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Satellite InSAR for Vegetated Landslide Analysis: Highway 4, Slovenia

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Abstract

Slovenia is characterized by complex geology and high landslide susceptibility, with a particular concentration in the Vipava Valley, an area situated near the border between Italy and Slovenia. This region is defined by a geologic fold-and-thrust structure, where Mesozoic carbonates are thrust over weaker Eocene flysch. Resulting in steep, fractured cliffs and vast quaternary superficial deposits, which are highly prone to deep-seated rotational slides and rapid debris flows. The presence of groundwater at the carbonate-flysch contact further destabilizes the terrain, posing a constant threat to the national motorway (Highway H4) crossing the Rebrnice slope.

This paper explores the application of InSAR satellite monitoring, specifically using ALOS-2 constellation data, to understand the dynamics of existing landslides in the Rebrnice area, which is crossed by a major national motorway.

Satellite radar interferometry (InSAR) is a space-based remote sensing technology capable of mapping ground and structural motions over small and wide areas with millimetres precision. Given its ability to monitor wide areas, it also helps assess the stability of slopes around linear infrastructures. InSAR products provide dense arrays of measurement points (thousands per km²) from reflections of pre-existing ground features (e.g. rocks and manmade structures). Furthermore, this technique does not rely on any ground-based instrumentation, offering significant cost savings and health/safety benefits by eliminating the need for site visits.

This paper will discuss InSAR's advantages in detecting millimetric movements over large, inaccessible areas, observed deformation velocities and active area identification. Integrating satellite data with in-situ observations and measurements is essential for comprehensive assessment and proactive landslide risk management.

Keywords

InSAR, ALOS-2, Highway, Landslide, Slovenia.

1 Introduction

Managing landslide risk is a global priority, especially in geologically complex and densely inhabited areas. Slovenia serves as a prime example; its position at the intersection of the Alps, the Pannonian Plain, and the Mediterranean makes it exceptionally susceptible to slope instability. Its complex geological and tectonic structure, combined with extreme weather events, contributes to the high incidence of landslides, with over 10,000 events recorded in the last 25 years (Jemec Auflič et al 2017). These phenomena have caused significant damage to infrastructure, buildings, agricultural land, and in some cases, have resulted in loss of human lives.

Landslide monitoring is a fundamental step to mitigate these risks; however, mountainous or densely vegetated areas present considerable logistical and economic challenges for traditional monitoring methods. In this context, satellite remote sensing techniques, such as InSAR, are promoted as powerful solutions for large-scale mapping and monitoring of ground deformations.

This paper focuses on the application of InSAR technology in the Vipava Valley, particularly in the Rebrnice area, a site of great interest due to its vulnerability and the presence of critical infrastructure. The objective is to analyse how L-Band InSAR can contribute to the monitoring of existing landslides in areas characterized by vegetation and difficult access, discussing the results obtained and the specific challenges encountered.

2 The Vipava Valley and Rebrnice Area

The Vipava Valley in southwestern Slovenia is a geologically complex corridor of strategic importance, linking Slovenia to Central Europe. It's instability is driven by a distinct asymmetric slope morphology created by the overthrusting of Mesozoic carbonates over younger, weaker Eocene flysch (sandstone and marlstone) (Jemec Auflič 2017; Auflic et al., 2017).

These geologic conditions can be further explained in the following three unique conditions:

- Upper Slopes: Steep, highly fractured carbonate cliffs that serve as a constant source of rockfalls and debris (Debevec et al., 2025).
- Lower Slopes: Gentler gradients composed of flysch bedrock, covered by vast Quaternary superficial deposits. In the Rebrnice area, these fossil landslide deposits reach thicknesses of up to 50 meters (Auflic et al., 2017).
- Hydrogeology: The porous carbonates allow rapid rainwater infiltration, which then discharges as groundwater at the boundary with the impermeable flysch. This process saturates the contact zones and weaker clay layers, triggering both shallow flows and deep-seated movements (Debevec et al., 2025).

A critical national motorway crosses the Rebrnice slope, built directly upon unstable carbonate debris and flysch. Despite extensive engineering support structures, the terrain remains highly active due to:

1. High Slope Inclination: Natural steepness exacerbated by tectonic fracturing.
2. Diverse Failure Modes: Phenomena range from large-scale, deep-seated rotational and translational slides to shallow landslides, slumps, and sedimentary gravity flows in the form of debris or mudflows reworking the carbonate scree and flysch material (Auflicet al., 2017; Jemec Auflič et al., 2017).
3. Active Displacement: Some sections exhibit reactivation and movements of several tens of centimeters per year, particularly following intense rainfall or historical seismic events (Debevec et al., 2025).

Below is one of the existing landslide inventory maps over the Highway 4, showing the geologic conditions along the corridor.

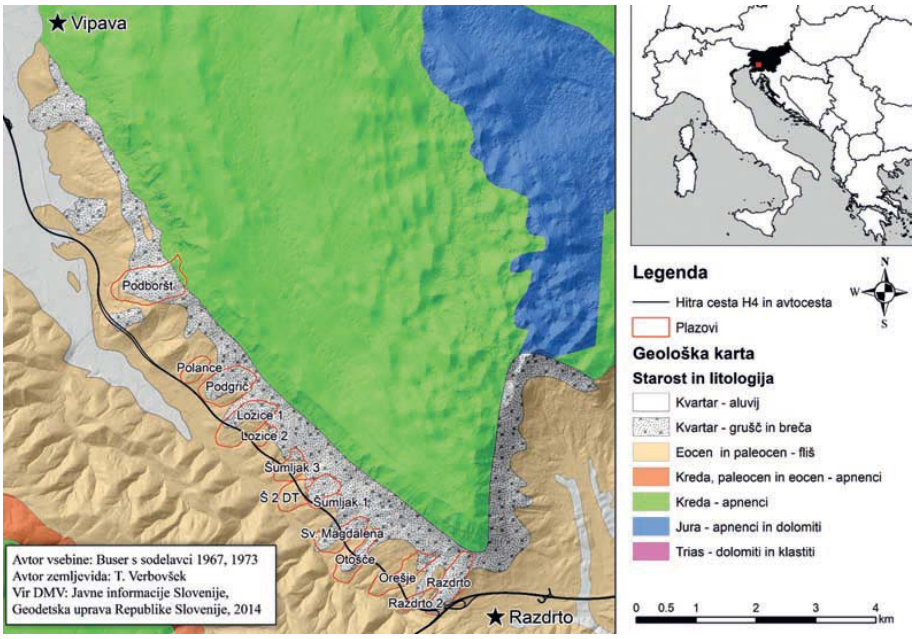


Fig. 1 Landslide activity map of Rebrnice, Verbovšek et al (2024).

3 The Challenges of monitoring in vegetated areas with InSAR

InSAR is a remote sensing technique capable of detecting ground displacement with millimetric precision, making it highly effective for different kinds of applications due to its regular data acquisition intervals and extensive coverage compared to ground-based methods.

SqueeSAR®, a patent of TRE Altamira, is an advanced multi-temporal InSAR technique developed to improve ground deformation monitoring by analysing both persistent scatterers (PS) and distributed scatterers (DS) in radar images (Chipola et al., 2025). Unlike traditional PS-InSAR, which relies only on stable, highly reflective targets such as buildings and exposed rock, SqueeSAR® extends the analysis to less coherent surfaces, including soil, vegetation, and man-made structures with lower radar reflectivity. By combining information from both PS and DS, SqueeSAR® significantly increases the density of measurement points, enhancing its ability to detect and monitor ground displacement in areas with sparse infrastructure or complex terrain.

Monitoring landslides in steep, vegetated, or remote terrain is notoriously difficult. Traditional in-situ sensors (e.g., inclinometers) are often too costly, logistically "onerous," and risky to install across vast networks like motorways. Furthermore, surface-level visual surveys often fail to detect the deep-seated, slow-moving instabilities that precede major failures.

Interferometric Synthetic Aperture Radar (InSAR) addresses traditional monitoring gaps by providing millimetres-scale deformation data without the requirement for ground-based hardware. This technology offers a distinct strategic advantage through its large-scale efficiency, providing continuous coverage over thousands of kilometres of infrastructure in a way that far outpaces traditional sensors. Furthermore, InSAR enables comprehensive historical analysis; by accessing satellite archives dating back as far as 2007 for L-band data, engineers can reconstruct deformation histories and identify long-term instability trends that might otherwise go unnoticed. This capability facilitates proactive risk management, as the early detection of "creep" or subsidence allows operators to target mitigation efforts precisely, ultimately reducing emergency maintenance costs and improving overall safety.

While InSAR quality can vary based on atmospheric noise and resolution, L-band satellites, characterized by a wavelength of approximately 23 cm, are uniquely suited for landslide contexts. Their primary strength lies in vegetation penetration; unlike X or C-bands, the L-band signal can pass through dense canopies to reach the ground, which is essential for monitoring forested mountainous regions. Additionally, the L-band maintains superior signal coherence on the heterogeneous surfaces typical of agricultural fields or active landslide slopes. Finally, the technology is specifically

optimized for displacement sensitivity, making it ideal for tracking the slow, large-scale movements that characterize geological settlements and creeping landslides.

InSAR datasets are variable in their quality due to many factors such as atmospheric noise, humidity, vegetation, wavelength, image resolution, number of images in the dataset. It's important to underline that all of these factors affect InSAR datasets and should be considered when comparing the statistics between two SAR datasets.

Previous analyses over the Rebrnice area have been conducted using the Sentinel-1 constellation (C band) between 2017 and 2023 (Jordanova, 2025 and Auflič et al., 2024).

Small Baseline Subset (SBAS) InSAR analysis using Sentinel-1 satellite images from 2017 to 2022 was conducted by Jordanova et. al (2025). The SBAS results didn't fully align with all the ground-based measurements (inclinometers), due to factors like vegetation and low coherence. Concurrently, the secondary study that was conducted over the active Rebrnice area was Persistent Scatterer InSAR (PS-InSAR) using Sentinel-1 data (from 2017 to 2023) by Auflič (2024), showed a high correlation with field observations and inclinometer data, allowing researchers to categorize the region into seven distinct zones of landslide activity.

It is crucial to highlight the limitations of the C band (used by Sentinel-1) in densely vegetated areas. C-band radar images have proven to be less reliable for monitoring landslides in areas primarily covered by vegetation due to low signal coherence and incompatibility with the C-Band wavelength. This can lead to incomplete results in vegetated areas, but a greater number of denser measurement points on roads, motorways, settlements and bare areas.

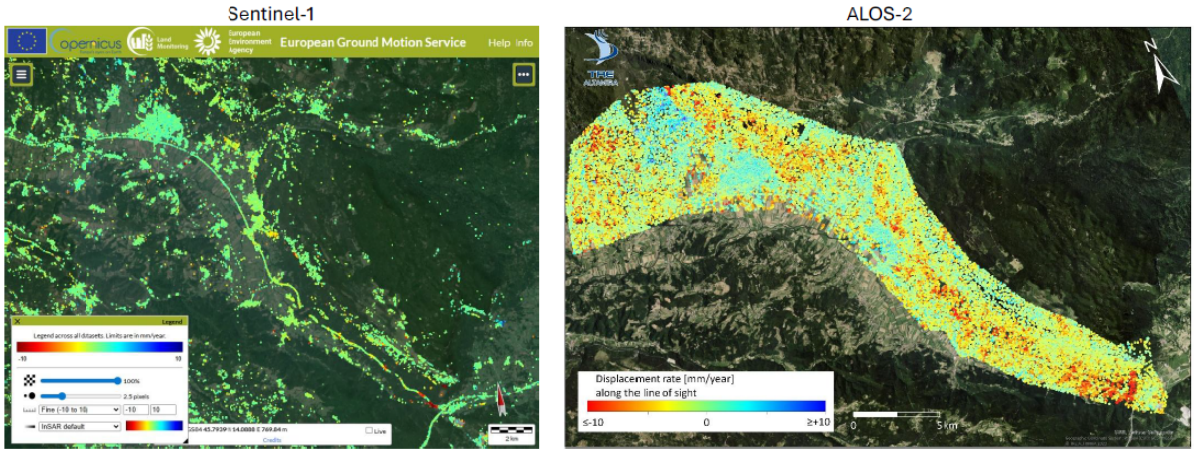


Fig. 2 Comparison between publicly available Sentinel-1 results (European Ground Motion Survey) on the left and ALOS-2 results (on the right) from TRE Altamira analysis over the Highway 4 area.

4 L-Band InSAR results over Vipava Valley

To optimise these analyses and obtain a more complete overview of the extent, size and movements of the landslides, TRE Altamira carried out an L-band analysis in 2024 using the commercial ALOS-2 satellite in Fine mode (9 x 5 metres) in single descending geometry. The properties of the SAR satellite used in this project are indicated inTable 1.

Table 1SAR image properties used in the monitoring over the Highway 4 area.

Satellite	Orbit	LOS Angle [°]	Wavelength	Time Frame	Cell Resolution
ALOS-2	Descending	36.3	~23.6 cm	15/04/2015 to 29/05/2024	9 x 5 m

The analysis was carried out from April 2015 until the last data available in May 2024, with a total of about 20 acquisitions. In addition to covering the Rebrnice area, an analysis was also carried out that included part of the Vipava valley around the motorway alignment, covering an area of approximately 104 km2.More than 60,000 measurement points were obtained on the ground in vegetated and non-vegetated areas. This result is more than four times the data produced by C-Band satellites in the same area.In general, the coverage from the ALOS-2 dataset provided more information over the vegetated

areas. Some of the data points that were identified with ALOS-2 highlighted areas of movement that were not identified in the previous analysis. The general overview of the ALOS-2 data over the area of Rebrnice landslides showed relatively consistent dimensions as those previously mapped. In Fig. 3 the labes correspond to the following landslide areas: 1 - Razdrto Landslide, 2 - Orešje Landslide, 3 - Sv. Magdalena Landslide and 4 - Šumljak Landslide.

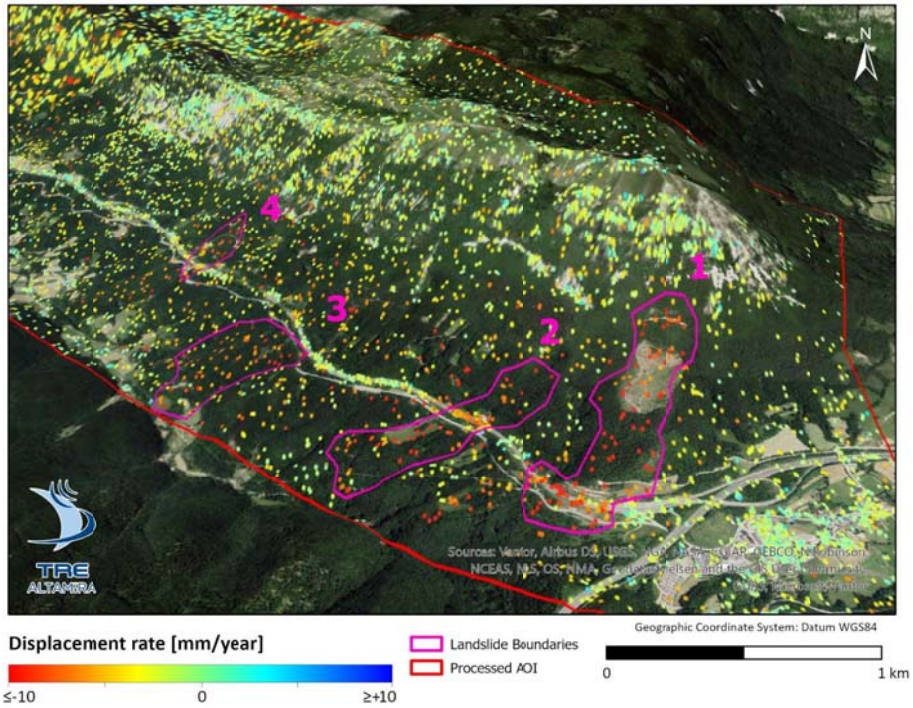


Fig. 3 ALOS-2 results over the southern portion of the processed area showing landslides in the Rebrnice area highlighting active areas as defined by Verbovšek et al (2024).

Fig. 4 below is a close up over the Podboršt landslide area of the highway showing the ALOS-2 data coverage. The point coverage with ALOS-2 defines a larger area that is affected by ground displacement in the area ofPodboršt landslide. The ALOS-2 data also shows displacements observed closer to the Highway 4 than previously described by the C-Band analysis in this area (Jemec Auflič et al., 2024 and Jordanova et al., 2025).

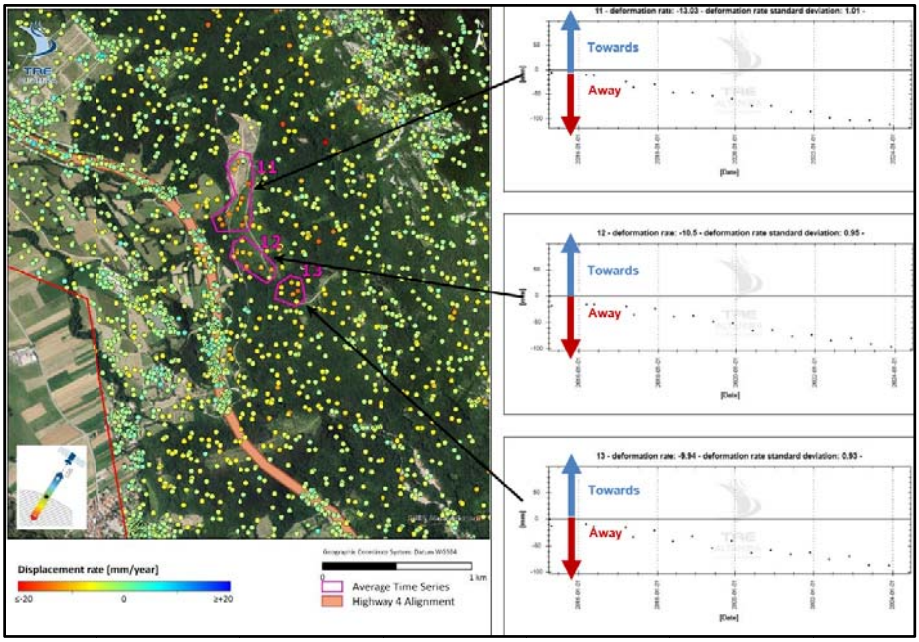


Fig. 4 Identified displacement areas northwest of the Podburšt landslide area, these show displacement rates between -9 and -13 mm/year.

In general, the ALOS-2 data identified twelve areas of potential hazard zones in the vicinity of Highway 4 in the processed area of interest. These areas had velocities with a magnitude greater than

10 mm/year and were observed in clusters of at least 5 points. These thresholds are different for every site and determined based on the typical displacements and velocities observed throughout the site.

5 Conclusions

The analysis identified several unknown hazard areas along the highway alignment, demonstrating that InSAR is a vital complementary tool to conventional methods for monitoring landslides in topographically challenging or inaccessible areas. In regions like Slovenia's Vipava Valley, where high landslide susceptibility threatens critical infrastructure, InSAR offers the unique capability to detect millimeter-scale deformations over vast areas.

The L-Band InSAR data refines previous displacement data for known landslides while validating historical trends. Furthermore, this study identifies several previously undocumented displacements and emerging active areas. Our analysis showed three additional active areas north of the Podburst landslide (1-3 kms northward) that were not previously identified with the previously defined landslide extents. We also identified an additional 4 active areas further upslope (2-5 kms from the highway) in the northern portion of H4.

By utilizing L-band data, this study successfully bypassed the limitations of other satellite bands in dense vegetation, ensuring high coherence and a detailed overview of active movements even in vegetated areas. These displacement results, provide essential data for identifying new instabilities and understanding the true dimensions of active landslides.

To ensure long-term resilience, a multidisciplinary approach is necessary, integrating satellite remote sensing with in-situ monitoring tools like GNSS and inclinometers. This synthesis of data allows for a complete understanding of landslide dynamics, supporting informed decision-making for risk mitigation. Based on this baseline, the owner of the asset can either establish a continuous InSAR monitoring program to track future trends or use the current instability map to strategically install ground-based topographic instrumentation in critical hotspots. Looking forward, the evolution of InSAR technology driven by the SAOCOM mission and the upcoming dual-band NISAR mission, will provide unprecedented revisit times and global coverage, significantly enhancing the ability to predict and manage geohazards across large-scale infrastructure networks.

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