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Proving compliance of satellite InSAR technology with geotechnical design codes

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ABSTRACT

In the planning stage of new infrastructure or when designing renovation of existing infrastructure, information about existing slope movements or settlements is essential to make informed design decisions. Interferometric Synthetic Aperture Radar (InSAR) techniques can be of value to identify these risks in an early stage of a project. InSAR can offer insight into the surface movements of an area from historic archives using satellite-based SAR data. Furthermore, InSAR observations can help identify zones with displacements larger than the average of an area, and be used to plan future soil investigation more effectively. Thanks to their high temporal and spatial resolution, InSAR observations can also complement in situ conventional monitoring during the construction and operational stage. Despite these possibilities, the use of InSAR is not yet standard practice in geotechnical projects and no formal guidelines are currently available to inform engineers, planners and infrastructure stakeholder on the use of InSAR-based monitoring within geotechnical design codes. Here we provide an operational framework for the practical integration of InSAR monitoring into current geotechnical design codes, such as Eurocode-7, for all project stages. The proposed framework is then demonstrated for the planning stage of a highway renovation project, focusing on an area potentially subjected to landslides where no conventional monitoring data was available at this stage. We concluded that the proposed framework is a practical and operational tool that can be used by planners and engineers in the whole lifecycle of an infrastructure project.

1. Introduction

Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technique that can monitor displacements of large areas of the earth surface with a high temporal and spatial resolution. As this data is available over the last decades, it can reveal past displacements. Many studies have demonstrated that InSAR application to geological and geotechnical projects can effectively complement in situ field investigation at all project stages, improving geological models and supporting georisk assessment. However, so far the potential of InSAR was hindered by the lack of systematic and generally accepted embedment into established geotechnical procedures. These procedures are detailed in geotechnical design codes such as the Eurocode-7 [30] in Europe, the SIA267 Geotechnik code in Switzerland [66] and the Geotechnical Site Characterization Publication No. FHWA NHI-16–072 of the Department of Transportation in the US [75].

To fill this gap, we developed an operational framework to combine InSAR with current geotechnical design codes, such as the Eurocode-7, in all stages of a project. In this paper we demonstrate the benefits of InSAR to obtain a better ground model and identify relevant geohazards.

Section 2 offers an overview of the current practice for assessing geohazards. Section 3 presents the proposed operational framework for the integration of InSAR monitoring within Geotechnical Design Codes, such as Eurocode-7, for the assessment of new or existing linear infrastructures. In Section 4 the framework is applied to an infrastructure retrofitting project.

2. Engineering practice

This section presents an overview of the current practice for the assessment of geohazards for infrastructure projects, the potential of exploting InSAR-based observations for such projects, and the use of

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InSAR within current geotechnical design codes.

2.1. Geohazard assessment

When planning new infrastructure or designing retrofitting measures for existing roads and railways, geotechnical engineers need information about potential geohazards such as settlements, slope instabilities, slow-moving slopes, landslides, earthquakes, or other geological processes that may lead to damage. The estimation of these potential hazards is based on knowledge of geological and hydrogeological conditions, and surface deformation rate [87]. However, at the initial project stage, geological and hydrogeological information is often lacking, and deformation data is almost never available. Surveying campaigns and field investigations are therefore initiated at this stage. The results of these measurements only become available months or years later, forcing engineers to work with insufficient temporal and spatial coverage of the area. This situation often results in unnecessarily conservative design choices.

In the current practice, the most common methods of investigation to obtain information about ground and ground water conditions, soil properties, and past use of the area are in situ intrusive field tests, geophysical tests, sampling, mapping, monitoring and remote sensing techniques. The geotechnical Design Codes, e.g. Eurocode-7, elaborate in detail the principles and requirements for such ground investigations, field and laboratory test, derivation of geotechnical ground properties and preparation of the ground model [30]. However, intrusive soil investigation such as boreholes, inclinometers, extensometers, piezometers, tilt-meters and crack measuring pins, only contains local point data. This is also true for conventional geodetic methods, such as total stations, theodolites, and photogrammetric cameras [53,11]. Frequent measuring is time consuming, labour intensive and challenging for areas with difficult access [46].

2.2. InSAR monitoring for geohazard assessment

Synthetic Aperture Radar (SAR) interferometry is a technique that can measure displacements of the ground surface or objects on it [40]. Spaceborne SAR consists of an imaging radar mounted on a satellite. Pulses of electromagnetic waves are sent to the earth and the satellite captures the complex backscattered signal. By combining two successive observations of the same resolution cell on the ground, it is possible to compute the phase difference between the two observations, and by doing this for multiple observations at different times for a selected area, an interferometric time series can be created.

As the wavelength of the radar is known, from the phase difference between successive observations it is possible to estimate the difference in distance between the two observations, for those resolution cells where the scattering mechanism remains unchanged. By doing this for successive SAR acquisitions over the same area, a time series of displacement estimates is obtained. Such a stack of acquisitions contains a multitude of points on the earth's surface, yielding a spatial distribution of estimated displacements over the entire area. Thus, InSAR is sensitive to slow movements with a precision in the order of a few millimeters.

As SAR satellites exist since 1992, archive data can be used to identify deformations prior to construction, and this information can be used as a baseline when planning new structures [64,67,8]. Additionally, InSAR was applied to monitor buildings [78,43,36,15], bridges [85,24,26,33,45,56,62,69,72], dams [55,72,41], levees [13,60], railways [74,45,79,63,61,18,17,16], pipelines [3], airport runways [34] and roads [6,86].

Also, InSAR proved to be capable to measure ground displacements in areas affected by slow-moving landslides [77]. With this information, inventory maps and landslide hazard assessments were produced [44,2,20,14,10,5,19,42,81,4,32,11,27,22,46,82,84]. InSAR information was used to identify critical sections in roads, affected by slow moving landslides [57,47]. Finally, historic settlements of the past decades in deltaic areas were measured with InSAR [83], and InSAR-based observations of consolidation settlements proved to match well with the results from geotechnical boreholes [88].

2.3. Geotechnical design codes

Within the mandatory European standards for structural design, the Eurocode-7 (EC7) contains general rules and calculation methods for the design of geotechnical structures. The EC7 provides principles and requirements for (i) planning the ground investigations, (ii) definition of field and laboratory tests, (iii) interpretation of test results, (iv) derivation of geotechnical ground properties and (v) preparation of the ground model and (vi) reporting of ground investigations in a Ground Investigation Report. The code also specifies the different stages of ground investigation [30]. Table B.1 of Eurocode 7 provides a guide for choosing the appropriate methods of ground investigation for the required ground information such as ground and ground water conditions, and soil properties (non exhaustive list).

In Eurocode-7 table B.1 and in other Eurocode-7 sections, the use of remote sensing for investigations is mentioned but not elaborated. As remote sensing covers a wide ranges of techniques such as optical or acoustic measurements, laser, InSAR and other measurement methods that do not require any physical contact with the object, the term remote sensing needs to be differentiated. Also the Eurocode-7 does not include any guidelines on how to use InSAR techniques in geotechnical projects but InSAR is already adopted by users of Eurocode-7.

Therefore, we expanded the Eurocode-7 table B.1 for InSAR. In Table 1, we show that InSAR can be applied for the acquisition of many information, with high potential for geotechnical projects.

3. Framework for InSAR deployment

This section presents the proposed operational framework for the integration of InSAR monitoring within Geotechnical Design Codes, such as the Eurocode-7.

3.1. Soil investigation stages

Soil investigation is used to build a ground model of the project site. This model includes the description of the site geomorphology, lithology, geotechnical and hydro(geo) logical conditions, and geotechnical properties. It also includes the variability and uncertainty of these conditions. Site investigations are the first major field expenses of an engineering project, prior to any contruction. To reduce these costs, the investigation is typically performed in stages [31].

Often, only a few widely spaced boreholes are drilled to get a general overview of the geological situation, and as the project progresses, more boreholes are drilled in a denser grid. Each different phase of soil investigation has its specific purpose and is characterized by a different level of detail. More information in an early stage results in reducing project uncertainties and risks [80] and leads to a better understanding and planning of the upcoming required site investigation.

According to Eurocode-7, Part 2 [30], the required investigation phases are desk study and site reconnaissance (1a), in situ testing for

Table 1
Activities with InSAR applicability. Adaptation of table B.1. of Eurocode-7.

Desk Study history and, past uses of site
Site Inspection - ground features and geomorphology
Disposition and nature of geotechnical units
Groundwater conditions
Geotechnical monitoring
Stiffness properties
Cyclic response and seismic properties
Presence of voids (natural or man-made)

preliminary design (1b), in situ testing for detail design and execution (1c), and monitoring during construction (2). Staged site investigation is common practice in engineering projects in a number of countries all over the world. During the projects, the ground model is progressively developed and updated with new information from the consecutive site investigation stages.

The *desk study* includes the collection of all available (existing) information on the site, such as geographical and topographical maps, drawings, previous soil investigation, geological and hydrogeological information, existing structures, and details of utilities. Archive aerial photographs and satellite imagery can be used to reveal the earlier use and state of the site. Additionally, specialists can do a site reconnaissance to verify or amplify the findings from the archive research. During this site reconnaissance, information is collected on topography, areas with slope instabilities, zones with loose or wet soil, water bodies, vegetation, presence of structures or waste disposal sites. Based on the desk study a first ground model can be developed and potential geological hazards can be identified, as requested by the European

Ground information needed (EN 1997-2 clauses			Desk Study - history and, past uses of site	Site Inspection – ground features and geomorphology	Disposition and nature of geotechnical units	Groundwater conditions	Geohydraulic properties	Conformity checks	Geotechnical monitoring	Description and classification of ground	Physical properties	Chemical properties	Strength properties	Stiffness properties	Cyclic response and seismic properties	Groundwater and geohydraulic properties	Geothermal properties	Presence of voids (natural or man-made)	Properties of material for reuse	Contaminated ground	Aggressive ground
Proposed structures and engineering works	Structures (EN 1997-3)	Excavations, cuttings	C	C	H	H	H	M	H	H	H	L	H	M	M	H	L	M	M	L	L
		Embankments	C	C	H	H	M	H	H	H	H	L	H	H	M	H	L	M	M	M	L
		Spread foundations	C	C	H	H	H	H	M	H	H	M	H	H	M	H	L	H	L	H	H
		Piled foundations	C	C	H	H	H	M	M	H	H	H	H	H	M	H	M	H	L	H	H
		Retaining structures	C	C	H	H	H	H	H	H	H	M	H	H	M	H	L	M	H	M	M
		Anchors	C		H	H	M	H	M	H	H	H	H	H	M	H	L	M	L	M	H
		Reinforced fill and soil structures	C	C	H	H	H	H	M	M	H	M	H	H	M	H	L	M	M	M	H
		Ground improvement	C	C	H	H	M	M	M	M	H	M	H	M	M	M	L	L	L	M	H
	Miscellaneous works	Linear - roads	C	C	H	H	M	M	M	H	H	M	H	H	M	H	L	H	H	H	H
		Linear - pipelines	C	C	H	H	H	M	M	H	H	H	H	H	M	H	L	M	H	H	H
		Dams and weirs	C	C	H	H	H	H	H	H	H	H	H	H	H	H	L	H	H	L	M
		Construction materials	C	C	H	H	L	M	M	H	H	H	H	H	L	H	L	L	H	H	H
		Ground source heat installations	C	C	H	H	H	M	L	H	H	H	L	L	L	H	H	L	L	M	H
			C = Compulsory for all GCs, H = High relevance, M = Medium relevance, L = Low relevance																		
Appropriate methods of investigation (Clause 6.1(4))		**Mapping and remote sensing**	H	H	M	H	L			M						L		H		M	M
		Probing		M	H	M	L	L	L	H	L	M	H	H	M	M	L	H	L	M	L
		Boreholes		L	H	H	H	M	M	H	H	M	M	M	L	H	M	M	M	H	M
		Test pits		M	H	H	M	L	L	H	H	M	M	L	L	H	L	L	H	H	H
		Geophysical tests		H	H	M	L	M	L	M	H	L	H	H	H	M	M	H	L	L	L
		Field Testing		M	H	H	H	H	H	M	H	H	H	H	H	H	H	L	M	L	M
		Sampling and laboratory testing		M	H		H	H	H	H	H	H	H	H	H	H	H		H	H	H
		Description and classification of ground	H	H	H			H	H	H	H	M	H	M	M	M	M	H	M	H	H
		Groundwater conditions	H	H		H	H	H	H			M			M	H	H	M		H	H
		Geohydraulic testing				H	H	H	H						M	H	H	H		H	H
		Geothermal testing															H				
		Monitoring						H	H								H	M		M	
		Large scale tests of prototypes									H		H	H	M	M			H		
		Back analysis of structures				H					H		H	H	H	M			M		
		Back analysis of slopes				H					H		H	H		H			M		
			H = High applicability, M = Medium applicability, L = Low applicability, (blank) = not applicable																		

Fig. 1. Table B.1 from Eurocode 7. The row ‘Mapping and remote sensing’ shows the applicability of remote sensing techniques for the required information.

Committee for Standardization [30].

A *physical site investigation* follows the desk study. First, a preliminary investigation is performed. This consists of subsurface intrusive soil investigations, such as trial pits, headings, boreholes, sounding and other subsurface testing methods, and groundwater measurements over a signification period of time. Next, a more detailed design investigation is performed.

Often the investigation for the *preliminary design* and *detail design* are carried out in one single site visit. In general, during the detailed ground investigation only specific locations with higher geotechnical risks, identified in the previous phases, are investigated in detail through laboratory and in situ field tests.

In the *construction phase*, additional soil investigation is used to verify the ground model in critical locations. Setting up a monitoring system and monitoring during the works is crucial in this phase. This enables to verify the design assumptions, assess the effects of the works on existing structures, ensure safe construction and safe working conditions and measure changes during construction. Usually ground movements, structural movements, water pressures and vibrations are monitored.

Finally, in the *operation phase*, monitoring and asset management is performed.

3.2. Framework per phase

In literature, a limited number of examples is available where satellite InSAR results are combined with soil investigation, monitoring, and recorded damages of existing infrastructure [84,47,61,29,21,7].

However, to the authors' knowledge, there is no systematic framework to assess where and how InSAR can be systematically and routinely used in all project phase, or how it can be combined with a soil investigation program to develop a geological model and assess the geological hazards. Table B.1 of Eurocode 7 (Fig. 1) does not distinguish between different type of remote sensing techniques and their use in different project stages. Fig. 2 presents an overview of the potential application of InSAR during all five generic project phases, as proposed in this paper. In 3.2.1,3.2.2 and 3.2.3 the value of InSAR combined with the soil investigation per phase is elaborated.

3.2.1. Pre-construction stage

The key challenges in the pre-construction stage are (1) a conservative design, (2) unknown georisks, (3) overly long planning, (4) incorrect planning decisions, and (5) cost overrun. These challenges depend on (a) uncertainty in ground conditions, (b) uncertainty in time-dependent hydrogeological behavior, and (c) late availability of site investigation [29]. Early identification of georisks, reliable geological information, and a good ground model are therefore crucial to avoid unforeseen situations in later project phases. If at the start of a project the geological structure of the site is misinterpreted, any subsequent sampling, testing, and calculation may be in vain [37].

In the *desk study*, InSAR can be used complementary to conventional data to set up a first ground model. The archived SAR data, typically available for the past 25 years, can help to detect zones with spatial and temporal ground movements in a wide area, and the degree of displacement variability, also outside the spatial project boundaries. This complies with current Geotechnical Design Codes [30] that state that monitoring before execution is required to establish reference conditions. InSAR results can be integrated and compared to the other available historic data, and by combining information from the different sources a ground model and risk overview are set up. Fig. 3 shows a scheme for implementing InSAR information in the desk study.

Examples of the application of InSAR at stage 1 include the correlation of point data from the soil investigation with the InSAR displacement estimates. Here, InSAR results contribute to an improved ground model of the whole area. This approach can be applied to piezometer data. Given several piezometers, a contour map of groundwater head decline can be made, and InSAR data used to estimate the subsidence and verify or extend the contour map [4,35]. Similarly, by performing settlement back analyses based on InSAR results and the available soil investigation, a settlement model can be obtained [83]. This results in a better prediction of future settlements. As a last example, changes in deformation can be detected in seismic areas and gradual land subsidence in karst areas can show the presence of voids in the subsoil [59,48]. All this information can be integrated in the baseline assessment of a the project.

In the *preliminary* and in the *design soil investigation* stage, archived SAR data can be used to better define the locations and scope of the intrusive and geophysical soil investigation in the subsequent stage. In this way the site investigation can be targeted more effectively and zones with a potentially higher hazard can be investigated more in detail. In addition, InSAR can reveal seasonal patterns that can be used to determine the amount of temporal measurements of piezometers, poor water pressure, and inclinometers. Fig. 3 shows how InSAR can support the planning of the required soil investigation in the desk study phase and the preliminary and design soil investigation phase.

After the preliminary and design soil investigation stage, single point measurements, e.g., boreholes, and geophysical measurements can be used in combination with InSAR results to update the ground model and geohazard information. Finally, in the pre-construction stage, a monitoring plan for the construction stage can be set-up, including InSAR results.

3.2.2. Construction stage

In the *construction stage*, the monitoring plan is implemented. Typically, monitoring systems provide information on deformations (i.e.,

Project phases	1. Pre-construction phase			2. Construction	3. Operation and maintenance
	1a. Conceptual planning and feasibility study	1b. Preliminary design and engineering	1c. Detailed design and engineering, procurement		
Site investigation phases	1a. Desk study and site reconnaissance	1b. Preliminary investigations	1c. Design investigations	2. Monitoring during construction	3. Monitoring during operation
Use of InSAR	- Ground movement detection - Hazard assessment - Project baseline definition	Use InSAR for more effective planning of site investigation	Complementary to in-situ temporal single point measurements	Monitoring of a large area, complementary to traditional survey	Monitoring after traditional survey has stopped

Fig. 2. Overview of project phases and site investigation phases that could benefit from InSAR deployment.

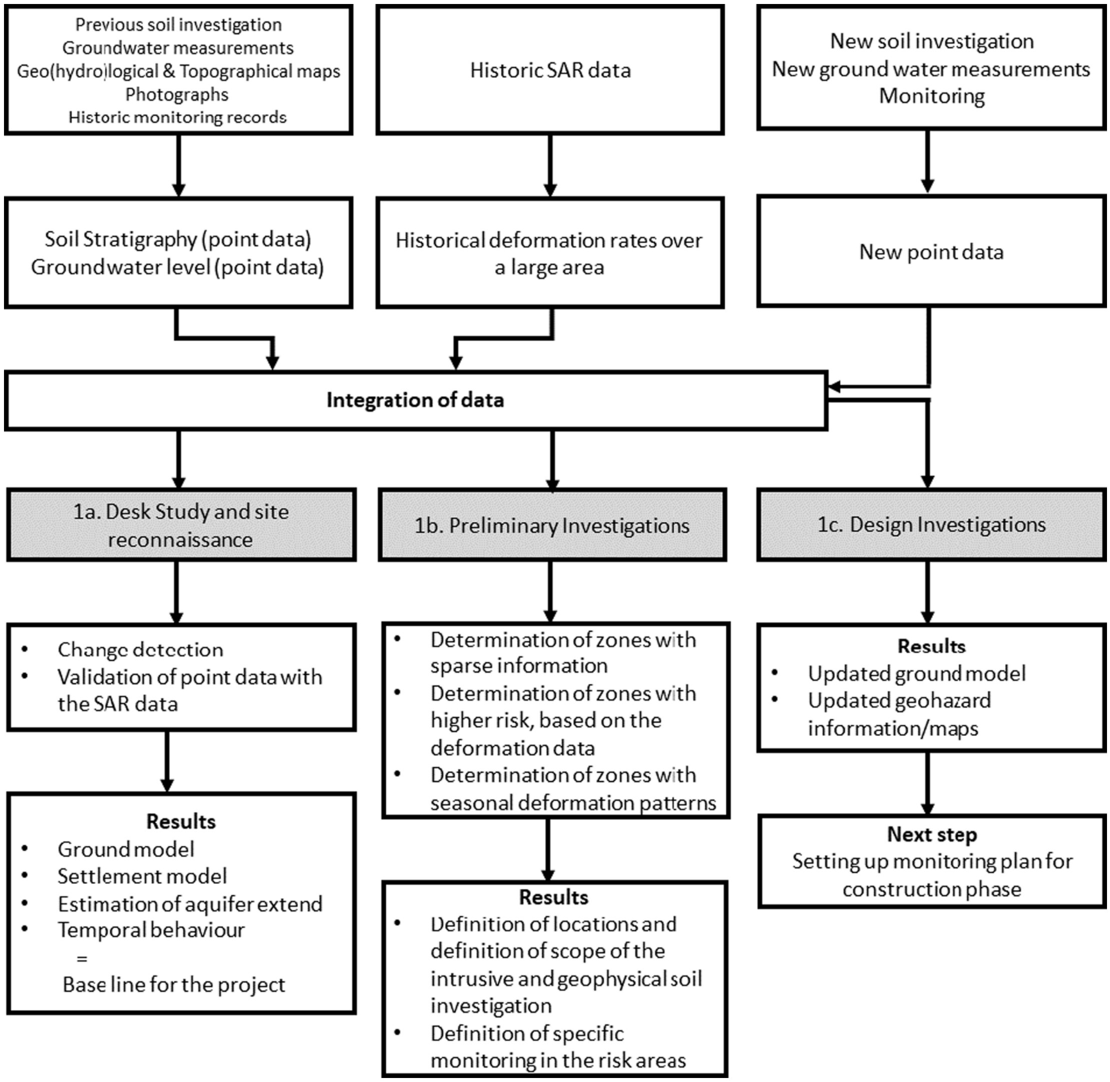

Fig. 3. Integration of InSAR in (i) the desk study phase, in (ii) the preliminary and design soil investigation phase. This shows how InSAR results can be used during the first three phases of a project.

settlements, slope movements, rotations, and displacements of adjacent structures), water level fluctuation, vibrations, and stress levels of soil and rock during excavation. In this phase, review levels are assigned to each measurement instrument, and a contingency plan is established in case these threshold values are reached. Monitoring systems must also have sufficient spatial coverage of the area of interest and should extend to areas where no change is expected, in order to provide a stable reference. This is not always the case for conventional monitoring, that typically consist of discrete survey points measured at several moments in time.

As InSAR can cover a wide area, it can be used as a complementary tool to conventional monitoring to measure displacements outside the area covered by surface levelling points during construction. Similarly to the pre-construction stage, this complies with the current Geotechnical Design Codes stating that monitoring during execution is required to check design assumptions, reduce adverse impact or damage to the surroundings and identify measures for altering the execution method. For example, in urban areas InSAR can provides measurements on a large number of buildings [51,28,36].

In vegetation areas, where InSAR results are often incoherent over longer time intervals, artificial reflectors can be used. This includes passive reflectors, typically 0.7–1.5 m in size, or compact active transponders. The latter are sub-meter in size, weigh less than 4 kg and are frequency-specific [25,52]. They can be solar-powered and are only active at the time of the satellite overpass. These small boxes are less susceptible to environmental impacts such as strong winds, precipitation, and debris accumulation.

3.2.3. Operation and maintenance stage

The maintenance plan includes the supervision, inspection, and monitoring of a new infrastructure asset to guarantee its performance, plan the necessary maintenance, and prevent future failures. Without appropriate maintenance, the risk of failure increases over time. All over the world a large number of transport infrastructure assets are reaching – or has already reached – their originally planned life cycle, and maintenance or retrofitting plans are required. Despite the great importance of geotechnical monitoring during the lifetime of infrastructure assets, currently there are no standard regulations for maintenance and management [54]. Often the geotechnical monitoring is reduced or even terminated after construction.

As SAR data can be acquired at a weekly or bi-weekly frequency, they facilitate long-term monitoring after construction with no need for costly in situ surveying [9,58]. Based on the ground model and risk assessment from the planning and design project phases, a suitable interval for InSAR evaluation can be selected. In higher risk zones, the interval can be shorter than in lower risk zones. InSAR may be able to localize potential failures in unknown areas and it can monitor evolving known phenomena and show an ongoing picture of change. If unexpected changes are revealed, these zones can be targeted with specific in situ survey and maintenance can be planned accordingly, see Fig. 4.

The above suggests that InSAR may be used as an early warning system. When precursors of failure are defined in the maintenance plan, and outliers are automatically identified from the InSAR results, InSAR can be incorporated into the structural health monitoring system. The areas where outliers are observed can subsequently be inspected more in detail with visual inspection and ground-based surveying techniques.

Alternatively, in case of damage or collapse during operation of the infrastructure, InSAR can be used as a forensic tool to investigate the displacements that may have led to observed damage or failure of a construction. Through historic InSAR observations, engineers can look back in time, analyze the behaviors of the area prior to the failure and understand the cause and nature of the collapse. Previous research showed that InSAR revealed displacements outside a threshold range of normal behavior prior collapse of dams and bridges [38,56,69,71], see Fig. 4.

Finally, the application of InSAR is useful when planning retrofitting works of existing infrastructure, where no other historic deformation data is available. InSAR archives may reveal historic displacements to be used as baseline for maintenance works. Based on the assessed deformations, asset managers can prioritize certain sections of the infrastructure and plan retrofitting works. Similarly, in the desk study phase of a new infrastructure project InSAR data can complement field data to provide a baseline and a ground model.

4. Case study

To demonstrate the proposed framework, we applied it to an infrastructure-retrofitting project. This case study shows how InSAR-based displacement estimates provide additional information on the landslide hazard and how this information can be used to plan the soil investigation and monitoring campaign more effectively.

4.1. Project and location

The project concerns the renovation of a 5 km long section of highway N06 between Muri and Rubigen in the canton of Bern, Switzerland, see Fig. 5. The highway was constructed in the early 1970's, taken in operation in 1973, and is located on a slope that faces southwest, with an average inclination of 10 to 15%.

The planned large-scale renovation aims to comply with current building code standards and environmental protection requirements by 2026–2028. All bridges, underpasses, retaining walls, and drainages within the 5 km section will be assessed and renovated if necessary.

According to historic data [50] and archive documents, the Raintalwald region is affected by a deep landslide with superficial secondary movements and a length of approximately 500 m along the road. The extension perpendicular to the road is unknown. Sliding problems occurred during the original construction of the road. Slope displacements of 2 cm/y were observed between 1971 and 1973 [50]. This suggests an extremely low to very low velocity, according to the classification by Cruden and Varnes [23]. After 1973 no record of slope deformation exists but if the displacement rate at Raintalwald was to continue for the last 50 years, about 1 m displacement would have

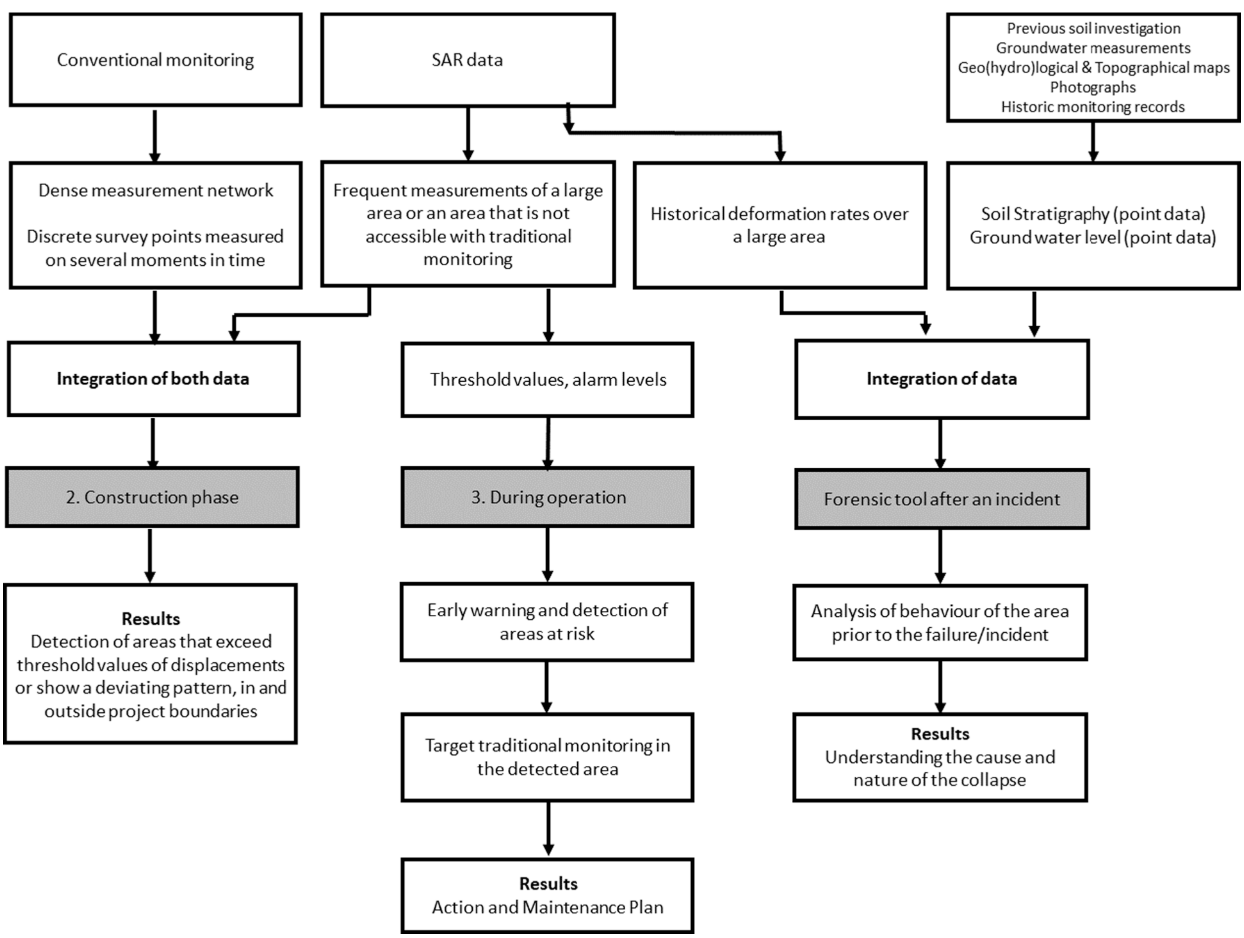

Fig. 4. Integration of InSAR with conventional monitoring during the construction stage and operational stage. Also the use of InSAR as a forensic tool is presented.

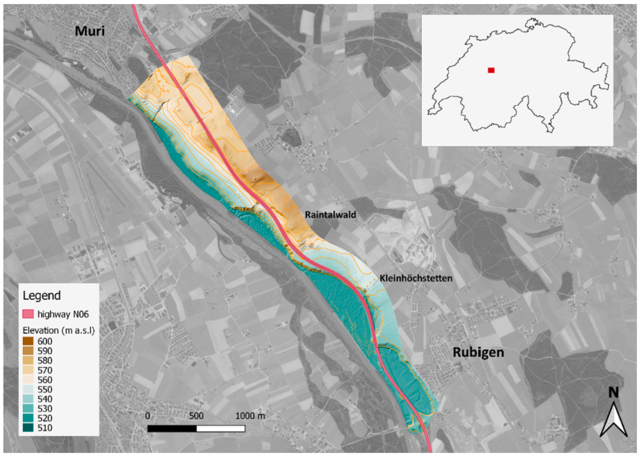

Fig. 5. Location and elevation of highway N06 between Muri and Rubigen, Switzerland.

occurred. However, only in the north of the Raintalwald signs of small slope movement are visible on the downhill side of the road.

Due to the forested area, the presence of the highway, and the traffic, access to the area is difficult and conventional periodic geodetic surveys of the Raintalwald landslide slope are almost impossible. An in situ monitoring campaign, consisting of inclinometers and piezometers in boreholes, would provide meaningful information about the state of the landslide only after at least six months of data collection. Therefore, to facilitate renovation design directly at the planning stage, we analyzed InSAR data acquired from 2015, to (i) confirm or update the landslides in the Raintalwald and Kleinhöchstetten area, (ii) estimate the displacement rate and possible driving mechanisms of these landslides, and (iii) identify possible areas of displacement that are still unknown. Moreover, we evaluated whether the results of these InSAR analyses could be used to target the location of soil investigation and monitoring campaign more effectively.

4.2. Geological setting

The near-surface geology of the study area is documented by several historic boreholes, mainly acquired during the highway construction, and geological maps [12,39]. The area is characterized by quaternary deposits that are deposited on a bedrock of upper marine molasse, i.e., silt- and sandstones. The bedrock-surface was carved by the Aare-Glacier and is assumed to be sub-parallel to the current topography. The depth of the bedrock is estimated between 30 and 50 m below the surface. The stratigraphy of the quaternary deposits reflects a typical glacially-driven history of several glacial and interglacial periods: an old moraine at the base covered by lacustrine clay, followed by another moraine with a natural and artificial cover layer. The boundaries of the different layers are diffuse, since they consist mainly of fine-grained material such as sand, silt, and clay with only minor gravel, and the sediments are reworked due to their position on a slope. The layers of interest are the lacustrine clays, which are highly compacted and hard at deeper levels. It is assumed that the sliding surface of the landslide is located within the lacustrine clays. These have a low permeability but contain areas with gravel, probably reworked moraine, where groundwater is present and groundwater circulates. Since the water might be the driving force for landslides, a drainage system was built during construction, to relieve the water pressure and stabilize the landslide mass.

For an overview of the (hydro) geology of the project area a geological model was created by using the 3D geological modelling software Leapfrog Works 4.04 [68]. The model includes underground information from archive boreholes [1] and new drillings, as well as geological maps from the Federal Office of Topography swisstopo [73]. In addition to lithological information, data on historic and current groundwater levels was also included. A sketch of the model is displayed in Fig. 6.

4.3. Hydrogeological setting

To obtain information about the precipitation and evapotranspiration, meteorological data from a measuring station in Bern-Zollikofen were retrieved from 2015 until present. This measuring station is the closest to the project location. By subtracting the evapotranspiration data from precipitation data the water balance was obtained, see Fig. 7. The data show a clear seasonal trend. In summer, most of the rainwater evaporates or is used by vegetation (evapotranspiration), and therefore a minimum amount of water seeps into the ground to contribute to groundwater recharge. In autumn and winter, evapotranspiration is significantly lower due to the lower temperatures and the reduced vegetation activity, and the precipitation water that accumulates is thus percolated and contributing to groundwater recharge. This pattern indicates a pluvial groundwater regime, which is characterized by a groundwater recharge that is essentially a consequence of the annual distribution of precipitation, taking into account evapotranspiration [65].

4.4. MT-InSAR

The area of interest is characterized by farmland, patches of forest, small villages, local roads and the N06 highway. For microwave frequencies, forests, grassland, and farmland change significantly over time due anthropogenic activities and seasons. Consequently, vegetated areas show inconsistent, i.e., incoherent, InSAR results over time. In this study we only used coherent scatterers of the road.

Since the road is directly founded on the slope, we assumed that the road and the slope move in an identical way. Our data consisted of point scatterers (PS), which typically have one dominant reflecting object, and distributed scatterers (DS), which are resolution cells that are the coherent sum of a multitude of small elementary scatterers [40], which may be coherent only for a limited subset of the time series [45]. Since InSAR results are relative both in time and space, a temporal and spatial reference have to be chosen. In the time domain, the first epoch in the displacement time series is set to zero. In the spatial domain, the average deformation rate of a network of points around and within the project area is set to zero. The movement of all other points within the analysis is relative to this network of points. These choices are arbitrary and do not influence the interpretation of the results.

In this study we used SAR data acquired between 2015 and 2020 from the Sentinel-1 satellite mission (Table 2). The dataset contains both ascending and descending orbits. The ascending satellites pass with heading, which is north-by-west (NbW) and since the antenna is pointing to the right, the viewing direction is east-by-north (EbN). The descending satellites pass south-by-west (SbW) with a west-by-north (WbN) viewing direction (Fig. 8). As the radar is only sensitive to the orthogonal projection of the displacement vector onto the line of sight (LOS) direction, a positive value implies a net projection of the displacement towards the radar, while a negative value means that the projection of the displacement vector points away from the radar. Therefore, for downslope motion on slopes facing west, the ascending orbit will typically give a small (positive) displacement while the descending orbit will give a negative displacement, with magnitudes depending on the slope angle, γ, slope orientation, β, and incidence angle, θ. For a slope facing east, this will be the other way around. Consequently, with viewing directions that are EbN and WbN, this results in a decreased sensitivity for downslope motion for slopes roughly facing north or south [18]. See Fig. 9 for the definitions of the angles mentioned above. The InSAR processing was done by SkyGeo with its own proprietary software package for PS (point scatterers) and DS (distributed scatterers) InSAR data processing [70], following

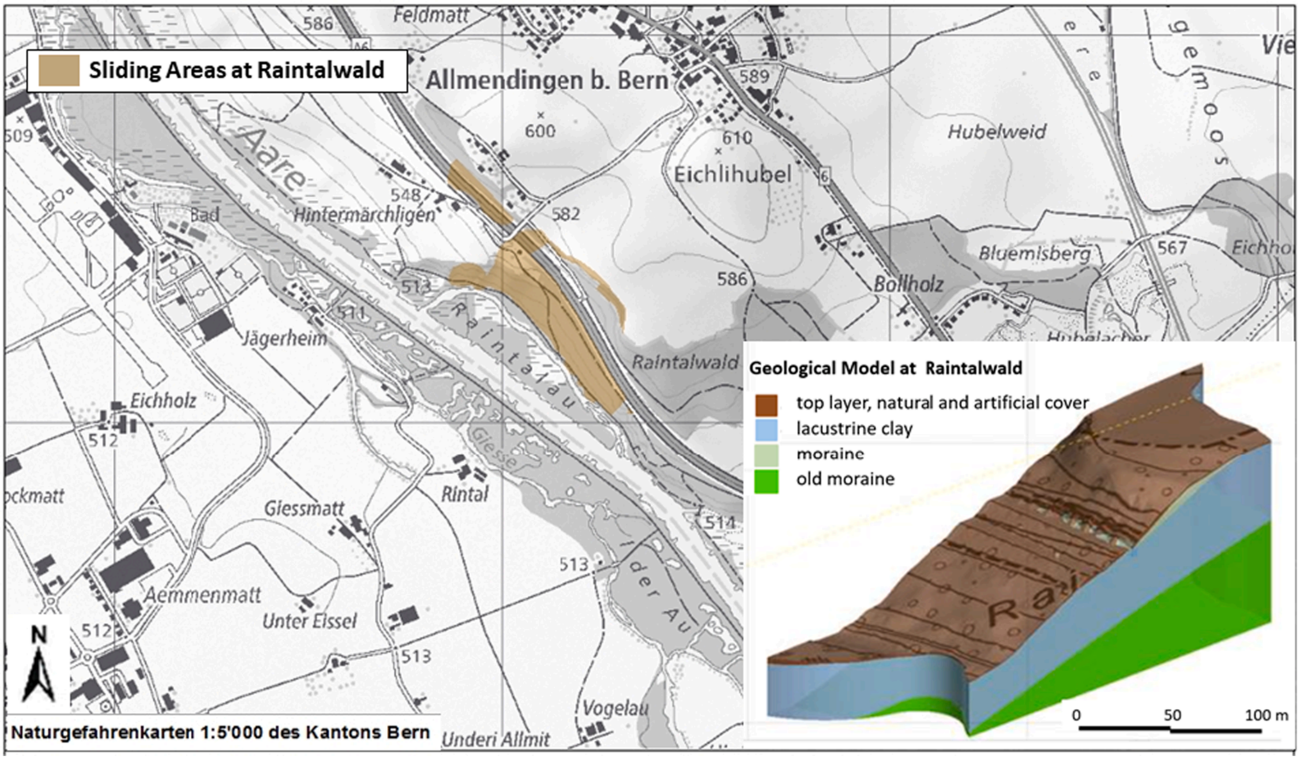

Fig. 6. Geological model of the area of interest Raintalwald with background map of landslide hazards of the Kanton Bern [1].

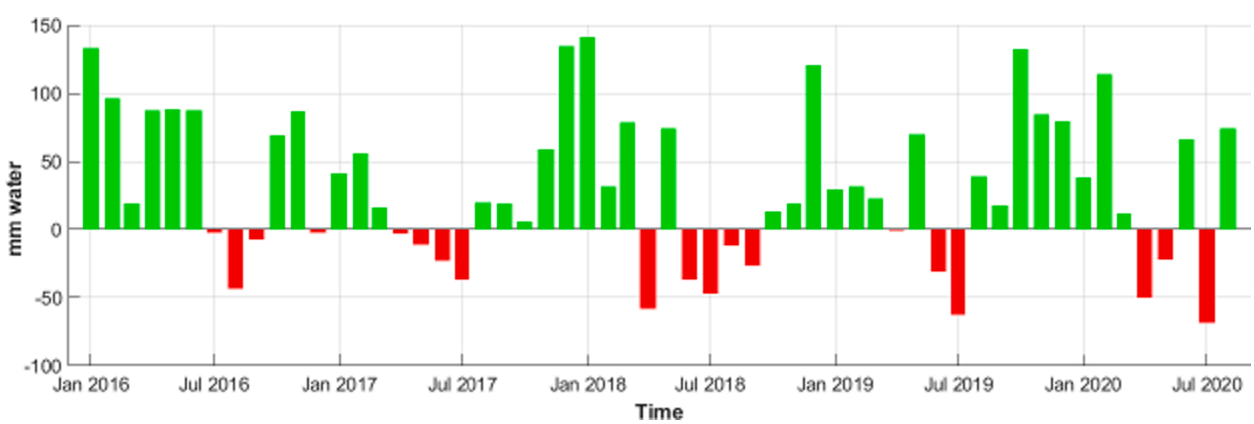

Fig. 7. Water balance Bern for 2016 to 2020 at Meteoschweiz measuring station Zollikofen.

Table 2
Sentinel-1 satellite data.

Mission	Orbit	Revisit time (days)	Number of Images	Period	Incidence Angle (°)	Spatial Resolution (m)	Band
Sentinel-1	ASC track 88	6	226	Dec 2015 to June 2020	39.4	13.2 × 3.5	C
Sentinel-1	ASC track 15	6	205	May 2016 to June 2020	39.4	13.2 × 3.5	C
Sentinel-1	DSC track 139	6	210	May 2015 to June 2020	39.4	13.2 × 3.5	C
Sentinel-1	DSC track 66	6	235	May 2016 to June 2020	39.4	13.2 × 3.5	C

methodology from Kampes [49], van Leijen [76] and Hanssen [40]. An equivalent single-master stack was built, with thresholds for temporal coherence have been chosen adaptively, as a trade-off between point density and point quality. No thresholds for maximum perpendicular baselines have been necessary.

4.5. *Data analysis*

After evaluating all the satellite data, we concluded that in our area of interest the descending orbit provided the most dense set of coherent reflections. A very limited amount of ascending data was available in the Raintalwald area. This is a consequence of the imaging geometry of the satellites in combination with the orientation of the road. Moreover, when the radar reflections are the summation of a (horizontal) road and

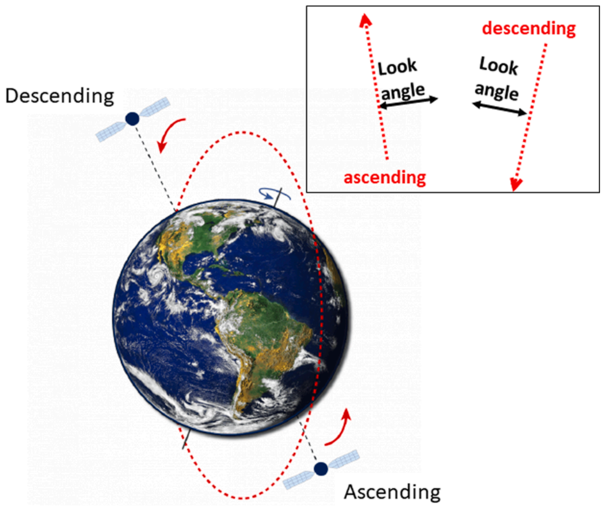

Fig. 8. Graphic representation of descending and ascending orbits.

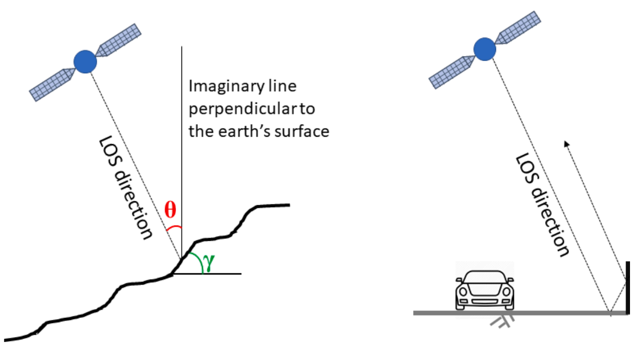

Fig. 9. (Left) Incidence angle θ and slope angle γ. (Right) Double-bounce, or dihedral radar reflection, via the ground and a vertical wall back to the satellite.

a (vertical) wall or guardrail, this will result in a 'double-bounce' reflection (Fig. 9b). In this case, double bounces were stronger for the descending then for the ascending acquisition geometry.

Fig. 10 shows the displacement rates for the descending orbit of Sentinel-1 in the LOS direction. In our analysis we only included points with an estimated temporal coherence equal or greater than 0.4. This coherence estimate is a goodness-of-fit metric, which describes how well a trend line fits a set of temporal observations. The results show that the average deformation rate is 0 to 1 mm/year, while locally a deformation rate of maximally 2 mm/year is reached. These areas are indicated by Area 1 to Area 7, and are relative to the chosen reference point. In our case study the most coherent scatters, i.e. points of high quality with a coherence estimate $\geqslant$0.8, are chosen to provide a network of points whose displacement rate is set to zero. The accuracy of the displacement rates depends on the type of sensor, the amount of images, the amount of points with high coherence, and the amount of points with similar deformation and deformation rates. In this case, many points have a deformation rate between -1.0 and 1.0 mm/year, while only a few clusters of points have a slightly higher deformation rate. Plotting all points in a histogram yields a narrow normal distribution with clearly detectable outliers. The accuracy is in the order of 1 mm/year.

We examined the identified areas in detail and applied the integration of InSAR in the desk study phase (Fig. 3). To evaluate the regions of interest, cross sections were drawn at these locations in the geological model (see Section 4.2) and and checked for lithological or groundwater information that could explain the higher deformation rates. For each area, we compared the existing soil investigation, the hydrogeological map, and the topographical map to the InSAR-based historical deformation rates (Fig. 11).

In area 1, downhill from the road, bored piles were installed during construction for stabilization against sliding. Uphill, a horizontal drain runs parallel to the road. The area where coherent InSAR observations were retrieved is located between the stabilization piles and the uphill drainage system. In the area above the road there is a wet zone, which possibly drains in the direction where the displacements were detected. Finally, in July 2007, there was a debris flow in this area, which indicates the presence of slope water. We concluded that the observed displacements are likely to have a geological and hydrogeological origin.

In area 2 large bored piles were also installed during constructing to prevent horizontal displacements. A big vertical drainage shaft is located between the two roadways. Moreover, due to the topographic conditions, i.e., the funnel shape, this area is likely to be very wet. The groundwater is near the surface in the roadway area. The lacustrine clay acts as a water-retaining layer and prevents the rainwater to percolate into the soil. Since the InSAR-derived movements are only a few millimeters per year, we assumed that the deep drainage is effective and thus the landslide is slowed down.

Area 3 includes a retaining wall at the downhill side. Moreover, the area is located above a very pronounced gully in the slope. The observed displacement may be caused by the fill in this gully.

In Area 4 no structures are present, except the horizontal drainage installation parallel to the road. The lacustrine clay and the groundwater are very close to the surface. Therefore, a geologically induced movement seems possible.

Area 5 is located in a known sliding area. On the downhill side of the highway a small slope instability (patch of the road) occurred recently but the InSAR scatterers are not located exactly on that spot. Most likely, the measured deformations originate from this slope instability.

So far, no landslide areas are known, and no instabilities have occurred in Area 6. No structures or other objects are known to be in this area. However, InSAR data showed some temporal anomalies in 2017, which caused a deformation change. The origin of this scatter could not be identified.

In area 7 no landslide areas are known or instabilities have occurred. The satellite data show only deformations on the valley side. Therefore, a large-scale landslide seems unlikely.

We conclude that in areas 1–5 it is very likely that the displacements that were detected with inSAR are of geological and hydrogeological origin. However, in areas 6 and 7, no landslide hazards are known or instabilities have occurred. A wide-scale landslide or any other hydrogeological cause seems unlikely. The origin of these small displacements detected by InSAR could not be identified. Finally, the InSAR results revealed a seasonal deformation signal, not previously known. The data shows an increase in movement in winter and a decrease in summer, (Fig. 12).

During summer, with a higher evaporation and evapotranspiration, the subsoil is mostly dry and groundwater levels are lower. In winter, a higher amount of the rainwater sinks into the ground leading to higher groundwater levels and higher pore water pressures. This might be a trigger for small slope displacements, especially in the water-sensitive lacustrine clay layers. In Fig. 12, the averaged water balance over three months and the InSAR-based displacements both show a seasonal fluctuation. This hypothesis will be verified after analysing in situ inclinometer and pore water pressure loggers measurements that will become available next year.

4.6. Results for the desk study phase

From the results above, we concluded that historic InSAR data could reveal and delimit known and unknown zones of the project area with small displacements, i.e. in the order of maximum 2 mm/y in the LOS direction. By combining this information with topographical and archived hydrogeological data, we identified the driving mechanisms

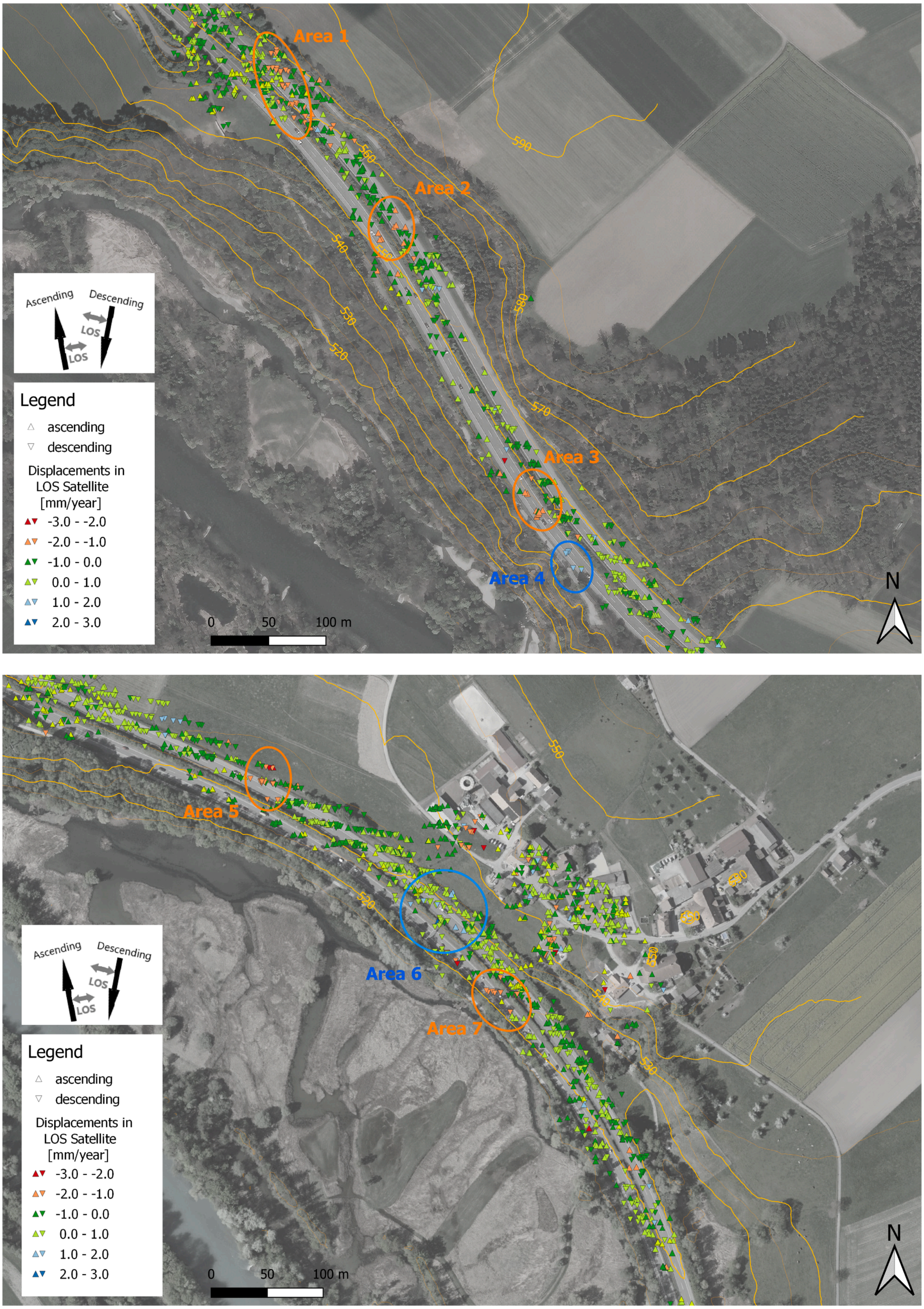

Fig. 10. Displacements in LOS direction from Raintalwald to Brüelmatt/Kleinhöchstetten. Sentinel-1. Positive displacements indicates a movement towards the satellite, negative displacements a movement further away from the satellite.

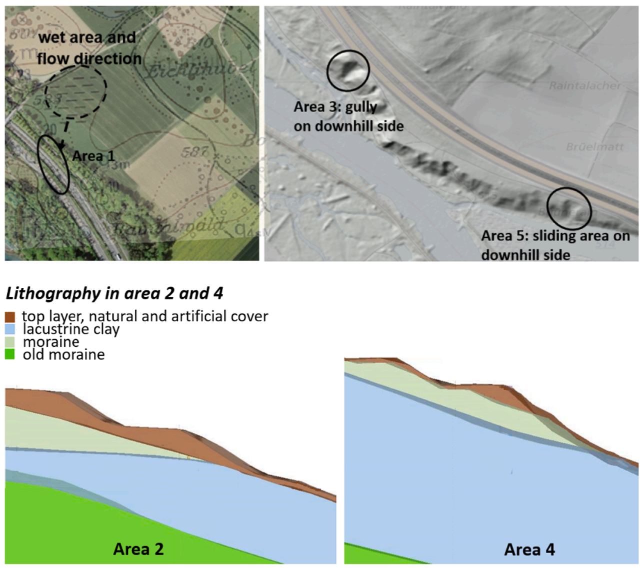

Fig. 11. Details of the individually analyzed areas. (Top left) Top view for area 1. (Top right) Top view for area 3 and 5. (Down left) Geological cross section for area 2. (Down right) Geological cross section for area 4.

for seven analysed areas. Moreover, based on InSAR observations we detected zones of displacement which were not previously known, and revealed an unknown seasonal signal. No conventional ground-based in situ measurements would have been able to provide comparable historical deformation maps at the same temporal and spatial resolution at this stage of the project. All this information resulted in a thorough baseline assessment.

Based on these findings, project engineers made the following decisions about the soil investigation stage of the project.

- Only the zones where the hydrogeological situation is likely to cause deformations will be investigated in detail with boreholes. An extensive network of boreholes with inclinometers, distributed over the entire area is considered unnecessary. This shows that InSAR can be used to target the site investigation more effectively and efficiently, focusing on higher risk zones.
- The boreholes will be equipped with inclinometers and continuously automatic loggers that record the pore water pressure to determine whether the seasonal deformation trend can be linked to the fluctuation of the yearly groundwater level. InSAR revealed seasonal patterns and this information was used by the project engineers to determine the amount of temporal measurements of pore water pressure loggers and inclinometers.

These InSAR-supported conclusions lead to significant reductions in costs, combined with a more efficient and effective spatial positioning of the boreholes.

4.7. Application of InSAR in the upcoming project phases

While the project is currently still in the pre-construction phase, the use of InSAR data is envisioned for all project phased.

4.7.1. Pre-construction stage

Following the acquisition of measurements from automatic pore water pressure loggers in the next six months to one year, InSAR data will be analyzed again and compared to the groundwater measurement. Based on the new soil investigation and the updated InSAR results, the ground model risk analyses will be also updated.

4.7.2. Construction stage

No large excavations are planned for this project. The influence on the surroundings will be small and no InSAR monitoring will be performed during construction. However, InSAR can be of value to continuesly monitor the road and detect unexecpected changes.

4.7.3. Operation and maintenance stage

During operation of the retrofitted highway, InSAR can be used to monitor the road regularly and detect zones that might have a deviating moving trend. This will replace the field survey, which was previously proven unfeasible due to the vegetation land cover and the difficult access to the area.

5. Conclusions and outlook

While the use of InSAR within the civil engineering field it is often still perceived as limited to the academic discussion, in this contribution we argue that the threshold for applying the technique in operational practice has become much lower. In fact, given the different stages in a typical construction project, InSAR techniques can be applied to every step, with objectives varying over time. In this work we evaluated the established standard procedures within the geotechnical design codes, such as the newly published Eurocode-7, and demonstrated that the use of InSAR technology fits well within the required activities. Moreover, this direct applicability can benefit a number of stakeholders, including engineers, contractors, asset managers and planners.

Without losing generality, we demonstrated this applicability for the actual renovation project of a highway located on a slope, where sliding

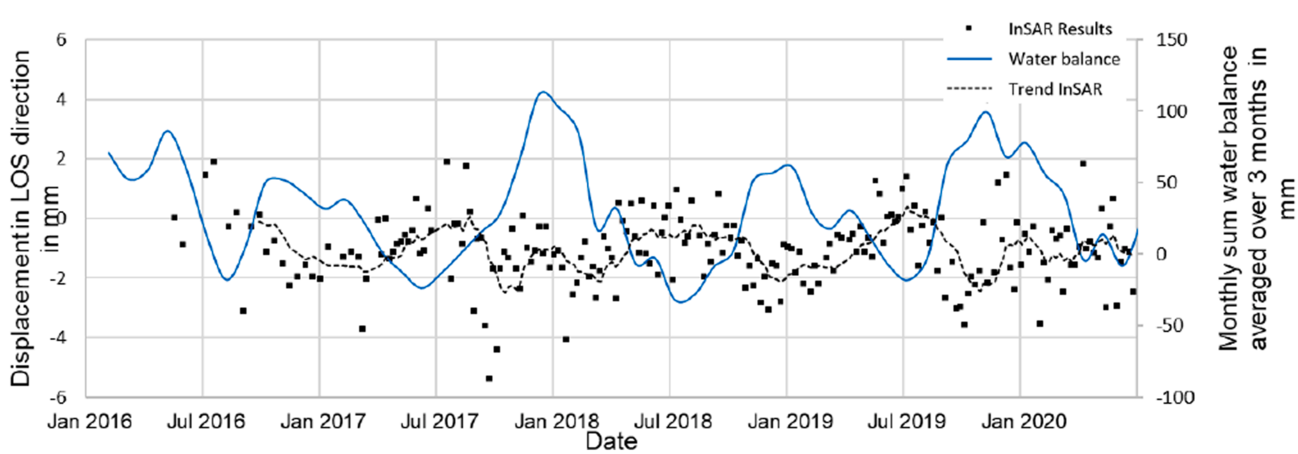

Fig. 12. Example of a seasonal trend in the InSAR estimates in the project area (black dots), and Water balance estimates (blue line), from the descending orbit.

zones were suspected. In the desk study stage, InSAR observations supported the detection of known and unknown zones with higher displacement rates, and an unknown seasonal deformation trend. By combining this information with hydrogeological data, the driving factors of the deformations were identified. These findings were then used to steer the new in situ soil investigation more effectively.

While the advantages of the application of InSAR are self-evident, we need to stress that by its very nature the application will always be dependent on the local situation, in terms of geometry, orientation, and other reflective conditions. Thus, the effectiveness of the use of InSAR observations should always be evaluated in relation to these local circumstances.

Data availability

All data presented in this paper have been obtained in the framework of commercial projects. Results cannot be shared or distributed by the authors without written consent of the final users.

Author contributions

KR wrote the paper, developed the framework and methodology, was in charge of data analyses and reporting activities. FZ set up the geological model. JR determined the conclusions for the future project planning and provided all information regarding existing structures and local situation. GG and RH acted as supervisor and reviewed the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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