Satellite-based monitoring of an open-pit mining site using Sentinel-1 advanced radar interferometry: a case study of the December 21, 2020, landslide in Toledo City, Philippines

Ryan Ramirez, Rajiv Eldon, Woojae Shin-Kyu, Tae-Hyuk Kwon

Abstract. Landslides and debris flows have become more frequent globally due to climate change. The topography, morphology, and climatic conditions contribute to frequent landslides and debris flows, resulting in monetary losses or even loss of life. Understanding the triggers and mechanisms behind these catastrophic events is crucial for accurate forecasting, risk mitigation, and management plans. With the higher frequency of extreme weather events combined with anthropic factors, landslide and debris flow monitoring and early warning systems are a possible cost-effective approach for disaster risk reduction [1–3].

Freely available synthetic aperture radar (SAR) data provide valuable information to complement ground-based instruments to understand the occurrence of landslides and debris flows. Advanced differential interferometric SAR (A-DInSAR) technology has been extensively applied in regional scales to improve landslide and debris flow susceptibility and hazard detection, mapping, and monitoring. Precisely, A-DInSAR technology has been used to update landslide and debris flow inventories and state activity [4–6] and estimate landslide and debris flow magnitude (i.e., area and volume of the source area) [7–9]. A-DInSAR technology has been exploited successfully to detect and monitor slope movements in open-pit mines [10–14]. A-DInSAR technology offers a high density of monitoring points over vast, dangerous, and inaccessible areas compared to conventional surveying techniques.

This paper presents how satellite remote sensing data, specifically the free-to-use Sentinel-1 SAR data, and the A-DInSAR technology, can detect and monitor slope movements to improve records and provide further information about the landslide and debris flow causes and triggers. This information can predict landslides and debris flows and warn when people and properties are at risk from landslides, potentially undergoing rapid accelerations and evolving into catastrophic debris flows. The case study presented in this paper focuses on applying the Sentinel-1 Persistent Scatterer InSAR (PSInSAR) [15] technique to monitor precursory slope movement over an open-pit mining site in Cebu Island in the Philippines.

1 Introduction

Landslides and debris flows have become more frequent globally due to climate change. The topography, morphology, and climatic conditions contribute to frequent landslides and debris flows, resulting in monetary losses or even loss of life. Understanding the triggers and mechanisms behind these catastrophic events is crucial for accurate forecasting, risk mitigation, and management plans. With the higher frequency of extreme weather events combined with anthropic factors, landslide and debris flow monitoring and early warning systems are a possible cost-effective approach for disaster risk reduction [1–3].

Freely available synthetic aperture radar (SAR) data provide valuable information to complement ground-based instruments to understand the occurrence of landslides and debris flows. Advanced differential interferometric SAR (A-DInSAR) technology has been extensively applied in regional scales to improve landslide and debris flow susceptibility and hazard detection, mapping, and monitoring. Precisely, A-DInSAR technology has been used to update landslide and debris flow inventories and state activity [4–6] and estimate landslide and debris flow magnitude (i.e., area and volume of the source area) [7–9]. A-DInSAR technology has been exploited successfully to detect and monitor slope movements in open-pit mines [10–14]. A-DInSAR technology offers a high density of monitoring points over vast, dangerous, and inaccessible areas compared to conventional surveying techniques.

This paper presents how satellite remote sensing data, specifically the free-to-use Sentinel-1 SAR data, and the A-DInSAR technology, can detect and monitor slope movements to improve records and provide further information about the landslide and debris flow causes and triggers. This information can predict landslides and debris flows and warn when people and properties are at risk from landslides, potentially undergoing rapid accelerations and evolving into catastrophic debris flows. The case study presented in this paper focuses on applying the Sentinel-1 Persistent Scatterer InSAR (PSInSAR) [15] technique to monitor precursory slope movement over an open-pit mining site in Cebu Island in the Philippines.

2 Materials and method

2.1 Study area

The Toledo Copper Mine in Toledo City in Cebu Island in the Philippines is between the North Barot and Cantabaco faults. The site is sustained by a basement complex of Cretaceous volcanic and metavolcanic rocks.
cloaked with Oligocene to the recent sedimentary unit [16–17]. Disseminated deposits, predominantly chalcopryite, bornite, and covellite, mainly compose the primary copper mineralization of the porphyritic intrusive rocks characteristics of the Cretaceous Lutopan Stock.

The site has three open pits: Carmen, Lutopan, and Biga. On December 21, 2020, a landslide occurred at the north wall of the Carmen pit. It resulted in eight injured personnel, four confirmed deceased personnel, six missing personnel, and eight missing equipment. The landslide footprint is plotted against the landslide hazard map (Figure 1), showing that the pit is an active landslide zone. On December 18, 2020, Toledo City was affected by the rain brought by Tropical Storm Krovanh.

Fig. 1. Location of the study area, landslide footprint, and hazard map over the open-pit mining site in Toledo City, Cebu Island, Philippines.

2.2 Sentinel-1 SAR dataset

The twin Sentinel-1 satellites provide SAR data in all-weather and day-and-night conditions for land and ocean services under the Copernicus joint initiative of the European Space Agency (ESA) and the European Commission (EC). Sentinel-1 satellites are equipped with C-band having a wavelength of 5.6 cm. In this study, 31 SAR images were collected from December 30, 2019, to December 12, 2020. Due to the Sentinel-1 satellites’ orbit being sun-synchronous and right-side-looking viewing geometry, the line-of-sight (LOS) displacement measurements are less sensitive in the north-south direction than in the east-west direction. As the pit slope is south-south-westerly facing, the dataset acquired by the descending Sentinel-1 mission was used. The data acquired on June 15, 2020, was set as the master image (Figure 2) to mitigate the effect of temporal decorrelation.

2.3 PSInSAR analysis

Two main processing stages were implemented for Sentinel-1 PSInSAR analysis.

2.3.1 Pre-processing using SNAP

The first stage was accomplished using the SeNtile Application Platform (SNAP) for the master image selection (i.e., InSAR Stack Overview) and the snap2stamps package tool for the single master-slave images coregistration, interferogram formation, and topographic phase removal utilizing the Shuttle Radar Topography Mission digital elevation model (SRTM DEM) 1 arcsec data in the SNAP Library [18].

2.3.2 Time series analysis using StaMPS

The second stage was accomplished using the Stanford Method for Persistent Scatterers (StaMPS) software for the time series InSAR analysis [19]. An amplitude dispersion index (ADI) of 0.35 was used to recognize introductory PS candidates (PSCs), launching the StaMPS processing. Afterward, the PSCs phase noise level was estimated iteratively. Based on the noise level, PSs were selected, and the strident ones were dropped. The remaining PSs in the wrapped phase were then amended for spatially uncorrelated look angle error. Afterward, the Statistical-cost, Network-flow Algorithm for Phase Unwrapping (SNAPHU) was used for phase unwrapping [20]. Then, the spatially correlated look angle error (i.e., the error in the DEM itself and the imprecise aligning of the DEM into radar coordinates) was approximated and removed from the unwrapped dataset. Lastly, atmospheric effects were mitigated using spatiotemporal filters.

3 Results and analysis

3.1 Pre-failure mean annual velocity map

Figure 3 displays the pre-failure LOS mean annual velocity map of the Toledo landslide retrieved from the Sentinel-1 dataset. PSs were detected over the initiation zone due to the absence of vegetation cover and

Fig. 2. Sentinel-1 synthetic aperture radar (SAR) dataset and interferometric pairs.
probably lesser mining operations during the analysis period. In contrast, there was a lack of PSs at lower elevations where most mining activities were undertaken. Red variant dots represent ground targets moving away from the satellite sensor. Blue variant dots indicate motion toward the satellite sensor. Most PSs show movement away from the sensor when the satellite descends north to south, and the pit slope is south-southwesterly facing. PSs within the initiation zone showed displacement velocities exceeding $-10$ mm/yr and reaching $-90$ mm/yr.

![Fig. 3. Line-of-sight (LOS) annual mean velocity map over the Toledo Copper Mine site.](image)

### 3.2 Pre-failure displacement time series

Figure 4a shows the cumulative LOS displacement time series of four representative PSs within the initiation zone. These four PSs are marked as D1–D4 in Fig. 3. The daily and accumulated rainfall values are also plotted in Fig. 4b. The rainfall data were acquired from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) Mactan Station ($10^\circ19'18.15''N, 123^\circ58'33.7''E$). Figure 4b also shows significant hydrometeorological events and hazards, particularly indicating the recorded landslip of Tropical Storm Krovanh and the day when the landslide occurred. Although previous powerful tropical cyclones (namely Typhoon Molave and Typhoon Goni) and a super typhoon (namely Typhoon Vamco) may not have made landfall on Cebu Island, the precipitation from these events led to the waterlogging of the ground on the open-pit site. The waterlog effect is evident in the displacement time series of PSs D1–D4, where a progressive movement was initiated in October 2020. Likewise, the significant accumulated rainfall in February 2020 also coincided when the displacement time series of PSs D1–D3 showed declining linear trends until an earthquake hit Cebu Island in July 2020. These trends seemed to shift after the earthquake until October 2020, before a series of typhoons hit Cebu Island from October 2020. Based on the accumulated precipitation, the landslide occurred 24–48 hours after the landfall of Tropical Storm Krovanh on the island. This observation suggests a lag time between peak rainfall and the landslide event, which can be attributed to infiltration and percolation time before ground saturation, thereby plausibly triggering the mass movement. At the end of the slope monitoring period, the cumulative LOS displacements of PSs D1, D2, D3, and D4 were $-26.16$ mm, $-50.70$ mm, $-69.80$ mm, and $-90.05$ mm, respectively. Although this may be the leading cause of the landslide, other contributing factors must be further explored and accounted for.

![Fig. 4. (a) Representative displacement time series of PSs in the initiation zone and (b) hydrometeorological and hazard events.](image)

### 3.3 Landslide causal factors

Earthquakes, hydrometeorological, and anthropic factors are hypothesized as potential triggers of the Toledo landslide. No seismicity was reported immediately before or during the landslide. However, a $M_s$ 4.2 tectonic earthquake occurred on July 17, 2020, in Cebu Island, with the epicenter at $10.28^\circ$N, $123.80^\circ$E, and an estimated focus depth of 7 km. Ground shaking was perceived about 11 km southwest of Cebu City, classified as seismic intensity IV according to the Philippine Institute of Volcanology and Seismology (PHIVOLCS) Earthquake Intensity Scale (PEIS). The epicenter of this earthquake is about 10 km from the Carmen pit. Ground ruptures were not reported in the Toledo copper mine. It is noted that the Barot fault, a minor fault line, traverses the Carmen pit where the landslide occurred, and this earthquake might have contributed to the initiation of the fault movement, eventually triggering the slope instability. The landslide occurred after a day or two after the downpour from Tropical Storm Krovanh. This rainfall event, along with the days of similarly significant
rainfall in Toledo City preceding it, might have weakened the contact of the limestone and mudstone layer in the site’s rock base, as there were already waterlogged. The waterlog caused an excess pore water pressure in the soil medium, which might have overcome the shear strength of the soil.

Moreover, according to Biga village residents, ground cracks appeared in residential areas, approximately 300 m from the mining site, in November 2020. Blasting activities before the landslide have been reported to cause ground vibrations leading to sustained cracks on the floors and walls of nearby structures and houses. Blasting operations were done twice daily and conducted about 350 m away from the Biga village. Residents have also reported that the groundwater spring that served as their water source has dried up.

4 Discussion and outlook

This paper highlights the application of the Sentinel-1 PSInSAR technique for detecting and monitoring precursory slope movement over an open-pit mining site in the city of Toledo, Cebu Island, in the Philippines. The topography, morphology, and hydrometeorological conditions combined with the anthropic activities over the mining site contributed to the catastrophic landslide on December 21, 2020. Mining slope instabilities indicating the active movements in the initiation zone were successfully detected and monitored using free SAR data and open-source software packages. Thus, rapid and reliable information can be extracted for decision-making, risk monitoring, and early warning for mines and other landscapes.

Sentinel-1 SAR data, leveraged in this case study, offer broader area coverage, encompassing the whole Toledo Copper Mine. Covering a broader area implies that even artificial hills, consisting of open-pit mining wastes accumulated on specific dump sites, can be monitored regularly in near-real time. Usually, these artificial hills comprise tens to hundreds of cubic meters of unconsolidated, loose earthen materials. These artificial hills also can reach a height of a hundred meters. With a suitable rainfall-duration threshold during an extreme downpour or at the onset of an intense earthquake event, collapses and debris flows are inevitable. Thus, slope stability monitoring using the Sentinel-1 PSInSAR technique can include these open-pit waste dump sites besides cut slopes during and after the entire open-pit mining process.

This work was also supported by the National Research Council of the Philippines (NRCP) through the Support to Research Dissemination in Local and International Platforms (RDLIP) component of the Basic Research Information Translation for Empowerment in the Regions (BRITER) Program.

References

- B. Berti, Geosci. J. (2020) 1–18
- G. Berti, Geosci. J. (2021) 1–16
- B. Berti, Geosci. J. (2020) 1–18
- G. Berti, Geosci. J. (2021) 1–16
- B. Berti, Geosci. J. (2020) 1–18
- G. Berti, Geosci. J. (2021) 1–16