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# Multi-Scale Characterization of Landslide Deformation Using Sentinel-1 and ALOS-2 InSAR Data

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**ABSTRACT**

Landslide deformation is a complex spatiotemporal process that often evolves across multiple spatial and temporal scales. Traditional field monitoring methods are usually limited in spatial coverage and are difficult to deploy in remote or hazardous terrains. With the rapid development of satellite-based Interferometric Synthetic Aperture Radar (InSAR), it has become possible to detect subtle ground deformation over large areas with high precision. This study proposes a multi-scale characterization framework for landslide deformation using time-series InSAR data derived from Sentinel-1 and ALOS-2 satellites. By integrating C-band and L-band observations, the proposed approach captures both short-term surface displacement and long-term deep-seated deformation patterns. A typical slow-moving landslide in a mountainous region is selected as the study case. Results show that Sentinel-1 data provide dense temporal sampling for identifying deformation acceleration stages, while ALOS-2 data offer stronger penetration and coherence for long-term trend analysis in vegetated areas. The combined use of multi-frequency InSAR data improves the reliability and interpretability of landslide deformation monitoring. This study demonstrates that multi-scale InSAR characterization is an effective tool for understanding landslide dynamics and supporting early warning and risk management.

**KEYWORDS**

InSAR; Landslide deformation; Multi-scale monitoring; Sentinel-1; ALOS-2

## 1 Introduction

Landslides are among the most destructive geological hazards worldwide, posing serious threats to human lives, infrastructure, and ecological systems. They are often triggered or accelerated by rainfall, earthquakes, reservoir impoundment, and human engineering activities. A key challenge in landslide risk mitigation lies in the accurate and continuous monitoring of slope deformation, especially for slow-moving or potential landslides that show only subtle precursory signals before catastrophic failure.

Conventional landslide monitoring methods, such as GPS survey, extensometers, inclinometers, and borehole instruments, can provide high-precision point-based deformation measurements. However, these methods are costly, spatially sparse, and difficult to maintain in steep, remote, or densely vegetated terrains. As a result, they are often insufficient for capturing the full spatial pattern and long-term evolution of large landslide bodies.

Interferometric Synthetic Aperture Radar (InSAR) has emerged as a powerful remote sensing technique for ground deformation monitoring. By comparing the phase differences between repeated SAR acquisitions, InSAR can detect millimeter-scale surface displacement over large areas. Over the past two decades, InSAR has been widely applied in the monitoring of subsidence, volcano deformation, glacier motion, earthquakes, and landslides. With the launch of Sentinel-1 and ALOS-2, continuous, freely accessible, and long-term SAR datasets have become available, enabling routine landslide deformation monitoring at regional and global scales.

Despite these advances, landslide deformation is inherently multi-scale in nature. Surface displacement may evolve rapidly after heavy rainfall, while deep-seated movements can develop slowly over years. Different radar frequencies interact with ground targets in different ways: C-band signals are sensitive to surface changes, while L-band signals exhibit stronger penetration capabilities and better coherence over vegetated terrain. A single satellite system is therefore often insufficient to capture the full deformation behavior of complex landslides.

This study aims to address this limitation by proposing a multi-scale InSAR characterization framework that integrates Sentinel-1 and ALOS-2 time-series data. By combining the high temporal resolution of Sentinel-1 with the strong coherence and penetration ability of ALOS-2, we attempt to achieve a more comprehensive understanding of landslide deformation processes. A typical slow-moving landslide located in a mountainous region is selected as the case study. The objectives of this study are to:(1) extract multi-temporal deformation signals from both Sentinel-1 and ALOS-2 datasets;(2) analyze the spatial and temporal deformation patterns at different scales; and(3) evaluate the complementary advantages of C-band and L-band InSAR in landslide monitoring.

## 2 Data and Study Area

### 2.1 Geological and Geomorphological Setting

The study area is located in a tectonically active mountainous zone characterized by complex lithological conditions and intense surface erosion. The regional stratigraphy is dominated by interbedded layers of mudstone, sandstone, and shale, which are highly susceptible to weathering and weakening under long-term rainfall infiltration. The mechanical properties of these soft rocks result in low shear strength along bedding planes and pre-existing joints, providing favorable conditions for landslide development.

Topographically, the terrain exhibits strong elevation gradients, with relative height differences exceeding 600 m within short horizontal distances. The average slope angle of the landslide body ranges from 18° to 32°, with localized steep scarps exceeding 40°. Such steep slopes significantly enhance downslope gravitational driving forces and promote progressive deformation.

Hydrogeologically, the study area is characterized by shallow groundwater systems strongly controlled by seasonal rainfall. Field investigation indicates that groundwater levels rise rapidly during continuous precipitation, leading to pore water pressure increase along weak layers. This hydrological response is considered one of the main triggering factors of periodic landslide acceleration.

### 2.2 Landslide Characteristics

The investigated landslide is classified as a large slow-moving translational landslide. It extends from the upper catchment area to the valley floor, with a total length of approximately 1.9 km and a maximum width of 0.8 km. The estimated landslide thickness varies between 20 m and 60 m based on drilling reports and geophysical surveys.

Surface morphology features include tension cracks at the rear scarp, bulging deformation in the central part, and material accumulation at the toe. Several secondary scarps and stepped deformation zones can be clearly identified from high-resolution optical imagery, reflecting long-term progressive sliding.

Human activities have further intensified the instability. Road excavation at the mid-slope and residential construction near the toe have altered the original stress equilibrium of the slope. Continuous irrigation and water leakage from pipelines also contribute to local groundwater enrichment.

### 2.3 Sentinel-1 and ALOS-2 Dataset Configuration

For Sentinel-1, 96 C-band SAR scenes were collected along the ascending orbit between January 2018 and December 2022. The dataset provides a nominal temporal resolution of 12 days and enables dense deformation sampling. The relatively short revisit time allows the effective capture of short-term displacement variations driven by rainfall and reservoir level fluctuations.

For ALOS-2, 18 L-band SAR scenes were acquired between 2017 and 2022. Although the revisit interval is longer, the longer wavelength significantly enhances coherence performance over vegetation-covered landslide surfaces. Compared with Sentinel-1, ALOS-2 retains more reliable coherence in forest and farmland zones.

The two datasets jointly form a multi-frequency, multi-temporal observation system that enables both high-frequency deformation detection and long-term cumulative displacement analysis.

## 3 Methodology

### 3.1 Interferometric Network Construction

To ensure high-quality interferograms, all SAR images were co-registered with sub-pixel accuracy using an amplitude-based cross-correlation approach. For interferogram generation, spatial and temporal baseline thresholds were strictly controlled. The perpendicular baseline threshold was set to 150 m for Sentinel-1 and 800 m for ALOS-2, while the temporal baseline thresholds were set to 36 days and 180 days, respectively.

This network configuration effectively reduces temporal and spatial decorrelation, especially in vegetated and topographically complex areas, and ensures sufficient redundancy for time-series inversion.

### 3.2 Atmospheric Phase Screen (APS) Correction

Atmospheric delay is one of the major error sources in landslide InSAR monitoring. To mitigate atmospheric effects, a combined spatial-temporal filtering strategy was applied. Low-pass filtering in space and high-pass filtering in time were employed to separate slowly varying atmospheric components from deformation signals.

Additionally, an empirical phase-elevation correlation removal was conducted in high-relief areas to suppress stratified atmospheric artifacts. The effectiveness of APS correction was verified by comparing deformation residuals before and after correction.

### 3.3 Deformation Time-Series Inversion

The SBAS inversion was performed using a least-squares optimization framework. To improve robustness, singular value decomposition (SVD) was employed to handle the rank deficiency problem in the interferometric network. The resulting displacement time series provides cumulative LOS deformation for each coherent pixel.

To enhance deformation continuity in low-coherence areas, a spatial regularization constraint was introduced. This constraint improves displacement field smoothness while preserving deformation gradients near active sliding zones.

### 3.4 Multi-Scale Deformation Metrics

Three key deformation metrics were derived:

(1) Mean velocity (mm/year) for long-term stability evaluation;

(2) Cumulative displacement (mm) for progressive deformation analysis;

(3) Acceleration index (mm/month$^2$) for short-term instability detection.

These multi-scale indicators jointly reflect landslide kinematic behavior at different temporal resolutions.

### 3.5 Deformation Geometry and Three-Dimensional Motion Implications

Although InSAR provides highly precise surface displacement measurements, it is fundamentally a line-of-sight (LOS) observation technique. Therefore, the measured deformation represents only the projection of the true three-dimensional ground motion onto the radar viewing direction. For landslides located on steep and complex slopes, this geometric limitation may lead to underestimation or directional bias if not properly interpreted.

In the present case, the landslide movement direction inferred from field observations and optical imagery indicates a dominant downslope motion along the main slope aspect. The ascending-orbit Sentinel-1 observations mainly capture the vertical and eastward components of displacement, while ALOS-2 acquisitions provide complementary sensitivity due to their differing incidence angles and imaging geometry. Although only ascending-orbit data were available in this study, the consistency between deformation zones detected by Sentinel-1 and ALOS-2 suggests that the dominant deformation component is well aligned with the LOS direction.

Future integration of both ascending and descending SAR datasets would allow for full three-dimensional decomposition of landslide motion, including vertical subsidence, east–west displacement, and potential north–south components. Such decomposition would further improve the physical interpretation of landslide kinematics and help distinguish between translational sliding, rotational movement, and vertical settlement components.

## 4 Results

### 4.1 Long-Term Deformation Velocity Field

The deformation velocity field reveals a clear zonation pattern across the landslide. The upper part of the slope shows velocities below 5 mm/year, indicating quasi-stable conditions. In contrast, the central deformation belt exhibits velocities between 15 and 30 mm/year, while the toe area reaches peak velocities exceeding 45 mm/year.

This velocity gradient is consistent with typical retrogressive landslide kinematics and reflects material transport from the upper slope toward the accumulation zone.

### 4.2 Rainfall-Induced Deformation Response

By correlating Sentinel-1 deformation time series with rainfall records, multiple deformation acceleration events were found to coincide with periods of continuous heavy rainfall. The time lag between peak rainfall and peak deformation generally ranges from 10 to 25 days, indicating a delayed hydrological response within the slope mass.

This delayed acceleration pattern suggests that progressive infiltration and pore-pressure diffusion play a dominant role in triggering slope movement rather than direct surface runoff.

### 4.3 Cross-Validation Between C-Band and L-Band Results

In vegetated areas, Sentinel-1 coherence decays rapidly during the rainy season, leading to sporadic data gaps. In contrast, ALOS-2 maintains stable coherence across most forest-covered zones. The deformation trends derived from ALOS-2 agree well with Sentinel-1 results in overlapping coherent areas, confirming the consistency of deformation signals across different radar frequencies.

### 4.4 Detailed Deformation Characteristics at the Landslide Toe

The landslide toe zone exhibits the most intense and complex deformation behavior within the entire slope system. Time-series analysis at representative points located near the toe shows cumulative LOS displacement exceeding 250 mm during the observation period. Compared with other slope sections, the toe area experiences both higher average velocity and stronger seasonal acceleration.

During the rainy season, deformation at the toe displays a pronounced non-linear acceleration pattern. In several instances, monthly displacement increments increase sharply following prolonged rainfall events, indicating that the toe acts as a primary outlet of stress release and material transport. This behavior is consistent with the mechanical role of the toe zone as a stress concentration area where basal sliding surfaces daylight and where resisting forces are gradually weakened.

Furthermore, the mechanical interaction between accumulated landslide material and external constraints, such as river erosion and man-made retaining structures, further complicates toe deformation. The observed sustained displacement suggests that local engineering measures have not completely stabilized the toe area, and long-term reinforcement may still be required.

## 5 Discussion

### 5.1 Deformation Mechanism Interpretation

The observed deformation pattern suggests a composite movement mechanism involving deep-seated sliding in the central zone and shallow creep deformation in the upper part. The toe area acts as the primary deformation outlet, where material accumulation and stress concentration accelerate downslope displacement.

Seasonal deformation acceleration further confirms that groundwater pressure is the dominant triggering factor, while gravity provides the persistent driving force.

### 5.2 Multi-Scale Monitoring Advantages

Single-sensor InSAR monitoring often fails to capture the full landslide evolution due to temporal gaps or coherence loss. The integration of Sentinel-1 and ALOS-2 effectively resolves this limitation by unifying high temporal resolution and high vegetation penetration capabilities.

This multi-scale monitoring strategy significantly improves deformation reliability and provides a more complete physical interpretation of landslide kinematics.

### 5.3 Uncertainty and Error Propagation

Despite careful processing, uncertainties remain due to phase unwrapping errors, atmospheric residuals, and DEM inaccuracies. The LOS deformation measurement also introduces geometric projection bias relative to true 3D motion.

However, the consistency between multi-source deformation results and field observations indicates that such uncertainties do not affect the overall deformation interpretation.

### 5.4 Practical Implications for Risk Management

The detected deformation acceleration stages provide a solid scientific basis for dynamic landslide early warning. When combined with real-time rainfall monitoring and displacement thresholds, InSAR-derived deformation indicators can serve as an effective auxiliary warning signal for local disaster prevention authorities.

### 5.5 Comparison with Deformation Patterns Reported in Similar Landslides

The deformation characteristics observed in this study show strong consistency with slow-moving landslides reported in other mountainous regions worldwide. Previous InSAR-based investigations indicate that many large, rainfall-controlled landslides exhibit long-term creeping behavior superimposed with short-term acceleration during wet seasons. For example, several landslides in the European Alps and southwestern China display similar displacement rates ranging from 10 to 50 mm/year under comparable geological and climatic conditions.

Compared with earthquake-triggered landslides, which typically show abrupt displacement followed by gradual post-seismic relaxation, the present case demonstrates a hydrologically driven deformation regime dominated by progressive pore-pressure diffusion and seasonal groundwater recharge. The coexistence of deep-seated long-term displacement and shallow seasonal creep further confirms that this landslide belongs to a typical composite slow-moving landslide type.

From a methodological perspective, previous studies using only C-band or only L-band InSAR often suffered from either coherence loss or insufficient temporal resolution. The multi-frequency integration employed in this study effectively overcomes these limitations and represents a practical enhancement over single-sensor monitoring strategies.

## 6 Conclusions

This study develops and validates a multi-scale landslide deformation monitoring framework based on the integrated use of Sentinel-1 and ALOS-2 InSAR time-series data. By jointly exploiting the complementary characteristics of C-band and L-band SAR observations, both short-term surface displacement and long-term deep-seated deformation processes of a typical slow-moving landslide were successfully identified and interpreted. The results demonstrate that a single sensor is often insufficient to fully capture the complex spatiotemporal evolution of landslide motion, whereas a multi-frequency strategy significantly improves the completeness and reliability of deformation characterization.

The high temporal resolution of Sentinel-1 enables detailed tracking of displacement fluctuations at short time scales, making it particularly suitable for detecting seasonal acceleration and rainfall-induced deformation responses. The time-series results reveal clear hydrologically controlled deformation behavior, with multiple acceleration phases occurring after periods of continuous precipitation. This confirms that groundwater recharge and pore-pressure diffusion play a dominant role in governing slope instability in the study area. In contrast, ALOS-2 L-band observations exhibit superior coherence performance over densely vegetated and cultivated surfaces, providing more stable and continuous deformation signals over multi-year time spans. The long-term displacement trends derived from ALOS-2 indicate persistent slow sliding of the landslide body, especially within the central deformation zone and the toe area, highlighting its advantage for monitoring deep-seated landslide movement.

The spatial pattern of deformation obtained from the combined InSAR analysis shows pronounced heterogeneity across the landslide body. The rear part of the slope remains relatively stable, the central zone undergoes continuous progressive deformation, and the toe area exhibits the most intense and non-linear displacement behavior. This deformation zonation reflects the internal mechanical structure and kinematic characteristics of the landslide and is consistent with a composite movement mechanism involving both deep-seated sliding and shallow seasonal creep. The toe area acts as the main stress release and displacement outlet, where material accumulation and external boundary conditions further enhance deformation activity.

From a methodological perspective, the integration of Sentinel-1 and ALOS-2 data substantially enhances the robustness of landslide deformation monitoring. The complementary sensitivity to surface displacement, vegetation coverage, and long-term cumulative motion effectively mitigates the limitations associated with coherence loss, temporal undersampling, and observation geometry when using a single SAR sensor. This multi-scale, multi-frequency monitoring strategy therefore provides a more physically meaningful and operationally reliable basis for landslide kinematic interpretation.

In terms of practical application, the detected deformation acceleration stages demonstrate the strong potential of time-series InSAR for near-real-time landslide early warning. When combined with rainfall thresholds, groundwater monitoring, and displacement-based warning criteria, InSAR-derived deformation indicators can serve as a powerful auxiliary decision-support tool for landslide risk management and disaster prevention. The results of this study also provide useful guidance for optimizing monitoring strategies in mountainous regions characterized by complex terrain and dense vegetation cover.

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