PS-InSAR Analysis of Precursory Deformation Before the September 2018 Naga Landslide, Philippines

Jeremy Brian E. Ricofuerto [1], Nathan Azriel S. Veracruz [1]

[1]Geospectrum Marketing Services, Ortigas Center, Pasig City, Philippines - {jeremyricofuerto,nasveracruz}@gmail.com

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Abstract

Persistent Scatterer Interferometry (PSI) has become a crucial remote sensing tool over the past decade for detecting and monitoring ground instabilities across various fields, including infrastructure development, geological hazards, and mining operations. By analyzing time-series radar data, PSI enables the detection of subtle surface displacements with millimeter-level accuracy, allowing for early warning and risk assessment. Human-induced activities, particularly mining and large-scale infrastructure projects, are known to cause excessive and often unintended ground deformation. On September 20, 2018, a deadly landslide occurred in Naga City, Cebu, Philippines, killing 78 people. The event was triggered by active quarrying operations conducted by a local mining company. In response to this tragedy, this study presents a retrospective remote analysis using the PS-InSAR (Persistent Scatterer Interferometric Synthetic Aperture Radar) technique to investigate the spatial and temporal characteristics of ground deformation in the affected area. By analyzing a time series of Sentinel-1B radar images prior to the landslide, this research aims to determine the significant displacements that began and how they evolved over time.

1. Introduction

Large-scale quarrying and open-pit mining supply much of the limestone and other aggregates that underpin the Philippine construction sector. Yet the continuous removal of lateral and basal support on already steep tropical slopes greatly amplifies landslide hazard. Recent disasters — most notably the 20 September 2018 Naga City, Cebu landslide that killed 78 people and displaced more than 8,000 residents (Catane et al., 2019; Lagmay et al., 2020) — highlight the human safety stakes of inadequate slope monitoring around active quarries. Back-analyses of the Naga event reveal that the progressive widening of tension cracks and the excavation of 70–85° cut faces significantly reduced the factor of safety, dropping it well below unity even under dry conditions, making failure likely without any extraordinary rainfall or seismic trigger (Catane et al., 2019).

Regulatory monitoring still relies mainly on ground surveys, total station prism networks, and GNSS pillars. Although these instruments deliver millimeter accuracy, they are costly, labor-intensive, and spatially sparse — a critical limitation for benches and haul roads that can extend over several square kilometers. In Naga, cracks were mapped at the quarry rim three weeks before failure; however, the progression of deformation farther downslope went unmeasured, and communities 1.2 km from the scarp were not evacuated (Catane et al., 2019; Lagmay et al., 2020).

Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) exploits long radar image stacks to isolate "permanent" reflectors and retrieve their displacement histories with sub-centimeter precision (Ferretti et al., 2001). Because coherence depends on target stability rather than daylight or cloud cover, PS-InSAR can yield thousands of measurement points on quarry walls, conveyor galleries, and nearby settlements without any in situ hardware. Sentinel-1 studies across the Philippines have already demonstrated the technique's value for urban subsidence and coastal reclamation; in Naga City, for example, PS-InSAR detected >50 mm of cumulative line-of-sight (LOS) subsidence and rates faster than -15 mm yr^{-1} between 2014 and 2018 (Ramirez et al., 2022) — signals recorded well before the fatal slope collapse. Despite such promise, PS-InSAR is still rarely used as an operational early warning layer for active mines and quarries.

This paper assesses how Sentinel-1 PS-InSAR and SARPROZ can both retrospectively reconstruct and proactively monitor quarry-induced ground deformation at the Naga landslide site. Specifically, we will (1) derive a multi-image PS-InSAR time-series for 2017–2018 and quantify spatial patterns of slope displacement relative to mapped quarry benches using SARPROZ; (2) correlate remotely sensed deformation with field-mapped tension cracks, geological structure, and excavation history to elucidate the role of quarry operations in destabilizing the slope; and (3) evaluate how a PS-InSAR-augmented monitoring framework could strengthen regulatory oversight and community early warning for similar Philippine quarry and mine sites.

By coupling established PS-InSAR methodology with detailed geological and engineering back-analysis of the Naga event, we propose a cost-effective pathway for turning routine satellite archives into actionable mine safety intelligence.

2. Literature Review

Satellite interferometry is now a mainstream tool for diagnosing ground deformation linked to resource extraction. In Vietnam's Phu Giao quarries, a 24-scene Sentinel-1 stack processed with PS-InSAR revealed subsidence bowls of -20 mm yr^{-1} and matched GNSS benchmarks to within ±2 mm yr^{-1} (Nam et al., 2021). Similar multi-temporal analyses have documented accelerating deformation at the Xinjing open-pit coal mine in Inner Mongolia, where PS-InSAR and optical imagery jointly captured >70 mm of downslope movement in the six months preceding the fatal February 2023 slope failure (Zhang et al., 2024).

For Philippine sites, Ramirez et al. (2022) processed 139 Sentinel-1 acquisitions (2014–2018) and detected cumulative LOS subsidence exceeding -50 mm on the coastal plain of Naga City, Cebu, attributing the non-linear signal partly to quarrying. A comparable workflow at the Carmen Copper open-pit in neighboring Toledo City documented progressive slope instabilities from December 30, 2019 to December 12, 2020 — nine days before the December 21, 2020 collapse — again demonstrating the method's value in active mine settings. Outside Asia, underground coal workings in Indiana, USA were tracked with C- and X-band images in SARPROZ, revealing concentric subsidence troughs up to 60 mm deep and demonstrating that PS workflows remain effective in vegetated, low-contrast terrains (Qin and Perissin, 2015). Collectively, these studies confirm that PS-based approaches can deliver millimetric accuracy over both open pits and underground panels, provided a sufficiently dense radar archive exists.

The PS technique isolates radar targets that maintain high phase stability over long periods, enabling:

- dense, instrument-free sampling on haul roads, conveyors, and building roofs;
- all-weather, day-night operability with Sentinel-1 revisit intervals of 6–12 days, allowing near real-time screening; and
- sub-centimeter precision after atmospheric phase screen mitigation, effectively creating a "virtual GNSS network" across the pit walls.

Nevertheless, three factors can degrade reliability in active quarries: (i) temporal decorrelation, where blasting or vegetation alters backscatter; (ii) geometric decorrelation and layover on very steep benches oriented away from the radar look angle; and (iii) residual tropospheric noise that can mimic subsidence gradients in humid tropical settings. These limitations highlight the need to integrate PS-InSAR with ground truth and to utilize both ascending and descending tracks for three-dimensional displacement decomposition.

3. Methodology

3.1 PS-InSAR for Mining Monitoring

To evaluate precursory ground deformation in Naga City, Cebu, this study adopted the Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) technique, which has been demonstrated as an effective tool for monitoring mining-induced landslides. Building on prior work, Ramirez et al. (2022) applied Sentinel-1 PS-InSAR to analyze nonlinear ground subsidence in Naga City leading up to the 2018 landslide. Their findings confirmed that PS-InSAR can detect subtle displacements that preceded the catastrophic slope failure, thereby underscoring its applicability for early warning. Similarly, PS-InSAR has been employed at the open-pit mining site in Toledo City, Cebu, where time-series analysis of Sentinel-1 data revealed progressive slope instabilities between December 30, 2019, and December 12, 2020, prior to the major slope collapse on December 21, 2020.

For broader monitoring applications, the University of the Philippines Resilience Institute (2018) recommended the use of PS-InSAR across Cebu Island to capture deformation fields at multiple scales. This approach allows differentiation between tectonic and quarrying-induced movements, and strengthens hazard assessment strategies. Based on these precedents, the present study applies Sentinel-1 PS-InSAR time-series analysis to characterize precursory slope movements in the Naga landslide site and to evaluate its potential as a component of an operational landslide early warning framework.

3.2 Sarproz Workflow Overview

SARPROZ is a MATLAB-based environment that integrates classic PS, quasi-PS, and non-linear time-series modules. Originally designed to co-process ERS and Envisat data, it now supports Sentinel-1, TerraSAR-X, and COSMO-SkyMed imagery (Perissin et al., 2011). Features valuable for mine monitoring include built-in atmospheric filtering, rapid coherence map inspection, and batch export of velocity rasters for GIS overlay. The software has been applied to landslides, subsidence, and infrastructure monitoring worldwide (e.g., Perissin et al., 2011, 2012; Qin et al., 2013), confirming its suitability for both retrospective failure forensics and prospective early warning schemes in mining and quarry environments. Its modular workflow — coregistration, interferogram network design, PS candidate selection, APS removal, and temporal modeling — parallels the processing sequence we adopt for the Naga study, ensuring methodological comparability with existing literature.

In this study, we analyzed a total of 35 Sentinel-1B Single Look Complex (SLC) images acquired in descending orbit and VV polarization, using the Interferometric Wide (IW) swath mode. These images span the period from August 2017 to early September 2018, specifically selected to capture precursory ground deformation leading up to the Naga, Cebu landslide event. The image selection was informed by the southeast-facing slope orientation, the expected direction of movement, and the satellite's line-of-sight (LOS) geometry. Previous research, particularly by Ramirez et al. (2022), has shown that descending track imagery offers a higher density of persistent scatters in the study area, particularly over residential zones located downslope to the south and east — directions commonly associated with slope failure. This makes descending data especially suitable for detecting early deformation signals in complex geological terrains (Catane et al., 2019; Hsieh & Lin, 2021; Zhang et al., 2023).

These datasets were processed using the SARPROZ software, employing the Persistent Scatterer Interferometry (PSI) technique to detect and monitor subtle ground displacement over time. In a study Virk et al. (2019), researchers applied an Amplitude Stability Index (ASI) threshold of 0.7 to select Persistent Scatterer Candidates (PSCs). Which later on used in this study because of its effective threshold that balanced the inclusion of reliable scatterers while minimizing noise, thereby enhancing the accuracy of the deformation analysis. Additionally, Atmospheric Phase Screen (APS) estimation was conducted to correct for atmospheric artifacts that could otherwise distort phase measurements. This step was critical in enhancing the reliability and accuracy of the displacement time series, particularly in areas with variable weather conditions or complex topography.

The process shown in Figure 1, begins with data gathering, where a time series of SAR images is collected. These images undergo co-registration to ensure precise pixel alignment, followed by the generation of reflectivity and amplitude maps to identify stable reflectors. Interferograms are then created by calculating phase differences between image pairs, which are further refined through multi-image InSAR processing to enhance signal quality and reduce noise. Geocoding is applied to convert radar coordinates into geographic locations, enabling spatial interpretation. Coherence maps are generated to pinpoint persistent scatterer points that consistently reflect radar signals over time. APS estimation is then performed to remove atmospheric noise, ensuring that the measured signals represent actual ground movement. Sparse point processing focuses on the most reliable PS points which is 0.7 threshold. Results in PS-InSAR processing in SARPROZ were cross-validated using ground truth data discovered by Catane et al. (2019). The final outputs include visualization in Google Earth Pro, such as displacement and time-series graphs, allowing users to interpret long-term deformation trends at the pixel level.

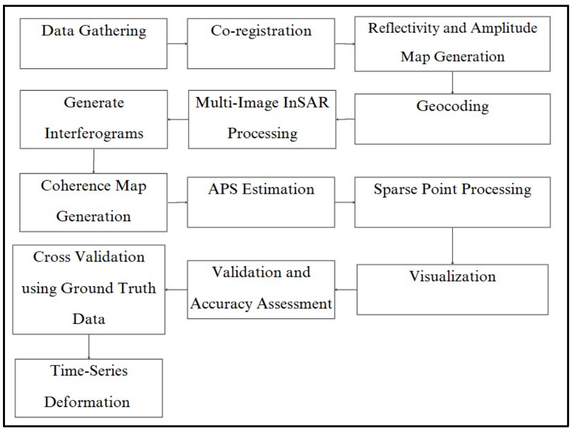

Figure 1. Workflow of the multi-image Persistent Scatterer Interferometric Synthetic Aperture Radar technique.

4. Results and Discussion

4.1 Landslide Hazard Assessment

The spatial distribution of Persistent Scatterer (PS) points, as shown in Figure 2, provides a comprehensive view of ground stability conditions surrounding the landslide area in Naga City, Cebu. The overlay of PS points on the landslide hazard map illustrates a clear concentration of red and blue markers along and around the delineated landslide footprint, confirming the presence of ground movement in areas previously identified as high risk. These points correspond to zones categorized under high and medium hazard levels, represented by dark and light orange tones, respectively. Notably, the PS points align with known geological features such as tension cracks (red hazard symbols labeled T1 and T2 series), suggesting strong spatial correlation between deformation signals and pre-existing structural weaknesses. The integration of PS-InSAR results with hazard zoning, as depicted in Figure 2, reinforces the effectiveness of SARPROZ in detecting early signs of slope instability. Furthermore, the presence of PS points both within and outside the mapped landslide zone indicates potential extension of the instability, underscoring the importance of continuous monitoring even beyond visibly affected areas. This visual synthesis highlights the role of PS-InSAR as a valuable decision-support tool for disaster preparedness and early warning in geohazard-prone environments.

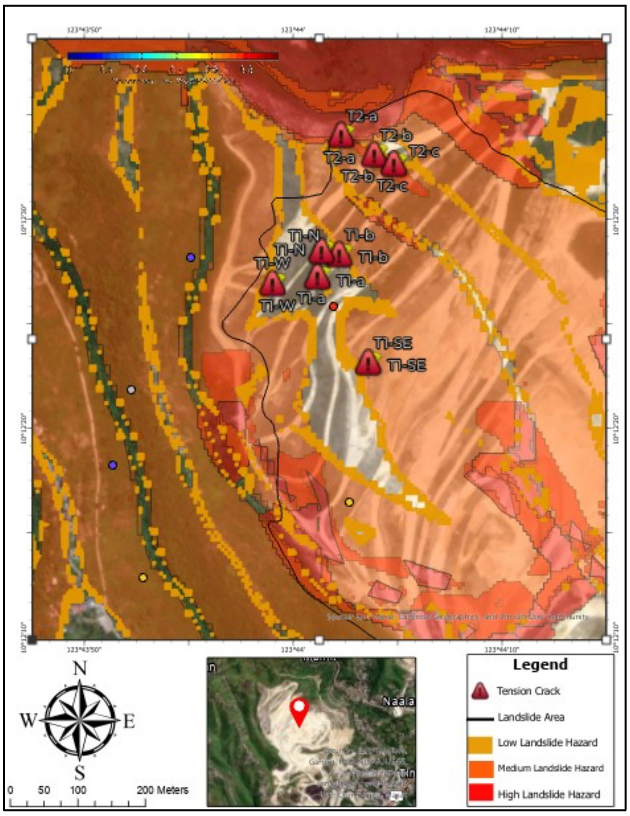

Figure 2. Map of the September 20, 2018 Naga landslide, which includes persistent scatterer points. The map also highlights mapped tension cracks from Catane et al. (2019) and delineates the landslide hazard zones from UPRI-NOAH.

4.2 Interpretation of deformation patterns

Figure 3 presents the time-series displacement data derived from SARPROZ using Sentinel-1B descending imagery between July 2017 and September 12, 2018. The selected Persistent Scatterer point (ID: 5), located near the quarry slope, demonstrates a gradual but significant acceleration of ground movement leading up to the 2018 Naga landslide. Initially, displacement remained relatively stable, with only minor fluctuations observed from mid-2017 through early 2018. However, beginning in August 2018, the time series indicates a clear negative line-of-sight (LOS) displacement trend, with cumulative deformation reaching –13 mm by September 12, just days before the catastrophic failure.

The temporal coherence value of 0.82 confirms that this scatterer provides reliable deformation measurements, while the sharp increase in displacement during the final weeks highlights the capability of PS-InSAR to capture subtle yet accelerating precursory signals. This pattern is consistent with field observations reported by Catane et al. (2019), which documented the rapid widening of cracks during the same period. The alignment between satellite-derived deformation and on-site measurements reinforces the potential of PS-InSAR as an early warning tool. Nevertheless, the relatively small LOS displacement compared to field crack dimensions suggests that SAR-derived motion may represent an averaged subsurface signal, whereas ground surveys capture localized surface deformation. This discrepancy underscores the importance of integrating satellite and field-based monitoring for comprehensive hazard assessment.

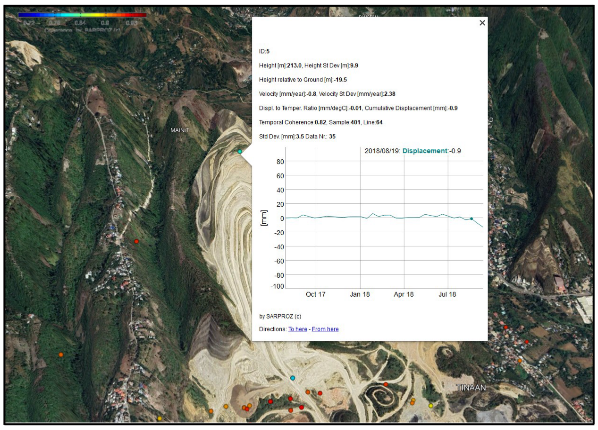

Figure 3. Time-series data from SARPROZ (July 2017 - September 12 2018)

In Figure 4 the selected Persistent Scatterer point (ID: 5) exhibits clear temporal deformation patterns in the weeks preceding the 2018 Naga City landslide. Time-series data from SARPROZ reveal a cumulative subsidence from on August 19 with a cumulative displacement of -0.9mm to -7.3mm by August 31, and reaching -13mm on September 12, just days before the catastrophic event. This progression, captured over a span of 24 days, highlights the capability of PS-InSAR to detect subtle but accelerating ground movements that could otherwise go unnoticed through visual inspections or periodic field surveys. The high temporal coherence value (0.82) supports the reliability of these measurements. These findings underscore the importance of high-frequency satellite acquisitions and time-series analysis in early warning systems, where even small precursory displacements can serve as critical indicators of impending slope failure.

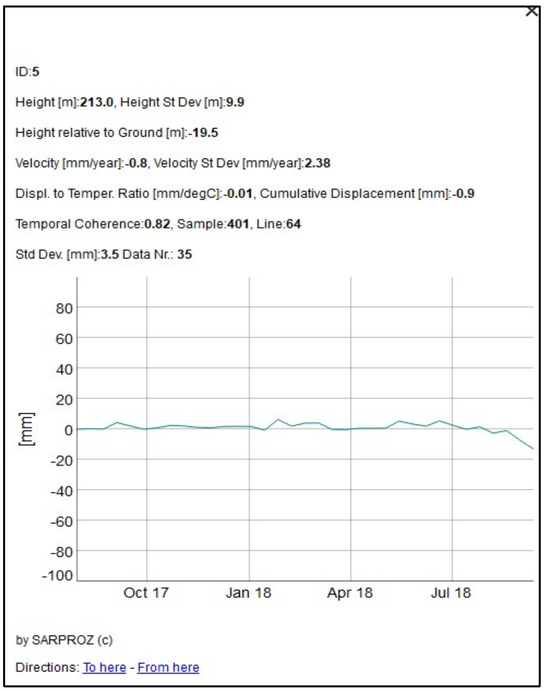

Figure 4. Time-Series Displacement Graph from SARPROZ (August 2017 - September 2018)

After processing the Sentinel-1B descending SAR images acquired from the Copernicus Open Access Hub using the SARPROZ software, Table 2 shows the resulting displacement data was visualized and geocoded for spatial interpretation. The process outputs, including persistent scatterer points and their corresponding displacement time series, were overlaid on high-resolution base maps within Google Earth Pro. This geocoded visualization enables the accurate localization of ground deformation patterns, particularly around the quarry and land-slide-prone areas in Tinaan, Naga City, Cebu, facilitating clearer correlation with topographic features, infrastructure, and ground truth observations. The PS point selected near the scarp recorded a clear precursory deformation signal with a sharp LOS displacement of -13 mm on September 12, 2018, just days before the Naga landslide. This strongly suggests that ground movement accelerated in the final week leading up to slope failure. The combination of positive LOS velocity, sharp displacement, and proximity to the scarp confirms this point was likely located on or near the active failure zone.

Parameter	**Value**
Height [m]	213.0 m
Velocity [mm/year]	-0.8 mm/year (LOS)
Cumulative Displacement	-0.9 mm (away from the radar)
Temporal Coherence	0.82 (Good PS Reliability)
Max Displacement Spike	-13 mm on 2018/09/12
Observation Period	August 2017 - September 2018
Sensor	Sentinel-1B Descending

Table 2. SARPROZ point summary (ID: 5)

The PS-InSAR results for Point ID:5 confirm a stable and reliable radar target based on consistent amplitude returns and low noise in quality indicators. The displacement time series shows a negative LOS velocity of −0.8 mm/year, interpreted as subsidence or downslope movement, which is consistent with the geologic activity observed near the 2018 Naga landslide area. The stable coherence and negligible thermal noise (KTemp ≈ 0) support the reliability of this signal as a precursor to slope.

Figure 5 illustrates the temporal baseline plot (top) and displacement time-series (bottom) for the selected Persistent

Scatterer point (ID: 5), processed using SARPROZ. The temporal baseline plot shows the distribution of interferometric pairs over time, with amplitude stability confirming the reliability of the scatterer across the observation period from 2017 to 2018. The consistent clustering of points around the trend line indicates good coherence, minimizing the likelihood of decorrelation effects that could distort displacement measurements.

The displacement time-series plot (bottom) reveals a gradual negative trend in the line-of-sight (LOS) direction, with a velocity of –0.8 mm/year and a maximum cumulative displacement of –13 mm recorded in September 2018, shortly before the Naga landslide. The relatively stable values in late 2017 and early 2018 contrast with the acceleration observed in mid to late 2018, which aligns with documented field evidence of crack propagation in the quarry slope (Catane et al., 2019). The temporal consistency of the PS point, supported by a coherence value of 0.82, validates this signal as a precursor to slope instability.

These results highlight the utility of PS-InSAR temporal analysis in identifying subtle but progressive deformation trends prior to catastrophic failure. However, the relatively small LOS displacement compared to field-measured crack widening suggests that SAR-derived deformation may represent deeper-seated or averaged slope movement, while ground surveys capture more localized and surface-level changes. This reinforces the importance of integrating both remote sensing and field data for comprehensive landslide hazard assessment.

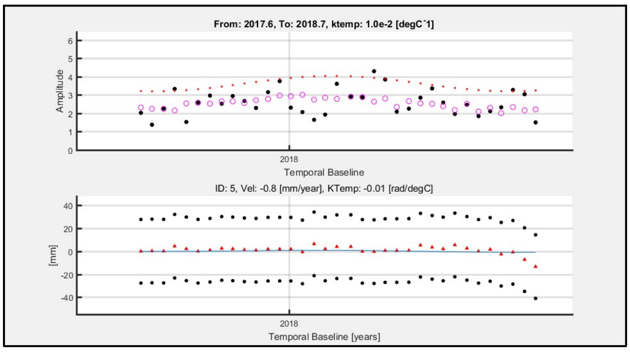

Figure 5. Temporal Baseline Plot and Displacement Time-Series

Table 3 compares the displacement recorded by PS-InSAR with ground truth crack measurements obtained prior to the Naga landslide. The PS-InSAR LOS velocity does not represent total ground movement but rather the projection of displacement along the satellite's line of sight. In the case of descending Sentinel-1 imagery, the LOS is most sensitive to vertical motion and the eastward component of horizontal motion. By contrast, the ground-based crack measurements primarily recorded horizontal opening and vertical subsidence, which are larger in magnitude than the LOS changes.

For example, over a ~12-day period before failure, the selected PS point (ID: 5) registered approximately –1.3 cm of LOS displacement, corresponding to a velocity of –0.08 cm/day. In the same interval, field mapping documented horizontal crack widening of 10.25 cm and vertical drop of 11.5 cm, with deformation rates of 0.51 cm/day (horizontal) and 0.57 cm/day (vertical). This disparity arises because LOS displacement is a projection of the true 3D deformation vector and therefore cannot fully capture lateral opening along the slope. Furthermore, the ground crack measurements spanned a slightly different interval and recorded maximum crack apertures at the surface, whereas PS-InSAR reflects displacement at coherent scatterers, which may respond differently to near-surface tensile failure.

Despite differences in magnitude, the close agreement in the timing and spatial coincidence of deformation signals strongly indicates accelerating precursory movement before the landslide. The comparison underscores the importance of interpreting LOS results in the context of slope geometry: the PS-InSAR measurements effectively represent only the downslope component resolved along the radar LOS, while the field data capture the full expression of near-surface crack opening. Together, these complementary datasets provide robust evidence of slope instability and highlight the value of integrating satellite and ground-based observations for landslide early warning.

Parameter	LOS (cm)	HD (cm)	VD (cm)	Date	Velocity cm/day
PS-InSAR Point (Point ID: 5)	-1.3	–	–	Aug. 31 - Sept. 12 (12 Days)	-0.08 cm/day
Ground cracks	–	10.25	11.5	Aug 29 - Sept. 18 (12 Days)	0.51 cm/day (HD) 0.57 cm/day (VD)

Table 3. Ground Truth Crack Dimension and PS-InSAR (LOS)

The PS-InSAR analysis in this study also found results consistent with those reported by Ramirez et al. (2022), who applied a two-parameter hyperbolic model to Sentinel-1 PS-InSAR time series to characterize nonlinear ground deformation in Naga City, Cebu. Their model demonstrated excellent agreement with satellite-derived displacements, indicating maximum subsidence exceeding –50 mm and deformation rates greater than –15 mm/yr. These findings confirm that ground deformation in Naga continues to evolve under both natural and anthropogenic influences, with stabilization yet to occur.

Together with the present analysis, this demonstrates that the PS-InSAR technique, particularly when combined with hyperbolic modeling, is capable of supporting large-scale ground deformation mapping, monitoring, and even forecasting. The approach provides a cost-effective and labor-efficient method applicable across varying meteorological conditions. Ongoing observation of ground subsidence, complemented by additional thematic datasets, is therefore essential for improving the understanding of the complex and nonlinear deformation patterns in Naga City and for strengthening geohazard early warning systems.

4.3 Limitations and Recommendations

The PS-InSAR results obtained from SARPROZ provide valuable insights into precursory ground deformation at the 2018 Naga landslide site. However, several limitations were observed, particularly in the comparison between line-of-sight (LOS)

displacement values from satellite analysis and the larger surface displacements recorded through field measurements.
For example, while ground crack mapping documented horizontal and vertical displacements exceeding 10 cm in the weeks prior to failure (Catane et al., 2019), the corresponding PS-InSAR LOS values at the same location registered only ~1.3 cm. This discrepancy highlights inherent constraints in SAR-based monitoring.

First, LOS displacement represents only the projection of three-dimensional ground motion onto the radar's viewing geometry. As such, movements occurring perpendicular to the satellite look direction, particularly near-horizontal translations common in quarry-induced landslides, are often underestimated. This limitation is compounded by the exclusive use of descending orbit data, which prevents full decomposition of displacement vectors into horizontal and vertical components.

Second, PS density in active quarry slopes can be sparse due to vegetation cover, blasting, and surface disturbances that degrade coherence. In such environments, Persistent Scatterer candidates may not fully capture localized zones of rapid deformation, leading to underrepresentation of movement magnitudes. In addition, the 6–12 day revisit interval of Sentinel-1 limits the temporal resolution of deformation monitoring, potentially missing rapid accelerations that occur in the final days before catastrophic failure.

Third, radar backscatter may preferentially reflect signals from deeper, more coherent structural elements, whereas field measurements of crack widening capture near-surface deformation. This difference in sampling depth partly explains why PS-InSAR tends to report lower cumulative displacement than ground-based surveys.

To address these limitations, several alternatives are recommended. The use of both ascending and descending Sentinel-1 tracks would enable vector decomposition and provide a more complete representation of slope movement. In zones with poor coherence, corner reflectors or artificial targets can be installed to improve PS stability and ensure reliable calibration. Complementary InSAR techniques such as Small Baseline Subset (SBAS) or Distributed Scatterer (DS-InSAR) approaches may also enhance deformation detection in vegetated or disturbed terrain. Furthermore, integration of UAV photogrammetry, ground-based radar, or GNSS surveys can provide higher-resolution validation of surface displacements.

By acknowledging these limitations and incorporating the proposed alternatives, PS-InSAR can be positioned as a robust and cost-effective component of a multi-sensor early warning framework for quarry-induced landslides.

5. Conclusion

This study applied the Persistent Scatterer Interferometry technique using Sentinel-1B SAR data processed in SARPROZ to investigate precursory ground deformation prior to the 2018 Naga City, Cebu landslide. The results revealed both gradual and abrupt displacement in the months before failure, with several PS points near the landslide scarp showing noticeable movement, including a significant displacement spike recorded days prior to the event. These findings confirm the capacity of PS-InSAR to capture early signs of slope instability in quarry environments.
Validation with field measurements reported by Catane et al. (2019) demonstrated strong temporal correspondence, reinforcing the reliability of satellite-derived results for landslide monitoring and risk assessment. However, comparison with ground crack measurements also highlighted a key limitation: the PS-InSAR line-of-sight (LOS) velocity underestimates total ground movement, as it represents only the projection of displacement onto the radar viewing geometry. While SARPROZ recorded ~1.3 cm of LOS displacement over 12 days, field surveys documented more than 10 cm of horizontal crack widening and 11 cm of vertical subsidence over a similar interval. This disparity arises from differences in motion direction, sampling intervals, and the nature of radar reflectors versus surface crack mapping. Nevertheless, the strong agreement in timing and location between LOS signals and field observations provides compelling evidence of accelerating precursory deformation.

Acknowledging these limitations points to practical alternatives. The integration of ascending and descending track data would enable vector decomposition of displacements, while the deployment of corner reflectors could enhance scatterer density in low-coherence quarry slopes. Complementary InSAR methods such as SBAS or DS-InSAR, as well as ground-based tools like GNSS and UAV photogrammetry, can improve resolution and accuracy.

Overall, this study demonstrates that Sentinel-1 PS-InSAR, when properly interpreted and validated, is a cost-effective and powerful tool for mapping, monitoring, and anticipating mining-induced landslides. Incorporating PS-InSAR into a multi-sensor early warning framework—supported by field validation, corner reflectors, and real-time monitoring dashboards—can significantly strengthen hazard preparedness and risk mitigation strategies in quarry and mining environments.

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References

Carlà, T., Intrieri, E., Raspini, F., Bardi, F., Farina, P., Ferretti, A., Colombo, D., Novali, F., & Casagli, N. (2019). Perspectives on the prediction of catastrophic slope failures from satellite InSAR. *Scientific Reports, 9*(1). https://doi.org/10.1038/s41598-019-50792-y

Catane, S. G., Veracruz, N. A. S., Flora, J. R. R., Go, C. M. M., Enrera, R. E., & Santos, E. R. U. (2019). Mechanism of a low-angle translational block slide: Evidence from the September 2018 Naga landslide, Philippines. *Landslides, 16*(9), 1709–1719. https://doi.org/10.1007/s10346-019-01212-9

Chen, Y., Dong, X., Qi, Y., Huang, P., Sun, W., Xu, W., Tan, W., Li, X., & Liu, X. (2023). Integration of DInSAR-PS-stacking and

SBAS-PS-InSAR methods to monitor mining-related surface subsidence. *Remote Sensing, 15*(10). https://doi.org/10.3390/rs15102691

Ferretti, A., Prati, C., & Rocca, F. (2001). Permanent scatterers in SAR interferometry. *IEEE Transactions on Geoscience and Remote Sensing, 39*(1).

Hartwig, M. E., de Lima, L. R., & Perissin, D. (2021). IW Sentinel-1 satellite scenes for the investigation of mine slope stability: Experiences from the Riacho dos Machados gold mine (Brazil). *Earth Sciences Research Journal, 25*(1), 93–99. https://doi.org/10.15446/esrj.v25n1.86563

Hsieh, C. S., & Lin, D. Y. (2020). Establish an efficient method to monitor slope deformation using PS-InSAR, MUAV, and surveillance cameras. *Terrestrial, Atmospheric and Oceanic Sciences, 31*(6), 663–675. https://doi.org/10.3319/TAO.2020.04.02.01

Ishwar, S. G., Kumar, D., & Malik, K. K. (2017). Mine surface subsidence monitoring due to impacts of underground mining using persistent scatterer interferometry. *Imaging Science Journal, 65*(3), 151–161. https://doi.org/10.1080/13682199.2017.1303957

Karanam, V. K. R., Motagh, M., & Jain, K. (2020). Land subsidence in Jharia coalfields, Jharkhand, India – Detection, estimation and analysis using persistent scatterer interferometry. https://doi.org/10.5194/egusphere-egu2020-21118

Mabaquiao, L. C. (2023). Performance evaluation of temporal model and spatial correlation methods for persistent scatterer determination in landslide-prone areas. *ISPRS Archives, XLVIII-4/W8-2023*, 343–348. https://doi.org/10.5194/isprs-archives-XLVIII-4-W8-2023-3432023

Mayuga, P. J., Tiongson, S. F., Abao, J. J., Mendoza, J. M., Pernez, G. A., & Ramirez, R. (2022). Landslide area mapping using synthetic aperture radar (SAR) data: The case of the 2018 Naga landslide. *International Geoscience and Remote Sensing Symposium (IGARSS), 2022-July*, 7883–7886. https://doi.org/10.1109/IGARSS46834.2022.9884207

Nam, B. X., van Anh, T., Bui, L. K., Long, N. Q., Le Thu Ha, T., & Goyal, R. (2021). Mining-induced land subsidence detection by persistent scatterer InSAR and Sentinel-1: Application to Phugiao quarries, Vietnam. In *Lecture Notes in Civil Engineering* (Vol. 108, pp. 18–38). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-3-030-60269-7_2

Perissin, D., Wang, Z., & Wang, T. (n.d.). The SARPROZ InSAR tool for urban subsidence/manmade structure stability monitoring in China.

Qin, Y., & Perissin, D. (n.d.). Monitoring underground mining subsidence in South Indiana with C- and L-band InSAR technique. http://coalminemaps.indiana.edu/

Ramirez, R. A., Abdullah, R. E. E., & Rubio, C. J. P. (2022). S1-PSInSAR monitoring and hyperbolic modeling of nonlinear ground subsidence in Naga City, Cebu Island in the Philippines. *International Journal of GEOMATE, 23*(100), 102–109. https://doi.org/10.21660/2022.100.g12121

Rana, N. M., Delaney, K. B., Evans, S. G., Deane, E., Small, A., Adria, D. A. M., McDougall, S., Ghahramani, N., & Take, W. A. (2024). Application of Sentinel-1 InSAR to monitor tailings dams and predict geotechnical instability: Practical considerations based on case study insights. *Bulletin of Engineering Geology and the Environment, 83*(5). https://doi.org/10.1007/s10064-024-03680-3

Ruiz-Armenteros, A. M., Bakon, M., Lazecky, M., Delgado, J. M., Sousa, J. J., Perissin, D., & Caro-Cuenca, M. (2016). Multi-temporal InSAR processing comparison in presence of high topography. *Procedia Computer Science, 100*, 1181–1190. https://doi.org/10.1016/j.procs.2016.09.278

Singh Virk, A., Singh, A., & Mittal, S. K. (2019). Monitoring and analysis of displacement using InSAR techniques. *Journal of Engineering Science and Technology, 14*(3).