in specific areas of the Midroc Gold Mine through satellite imagery, indicating gradual transformations over time. The study highlights the efficacy of the Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) method in enhancing the monitoring of subsidence in mining areas with dense vegetation. However, incorporating ground water table data would further enhance the validation process.

Decorrelation and phase ambiguity issues arising from mining operations can be addressed through the use of single-pass InSAR data, such as TanDEM-X, offering higher height and spatial resolutions along with better coverage of the research area. Continuous InSAR technology proves effective in monitoring mine surface subsidence, yet challenges arise due to interference decorrelation caused by substantial deformation gradients in mining areas. The results suggest that large-scale mining-induced surface changes can be effectively monitored using PS-InSAR measurements over the Midroc Lega Dembi Gold Mine.

To bridge measurement gaps, traditional monitoring approaches with limited spatial and temporal coverage can complement continuous InSAR technology, particularly in sparsely vegetated and developed mining operation areas. The study proposes that multi-temporal analysis of C-band data using the adopted methodology is practical for measuring, monitoring, and mapping slow rates of surface subsidence in mineral operations.

In conclusion, PS-InSAR technology emerges as a promising tool for analyzing subsidence in mining areas, especially in situations with limited ground survey data and varying vegetation densities. The presented results underscore the effectiveness and relevance of the investigated InSAR approach for spatial analysis in mining-induced ground surface deformation.

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REFERENCES

Abdikan, S., Mahmut, A., Fusun, B.S., and Ziyadin, C., 2014. Monitoring of Coal Mining Subsidence in Peri-Urban Area of Zonguldak City (NW Turkey) with Persistent Scatterer Interferometry Using ALOS-PALSAR. Environmental Earth Sciences, 71 (9), Pp. 4081–89. https://doi.org/10.1007/s12665-013-2793-1.

Azeriansyah, R., Prasetyo, Y., and Yuwono, B.D., 2019. Land Subsidence Monitoring in Semarang and Demak Coastal Areas 2016-2017 Using Persistent Scatterer Interferometric Synthetic Aperture Radar. IOP Conference Series: Earth and Environmental Science, 313 (1). https://doi.org/10.1088/1755-1315/313/1/012040.

Bamler, R., Eineder, M., 2005. Accuracy of differential shift estimation by correlation and split- bandwidth interferometry for wideband and delta-k sar systems, IEEE Geosci. Remote Sens. Lett., 2 , pp. 151-155

Carnec, C., Delacourt, C., 2000. Three years of mining subsidence monitored by SAR interferometry, near gardanne. France, J. Appl. Geophys., 43, Pp. 43-54.

Carnec, C., Massonnet, D., King, C., 1996. Two examples of the use of sar interferometry on displacement fields of small spatial extent Geophysics. Res. Lett., 23, Pp. 3579-3582

Du, Z., Linlin G., Alex, H.M.N., and Xiaojing, L., 2017. Satellite-Based Estimates of Ground Subsidence in Ordos Basin, China. Journal of Applied Geodesy., 11 (1), pp. 9–20. https://doi.org/10.1515/jag-2016-0025.

Ferretti, A., Andrea, M., Claudio, P., Fabio, R., and Didier, M., 2007. InSAR Principles: Guidelines for SAR Interferometry Processing and Interpretation. ESA Publications, no. January: Pp. 1–48.

Ferretti, A., Claudio, P., and Fabio, R., 2001. Permanent Scatterers in SAR Interferometry. IEEE Transactions on Geoscience and Remote Sensing, 39 (1), pp. 8–20. https://doi.org/10.1109/36.898661.

Fydrych, M., 2021. Evaluating Multi-Temporal DInSAR Measurements of Ground Surface Deformation around the Rhenish Coalfields in Germany Using Sentinel-1 SAR Imagery. Waterloo University. Master Thesis, Unpublished Thesis.

Ge, L., Chang, H.C., Rizos, C., 2007. Mine subsidence monitoring using multi-source satellite SAR images Photogramm. Eng. Remote Sens., 73, Pp. 259-266

Goldstein, R.M., Howard, A.Z., and Charles, L.W., 1988. Satellite Radar Interferometry: Two-dimensional Phase Unwrapping. Radio Science, 23 (4), Pp. 713–20. https://doi.org/10.1029/RS023i004p00713.

Gueguen, Y., and Rr. 2009. Monitoring Residual Mining Subsidence of Nord/Pas-de-Calais Coal Basin from Differential and Persistent Scatterer Interferometry (Northern France)." Journal of Applied Geophysics., 69 (1), Pp. 24–34. https://doi.org/10.1016/j.jappgeo.2009.02.008.

Gupta, R.P., 2005. Remote Sensing Geology. Second edition, Springer International Edition, Pp. 627.

Haghighi, M.H., and Mahdi, M., 2017. Sentinel-1 InSAR over Germany: Large-Scale Interferometry, Atmospheric Effects, and Ground Deformation Mapping. ZFV - Zeitschrift Fur Geodasie, Geoinformation Und Landmanagement, 142 (4), Pp. 245–56. https://doi.org/10.12902/zfv-0174-2017.

Henschel, M.D., Morin, R., McParland, M.A., Sato, S., and Ahola, R., 2014. InSAR Ground Deformation Monitoring of Mining Regions Using Multi-Track Interferometry" International Discreate Fracture Network Engineering Conference, Canada: Conference paper.

Hongdong, F., Lu, L., and Yahui, Y., 2018. Method Combining Probability Integration Modeland a Small Baseline Subset for Time Series Monitoring of Mining Subsidence" Remote Sensing, MDPI, 10, Pp. 1444; doi:10.3390/rs10091444

Hooper, A., David, B., Karsten, S., and Mahmut, A., 2012. Recent Advances in SAR Interferometry Time Series Analysis for Measuring Crustal Deformation. Tectonophysics Pp. 514–517 (January): 1–13. https://doi.org/10.1016/j.tecto.2011.10.013.

Ji, L., Yong, Z., Qingliang, W., Yuling, X., and Jin L., 2016. Detecting Land Uplift Associated with Enhanced Oil Recovery Using InSAR in the Karamay Oil Field, Xinjiang, China. International Journal of Remote Sensing, 37 (7), Pp. 1527–40. https://doi.org/10.1080/01431161.2016.1154222.

Kumar, S., Dheeraj, K., Sumit, K.C., Narendra, S., and Kapil, K.M., 2020. Land Subsidence Mapping and Monitoring Using Modified Persistent Scatterer Interferometric Synthetic Aperture Radar in Jharia Coalfield, India. Journal of Earth System Science, 129 (1). https://doi.org/10.1007/s12040-020-01413-0.

Lazecky, M., Eva, J., and Dagmar, B., 2010. Usage of InSAR Techniques to Detect and Monitor Terrain Subsidence Due to the Mining Activities. GeoScience Engineering Volume LVI 2010, Pp. 32–49.

Li, Q., Wu, L., Chen, B., 2005. The application research on subsidence monitoring of coal mining area with D-InSAR Proceedings. IEEE International Geoscience and Remote Sensing Symposium, IGARSS'05. IEEE, Pp. 5216-5218

Lillsand, T.M., Kiefer, R.W., and Chipman, J.W., 2009: Remote Sensing and Image Interpretation. 5th edition. New York: John Wiley and Sons, Inc. Pp. 753.

Liu, L., Jie, Y., Beibei, C., and Yanbing, W., 2020. Urban Subsidence Monitoring by SBAS-InSAR Technique with Multi-Platform SAR Images: A Case Study of Beijing Plain, China. European Journal of Remote Sensing, 53 (sup1), Pp. 141–53. https://doi.org/10.1080/22797254.2020.1728582.

Madsen, S.N., Zebker, H.A., 1992. Automated absolute phase retrieval in across-track interferometry, 12th Annual International Geoscience and Remote Sensing Symposium, IEEE, Houston, TX , 10.1109/IGARSS.1992.578639

Nassir, W., 2019. Structural Deformation Monitoring In Urban Area Using In SAR: A Case of Addis Ababa, Ethiopia. Master Thesis, Unpublished thesis.

Ng, A.H.M., Chang, H.C., Ge, L., Rizos, C., Omura, M., 2009. Assessment of radar interferometry performance for ground subsidence monitoring due to underground mining Earth, Planets Space, 61, Pp. 733-745.

Pawluszek-Filipiak, K., and Andrzej, B., 2020a. Integration of DInSAR and SBAS Techniques to Determine Mining-Related Deformations Using Sentinel-1 Data: The Case Study of Rydultowy Mine in Poland. Remote Sensing, 12 (2), https://doi.org/10.3390/rs12020242.

Pawluszek-Filipiak, K., and Andrzej, B., 2021. Monitoring Mining-Induced Subsidence by Integrating Differential Radar Interferometry and Persistent Scatterer Techniques." European Journal of Remote Sensing, 54 (sup1), Pp. 18–30. https://doi.org/10.1080/22797254.2020.1759455.

Prats-Iraola, P., Matteo, N., Rolf, S., Francesco, D.Z., Steffen, W., Federico, M., Francesco, V., 2015. Sentinel-1 Assessment of the Interferometric Wide- Swath Mode. International Geoscience and Remote Sensing Symposium (IGARSS) 2015- Novem (July), Pp. 5248–51. https://doi.org/10.1109/IGARSS.2015.7327018.

Simons, M., Yuri, F., and Luis, R., 2002. Coseismic Deformation from the 1999 Mw 7.1 Hector Mine, California, Earthquake as Inferred from InSAR and GPS Observations." Bulletin of the Seismological Society of America 92 vol.4, 1390–1402. https://doi.org/10.1785/0120000933.

Tang, W., Mahdi, M., and Wei, Z., 2020. Monitoring Active Open-Pit Mine Stability in the Rhenish Coalfields of Germany Using a Coherence-Based SBAS Method. International Journal of Applied Earth Observation and Geoinformation 93 (August): 102217. https://doi.org/10.1016/j.jag.2020.102217.

Valentino, B.R., 2016. Application Of Insar To Salt Mine Subsidence. Cornell University. Master Thesis, Unpublished Thesis.

Wajs, J., and Wojciech, J.M., 2018. Detection of Surface Subsidence Using SAR SENTINEL 1A Imagery and the DInSAR Method-a Case Study of the Belchatow Open Pit Mine, Central Poland. E3S Web of Conferences, 55, Pp. 3–8. https://doi.org/10.1051/e3sconf/20175500004.

Wang, L., Kazhong, D., and Meinan, Z., 2020. Research on ground deformation monitoring method in mining areas using the probability integral model fusion D-InSAR, sub- band InSAR and offset-tracking, International Journal of Applied Earth Observation and Geoinformation, Elsevier,Vol.85, https://doi.org/10.1016/j.jag.2019.101981

Yue, H., Guang, L., Zbigniew, P., and Huadong, G., 2011. Satellite Radar Reveals Land Subsidence over Coal Mines. SPIE Newsroom, no. November. https://doi.org/10.1117/2.1201110.003898.

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