Investigating the effect of intense rainfall events in estimating the displacements of an active and fast-moving landslide using A-InSAR analysis: the case Study of Pissouri Village in Cyprus

Kyriaki Fotiou*[a,b], Dimitris Kakoullis[a], Christopher Kotsakis[a,c], Miltiades Hatzinikos[a], Diofantos Hadjimitsis[a,b], Chris Danezis[a,b]

[a]Department of Civil Engineering and Geomatics, Cyprus University of Technology, Limassol 3036, Cyprus; [b]ERATOSTHENES Centre of Excellence, Limassol 3012, Cyprus; [c]Department of Geodesy & Surveying Faculty of Engineering Aristotle University of Thessaloniki University Postal Box 440 Thessaloniki, 54124, Greece

ABSTRACT

Pissouri village located in Limassol, Cyprus, has been experiencing an active and fast-moving landslide, resulting to devastating consequences in the village. Since 2017, the impact of the landslide, especially during intense rainfall events in winters, has led to necessitated evacuations, severe damage to properties and the wider landscape. Since 2021, the Laboratory of Geodesy of Cyprus University of Technology has established the CyCLOPS (Cyprus Continuously Operating Natural Hazards Monitoring and Prevention System). One of the case studies that CyCLOPS focuses on is Pissouri, installing three (3) GNSS mobile stations, three (3) GNSS antennas withing the sliding zone, resulting to continuous monitoring of the landslide-affected zone. This study presents an initial attempt to investigate the displacement rates of the landslide, especially during heavy rainfalls seasons, utilizing the CyCLOPS strategic infrastructure unit. Sentinel-1 acquisitions are obtained in ascending mode, covering an interval time from July 2021 to January 2023. Amongst others, rainfall data are complementary used and processed in a GIS environment for visualization purposes. The results of the study indicated that there is a significant relationship between the heavy rainfall seasons and the displacement trends. In cases of an active and fast-moving landslide, the integration of both Synthetic Aperture Radar (SAR) and Global Navigation Satellite System (GNSS) data is essential to monitor, estimate and understand the displacement rates of the landslide and the impact of the intense rainfall events in those cases.

Keywords: SAR, GNSS, CyCLOPS, Pissouri landslide, Rainfall, Cyprus

1. INTRODUCTION

Land movements can be triggered by a combination of geological, human, and physical factors. Geology and geomorphology, lithology, massive development, earthquakes, and rainfall can impact and trigger a landslide[1]. Landslides are classified among the most destructive categories of natural hazards causing major damages on infrastructure and landscape, loss of lives and impact the socio-economic level of a country[2]. At a pan-European lever, Cyprus country exhibits a major number of landslides despite of its small size[3]. One of the most highly affected by natural hazards areas in Cyprus is the Pissouri region. Pissouri is challenging an active and fast-moving landslide resulting in devastating consequences to the community, the broader landscape and infrastructures, as depicted in Figure **1**. Following the re-activated ground movements within the Limnes area in Pissouri community, continuing significant architectural and structural damages have been noticed to many properties, up to the present. Since 2017, the effect of the landslide led to consecutive evacuations beginning from the Limnes area and culminating to the village center. Especially during the heavy rainfall seasons, the extent and magnitude of the landslide increases the negative impact, at a regional level. Based on the latter, the continuous monitoring of the landslide occurring in Pissouri is crucial for effective landslide risk management and mitigation strategies.

Various satellite and ground-based methodologies and techniques are used for the continuous monitoring of the landslides. Global Navigation Satellite Systems (GNSS) techniques are widely used for the real-time monitoring of landslides[4,5]. However, achieving a denser spatial distribution and estimating displacement at a regional scale, the GNSS stations need to be augmented. The latter is cost-inefficient and non-vital, therefore, the leveraging of other techniques of similar

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accuracy levels must be used. Interferometric Synthetic Aperture Radar (InSAR) has been one of the most used techniques for monitoring the potential displacements on the earth's surface, since it provides efficiency and economy, enabling the remote monitoring of large-scale areas. Techniques such as Persistent Scatterer Interferometry (PSI)[6] and Small Baseline Subset (SBAS)[7] are the advanced InSAR techniques that are used for the landslide monitoring, extracting a time-series analysis of displacements. In the case of Pissouri landslide, several studies including traditional investigations[8–11] along with satellite-based techniques such as Differential Interferometry (DInSAR)[12–15], Persistent Scatterer Interferometry (PSI) and Small Baseline Subset (SBAS)[16,17] have been published. However, due to the geodynamic environment of the landslide, the remaining uncertainties over the depth(s) of sliding, the acceleration, and the direction of the landslides, Limnes area and Pissouri region are generally monitoring through the CyCLOPS project.

The current research endeavor focuses on specific objectives, aimed at advancing the knowledge of landslide dynamics and enhancing the ability to mitigate landslide hazards. Specifically, by building upon the findings of previous SAR interferometry studies, the aim is to expand the understanding of landslide dynamics and enhance the accuracy of the displacement monitoring efforts. Also, the selection of the optimal SAR processing method is critical for obtaining reliable displacement measurements. Apart from that, by integrating data from the CyCLOPS Strategic Infrastructure Unit, the study focuses on enhancing the precision of the displacement monitoring and improve the effectiveness and reliability of the displacement's results in Pissouri Village. Last but not least, this approach enables to gain insights into the influence of rainfall on landslide dynamics and enhances the understanding of landslide hazard assessment in the study area. Finally, the analysis of the temporal correlation between intense rainfall events and variations in displacement rates, can drive into quantifying the impact of rainfall on landslide activity.

Figure 1: Photos showcasing the aftermath of the landslide

Study Area

Pissouri village is located in the western part of Limassol city in Cyprus and has a coverage of about 40.234 square kilometers, as depicted in Figure 2. Its elevation reaches up to 230m above mean-sea level with a North-East and South-West general orientation. The area geologically consisted of Nicosia, Kalavassos and Pachna formation and described in detail by Stow et.al[18]. Regarding the climate of the area, Pissouri and Cyprus in general, is characterized by hot and dry summers and mild winters. According to the Department of Meteorology in Cyprus, the rainfall events are limited to winter seasons, with an average of annual precipitation of about 300mm at the coast and over 500mm at Troodos mountains[19]. In the last few years, Pissouri has been experiencing a massive development not only in the center of the village, but also in the surrounding areas. Following the re-activated ground movements within the Limnes in Pissouri, first noticed by residents in 2012, the devastating consequences including damage in buildings and the broader landscape, exhibits in the broader area, up to the present. The combination of the rainfall precipitation, geological and massive development factors, along with the re-activation of the Pissouri landslide result in the triggering of the landslide in the surrounding area as well.

Figure 2: Location of the Pissouri community in Limassol, Cyprus

2. THE CYCLOPS INFRASTRUCTURE UNIT AT PISSOURI VILLAGE

Since 2021, the Laboratory of Geodesy of Cyprus University of Technology has established the CyCLOPS (Cyprus Continuously Operating Natural Hazards Monitoring and Prevention System), the Largest Scientific Integrated GNSS and InSAR Permanent Array in Cyprus[20]. CyCLOPS is a Strategic Research Infrastructure co-funded by the European Union and the Republic of Cyprus with main objectives of promoting the study of solid earth processes and geohazards in Cyprus and the EMENA region and the establishment of a novel calibration and validation site for EO satellite missions. Concordantly, CyCLOPS aimed to augment and modernize the national geodetic infrastructure and to support critical geodetic and geophysical initiatives. One of the case studies that CyCLOPS focuses on is the Pissouri community. Thus, a GNSS network of six (6) stations was installed, covering the region, as presented in Figure 3. The CyCLOPS network in the Pissouri community consists of three (3) GNSS mobile stations (Figure 4), three (3) GNSS antennas withing the sliding zone (), resulting to continuous monitoring of the landslide-affected zone.

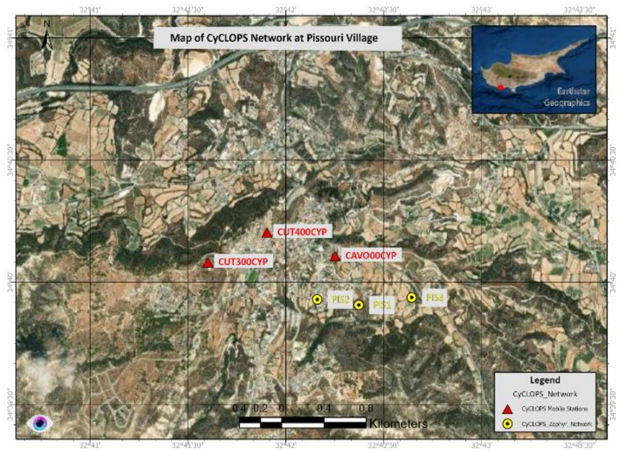
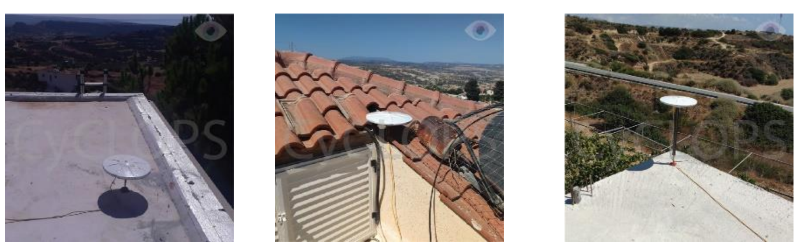


Figure 3: The CyCLOPS Network at Pissouri Community

(a) (b) (c)

Figure 4: CyCLOPS GNSS Mobile Stations at Pissouri, where (a) CUT300CYP, (b) CUT400CYP and (c) CAVO00CYP



(a) (b) (c)

Figure 5: CyCLOPS GNSS Antennas at Limnes area in Pissouri, where (a) PIS1, (b) PIS2 and (c) PIS3

3. METHODOLOGY

Satellite Data and Processing

The current study leverages the freely available Copernicus Sentinel-1A satellite constellation, enabling the reusability of this endeavor for future study on a larger scale and temporal manner. Copernicus program provides openly accessible data with global coverage with a temporal resolution of twelve (12) days[21]. The dataset of satellite data is consisted of thirty-one (31) Sentinel-1A acquisitions spanning from September 2022 to August 2023, as shown in Table 1. The studied period was selected due to the installation date of the CyCLOPS network at Pissouri community. The acquisitions were obtained in ascending mode, covering path 160 and frame 107, to ensure comprehensive coverage of the study area.

Table 1: Calendar of Sentinel-1A acquisitions

Month	2022	2023
January	-	02, 14, 26*
February	-	07, 19
March	-	03, 15, 27
April	-	08, 20
May	-	02, 14, 26
June	-	07, 19
July	-	01, 13, 25
August	-	06, 18, 30
September	04, 16, 28	-
October	10, 22	-
November	03, 15, 27	-
December	09, 21	-

The workflow of the PSI analysis is presented in Figure 6. Overall, the PSI methodology was divided into three (3) main parts. The first part concerns the pre-processing of the dataset and the preparation of the pairs for the PSI analysis using the 'snap2stamps' v.2 open-source toolbox[22]. As the primary image, the 26th of January 2023 was selected, due to that the specific image minimized the temporal and spatial statistical characteristics of the baselines[23]. The data pre-processing included the splitting of the AoI, in order to reduce the time and the capacity of the processing. Also, the co-registration of primary and secondaries images were performed in that stage, using the SRTM external digital elevation model from USGS[24], along with the generation of the interferograms of each pair. Following the first part, the second part regards the PSI analysis, using the StaMPS/MTI v4.0 open-source toolbox[25,26]. Specifically, in the second part the PS candidate selection, as well as the selection of the reference point selection were carried out. This section included setting the reference point that served as a crucial anchor for the accurate displacement measurements. Located at the Souni location, a triangular trihedral corner reflector was identified as the reference point for our study. The Souni location is part of the permanent segment of CyCLOPS, which comprises 12 corner reflectors collocated with GNSS CORS (Continuous Operating Reference Station) stations. Specifically, the corner reflector named SOUN01CYP, operating in ascending mode, was utilized as the reference point for our analysis, as depicted in Figure 7. The performance assessment of the corner reflector, as well as its radiometric and geolocation accuracy is described in detail, thus, the specific point was used as the most reliable persistent scatterer next to the study area[27]. The coherence threshold of the persistent scatterers was set to 0.6, enabling to avoid including potential noise or errors in the persistent scatterers' performance. Finally, the Line-of-Sight (LoS) displacement rates from the PSI analysis in ascending mode were imported into a GIS environment (ESRI ArcGIS Pro) for further analysis and visualization.

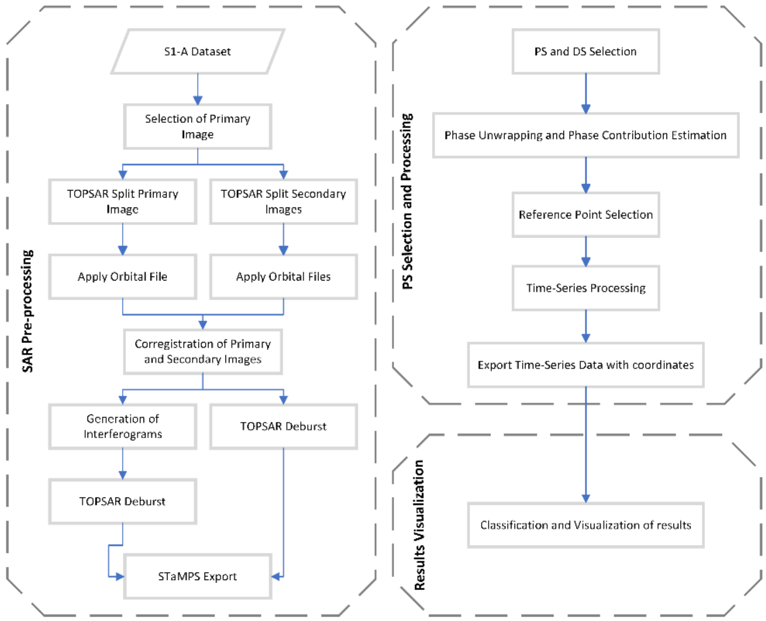


Figure 6: Overall methodology of the PSI analysis

(a) (b)

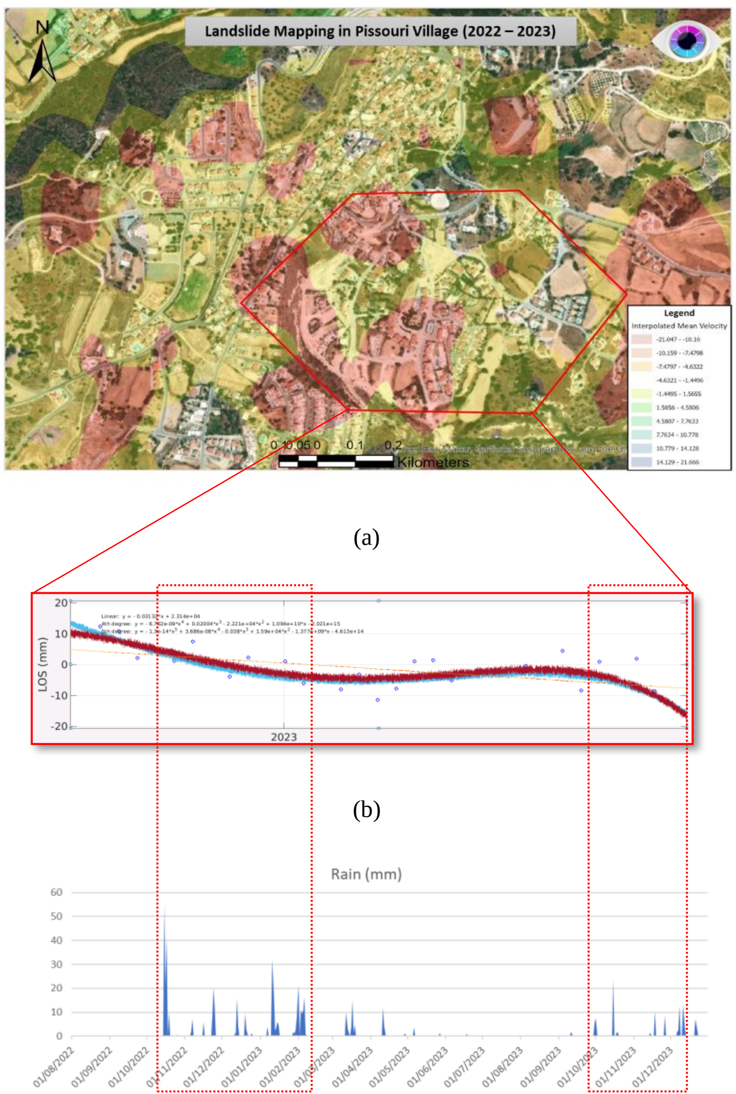
Figure 7: (a) CyCLOPS SOUN01CYP SAR Station and (b) intensity image of the Souni location captured in ascending mode

Rainfall Precipitation Data and Processing

Complementary to the satellite data and processing, the precipitation data of rainfall were used. Rainfall data are crucial for the study that were sourced from the Department of Meteorology[19]. The data provided by the responsible authority were obtained in a daily manner. For the sake of comparison with the displacement rates obtained from the satellite-based analysis, the rainfall data were isolated only in the days of the corresponding satellite acquisitions. The nearest meteorological station to the area of interest was the Petra tou Romiou/Kouklia station. Thus, the precipitation data concerned only this station. These data provide essential insights into the temporal patterns and intensity of rainfall events occurring near the study area. Therefore, their visualization was a critical stage in the overall processing. From October 2022 to February 2023 an average rate of 45mm/day was recorded. By the middle of the month March 2023 an average value of 15mm/day of rain, as well as, during the October 2023 to December 2023 an average range of 10mm/day rain were recorded, accordingly. By integrating rainfall data with satellite observations, the ultimate goal is to investigate the relationship between precipitation dynamics and landslide occurrences in Pissouri Village.

4. RESULTS AND DISCUSSION

The results of the current study were visualized and analyzed in order to be interpretable and understandable. PSI processing indicated displacement rates up to -26 mm/year. Within the Limnes area, especially in the western part of the area of interest, the displacement rates are visible, as shown in Figure 8. It must be noted that these displacement rates need to be improved since the GNSS data showed significant differences. The time-series analysis of an indicative example within the area of interest reveals correlations between rainfall precipitation and landslide displacement. Specifically, when comparing the displacement trend with rainfall data, a strong correlation is presented regarding the downward trend of the ground displacements to the corresponding heavy rainfall periods. During seasons characterized by intense rainfall precipitation, the displacement graph exhibits a downward trend. This downward trend indicates that intense rainfall events have a significant impact on the displacement of the landslide. By finding out the relationship between rainfall intensity and landslide displacement, the analysis underscores the influence of environmental factors on landslide dynamics. These findings highlight the importance of considering rainfall patterns in landslide risk assessment and mitigation strategies, particularly in vulnerable areas like Pissouri Village.



(a)

(b)

(c)

Figure 8: (a) PSI analysis, (b) the average LoS velocity rates included in the red polygon and (c) precipitation of rainfall data from 2022-2023

CONCLUSION AND OUTLOOK FOR THE FUTURE

In conclusion, the research highlights the environmental factors and landslide dynamics in Pissouri Village, Cyprus. The findings emphasize the critical importance of incorporating rainfall patterns into landslide risk assessment and displacement monitoring. By understanding the influence of environmental factors, such as rainfall, the enabling to enhance early warning systems and improve the resilience of communities vulnerable to landslide hazards. This study aimed to perform an initial attempt to investigate the displacement rates in the Pissouri community, especially during heavy rainfalls seasons, utilizing the CyCLOPS strategic infrastructure unit. In cases of an active and fast-moving landslide, the integration of both Synthetic Aperture Radar (SAR) and Global Navigation Satellite System (GNSS) data is essential to monitor, estimate and understand the displacement rates of the landslide and the impact of the intense rainfall events in those cases. Overall, as proved by the current study, in seasons with heavy rainfall the displacement rates showed a slight subsidence.

As for the future steps, the study of seasonal displacement rates could be performed. The PSI or SBAS methodology will be carried out using various software that can be more dedicated to use the state-of-the-art technologies of GNSS and SAR, such as the Gamma software. Last but not least, satellite processing will be performed for the data obtained in descending pass, to identify any potential differences. Finally, due to the dynamic environment of the landslide and the potential of calibrating the Sentinel-1 acquisitions by leveraging the CyCLOPS strategic Infrastructure Unit, the next stage will involve the decomposition of results to determine the East-West-Up components and integrate the SAR with the GNSS dataset.

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