

Lecture Notes in Civil Engineering

Hemanta Hazarika ·
Stuart Kenneth Haigh ·
Babloo Chaudhary · Masanori Murai ·
Suman Manandhar *Editors*

Natural Geo-Disasters and Resiliency

Select Proceedings of CREST 2023

 Springer

Slope Movement Monitoring in Colluvium Deposit Landslide at Doi Chang, Thailand by Sentinel-1 Differential InSAR



Sartsin Phakdimek , Daisuke Komori , Thapthai Chaithong ,
and Suttisak Soralump

Abstract Differential interferometric synthetic aperture radar (D-InSAR) techniques are a well-established remote sensing tool used for natural hazard detection and monitoring. The Sentinel-1 satellite mission provides extensive spatial coverage, regular temporal sampling, and accessible data availability, making it an ideal source for D-InSAR analysis. In this study, D-InSAR analysis was performed over the potential slope deformation area in the colluvium deposit at Doi Chang, Chiang Rai province, Thailand, using all Sentinel-1 images acquired between March 2016 and March 2017. The results show that the slope movement in colluvium deposits at Doi Chang was slow during the dry season, but its velocity significantly increased during the rainy season, confirming the slope movement behavior observed during site investigation data. The movement rate was sufficient to cause recurrent damage to infrastructure, such as roads and buildings, resulting in economic loss and public concerns. The D-InSAR results revealed substantial activity and displacement behavior on the spatial–temporal evolution. Furthermore, observations were validated, and their accuracy was confirmed via comparison to ground truth data from borehole inclinometers. The detected displacement time series provides an understanding of the spatial–temporal evolution of the corresponding deformation phenomena.

Keywords Differential InSAR · Sentinel-1 · Slope movement · Landslide · Colluvium deposits

S. Phakdimek (✉)

Graduate School of Environmental Studies, Tohoku University, Sendai, Miyagi, Japan
e-mail: sartsin.p@gmail.com

D. Komori

Green Goals Initiative, Tohoku University, Sendai, Miyagi, Japan

T. Chaithong

Department of Geography, Kasetsart University, Chatuchak, Bangkok, Thailand

S. Soralump

Department of Civil Engineering, Kasetsart University, Chatuchak, Bangkok, Thailand

1 Introduction

Landslides are among the most significant geohazards, causing substantial loss of life, property damage, and damage to infrastructure and human settlements. A landslide is a mass movement on a slope caused by rainfalls, earthquakes, and human activities. Effective detection and continuous monitoring of landslides is crucial for reducing and mitigating associated risks. Traditional methods for landslide investigation and slope stability monitoring include remote sensing techniques and in-situ field observations [1, 2].

In rural areas that are physically difficult to access and where it is not practical to monitor potential landslides or slope deformation from the ground, interferometric synthetic aperture radar (InSAR) has proven to be a valuable tool for monitoring slope movements at a fine scale, ranging from millimeters (mm) to centimeters (cm), since the 1990s. InSAR has been extensively used for landslide monitoring using the differential InSAR (D-InSAR) [3, 4], which is widely used to monitor slow-moving landslides with a movement rate of mm or cm per year. D-InSAR is an active remote sensing technique based on the principle of the very high stability of the satellite orbits. The informative contribution of the phase difference between two or more SAR images at the same location from comparable geometries can be exploited. The availability of an extensive data set and multiple D-InSAR approaches leads to a more accurate estimation of atmospheric contribution and topographic phase components, reducing sources of error. In addition, the availability of numerous temporal SAR images enables the temporal monitoring of phenomena and provides time series data and insights into the rate of deformation processes. The spatial and temporal characteristics of active satellite sensors used in remote sensing, with their short revisit times and extensive coverage, help overcome the challenges associated with remote or inaccessible areas, where traditional ground-based monitoring is unfeasible. D-InSAR has demonstrated significant success in detecting and assessing the impact of natural hazards by tracking ground deformations due to events such as landslides and earthquakes [5].

The selection of SAR data type is crucial to consider the properties and characteristics of the area of interest based on the impact assessment of natural hazards for D-InSAR detection. C-band and X-band SAR data, characterized by their shorter wavelengths, provide significantly enhanced spatial resolution for measurements [6]. Consequently, they are preferred to be used with D-InSAR techniques, because they must improve the accuracy of deformation estimation due to the sensitivity of vegetation cover and temporal decorrelation. Nevertheless, the limitations of these SAR techniques can be overcome by integrating them with other SAR techniques or other Earth observation imagery to combine their advantages [7].

This study utilizes the D-InSAR technique with the freely available Sentinel-1 and the free Sentinel's Application Platform (SNAP) software, which is coupled with in-situ ground-based monitoring techniques to analyze slope movement in colluvium deposits at Doi Chang, Thailand. This landslide shows a complex spatial and temporal displacement pattern for site monitoring as an inclinometer, rain gauge,

and groundwater observation well. That behavior is challenging to monitor with SAR images because of changes in the soil surface and seasonal, inducing changes in the ground scattering properties between two or more consecutive image acquisitions during seasonal changes. The combination of instruments and D-InSAR aims to observe movement patterns in local and larger areas. Furthermore, it remains a significant difficulty in natural hazard risk mitigation and it has been suggested that landslide behavior prediction is a remote area of applied science that has not been well developed. Therefore, this study aims to demonstrate the D-InSAR techniques and instruments used to investigate landslide movement during seasonal variations in the colluvium deposit at Doi Chang, Thailand from January 2016 until March 2017.

2 Description of Study Area and Site Instrumentation Data

2.1 Study Area

The study area, located at Doi Chang village, Vavee sub-district, Mae Suai District, Chiang Rai province, Thailand (Fig. 1a), is characterized by a geological composition primarily consisting of Silurian-Devonian metamorphic rocks, specifically metavolcanic rocks. During site investigations, various rock types, including basaltic andesite, schist, and phyllite, were identified. The elevation within this region ranges from 1000 to 1800 m above sea level (m.s.l.), and the slopes vary between 0° and 20°. Notably, this area is renowned for its coffee bean production, with these commercial products being exported both domestically and internationally. Consequently, the region has experienced consistent growth in terms of human settlement and business activities. The human settlement is mainly located at the middle portion of the slope (Fig. 1b), and the locals have reported recurrent damage to infrastructure. Initially, it was deemed improbable that the gentle average slope of approximately 10 degrees could induce the reported damages. The human settlement is surrounded, including residential houses, gas stations, schools, roads, and coffee farms. The result of field investigation, including in-situ tests such as standard penetration tests (SPT) and electrical resistivity tests (ERT), indicated the thickness of colluvium material deposited at the underlying layer [8]. Colluvium materials are defined as unconsolidated sediments deposited at the base of hill slopes, consisting of soil and rock debris with a heterogeneous mixture of grain sizes varying from large boulders to clay particles. Colluvium is often of marginal stability and disturbance can cause recurrent downward movement [9]. The climate of the study area is a tropical wet and dry climate pattern with a high relative humidity of air and a large amount of precipitation. The annual rainfall averages between 900 and 1400 mm, with the monsoon season extending from June to November. The average temperature in the region hovers around 20 °C.

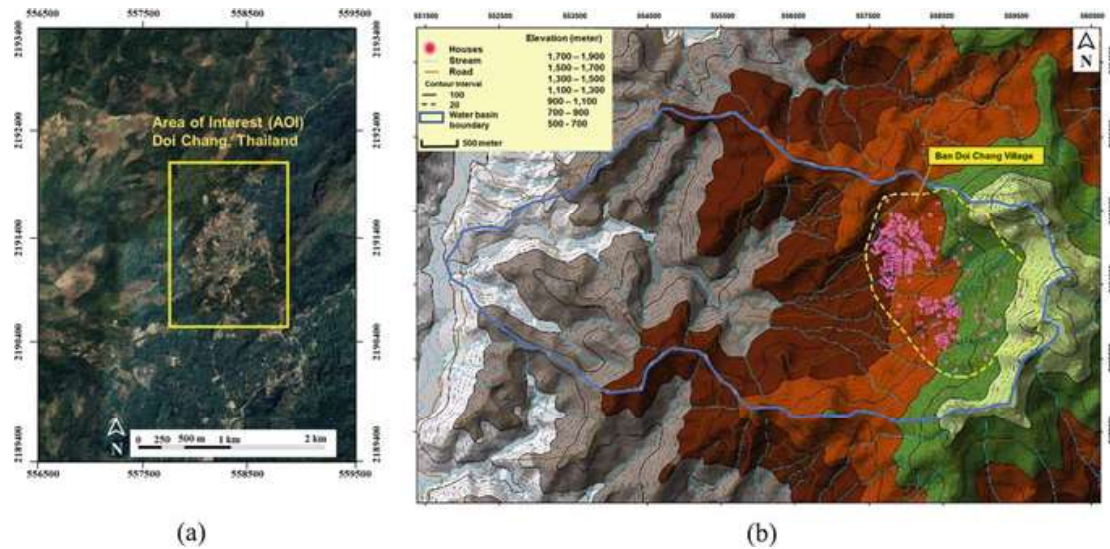


Fig. 1 **a** Location of Doi Chang village, **b** contour map of study area along with human settlement [8]

2.2 Site Instrumentation Data

In this study, in-situ ground-based monitoring techniques were utilized to monitor the potential slope displacement and measure the changes in attributes of landslide triggering, particularly rainfall. These techniques consist of monitoring rainfall, slope displacement, and hydrogeological and mechanical properties of the soil. Previous researchers have implemented these monitoring techniques, and their results are explained in three parts [8]. First, five official geodetic marks and 12 temporary benchmarks were used to determine the direction of the movement, with GPS stations distributed over a large area. The measurement of the GPS station's movement showed that the range of slope mass movement in the dry season was 0.66–3.8 mm per month, and the direction of movement was toward the southwest of the village to the downslope area. However, during the rainy season, the GPS stations did not provide data due to a lack of signal connectivity with the satellites (Fig. 2a). Second, the total accumulated movement in 2016–2017 was about 92 mm with an average movement rate of 19.45 mm per month, and the shear plane was found at a depth of 3–5 m from the ground (Fig. 2b). The characteristic movement of the slope, a slow creep movement, was observed with the slope inclinometer [10]. The maximum movement rate was 66 mm per month during the rainy season in September. Finally, the variations of groundwater level were observed by observation wells during the dry and rainy seasons. (Fig. 3). These variations are a function of seasonality and are directly related to the slope displacement rate.

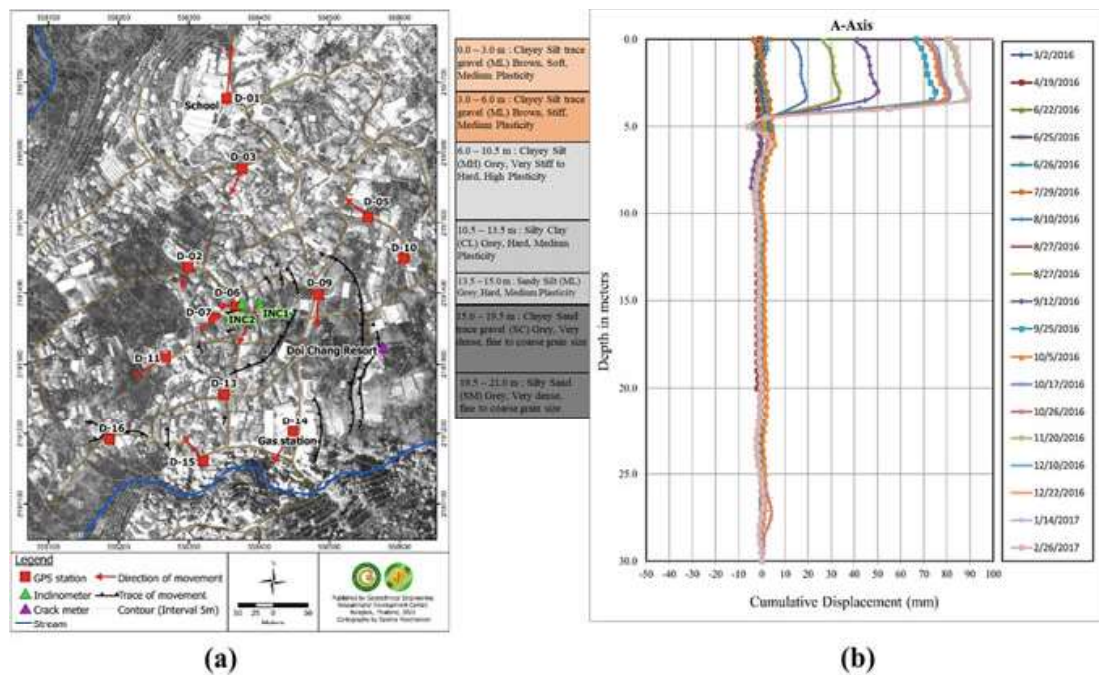


Fig. 2 **a** Direction of the slope movement by GPS station. **b** Observation of inclinometer in 2016–2017. Modified from Soralump et al. [8]

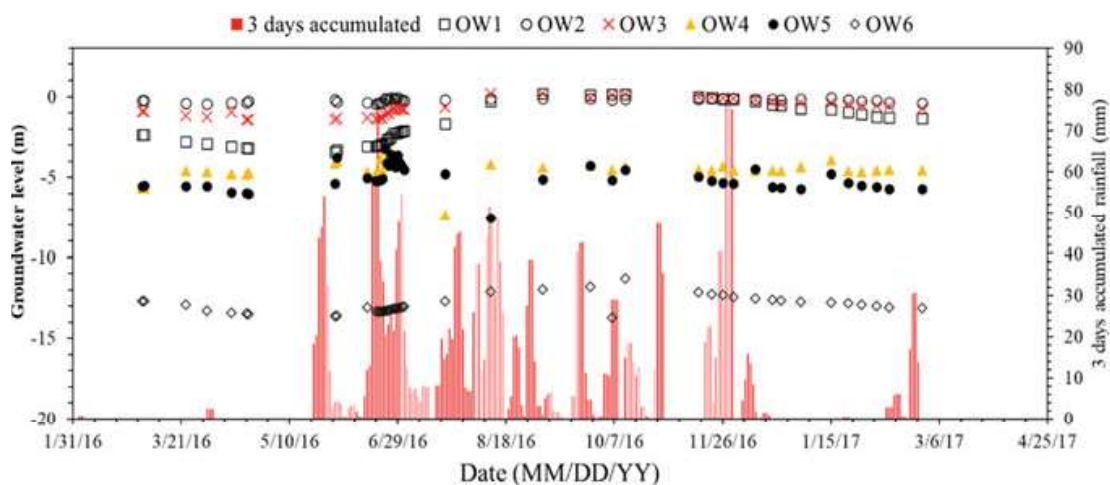


Fig. 3 Groundwater level readings recorded in 2016–2017. Modified from Soralump et al. [8]

3 Material and Methods

The monitoring of slope movement at Doi Chang village utilized the Sentinel-1 satellite, which operates in the C-band with a wavelength of approximately 5.55 cm. A total of 49 Sentinel-1A images were downloaded from the Copernicus Open Access Hub for the period between January 4, 2016 and March 11, 2017. These images included 17 ascending and 32 descending Interferometric Wide (IW) swath SLC images of VV polarization for the ascending pass direction and VV + VH

polarization for the descending pass direction. The images were acquired prior to the interferometric processing, which was carried out to perform a comprehensive study on the potential landslides at Doi Chang village.

D-InSAR was used to calculate the interferometric phase, which is the phase difference between two images acquired at two different times from almost the same satellite position. However, the interferometric phase is also affected by other factors, such as the atmosphere, pixel reflectivity, phase noise of radar system, and the uncertainty in determination of the platform position and baseline, as shown in Eq. (1) [11].

$$\Delta\varphi = \Delta\varphi_{\text{flat}} + \Delta\varphi_{\text{height}} + \Delta\varphi_{\text{displacement}} + \Delta\varphi_{\text{atmosphere}} + \Delta\varphi_{\text{noise}} \quad (1)$$

where $\Delta\varphi_{\text{flat}}$ is the phase contribution of the flat earth, $\Delta\varphi_{\text{height}}$ is the phase contribution of the topography, $\Delta\varphi_{\text{displacement}}$ is the part of the phase which represents the ground deformation measured along the line of sight (LOS), $\Delta\varphi_{\text{atmosphere}}$ is the contribution of the phase caused by the delay of radar wave propagation through the atmosphere, and $\Delta\varphi_{\text{noise}}$ is residual noise. However, the error associated with the atmospheric effect can be corrected by stacking or averaging many interferograms, since the atmospheric effect has a short spatial correlation length with virtually no temporal correlation between data acquisition times.

For conventional D-InSAR, the open-source software Sentinel-1 Applications Platform (SNAP) is used to analyze Sentinel-1 SAR acquisitions [12]. In addition, the SNAPHU software plugin is utilized for the phase unwrapping step in the interferometric processing of multiple SAR images in the environment of SNAP software [13].

Sentinel Precise Orbits and the SRTM (Shuttle Radar Topography Mission) 1 s HGT Digital Elevation Model (DEM) were automatically downloaded through SNAP software and used to remove the noise of topography component through the provided DEM during the step of co-registration. The interferograms and coherence maps were generated for the interferometric pairs at the step of interferogram generation. Finally, the Goldstein phase filter was applied to enhance the developed interferograms and make clear the interferometric fringes. The final interferograms and coherence maps were generated. The phase unwrapping step of the interferometric processing of the multiple SAR images is performed using the SNAPHU plugin. The unwrapped interferogram produced from the previous step was used to convert phase to the line of sight (LOS) displacement.

The multiple processing was used to stack the single-pair displacement from LOS displacement maps. Then, the Range Doppler Terrain Correction was applied to geo-locate the displacement map products. In this step, the resampling method of bilinear interpolation and the map projection of WGS84 are selected, and the output products are masked out from the geo-referenced displacement map. The D-InSAR processing flowchart is presented in Fig. 4. Multiple D-InSAR approaches are applied to reduce noise from single-pair InSAR, and these techniques could also observe slope movement behavior during seasonal changes.

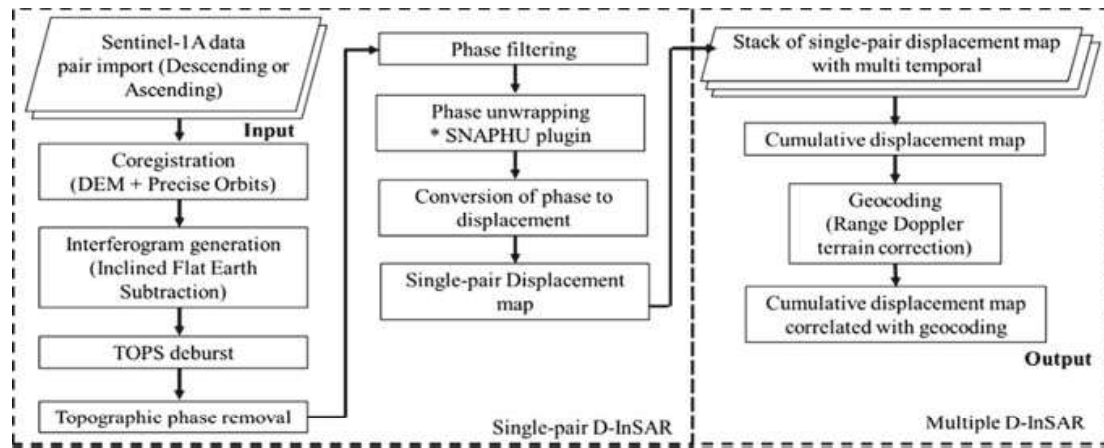


Fig. 4 Multiple D-InSAR workflow in SNAP

The LOS displacement from multiple D-InSAR was converted to vertical (up/down) and horizontal (east/west only) components. The up represents uplift and down represents subsidence, respectively. The north–south part of the horizontal displacement requires different processing with various combinations of ascending and descending SAR images [14]. The calculation of the vertical (uplift/subsidence) and east–west displacement components can be analyzed using the average LOS displacement products from the ascending and descending image pairs, together with the incidence angle by Eqs. (2) and (3) [15]

$$\text{Displacement}_{\text{up-down}} = \frac{\text{Displacement}_{\text{LoS}}}{\cos \theta_{\text{incidence}}} \quad (2)$$

$$\text{Displacement}_{\text{east-west}} = \frac{\text{Displacement}_{\text{LoS}}}{\sin \theta_{\text{incidence}}} \quad (3)$$

The multiple D-InSAR has been analyzed in dry and rainy seasons for slope movement monitoring during seasonal changes. For the dry season, the multiple D-InSAR was applied from January 2016 to May 2016 and from December 2016 to March 2017. The multiple D-InSAR was applied for the rainy season from June 2016 to November 2016. Then, the cumulative displacement and displacement rate were obtained and compared to in-situ ground-based instruments.

4 Result and Discussion

The study obtained slope displacement maps over Doi Chang using multiple D-InSAR processing, which is presented in Fig. 5. These maps show that surface ground displacements were influenced by seasonal variations. During the dry season from January 2016 to May 2016, the cumulative surface ground displacements in the vertical and horizontal directions were -4.20 mm (subsidence) and -5.25 mm

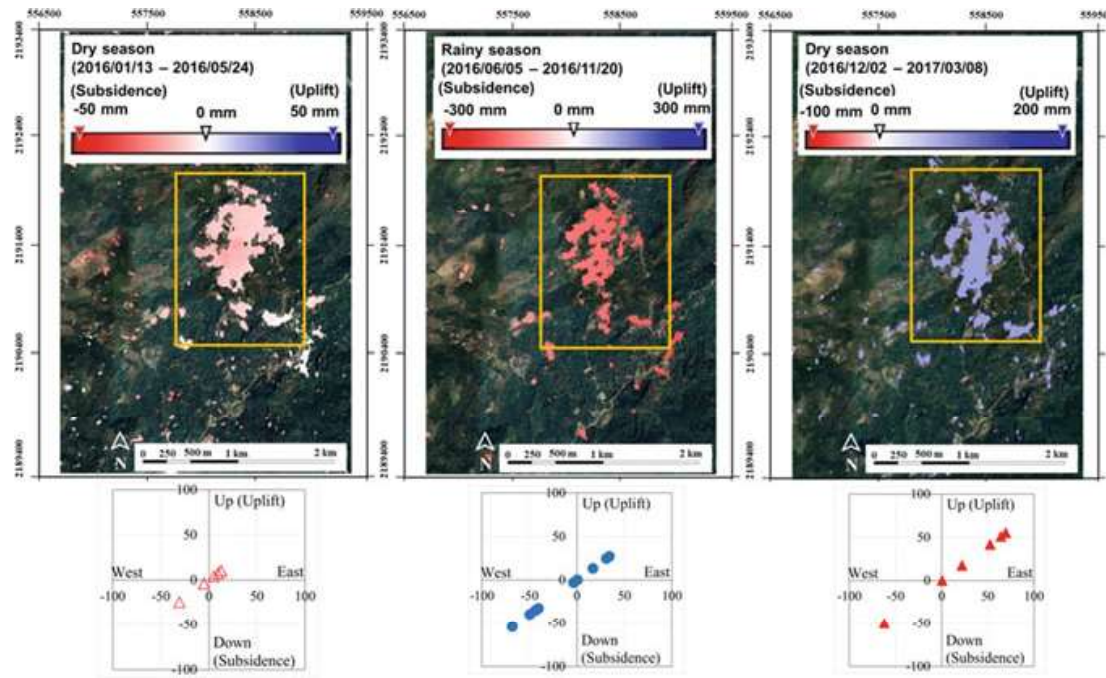


Fig. 5 Displacement map during seasonal changes from January 2016 to March 2017

(west), respectively. However, in the rainy season from June 2016 to November 2016, the cumulative surface ground displacement was -228.30 mm (subsidence) and -284.90 mm (west), indicating slope movement in the downslope direction. In contrast, an uplift was observed during the dry season from December 2016 to March 2017, moving eastward due to decreased groundwater levels. The direction of surface ground displacement measured by D-InSAR was toward the west, which is consistent with the movement observed by the GPS stations, indicating movement toward the downslope direction in the west. Figure 6 shows the relationship between surface ground displacement by multiple D-InSAR and inclinometer, factor of safety (FS), and groundwater level.

The increment of surface ground displacement by D-InSAR was similar to the inclinometer, and the movement direction seemed to align with GPS stations for westward movement. The rate of ground displacement by D-InSAR varied from -10.72 to -75.09 mm per month in the rainy season (negative is subsidence) and 19.417 – 53.09 mm per month in the dry season (positive is uplift). Accordingly, the result of the displacement rate classified the movement as very slow landslides in class 2 [10]. The FS value, which was calculated as the ratio of resisting force and driving force by a physically based model coupled with an infinite slope model and changing water table [16], varied from 0.86 to 1.27, as reported in previous studies [8]. The FS decreased below 1.0 as the groundwater level rose to 0.3 cm from the ground surface, indicating a reduction in shear resistance and an increase in landslide velocity and displacement. The increase and decrease in surface ground displacement by D-InSAR are in sync with groundwater changes during seasonal variation. The comparison between the rate of surface ground displacement measured by D-InSAR and inclinometer shows that the rate of displacement increased in the rainy season

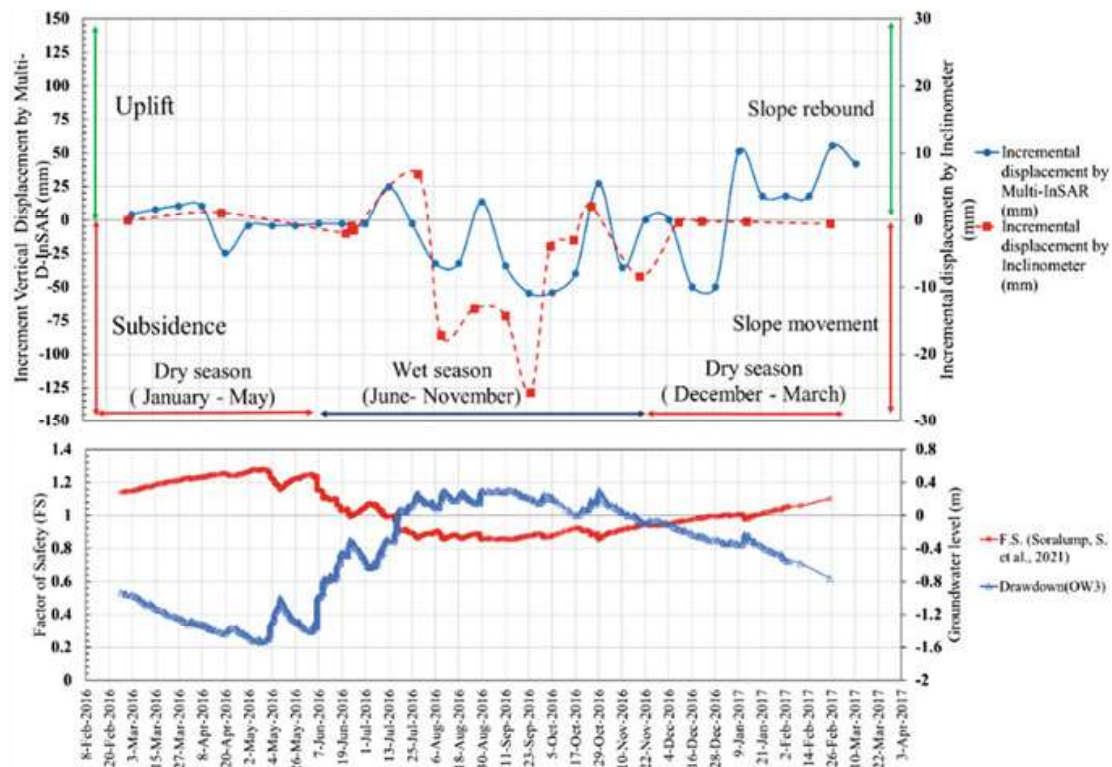


Fig. 6 Relation between D-InSAR and inclinometer increment vertical displacement, FS and groundwater table from January 2016 to March 2017

when FS was less than 1.0 and the groundwater level rose. This behavior indicates a potential for downward movement of the colluvium slope along with the slope gradient. Surface ground displacement was observed to be uplift during the dry season from December 2016 to March 2017, and also from January 2016 to May 2016 when the factor of safety (FS) was above 1.0. This behavior can be attributed to the decreased groundwater levels during the dry season, which increased the shear resistance of the colluvium deposit and decreased the velocity of the landslide movement. As the result, it can be concluded that the surface ground displacement observed by multiple D-InSAR, which was consistent with the obtained data from the inclinometer and GPS stations. This result indicates that D-InSAR could be a reliable tool for monitoring surface ground displacement in colluvium slopes. The movement direction of the surface ground displacement by D-InSAR seemed to align with the GPS stations, suggesting that D-InSAR could also provide valuable information about the direction of the slope movement. Overall, the findings of this study demonstrate the potential of D-InSAR for monitoring colluvium slopes and enhancing an understanding of slope stability and movement. However, it is important to note that the surface displacement measured by D-InSAR could be overestimated due to various human activities such as settlement, farming, etc. These factors affected the proposed method, which increased the displacement magnitude. Therefore, to enhance the accuracy of displacement observation by multiple D-InSAR, more SAR images and orbits in the same area are required.

5 Conclusion

The slope movement in the colluvium deposit of Doi Chang, Thailand, has been extensively studied using multiple D-InSAR with ground-based monitoring techniques. This study discusses the ground displacement behavior observed through multiple D-InSAR, which was affected by seasonal variation. The increment of vertical displacement and displacement map reveals that subsidence or slope downward movement could be observed during the rainy season, while uplift or slope upward movement could be observed during the dry season. The rate of displacement by multiple D-InSAR was found to be responsive to changes in groundwater level, as observed by inclinometer and FS of infinite slope stability. Furthermore, the rate of displacement has been classified as a very slow landslide based on ground-based instrumentation.

The slope movement observed through multiple D-InSAR was found to be westward, similar to the GPS station data. However, displacement data by GPS stations were lost due to a lack of signal connectivity with satellites in the rainy season. Multiple D-InSAR can overcome this issue by penetrating the cloud and orbit during dry and night time, thus allowing for continuous monitoring during seasonal changes. Moreover, the SAR images of Sentinel-1 are freely available SAR images provided by the Copernicus Open Access Hub.

The observation of the causes of the slope movement through D-InSAR and ground-based monitoring techniques has raised awareness and is essential for the community. Though catastrophic slope failure is unexpected, people still suffer from recurrent damage to the structures. Therefore, mitigation plan preparations are essential for preventing human life and property.

Acknowledgements All the authors thank the Geotechnical Research and Development Center (GERD) for supporting the general information and ground-based monitoring data in this research.

References

1. Akbarimehr M, Motagh M, Haghenas-Haghihi M (2013) Slope stability assessment of the Sarcheshmeh landslide, Northeast Iran, investigated using InSAR and GPS observations. *Remote Sens* 5(8):3681–3700. <https://doi.org/10.3390/rs5083681>
2. Choe B-H, Blais-Stevens A, Samsonov S, Dudley J (2021) Sentinel-1 and RADARSAT constellation mission InSAR assessment of slope movements in the Southern interior of British Columbia, Canada. *Remote Sens* 13(19):3999
3. Gabriel AK, Goldstein RM, Zebker HA (1989) Mapping small elevation changes over large areas: differential radar interferometry. *J Geophys Res* 94:9183–9191
4. Raspini F, Bardi F, Bianchini S, Ciampalini A, Del Ventisette C, Farina P, Ferrigno F, Solari L, Casagli N (2017) The contribution of satellite SAR-derived displacement measurements in landslide risk management practices. *Nat Hazard* 86:327–351
5. Schlögel R, Doubre C, Malet J-P, Masson F (2015) Landslide deformation monitoring with ALOS/PALSAR imagery: a D-Insar geomorphological interpretation method. *Geomorphology* 231:314–330

6. Howell SEL, Komarov AS, Dabboor M, Montpetit B, Brady M, Scharien RK, Mahmud MS, Nandan V, Geldsetzer T, Yackel JJ (2018) Comparing L- and C-band synthetic aperture radar estimates of sea ice motion over different ice regimes. *Remote Sens Environ* 204:380–391
7. Zhou W, Chen F, Guo H (2015) Differential radar interferometry for structural and ground deformation monitoring: a new tool for the conservation and sustainability of cultural heritage sites. *Sustainability* 7:1712–1729. <https://doi.org/10.3390/su7021712>
8. Soralump S, Shrestha A, Thowiwat W, Sukjaroen R, Chaithong T, Yangsanphu S, Koirala A, Jotisankasa A (2021) Assessment of landslide behaviour in colluvium deposit at Doi Chang, Thailand. *Sci Rep* 11
9. Jeng C-J, Sue D-Z (2016) Characteristics of ground motion and threshold values for colluvium slope displacement induced by heavy rainfall: a case study in northern Taiwan. *Nat Hazard* 16:1309–1321
10. Cruden D, Varnes D (1996) Landslide types and processes. In: Turner AK, Schuster RL (eds) *Landslides: investigation and mitigation*. Transportation Research Board, pp 36–75
11. Hanssen RF (2001) *Radar interferometry: data interpretation and error analysis*. Kluwer Academic, Springer, Dordrecht, The Netherlands
12. ESA Sentinel Online. Available online: <https://sentinel.esa.int>. Last accessed on 03 Oct 2022
13. Stanford Radar Interferometry Research Group (2022) SNAPHU: statistical-cost, network-flow algorithm for phase unwrapping. Available online: <https://web.stanford.edu/group/radar/softwareandlinks/sw/snaphu>. Last accessed on 03 Oct 2022
14. Dalla Via G, Crosetto M, Crippa B (2012) Resolving vertical and east-west horizontal motion from differential interferometric synthetic aperture radar: the L'Aquila earthquake. *J Geophys Res Solid Earth* 117
15. Tzouvaras M, Danezis C, Hadjimitsis DG (2020) Differential SAR interferometry using Sentinel-1 imagery-limitations in monitoring fast moving landslides: the case study of cyprus. *Geosciences* 10:236. <https://doi.org/10.3390/geosciences10060236>
16. Duncan JM, Wright SG, Brandon TL (2014) *Soil strength and slope stability*. Wiley, New York