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Reinders, K.J.

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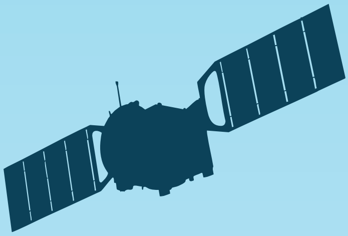

ON THE APPLICATION OF INSAR IN CIVIL-, GEO-ENGINEERING AND NATURAL HAZARD PROJECTS

Opportunities, obstacles and recommendations

Kristina Reinders

On the application of InSAR in civil-, geo-engineering and natural hazard projects

Opportunities, obstacles and recommendations

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by

Kristina Juliana REINDERS

Master of Science in Civil Engineering
Delft University of Technology, The Netherlands
born in Vilvoorde, Belgium

This dissertation has been approved by the promotor[s]:

Prof.dr.ir. R.F. Hanssen
Dr.ir. M. Korff

Composition of the doctoral committee:

Rector Magnificus	chairperson
Prof.dr.ir. R.F. Hanssen	Delft University of Technology, *promotor*
Dr.ir. M. Korff	Delft University of Technology, *copromotor*

Independent members:

Prof.dr. T.A. Bogaard	Delft University of Technology
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Prof.dr. A. Wieser	ETH Zürich
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Dr.ir. W. Broere	Delft University of Technology

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Preface

In 2018, I started working with interferometric synthetic aperture radar (InSAR) for geotechnical applications. As a geotechnical engineer with no previous experience of satellite geodetic monitoring techniques, this required to familiarise myself with a new area of work and gain knowledge of data I had not previously known. Later I was involved in business development of InSAR products for geotechnical and civil engineering projects. I had meetings with more than 30 potential SAR users, such as civil engineering companies, government organisations, railway companies and asset managers. I discovered that different disciplines speak different languages and that InSAR users and providers have different technical knowledge. Understanding each other could be difficult. Although InSAR providers often saw opportunities for InSAR applications, potential users could not always be convinced. Either they did not understand the technology, they were not fully aware of the possibilities and benefits, they had misconceptions about the challenges, they thought InSAR would not be feasible in their specific projects or they thought it was too expensive. During this time, I became aware that many geotechnical engineers, geologists and other potential InSAR users were in the same situation as I was in 2018, with no or little experience of InSAR and not yet using the technique. I also discovered that, in my opinion, InSAR engineers did not always understand the needs of potential customers and their problems. In short, there seemed to be a gap between the fields of InSAR on the one hand and civil and geotechnical engineering and natural hazards on the other. I also noticed that there was no clear overview of why InSAR had been used successfully in certain projects, why it had failed, or why it was not even being considered. While personal experience is valuable, it is of little value for generalisations. I therefore decided to conduct scientific research to assess the use of InSAR in civil, geo-engineering and natural hazards projects on a larger scale. That was the start of this research, in which I identify the factors that influence the use of InSAR in civil, geo-engineering and natural hazards projects, provide recommendations and solutions to improve InSAR applications in practice and enhance collaboration between the civil, geo-engineering and natural hazards communities and the InSAR community.

Summary

Ground deformations caused by natural hazards or construction activities can pose risks to people, infrastructure, and the economy. To assess these risks, it is essential to monitor the extent, magnitude, direction, and change over time of these deformations. Traditional methods involve in-situ tests and terrestrial monitoring, but over the last 40 years, a new technique, Interferometric Synthetic Aperture Radar (InSAR), has emerged. This satellite-based radar method has proven effective in detecting surface deformations, particularly relevant for civil-, geo-engineering, and natural hazard projects. However, despite its potential, InSAR adoption in civil and geo- engineering projects and for natural hazard evaluation is still limited. This research studies the factors that hamper the adoption of InSAR in practice and provides recommendations for advancing the deployment of InSAR in civil-, geo-engineering and natural hazard related projects.

First, based on the literature study, this research gives an overview of the possibilities and advantages of InSAR for monitoring ground surface deformations. The intrinsic technical obstacles of the InSAR technique are also discussed in detail. The advantages of InSAR for projects involving civil engineering, geo-engineering, and natural hazards include the availability of precise point deformation measurements over wide areas at fine spatial resolution, the availability of data outside the area of the conventional surveying benchmarks, the availability of data in remote and difficult to access areas without the need for people and equipment on site, availability of historical ground displacement data and use for baseline assessments at the start of a project. However, InSAR is an opportunistic method and the locations and distribution of monitoring points are unknown in advance. Other intrinsic obstacles include the fact that the detection of stable reflectors is influenced by the land use, that the range of detectable displacement velocities is limited, that unwrapping errors can occur due to the phase ambiguity, that the displacements are in the Line of Sight (LoS) of the satellite and that geometric distortion can occur. Also, due to the near-polar orbits of the current satellite mission, the sensitivity to translational displacements along the north-south direction is limited when it comes to slopes facing north or south.

While the technical characteristics of the technique are well documented in the literature, the non-technical factors are less explored. Only a few scientific articles address them and mention the need for experienced SAR data interpreters, basic knowledge of InSAR for potential users, uniform standards and criteria for assessing the quality of InSAR results and sufficient resources for data storage and processing. In this research, the non-technical factors that may influence the use of InSAR in civil, geotechnical and natural hazards projects are explored in depth through qualitative research, namely semi-structured interviews with InSAR users and InSAR providers. Also, the practical experiences of using InSAR in civil engineering, geo-engineering, and natural hazards are investigated.

The interviews confirm the findings from the literature on the technical benefits and obstacles of InSAR in projects. But more importantly, the interviews reveal critical success factors and obstacles for a successful InSAR implementation in an operational project. Key success factors for a successful implementation are clear communication, knowledge of each other's discipline by both InSAR users and InSAR providers, qualified personnel and aligned expectations. Obstacles are a different way of thinking and language between InSAR users and providers, a lack of standards for quality assessment, lack of regulations and guidelines in the InSAR market, and high costs. In addition, InSAR is still an unknown technology in the industry,

The literature and the interviewees also provide recommendations. These include fostering a better understanding of each other's needs through education, transparent communication about InSAR's intrinsic challenges and sharing data and information about project challenges with each other. Case studies and pre-analyses, as well as a step-by-step implementation of InSAR in a project, can also help to raise awareness and demonstrate the benefits of InSAR. Regarding the use of readily and freely available Persistent Scatterer Interferometry (PSI) products, which is a commonly used InSAR method, it is recommended to clearly communicate the limitations of PSI maps, as users of these maps have limited background knowledge of SAR.

One way to educate InSAR users and improve civil and geotechnical engineers' understanding of InSAR is by developing guidelines. In this study the applicability and compatibility of InSAR with the existing geo-engineering design codes is examined. Established standard procedures, such as those in the newly published Eurocode-7, are reviewed to assess InSAR's potential applications throughout the life cycle of a civil engineering project, i.e the pre-construction, construction, and operation and maintenance stages. An operational framework is developed to integrate InSAR into current geotechnical design codes, such as Eurocode-7, at all stages, demonstrating that InSAR technology aligns well with required activities. InSAR can offer insight into the surface movements of an area from historic satellite-based SAR data. Furthermore, InSAR observations can help identify zones with displacements larger than the average of an area and can be used to plan future soil investigations 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. The proposed framework was 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. This proposed framework is a practical and operational tool that can be used by planners and engineers in the whole lifecycle of an infrastructure project.

The study also delves into two specific applications of InSAR: shield tunnelling in soft soil in urban areas and the use of free PSI maps for permafrost assessment.

For tunnelling projects, InSAR proves to be valuable for monitoring deformations before, during, and after construction. InSAR is a useful complementary source of information as it provides data outside the area of the conventional surveying benchmarks and it reveals relevant information about settlement patterns before and after traditional construction monitoring periods, without the need to install instruments on the ground. However, one particular challenge in tunnelling projects, where abrupt settlements over short spatial distances with magnitudes close to the wrapping threshold can occur, is resolving the correct ambiguity level in InSAR data. To obtain unbiased displacement estimates, prior knowledge of the expected settlement is essential. For this, analytical settlement prediction methods can be effectively used to identify the most likely ambiguity level in InSAR measurements. This approach allows augmented InSAR to capture short-term settlements occurring during the construction of shield tunnels. The proposed methodology to select the most probable ambiguity level can help in the development of a practical tool that is able to quantify and insert the prior information on the displacement dynamics in the InSAR displacement estimation software. As such, augmented InSAR can be integrated in the monitoring framework of more civil engineering projects.

Readily available public PSI products, based on freely available SAR data from satellite missions such as ESA's Copernicus Sentinel-1, are increasingly being produced. Although they provide new opportunities for wide-area ground motion detection and monitoring, they are application-agnostic, meaning that they are not optimised for a particular application or location. Despite this, they are used for hazard assessments by engineers and stakeholders who are not always aware of these constraints. The potential of using Sentinel-1-based PSI (Persistent Scatterer Interferometry) maps to detect alpine permafrost in the Swiss Alps is assessed. The study shows that the majority of areas currently classified as permafrost meet the geometric visibility criteria when combining ascending and descending Sentinel-1 orbits. Additionally, a regional PSI dataset over Canton Valais reveals that mean surface velocities are higher in zones identified as permafrost than in areas without permafrost. Regarding structures and infrastructures in permafrost areas, the research shows that while many areas around buildings in Canton Valais have sufficient sensitivity to Sentinel-1 radar detection, the available regional PSI map is not suitable for monitoring buildings. The resolution of C-Band data is insufficient for structural health monitoring, necessitating the use of higher resolution SAR data. However, as terrestrial monitoring data is scarce at high altitudes, regional PSI can be used as a valuable additional source of information.

In summary, the study explores the challenges and potential of using Interferometric Synthetic Aperture Radar (InSAR) for monitoring ground deformations in civil engineering, geo-engineering, and natural hazard projects. Technical and non-technical obstacles are discussed and recommendations are provided for improving InSAR's adoption in practice.

Samenvatting

Bouwactiviteiten, natuurlijke processen en natuurrampen kunnen bodembewegingen zoals maaiveldzakkingen en aardverschuivingen veroorzaken. Indien deze verplaatsingen zich bevinden in bewoonde omgevingen, in economisch belangrijke gebieden of op plaatsen waar menselijke activiteiten plaatsvinden, is het vaststellen van de grootte, de richting en de verandering in de tijd van deze deformaties essentieel om de veiligheid van bouwwerken, infrastructuur en mensen te waarborgen. Traditioneel worden verplaatsingen gemeten met terrestrische landmeetinstrumenten zoals bijvoorbeeld waterpasinstrumenten of total-stations. De afgelopen 40 jaar is echter een satellietgebaseerde radarmethode ontwikkeld waarmee vervormingen aan het aardoppervlak nauwkeurig kunnen worden vastgesteld. Deze techniek wordt Interferometrische Synthetic Aperture Radar (InSAR) genoemd en wordt al geruime tijd toegepast om verschillende deformatieprocessen aan het aardoppervlak te meten. Het potentieel van deze techniek is ook in de wetenschappelijke literatuur uitgebreid beschreven. Desondanks wordt InSAR in de praktijk voor civiele en geotechnische projecten en voor de evaluatie van natuurrisico's nog maar beperkt toegepast.

In dit onderzoek is onderzocht welke factoren de toepassing van InSAR in de praktijk beïnvloeden, belemmeren of bevorderen. Vervolgens zijn aanbevelingen geformuleerd om het gebruik van InSAR in civiele- en geotechnische projecten en voor het evalueren van verplaatsingen ten gevolge van natuurlijke processen en natuurrampen te vergroten.

Als eerste is een uitgebreide literatuurstudie uitgevoerd waarin de mogelijkheden, voordelen en beperkingen van InSAR zijn onderzocht voor het monitoren van verplaatsingen bij civiele en geotechnische projecten en voor de evaluatie van verplaatsingen veroorzaakt door natuurrisico's. De voordelen van InSAR zijn onder andere het kunnen bepalen van nauwkeurige maaiveldverplaatsingen met hoge dichtheid over grote gebieden, het feit dat er geen mensen en apparatuur op locatie nodig zijn en de beschikbaarheid van historische SAR opnames tot in de jaren negentig.

Enkele technische belemmeringen zijn het feit dat de detectie van stabiele reflectoren wordt beïnvloed door het landgebruik, dat de detecteerbare verplaatsingssnelheden beperkt zijn en dat de grootte van de beweging alleen in de kijkrichting van de satelliet is vast te stellen. Bovendien kunnen er bij het omzetten van de SAR data naar verplaatsingsdata fouten ontstaan, met name bij abrupte zettingen en verplaatsingen met een grootte die in de buurt ligt van 1/4 van de golflengte tussen twee SAR opnames. Daarnaast kunnen verplaatsingen in noord-zuid richting maar beperkt worden gemeten omdat de huidige satellieten in polaire banen om de aarde vliegen. Tenslotte is InSAR een opportunistische methode, wat betekent dat de locaties en verdeling van meetpunten vooraf onbekend zijn.

De technische aspecten van InSAR zijn in de wetenschappelijke literatuur goed gedocumenteerd. Echter, de niet-technische factoren die een succesvolle toepassing in de praktijk beïnvloeden zijn minder goed onderzocht. Enkele niet-technische belemmeringen die in de literatuur genoemd worden zijn, dat alleen ervaren SAR-data-specialisten de data kunnen verwerken, dat potentiële InSAR gebruikers ontoereikende basiskennis van InSAR hebben, dat er geen uniforme normen en criteria voor de kwaliteitsbeoordeling van InSAR-resultaten zijn en dat er onvoldoende computercapaciteit en gekwalificeerde mensen zijn voor de dataverwerking en dataopslag.

In dit onderzoek zijn de niet-technische factoren die het gebruik van InSAR in civiele, geotechnische en natuurrampenprojecten kunnen beïnvloeden uitvoeriger onderzocht aan de hand van semi-gestructureerde interviews met InSAR-gebruikers en InSAR-leveranciers. De interviews bevestigen de bevindingen uit de literatuur maar geven ook interessante nieuwe aanvullende informatie. Essentieel voor een succesvolle toepassing zijn duidelijke communicatie, kennis van elkaars vakgebied en gekwalificeerd personeel. Ook is het belangrijk dat zowel InSAR-gebruikers als InSAR-leveranciers hun verwachtingen bespreken en afstemmen. Belemmeringen voor een succesvolle toepassing in de praktijk zijn een andere manier van denken tussen InSAR-gebruikers en InSAR-leveranciers, verschillend vakjargon en de hoge kosten van een SAR analyse. Daarnaast kwam naar voren dat InSAR nog steeds relatief onbekend is in de civiele en geotechnische industrie.

De literatuur en de geïnterviewden geven ook aanbevelingen voor het verbeteren van de toepassing van InSAR in de praktijk door civiele en geotechnische ingenieurs. Enkele aanbevelingen zijn onder andere het bevorderen van een beter begrip van elkaars vakdiscipline door middel van trainingen en opleidingen, transparante communicatie over de technische beperkingen van InSAR en het delen van gegevens en informatie over het betreffende project. Ook kunnen voorbeeldprojecten en vooranalyses, evenals een stapsgewijze implementatie van InSAR in een project helpen om de toepassingsmogelijkheden aan te tonen. Er is ook onderzocht hoe Persistent

Scatterer Interferometry (PSI) producten worden gebruikt in de dagelijkse praktijk van ingenieurs. PSI is een veel gebruikte InSAR techniek en de afgelopen jaren zijn er steeds meer PSI-producten ontwikkeld die toegankelijk zijn voor iedereen. Ze zijn meestal gebaseerd op gratis beschikbare C-Band data van satellietmissies zoals ESA's Copernicus Sentinel-1. Deze beschikbare producten zijn vaak PSI-kaarten die maaiveldverplaatsingen laten zien over grote gebieden. Deze kaarten zijn echter niet geschikt voor een gedetailleerde analyse van een bepaalde locatie. Desondanks worden ze gebruikt voor het beoordelen van verplaatsingen bij specifieke projecten. De gebruikers zijn zich namelijk niet altijd bewust van de beperkingen van het betreffende product aangezien zij vaak slechts beperkte achtergrondkennis hebben van SAR. Aanbevolen wordt om de beperkingen van PSI producten duidelijk te communiceren.

In het tweede deel van dit onderzoek wordt ingegaan op een van de aanbevelingen uit het eerste deel, namelijk dat civiel- en geotechnische ingenieurs basiskennis van de InSAR techniek moeten verkrijgen om de data beter te kunnen toepassen. Een manier hiervoor is het ontwikkelen van praktische richtlijnen voor het gebruik van InSAR in projecten. Hiervoor is eerst onderzocht hoe InSAR kan worden gebruikt in overeenstemming met de bestaande geotechnische ontwerpcodes codes, zoals de Eurocode-7, de Europese norm voor het ontwerpen van geotechnische constructies. Uit deze evaluatie blijkt dat InSAR goed toepasbaar is bij de vereiste geotechnische activiteiten in alle fases van een project. In de ontwerpfase kan historische SAR data inzicht bieden in vroegere en huidige verplaatsingen van een gebied en kan de data zones met afwijkende verplaatsingen identificeren. Met deze informatie kan toekomstig grondonderzoek effectiever worden gepland. Tijdens de bouw- en gebruiksfase is InSAR een aanvulling op de conventionele monitoring, dankzij de hoge temporele en ruimtelijke dichtheid van de metingen. Uiteindelijk is een richtlijn ontwikkeld die aansluit bij Eurocode 7, voor het gebruik van InSAR in geotechnische projecten.

Het laatste deel van dit onderzoek gaat in op twee specifieke toepassingen van InSAR. De eerste toepassing is stedelijke tunnelbouw. De tweede toepassing gaat over het gebruik van Persistent Scatterer Interferometry (PSI) producten voor de beoordeling van alpiene permafrostgebieden.

In tunnelbouwprojecten kan InSAR gebruikt worden voor het monitoren van maaiveldzakkingen voor, tijdens en na de bouw. Ten eerste levert InSAR verplaatsingsdata buiten het gebied van de conventionele meetpunten. Ten tweede levert InSAR ook verplaatsingsdata voordat en nadat de traditionele terrestrische monitoring is uitgevoerd. Dit is waardevolle aanvullende informatie. Echter, een specifieke beperking bij tunnelprojecten, waar abrupte verzakkingen over korte ruimtelijke afstanden kunnen optreden, is het correct vaststellen van het faseverschil van de

SAR data. Om in zo een situatie het correcte faseverschil tussen SAR opnames te bepalen is voorkennis nodig van de verwachte verzakking. Dit onderzoek toont aan dat analytische zettingsvoorspellingen kunnen worden gebruikt om het meest waarschijnlijke faseverschil te bepalen. De voorgestelde methode om het meest waarschijnlijke faseverschil te selecteren kan helpen om InSAR te integreren in het monitoringsprogramma van meer civieltechnische projecten.

PSI-kaarten worden steeds vaker gebruikt voor het detecteren van verplaatsingen in hoogalpiene gebieden. In dit onderzoek is het gebruik van een Sentinel-1-gebaseerde PSI-kaart voor de detectie van verplaatsingen in permafrostgebieden in Kanton Wallis in Zwitserland beoordeeld. Aan de hand van deze PSI kaart is aangetoond dat de gemiddelde verplaatsingen groter zijn in zones die als permafrost zijn geclassificeerd dan in gebieden zonder permafrost. Dit komt overeen met de verwachting dat permafrost gebieden meer bewegen. Tegelijkertijd laat dit onderzoek ook zien dat regionale PSI-kaarten niet geschikt zijn voor het monitoren van gebouwen en infrastructuur in permafrost omdat de resolutie van C-band data hiervoor onvoldoende is. Echter, aangezien er op grote hoogten en in afgelegen gebieden vaak weinig andere monitoringsgegevens beschikbaar zijn, kunnen regionale PSI-kaarten wel worden gebruikt als waardevolle aanvullende informatiebron.

Contents

Chapter 1

Introduction

1.1 Research Rationale

Natural hazards and construction activities can cause ground deformations. If these ground deformations occur in populated regions, in areas that are frequented by people, or in areas with infrastructure, they may pose a risk to persons, structures and the economy. To evaluate these hazards, the spatial extent, the magnitude, the direction, and the temporal change of these deformations need to be known.

In the current practice, in-situ field tests and terrestrial monitoring are performed to obtain information about ground deformations. The most common investigation methods are in-situ intrusive field tests, soil sampling, geophysical tests, traditional ground-based measuring and geodetic surveying techniques. However, intrusive soil investigation such as boreholes, inclinometers, extensometers, piezometers, tilt-meters and crack measuring pins only contain local point or line data (Mazzanti, 2017) and do not have a large spatial and temporal coverage. This is also true for conventional geodetic methods, such as total stations, theodolites, and photogrammetric cameras (Mansour et al., 2011; Bru et al., 2018). Moreover, most of these investigations require physical access to the area, and frequent measuring is time-consuming, labour-intensive and especially challenging in remote and poorly accessible areas (Huang Lin et al., 2019). Additionally, in case of monitoring structures, often the monitoring is stopped after construction and no long-term post-construction monitoring data is available. Also, the data often only becomes available after the start of a surveying campaign and does not provide information about past events.

A monitoring technique that has proven its value to assess deformations in a large area without the need for physical access of material and people is Interferometric Synthetic Aperture Radar (InSAR) (Crosetto et al., 2016a; Ferretti et al., 2002; Hanssen, 2001; Gabriel et al., 1989; Massonnet et al., 1993). This method uses radar mounted on a satellite to detect deformations of the earth's surface. As the satellite passes over the same area every couple of days or weeks, the same area can be looked at repeatedly. Radar acquisitions of the same resolution cell on the ground, collected at different times and different locations in space, can be compared and differences in earth deformation between the acquisitions can be derived. With many acquisitions in time of the same area, deformation time series can be produced.

The advantages and challenges of this technique for monitoring ground deformations have been elaborated extensively in scientific literature and the possibilities of InSAR for civil-, geo-engineering and natural hazard projects are well established. See Chapter 2 for an overview of successful InSAR applications in engineering practice. However, based on experiences and meetings with potential InSAR users, it is observed that although the opportunities for using InSAR in civil engineering projects are huge, this technique is still not a commodity in the civil engineering industry, and many potential users do not use the technique yet. Moreover, it is hypothesised that there is still limited insight into why the technique is successfully used in projects in practice and why, in other cases, it hampers the use or even fails. Do clients have different expectations of an InSAR product than InSAR providers? Is InSAR still not widely known in the civil-, geo-engineering and natural hazard community yet? Are there biases about the intrinsic characteristics of the technique? Are the technical challenges of the technique preventing a successful application?

Understanding the factors that enable or hamper the adoption of InSAR in practice is important. By knowing the causes, solutions and recommendations for improvement can be provided. This allows the civil- and geo-engineering industry and the natural hazard experts to exploit the full potential of the InSAR technique and benefit better from its advantages for monitoring natural hazards and structures.

1.2 Research Aim

In this research, the implementation of InSAR in operational civil and geotechnical engineering projects and in the natural hazard evaluation practice is investigated. This research aims to identify the factors that influence the deployment of InSAR in such projects. Based on the outcome, solutions and guidance for stakeholders for a successful and effective implementation of InSAR in civil engineering, geo-engineering and natural hazard projects will be provided. Moreover possibilities to overcome some of the challenges will be presented.

This research aim is translated into four research questions.

1. The first objective of this research is to identify technical and non-technical factors that influence the adoption of InSAR in civil-, geo-engineering and natural hazards projects.

   Research question 1:
   What factors influence a successful InSAR deployment in civil engineering, geo-engineering or natural hazard projects?

2. Our second objective is to help bring together the fields of InSAR on the one hand, and civil engineering, geotechnical engineering and natural hazards on the other, for practical application in projects by developing an operational framework that shows how InSAR can be combined with current geotechnical design codes at all stages of a project. So far, no systematic and generally accepted embedment of InSAR into the established procedures in the engineering practice, such as the geotechnical design codes, exists.

   Research question 2:
   How can InSAR be used in a way that is compatible with the existing geo-engineering design codes?

3. One of the technical challenges which prevents the successful use of InSAR may be the phase ambiguity in projects where abrupt settlements over short spatial distances with magnitudes close to the wrapping threshold may occur. For example, these sudden settlements can happen during tunnelling construction works. Our third objective is to present a method for determining the correct ambiguity level making the technique useful in tunnelling projects.

   Research question 3:
   How can the ambiguity problem be solved for a real tunnelling project and provide a method to use InSAR effectively for the assessment of ground deformations in similar tunnelling projects?

4. Freely available SAR data from satellite missions such as the ESA Copernicus Sentinel-1 mission provide new opportunities for wide-area ground motion detection and monitoring. Readily available public datasets, e.g. Persistent Scatterer Interferometry (PSI) products, have been produced in the past years and this data is used for hazard assessments by geo-engineers, asset managers and stakeholders, especially in remote and difficult accessible areas. One type of PSI products are PSI maps. However, these maps are application-agnostic, meaning that they are not optimised for a particular application or location. This is not always known by the users of these products. The fourth objective

is to assess the possibilities and challenges of freely available InSAR data for assessing natural hazards for one particular type of area, namely permafrost areas in the Alps.

Research question 4:
What are the possibilities and obstacles of free available Sentinel-1 based Persistent Scatterer Interferometry (PSI) maps for alpine permafrost detection in the Swiss Alps?

1.3 Research Setting

1.3.1 Civil- and Geo-engineering

The topic of this research is in the field of civil- and geo-engineering. This is a broad field with many challenges. For example, the construction of new structures can have an impact on the existing environment and buildings. Ground subsidence due to construction and groundwater extraction can lead to settlement, threatening building integrity and infrastructure. Especially in urban areas, where space is scarce, new structures cannot be planned without considering the existing situation. Therefore the environment needs to be considered at the design stage and monitored prior, during and after construction. Also the condition of existing structures is a current problem. Many structures, such as bridges, tunnels, roads and water systems, were built decades ago and may be deteriorating over time due to the effects of the environment or more traffic than they were designed for. This ageing infrastructure needs to be monitored in order to decide on measures such as retrofitting or renewal to ensure they remain safe, functional, and capable of serving modern needs. Further, natural hazards such as landslides, floods, ground deformations, permafrost degradation, and earthquakes can have a significant impact on new and existing structures, resulting in damage, deterioration or complete destruction. Monitoring deformation in areas prone to such natural hazards, and knowing historical ground movements, provides an understanding of the hazard. This is important information when planning and designing new infrastructure or adapting existing structures in such a region. The above list is only a brief overview of some of the challenges and is certainly not exhaustive. However, it gives an idea of the context and importance of this research.

1.3.2 Interface of Disciplines

This research discusses the commercial and operational applications of the InSAR technology to address the challenges outlined in the previous section. This means that this research is in the field of applied research and at the interface between different disciplines. As knowledge of these different disciplines is needed, working on the interface of disciplines comes at the expense of in-depth knowledge of each discipline. First, expertise in civil- and geo-engineering is required. Civil engineers are concerned with the design, construction and maintenance of the built and natural environment and require knowledge of structural mechanics, hydraulics, building materials, construction methods and the environmental impact of structures (non-exhaustive list). Geotechnical engineers deal with the behaviour of earth materials, the determination and description of the technical properties of the subsoil, and soil mechanical calculations when building on or in the ground. Engineering geology is also involved and requires knowledge of the behaviour of near-surface loose and solid soils and rocks, geological structures, and the mechanical and hydraulic processes and properties of earth materials. In addition, the assessment of potential natural hazards, i.e. environmental phenomena that have the potential to affect society and the human environment, is a key skill within the field.

Then, this research requires knowledge about geodesy, which is the discipline that is concerned with accurately measuring the earth's size, shape, orientation, mass distribution and how these vary with time. One geodetic technique is Interferometric Synthetic Aperture Radar (InSAR), which can be used to represent quantitative estimates of geometry and geometry changes, in the unit metre, with quality descriptions using variance-covariance matrices. This requires knowledge about radar data, statistics, handling large amounts of data and modelling and interpreting the data (non-exhaustive list).

Besides the technical disciplines, expertise from the human sciences is needed for this research. Qualitative research methods, as used in psychological and social studies, are used and a basic understanding of business development and innovation processes are required.

Working on the interface of disciplines means understanding different languages and working outside established standards, which can be challenging. However, in the working environment, projects are often multidisciplinary, involving experts from various working fields, and therefore, for solving today's real-world problems, interdisciplinary research is necessary. The present research is important because it deals with actual practical problems in industry and bridges the gap between different disciplines.

1.4 Research Methods and Outline

The following research activities are performed to address the research aim and questions.

1. Identifying knowledge gaps based on the scientific literature.

   The application possibilities, advantages, and potential of Interferometric Synthetic Aperture Radar (InSAR) for monitoring ground deformations in civil- and geo-engineering projects and natural hazard evaluation have been extensively researched in the scientific literature. However, despite the large amount of literature, few papers exist that describe the non-technical aspects that may influence a successful or unsuccessful deployment of InSAR in geo-engineering projects. In this research, an overview of the currently available literature, including the technical benefits and challenges of InSAR and the non-technical factors influencing a successful InSAR deployment, are provided. Moreover, the implementation of innovations in other industries is looked at. See **Chapter 2**

2. Revealing success factors and challenges of practical InSAR deployment.

   Live interviews with InSAR users and InSAR providers, using a semi-structured interview format, are performed to examine how and why InSAR is successfully or unsuccessfully applied in their geo-engineering projects. Questions are asked about why potential users, clients and stakeholders do, or do not consider the use of InSAR and where it hampers when the technique is being considered and could be beneficial.

   The format of a semi-structured interview is a qualitative research method that combines a pre-determined set of open-ended questions and encourages discussion. The interviews are transcribed, and then recurring patterns, themes, and insights are identified (Mayring and Fenzl, 2019). The goal is to identify key themes across the qualitative data results. Then this information is included with the literature study to obtain an overview of the success criteria and critical success factors of an InSAR deployment in geo-projects. Finally, the data is interpreted, conclusions are drawn and recommendations are summarised. The results are presented in **Chapter 3**

3. Providing a framework for deployment of InSAR in agreement with geotechnical design codes.

   The interviews show that despite the possibilities, the use of InSAR is not yet standard practice in geotechnical projects. Also, the CIRIA report C805 with title InSAR and Earth Observation techniques for infrastructure (Mason et al.,

2022) shows only very limited how InSAR can be systematically and routinely used in all project phases or how it can be combined with a soil investigation program to develop a geological model and assess the geological hazards.

However, in the planning stage of new infrastructure or when designing the renovation of existing infrastructure, information about existing movements is essential to make informed design decisions. InSAR techniques can be of value to identify these risks. This research evaluates how InSAR can be used in all project phases, from desk study to operation and maintenance. The established standard procedures within the geotechnical design codes, such as the Eurocode-7 European Committee for Standardization (2020), are assessed, and it is analysed how InSAR can be implemented within the required activities and can contribute to monitoring activities.

In **Chapter 4** an operational framework is provided for the practical integration of InSAR monitoring into current geotechnical design codes, such as Eurocode-7, for all project stages. The proposed framework is also demonstrated for the use of Sentinel-1 data in 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. Chapter 4 is already published under:

Reinders, K.J., Giardina, G., Zurfluh, F., Ryser, J., Hanssen, R.F., 2022. Proving compliance of satellite InSAR technology with geotechnical design codes. Transportation Geotechnics 33, 100722.

4. Possibilities of InSAR when assessing ground settlements induced by tunnelling construction.

The applicability of InSAR in tunnel projects has already been demonstrated in the scientific literature (Ramirez et al., 2022; Bischoff et al., 2019; Giardina et al., 2019; Barla et al., 2016; Schindler et al., 2016; Mark et al., 2012) and guidelines (Schneider et al., 2015). This showed that InSAR can be used for (i) the detection of tunnelling-induced settlements, resulting in localization and timing of the settlement, complemented by (ii) an estimation of the quantitative amount of settlement. Particularly for long-term settlements, occurring years to decades after the construction phase ends (Shirlaw, 1995; Mair, 2008; Wongsaroj et al., 2013), InSAR is probably the only economically feasible monitoring option.

However, resolving the correct ambiguity level in InSAR data can be challenging, especially in the case of abrupt settlements over short spatial distances with magnitudes close to the wrapping threshold. In this research, the applicability of InSAR prior to, during, and after tunnel construction is evaluated with special emphasis on the influence of the InSAR phase ambiguities in relation to short-term settlements that may occur during tunnel construction.

As case study, the twin shield tunnels of the north-south metro line in Amsterdam that were excavated in 2011 and 2012 are used to demonstrate the applicability. Surface settlements larger than or close to the wrapping threshold occurred during this project.

This is outlined in **Chapter 5** and already published under:

Reinders, K.J., Hanssen, R.F., van Leijen, F.J., Korff, M., 2021. Augmented satellite InSAR for assessing short-term and long-term surface deformation due to shield tunnelling. Tunnelling and Underground Space Technology 110, 103745.

5. Possibilities of freely available persistent Scatterer Interferometry (PSI) products for permafrost assessment

   Freely available SAR data from satellite missions such as ESA's Copernicus Sentinel-1 have made InSAR technology even more accessible, and PSI products are being created and made available to a wider public. These PSI products, in particular the PSI maps, are used by the non-InSAR community, such as authorities, engineering companies, geologists, asset managers, energy service operators, surveying companies, mining and oil and gas industry, insurance providers, research centres, universities and also citizens (Crosetto et al., 2020). However, these maps are 'application agnostic', which means they are not optimised for a specific application or location. Users may not always be aware of the limitations of these maps.

   In **Chapter 6** the use of freely available Sentinel-1 data and a publicly available PSI maps for geo-engineers for one specific application, i.e. permafrost in the Swiss alps, are evaluated. Based on the Sentinel-1 PSI map of Canton Wallis in Switzerland (Kanton Wallis, 2022) ground deformation trends estimated from this map are examined and it is assessed whether those can be correlated with the known permafrost zones, as mapped in the permafrost and ground ice map (PGIM) of the Swiss Institute for Snow and Avalanche Research (Kenner et al., 2019; SLF, 2019). Also the use of these maps for monitoring structures and infrastructures in permafrost is evaluated. Chapter 6 is submitted to the journal The Cryosphere.

   Submitted: Reinders, K.J., Verhoeven, G.F., Sartorelli, L., Hanssen, R., Manconi, A., 2023. Exploring the use of sentinel-1 to monitor spatial and temporal evolution of permafrost in the swiss alps. EGUsphere 2023, 1–21.

6. **Chapter 7** includes the overall discussion.
7. In the final **Chapter 8** the conclusions are presented and recommendations to improve the deployment of InSAR in civil-, geo-engineering and natural hazard projects are provided.

Chapter 2

Literature Study

2.1 A Short Introduction to InSAR

Synthetic aperture radar (SAR) is a geodetic technique that can measure displacements of the ground or objects on it (Elachi, 1987). Satellite SAR data is produced with a side-looking imaging radar mounted on a satellite that sends pulses of electromagnetic waves to the earth. See Fig. 2.1.1 and 2.1.2. Part of these pulses reflect back towards the satellite's antenna and the amplitude and the phase of the incoming signal are recorded. The amplitude is a measure of the magnitude of the reflected signal. The phase depends on the two-way travel time of the signal. Based on the phase difference between images taken over the same region by subsequent satellite passes, ground surface movements in time can be derived. This imaging technique of superimposing waves from subsequent images is called interferometry. The technique of combining two or more SAR images of the same region to reveal surface topography or motion is called Interferometric synthetic aperture radar (InSAR). So far SAR satellites are in near-polar sun-synchronous orbits, which means that these satellites travel from north to south on the descending part of the orbit and then from south to north on the ascending part of the orbit around the Earth.

One specific class of InSAR methods is Persistent Scatterer Interferometry (PSI). PSI combines multiple images over the same area, resulting in mean surface velocity maps and displacement times series (Hanssen, 2001; Ferretti et al., 2007). This approach exploits reflections from objects. A reflection from the ground may stem from two types of scatterers, i.e. distributed scatterers (DS) and point scatterers (PS). PS are pixels which have one dominant reflecting object within the pixel's footprint. DS are pixels which contain multiple objects.

SAR systems have existed for more than 40 years but especially since the nineties, the use of radar interferometry to measure changes in the Earth's surface has increased (Massonnet and Feigl, 1998). Section 2.3.1 provides an overview of possible applications.

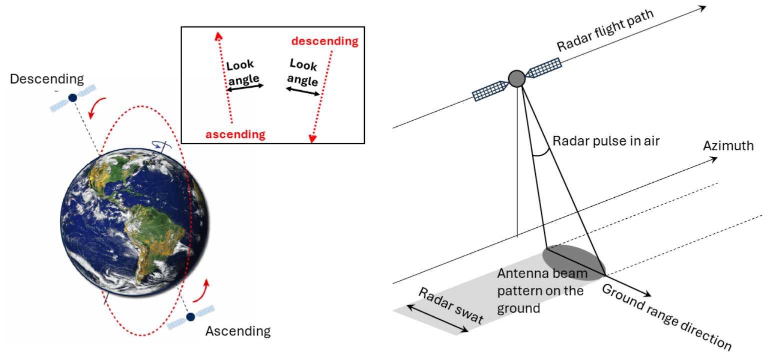

Figure 2.1.1: Graphic representation of descending and ascending orbits (left). Imaging geometry for a side-looking radar system (right).

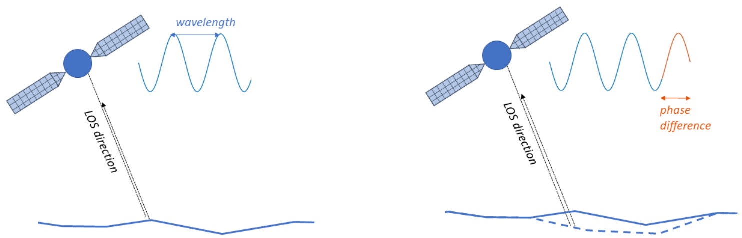

Figure 2.1.2: Two sequential InSAR measurement before and after surface deformation (after Özer et al. (2019)). The LOS is the line of sight direction of the radar signal and usually also called the slant-range direction.

2.2 Reflection on the Literature on InSAR Applications

In the scientific community an enormous number of papers have been published on the topic of Interferometric Synthetic Aperture Radar. The first articles about InSAR appear in the nineties. Since then, the amount of articles increased steadily, but especially since 2018, the amount has taken a leap. In Fig. 2.2.1 the number of articles according to Scopus are presented for the following search:

TITLE-ABS-KEY ("SAR" OR "DInSAR" OR "InSAR" OR "MT-InSAR" OR "Interferometric Synthetic Aperture Radar" OR "Interferometry" OR "PSI") AND TITLE-ABS-KEY ("subsidence" OR "settlement") AND PUBYEAR > 1999 AND PUBYEAR < 2025

The figure shows an increase in the number of published articles per year. A total amount of around 5500 documents were found in Scopus, only for the topic of InSAR in combination with ground settlements.

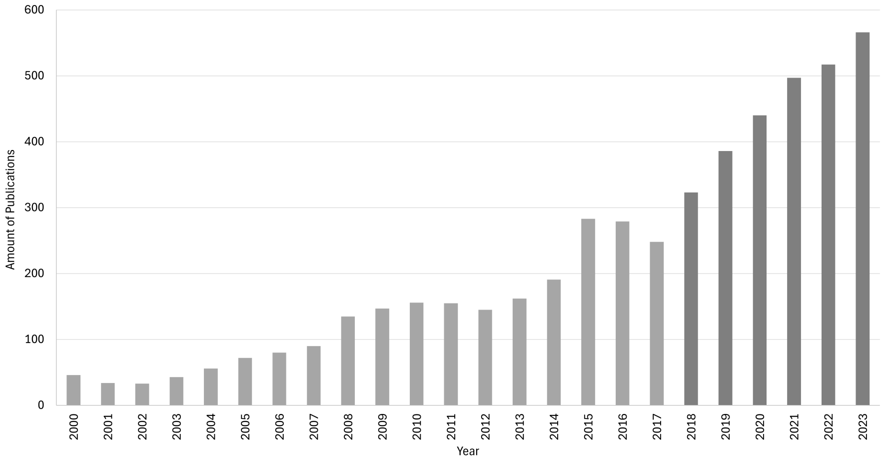

Figure 2.2.1: Amount of publications on the topic of InSAR and ground settlements.

When also including landslides, slope stability, natural hazards, geotechnical and structural engineering, geology and permafrost, but restricting the search to English papers and to papers in engineering, environmental science and earth and planetary science, the amount increases to more than 10000 publications with the following search:

TITLE-ABS-KEY ("SAR" OR "DInSAR" OR "InSAR" OR "MT-InSAR" OR "Interferometric Synthetic Aperture Radar" OR "PSI") AND TITLE-ABS-KEY ("landslides" OR "subsidence" OR "settlement" OR "slope stability" OR "natural hazard" OR "geotechnical" OR "geology" OR "structural engineering" OR "permafrost") AND (LIMIT-TO (SUBJAREA,"EART") OR LIMIT-TO (SUBJAREA,"ENGI") OR LIMIT-TO (SUBJAREA,"ENVI")) AND (LIMIT-TO (LANGUAGE,"English"))

This amount is too large to assess completely and a selection based on personal judgment of peer-reviewed papers closely related to the research topic was made. 2.3.1 comprises the literature study with the assessed articles.

It is observed that the abstracts often do not contain information regarding the obstacles of InSAR for practical applications. In abstracts, often the ‘potential’ is mentioned, ‘further investigation’ is recommended, ‘future opportunities’ are mentioned, or formulations such as ‘satellite-based monitoring techniques may help’, ‘this paper shows the use of InSAR for…’. Even when in research or projects InSAR did not give the expected result, the authors still mention the ‘potential’ and do not highlight the challenges in the abstract. Challenges are often only mentioned in the discussion and conclusion part of papers. In the literature study, no articles with case studies in which InSAR was not successfully applied were found. It is hypothesised that all this leads to a strong positive bias regarding the InSAR technology.

Finally, the literature does not include personal experiences of InSAR users and providers and no qualitative data, such as interviews or questionnaires, is available. The scientific articles are always based on SAR data and the possibilities of using the data for specific applications. Only the CIRIA Report 805 (Mason et al., 2022) has performed a questionnaire survey among potential users to gauge the experience and current application areas of the use of several earth observation methods.

The next section provides an overview of the assessed literature.

2.3 Literature Review on InSAR Applications

2.3.1 InSAR Applications in Practice

According to Biggs and Wright (2020), the past 10 years, InSAR has become a global monitoring tool with enormous potential, which provides relevant information about the earth’s surface deformation. Interferometric synthetic aperture radar can be used to detect temporal and spatial changes and trends in ground deformations. Especially, the use of SAR data for **landslide monitoring** and detection is extensively researched. InSAR and PSI were used for the verification and updating the **state of activity of known landslides** (Antonielli et al., 2019; Crosetto et al., 2018; Bianchini et al., 2012), **identification of active landslide areas** Huang Lin et al. (2019), **identification of the precise boundaries of an actively moving landslide** (Greif and Vlcko, 2012), **estimation of the kinematic behaviour of landslides** (Frattini et al., 2018) and **monitoring of very slow landslides** (Herrera et al., 2013). Moreover, InSAR retrospective analyses show that InSAR could have been able to **reveal precursors prior to a catastrophic slope failure** (Carlà et al., 2019). More recently, Mondini et al. (2021) performed an extensive literature study and investigated the scientific literature between 1995 and 2020 on the identification and mapping of landslide failure events with InSAR. They conclude that InSAR is a valuable asset to identify and map unstable areas, provided the presence of sufficient scatterers.

Also, for **subsidence observation**, InSAR was used. **Historic ground settlement rates in urban areas** between 2014-2015 and 2020 (Wu et al., 2022; Cigna and Tapete, 2021) were identified and SAR data from the past 20 years was used to assess **subsidence in areas prone to settlements** (Wu et al., 2020; Bonì et al., 2015). Moreover, **historic deformations at a single-building scale in combination with ground settlements** were detected (Minderhoud et al., 2020; Cigna et al., 2014). Recently, Raspini et al. (2022) performed a review of more than 1000 papers in the available literature on the use of satellite SAR imagery for subsidence analysis. They show that satellite interferometry has been largely used to **detect, map and quantify subsidence in urbanised areas**. However most studies have focused on retrospectively, back-analysing of already established motion in areas where it is known that there is subsidence. Their literature study reveals that dynamic monitoring and prediction of ground displacement remains uncommon in literature.

Other natural hazards such as **volcanic and tectonic-related surface deformations**(Ducrocq et al., 2021; De Novellis et al., 2019; Milillo et al., 2015; Kobayashi et al., 2015; Tizzani et al., 2013; Massonnet et al., 1993) and **degradation of permafrost areas** (Wang et al., 2023; Liu et al., 2022; Li et al., 2021; Abe et al., 2020; Rouyet et al., 2019; Daout et al., 2017; Liu et al., 2015; Barboux et al., 2013) were assessed with this technique.

The SAR data has also been used to assess **building damage and perform structural health monitoring of buildings** (Macchiarulo et al., 2021; Venmans et al., 2020; Giardina et al., 2019; Milillo et al., 2018; Zhu et al., 2018; Cerchiello et al., 2017; Peduto et al., 2017b; Béjar-Pizarro et al., 2017; Ciampalini et al., 2014) and **bridges** (Tonelli et al., 2023; Cusson et al., 2021; Selvakumaran et al., 2018; Milillo et al., 2019; Peduto et al., 2018; Sousa et al., 2014). Moreover **monitoring of transport infrastructure such as roads** (Macchiarulo et al., 2022; Bianchini Ciampoli et al., 2020; Nappo et al., 2019; Infante et al., 2018; Cerchiello et al., 2017; Yu et al., 2013) and **railways** (Hu et al., 2019; Wang et al., 2018; Chang et al., 2018; Qin et al., 2017; Chang et al., 2016) and **monitoring of settlements caused by tunnelling works** (Ramirez et al., 2022; Bischoff et al., 2019; Barla et al., 2016; Schindler et al., 2016; Mark et al., 2012) was performed.

InSAR was also used to assess the **deformations and settlements of dams and levees** (Aswathi et al., 2022; Roque et al., 2021; Özer et al., 2019; Peduto et al., 2017a; Milillo et al., 2016b,0; Sousa et al., 2014; Hanssen and Van Leijen, 2008). For **tailing dams**, the comparison of InSAR results to prism monitoring and finite element models showed that InSAR was able to capture spatial and temporal variability of the dam deformations, which which was not possible with traditional point-based prism monitoring (Bayaraa et al., 2022). **Post-mining ground deformations** were revealed with InSAR (Declercq et al., 2023), **retrospective analyses of slope instability in open pit mines** were performed (Carlà et al., 2018), and with InSAR, an **improved understanding of existing geotechnical hazards** was possible (Bar and Dixon, 2021). Also, using InSAR for **baseline assessments in projects** has been proven (Mason et al., 2022; Scoular et al., 2020; Bischoff et al., 2019). InSAR was used to **complement in-situ monitoring techniques**, for example by combining it with data obtained with automated total station, ground penetrating radar data or ground-based global navigation satellite system (GNSS) data (Fabris et al., 2022; Selvakumaran et al., 2020; D'Amico et al., 2020; Venmans et al., 2020).

Due to the large historical archive of data, **hindcasting and forensic engineering** can be performed and deformation of the past can be detected (Korff et al., 2022; Mason et al., 2022). This enables the study of past structural failures and construction incidents for which monitoring data is unavailable.

Recently, CIRIA, the Construction Industry Research and Information Association in the United Kingdom, has provided an introductory guide for using earth observation techniques in infrastructure projects (Mason et al., 2022). This report provides an overview of different earth observation techniques and their capabilities and guidance for using the most suitable earth observation technique for a project. CIRIA investigated the experiences, readiness and satisfaction with the different technologies for the use of earth observation technologies by sending a questionnaire to the infrastructure community. Concerning InSAR, the most common applications mentioned by the 50 respondents were bridges, tunnels, buildings, highways, railways, dams and slope instabilities. In general, satisfaction among those who had used InSAR was very high. The most common complaints of the respondents were low spatial resolution and insufficient measurement points, low precision and accuracy and low imaging frequency.

Finally, freely available SAR data from satellite missions such as the ESA Copernicus Sentinel-1 mission have become accessible. This data provides new opportunities for wide-area ground motion detection and monitoring. More and more **regional and national scale publicly available Persistent Scatterer Interferometry (PSI) maps** are being produced (Crosetto et al., 2020; Dehls et al., 2019), which makes the results available for a wider public. Examples of regional publicly available Persistent Scatterer Interferometry (PSI) maps are (NCG, 2022; Kanton Wallis, 2022; WSP and Skygeo, 2021; NGU et al., 2018; BGR, 2021; UNIFI, 2022). Also, the European Ground Motion Service (EGMS) provides ground deformation over most of Europe, based on Sentinel-1 SAR data (EGMS, 2022). However, these maps are 'application-agnostic', indicating that they are not optimised for a particular application or location. In most cases, data from publicly available PSI maps are only suitable for semi-quantitative historical analysis and are of very limited use for monitoring as these maps are only updated annually (Ronczyk et al., 2022). Despite this, tools and methodologies for the automatic detection of areas prone to displacements and the generation of potential damage maps based on these PSI displacement maps are being produced, accessible to non-expert InSAR users (Crosetto et al., 2023; Barra et al., 2022), who may or may not be aware of the appropriate application possibilities and correct interpretations.

2.3.2 Technical Benefits

The possibilities and benefits of InSAR for civil- and geo-engineering applications and for monitoring natural hazards are elaborated in the literature listed in the previous section. This section provides a short summary of the benefits of InSAR based on the literature. InSAR can

- provide accurate displacement point measurements over wide areas at fine spatial resolution, even in bad weather conditions and at night (Bar and Dixon, 2021; Tomás et al., 2014).
- provide data outside the area of the conventional surveying benchmarks (Ramirez et al., 2022).
- Provide data in remote areas that are difficult to access without the need for people and equipment on site (Aswathi et al., 2022; Selvakumaran et al., 2020; Carlà et al., 2019).
- be used for predictive maintenance planning of infrastructure systems (Magnall et al., 2024).
- be used for structural health monitoring (Macchiarulo et al., 2021; Venmans et al., 2020; Giardina et al., 2019; Milillo et al., 2018; Zhu et al., 2018; Cerchiello

et al., 2017; Peduto et al., 2017b; Béjar-Pizarro et al., 2017; Ciampalini et al., 2014; Tonelli et al., 2023; Cusson et al., 2021; Selvakumaran et al., 2018; Milillo et al., 2019; Peduto et al., 2018; Sousa et al., 2014).

- be used for baseline assessments at the start of a project (Mason et al., 2022; Scoular et al., 2020; Bischoff et al., 2019).
- reveal precursors and be used as an early warning system (Carlà et al., 2019).
- provide historical ground displacement data (Bar and Dixon, 2021; Tomás et al., 2014).
- be used for hindcasting of deformation of the past, forensic engineering (Korff et al., 2022) and pre-failure analyses (Moretto et al., 2021).
- complement in-situ monitoring techniques (Fabris et al., 2022; Selvakumaran et al., 2020; D'Amico et al., 2020; Venmans et al., 2020).

2.3.3 Technical Obstacles

Most of the cited articles highlight the advantages and potential of Interferometric Synthetic Aperture Radar. However, some articles also emphasise the technical obstacles of InSAR clearly (Casagli et al., 2023; Aswathi et al., 2022; Macchiarulo et al., 2022; Schlögl et al., 2022; Mondini et al., 2021; Moretto et al., 2021; Manconi, 2021; Carlà et al., 2019; Hu et al., 2019; Antonielli et al., 2019; Crosetto et al., 2016a; Selvakumaran et al., 2018; Chang et al., 2016; Sousa et al., 2014; Cigna et al., 2013; Barboux et al., 2013; Colesanti and Wasowski, 2006; Metternicht et al., 2005) and also the constraints of national persistent scatterer interferometry (PSI) maps are described (Ronczyk et al., 2022). Especially Schlögl et al. (2022), Wasowski and Bovenga (2014) and Colesanti and Wasowski (2006) list the technical challenges and the data interpretation issues that have to be taken into account when using SAR interferometry for the assessments of displacements. The most important technical obstacles are:

- Locations and distribution of monitoring points are unknown in advance and their position cannot be chosen freely in advance. It is an opportunistic method (Macchiarulo et al., 2022; Aswathi et al., 2022; Crosetto et al., 2016a; Wasowski and Bovenga, 2014) and the land use influences the detection of viable reflectors. Also decorrelation can occur. The loss of coherence is especially more likely if the area of interest is vegetated, covered with snow, or if excessive landslide deformation has occurred and the terrain is destructed (Casagli et al., 2023; Magnall et al., 2024; Antonielli et al., 2019; Wasowski and Bovenga, 2014; Cigna et al., 2013; Colesanti and Wasowski, 2006; Metternicht et al., 2005).

- The maximum detectable deformation depends on the combination of the wavelength and the spatial and the temporal displacement gradients (Macchiarulo et al., 2022; Mason et al., 2022).
- Unwrapping errors can occur when processing the data due to the phase ambiguity (Macchiarulo et al., 2022; Aswathi et al., 2022; Manconi, 2021).
- Correctly associating monitoring points to the corresponding structure may be difficult as the precision and accuracy of the geolocation of scatterers is usually poor (Hu et al., 2019; Macchiarulo et al., 2022).
- Real-time monitoring and prediction are not possible if the precursors are too instantaneous with respect to the satellite revisit time (days to weeks) or if the area is too small for the spatial resolution of the sensor (Ramirez et al., 2022; Raspini et al., 2022; Carlà et al., 2019).
- The displacements are projected onto the Line of Sight (LoS) of the satellite. To convert these LoS displacements into a horizontal and vertical component, data from an ascending and descending orbit at the same location are necessary (Brouwer and Hanssen, 2023; Mondini et al., 2021).
- Geometric distortion, such as layover and foreshortening affect the correct association of monitoring points to the corresponding structure or areas. No SAR signal is detected in radar shadows (Macchiarulo et al., 2022; Aswathi et al., 2022; Antonielli et al., 2019; Barboux et al., 2013; Colesanti and Wasowski, 2006).
- Because of its near-polar orbit, the Sentinel satellite mission is well-suited to detect east-west displacements. However, its sensitivity to translational displacements along the north–south direction is limited (van Natijne et al., 2022a; Mason et al., 2022; Wasowski and Bovenga, 2014).
- SAR data availability is unevenly distributed around the globe (Crosetto et al., 2018).
- Choosing a stable reference point is impossible and the stability of the reference point is unknown. Although the location of a reference point can be known from independent GNSS or other in-situ measurements, the point can be affected by periodic displacements or has undergone deformation. This will then propagate to other coherent target time series as any displacement value is relative to this reference point (Wasowski and Bovenga, 2014).

2.3.4 Non-Technical Factors Influencing a Succesfull InSAR Deployment

A small number of publications identify other challenges, in addition to the technical ones. According to Mondini et al. (2021) two important challenges are the **lack of experienced image interpreters** and the **lack of standards for the quality assessment of the InSAR results and products**. Also, Crosetto et al. (2016b) state that PSI exploitation is often done by non-PSI experts who may not be aware of the technical challenges mentioned in section 2.3.3. Wasowski and Bovenga (2014) write that the extent to which SAR data can be successfully used depends on the **users' background knowledge of the technique and on the user's ability to correctly interpret SAR results** and to extract useful information. Mondini et al. (2021) state that, to be successful, an operational landslide detection and mapping service has to rely on a **team that can cover multiple areas of expertise** including, e.g., geodesy, visualisation, machine learning, geomorphology, landslide interpretation and analysis'. Raspini et al. (2022) state that a **common interest within the wide community of end users and decision makers** for a systematic exploitation of SAR imagery is missing. Also Macchiarulo et al. (2022) mention that the **lack of independent criteria for the assessment of the quality and reliability of SAR measurements** is a challenge. The authors state that, due to the **required specialised SAR data processing skills**, the accessibility of the technology to the civil engineering industry remains a barrier to the widespread operational use of InSAR. **Inexperienced users may adopt incorrect assumptions or unsuitable input settings when using software packages that process SAR data**, which could compromise the outcome. Chang et al. (2016) states that **handling and homogenizing huge SAR data amounts is challenging** and that **expert knowledge is needed** to identify risk areas. Also Magnall et al. (2024) mentions that **separating the critical information from the background data**, when handling the large data volumes is very difficult for an end-user.

Schlögl et al. (2022) point out the **lack of resources to store and process the data**. According to Crosetto et al. (2016a) there is a **need to increase the processing capability of current PSI algorithms**. Also, the various PSI approaches often **lack a full characterisation of their processing steps** (Crosetto et al., 2016a). Crosetto et al. (2018) mentions that the high **price of very high-resolution imagery** can be an obstacle. Also Mondini et al. (2021) mention that **sufficient computer processing and storage facilities, appropriate processing, modelling and visualization tools** are key issues.

Moreover, Mondini et al. (2021) and Wasowski and Bovenga (2014) write that the success of SAR applications depends on the **availability of sufficient SAR**

imagery, **the availability of additional data, such as digital elevation models, geological information and land-cover maps** and **the suitability of the area of interest in terms of sufficient coverage** by radar satellites.

Finally, the CIRIA Report 805 (Mason et al., 2022) has included the results of a questionnaire survey among potential earth observation users. Concerning the use of InSAR, users were generally satisfied. Only a few respondents had experienced difficulties with managing and interpreting the data or had limited GIS experience to make full use of data and analysis tools.

Summarising, the most mentioned non-technical factors that influence a successful InSAR deployment are the level of knowledge and expertise of SAR data interpreters and potential users, quality standards and criteria for the assessment of the InSAR results, sufficient resources for storage and computation of the data and the price of the images.

2.3.5 Current Recommendations

Technical Recommendations

The scientific literature provides recommendations on how to deal with the technical obstacles. Wasowski and Bovenga (2014) present tables with guidelines in order to mitigate the technical obstacles and avoid erroneous interpretations. They recommend **using both ascending and descending radar datasets, selecting data from other sensors with suitable radar LOS geometry, making a prior estimate about the likelihood of sufficient scatterers in the area of interest, including independent field measurement data and geological data, performing site visits and using satellites with higher revisit times** (non-exhaustive list).

Non-Technical Recommendations

The literature only provides few recommendations to overcome some of the non-technical challenges. Mondini et al. (2021) plead to **improve the cooperation** between radar experts and civil engineers, **adopt standard approaches and interpretation** criteria for landslide detection and mapping, **define uniform methods of quality evaluation**, and provide **examples of best practices**. Also the CIRIA Report 805 (Mason et al., 2022) states that deformation measurements require a set of **commonly adopted standards**. Raspini et al. (2022) recommend that end users and researchers should create **tools to transform InSAR data and geological knowledge into understandable and usable information**. They also recommend to define **standardised methodologies, interpretation criteria and guidelines for data analysis**. Crosetto et al. (2016b) mention that the capability to exploit the PSI results needs to be improved, that there is a need to **properly document and communicate the characteristics of PSI products** and to increase the collaboration between PSI experts and people in charge of the interpretation and exploitation of the PSI results. Macchiarulo et al. (2022) advise to **develop user-ready SAR products** to guide users with no radar experience and to explain the practical impact of different assumptions. Also, data should be provided in a format that is **user-friendly and easily accessible** through standard GIS platforms.

Magnall et al. (2024) state there are knowledge gaps when it comes to correctly interpreting the data and that expertise and training are necessary. The authors recommend to develop the **tools and training for end-users** to understand and exploit the data correctly. They also argue that **machine learning and statistical approaches are needed** to identify critical locations that require further investigation within a large area. Also in the CIRIA Report 805 (Mason et al., 2022) it is recommended that **geotechnical and structural engineering experts should gain some understanding of the methods** by which InSAR data products are derived and should **work iteratively alongside the data processors**, to get the most out of the results. Finally, the CIRIA Report (Mason et al., 2022) recommends that for infrastructure projects, the most straightforward method of validation is to **compare the InSAR time-series with in-situ instruments**, such as levelling, and tiltmeters, if the time periods overlap.

Summarising, the most mentioned recommendations are improving the cooperation between InSAR providers and InSAR users, properly communicating the characteristics of PSI products, employing adequate staff, developing standard approaches and interpretation criteria for SAR data, providing tools for end-users to understand and exploit the data correctly, defining uniform methods of quality evaluation, providing show-cases of example projects,and training end-users to gain understanding of SAR data.

2.4 Diffusion of Innovation

2.4.1 Characteristics of Diffusion of Innovations

This research examines the use of Interferometric Synthetic Aperture Radar (InSAR) technology in the civil-, geo-engineering and natural hazards industries. This technology has been developed over the last 40 years and has since been increasingly adopted by industry and used in practical projects. However, there is no scientific literature available on the diffusion of InSAR technology in the aforementioned industries. Therefore, a literature review on the diffusion of technologies in general is carried out. Rogers and Williams (1983) developed the theory of diffusion of innovation. This model tries to describe how **innovations** are **communicated** over **time** among the members of a **social system**. These four factors are described below.

1. An **innovation** is an idea, behaviour or technology that does not necessarily have to be new, but must be perceived as new by individuals or groups.

2. **Communication** is essential for the diffusion and is defined as the process by which participants create and share information with each other.

3. The **time** dimension is the element in the process that determines the relative earliness/lateness with which an innovation is adopted. This element depends on the *innovation-decision process*, the *innovativeness and adopter categories* and the *rate of adoption*.

    - According to Rogers and Williams (1983), diffusion occurs through a five-step *innovation-decision process*, which are awareness, interest, evaluation, trial and adoption. The awareness stage involves learning that the innovation exists, gaining some comprehension of how it works, and becoming interested in understanding its functions. Then, individuals or groups form a positive or negative view of the innovation. Next, an innovation is adopted or rejected. Finally, the innovation is tested in practice and adopted or not.

    - The degree to which a person or group adopts new concepts relatively sooner than others is known as *innovativeness*. Rogers and Williams (1983) define five categories of adopters: innovators (2.5%), early adopters (13.5%), early majority (34%), late majority (34%), laggards (16%). Innovators are knowledgeable about technology and introduce new ideas into local social systems. Early adopters serve as role models and reduce uncertainty by introducing new products, innovations or technologies. The early majority is a less technologically skilled group and adopts innovations before the average members, often under peer pressure. The late majority is the large group that buys or uses new products only after others have tried them first. They are more sceptical and do not adopt until most others in the system have done so. The laggards are the last to adopt an innovation. See Fig. 2.4.1. The diffusion model follows a more or less normal distribution.

    - The *rate of adoption* is the rate at which a new technology is accepted by a given proportion of the social system. Typically, early adopters of an innovation require a shorter adoption process than late adopters. In addition, once the opinion leaders in the early adopter category adopt, they inform their network. This larger group is then influenced to adopt the new idea. Therefore, most innovations have an S-shaped adoption rate. See Fig. 2.4.2. In the next section the characteristics that influence the rate of adoption are explained in detail.

4. Rogers and Williams (1983) define the **social system** as 'a set of interrelated units engaged in joint problem solving to achieve a common goal'. In our research, the social systems are the civil- and geo-engineering industry, the natural hazards community, companies that are processing and interpreting the SAR data and the academic field of these 3 disciplines.

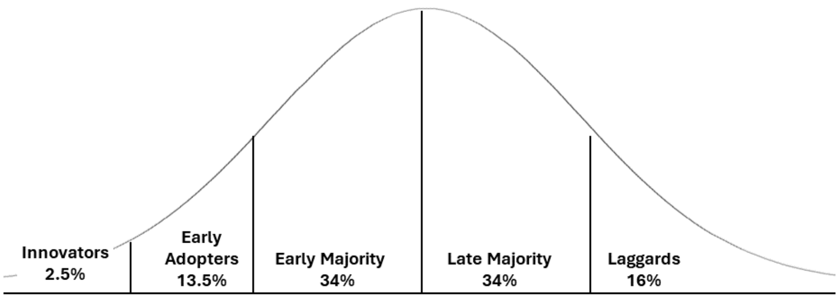

Figure 2.4.1: Adopter categorisation on the basis of innovativeness according to Rogers and Williams (1983).

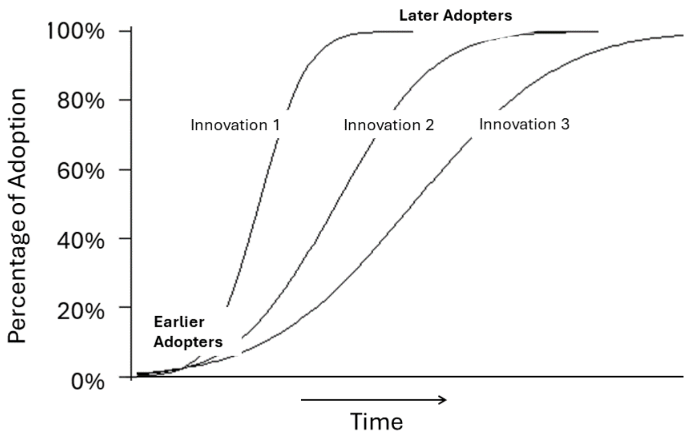

Figure 2.4.2: Diffusion process according to Rogers and Williams (1983).

2.4.2 Rate of Adoption

Rogers and Williams (1983) identify five characteristics that potential adopters evaluate when deciding whether to adopt an innovation.

1. Relative advantage is the degree to which an innovation is perceived as better than the one it replaces. The greater the advantage, the faster it diffuses.
2. Compatibility is the degree to which an innovation is perceived as compatible with existing values, past experiences, behaviours or tools. The greater the compatibility, the faster the diffusion.
3. Complexity is the degree to which an innovation is relatively difficult to understand and use. The easier it is to learn or understand the innovation, the faster it diffuses.
4. Triability is the extent to which a new idea can be tested. The easier it is to try out an innovation, the faster it will spread.
5. Observability or communicability is the extent to which the innovation is visible to others. If an innovation is easy to observe and communicate, it will spread faster.

Other influencing factors include (i) the intensity of promotional efforts; (ii) the timing and nature of communication channels, such as mass media or interpersonal channels; (iii) whether the decision to adopt is taken individually, collectively by consensus or authoritatively by the state or company management; and (iv) the nature of the social system. Some social systems adopt more quickly than others.

Moreover, according to Rogers and Williams (1983), questions such as 'What is the innovation?', 'How does it work?' and 'Why does it work?' are the main concerns of individuals, once they are aware that an innovation exists. The adopter needs to understand how to use the innovation optimally. In the case of more complex innovations, the amount of knowledge required for proper adoption is much greater than in the case of less complex ideas. They write that it may be possible to adopt an innovation without basic knowledge of it. However, the risk of misusing the new idea is greater. They also state that there is a relationship between the level of knowledge about an innovation in a system and its rate of adoption. Therefore, the process of adopting an innovation is a learning process.

2.4.3 Innovations in the AEC and Natural Hazard Industry

In this research, the social systems are the civil- and geo-engineering industry and the natural hazard community. First, the architectural, engineering and construction (AEC) industry, which can be considered part of the civil and geotechnical engineering industry, is examined in more detail. The integration and diffusion of innovations in this industry is well researched and from the literature it can be concluded that this industry is more **reluctant** to adopt new technologies than other industries, despite being one of the largest and most complex industries in the world (Alaloul et al., 2020). One of the biggest barriers to the adoption of new technologies in construction is the **lack of standardisation and interoperability** (Lombardi, 2023; Evans and Farrell, 2021; Maradza et al., 2013)). Moreover, this **industry is fragmented**, with many **different stakeholders and domain experts** involved in the process, such as owners, project developers, architects, civil engineers, geologists, surveyors, planners and contractors (non-exhaustive list). Each is involved at different stages of a project and uses different tools and processes (Knotten et al., 2015). Often there is **limited communication and coordination** between them.

As mentioned in the section 2.3.4, there are almost no articles on the factors that lead to the successful use of InSAR in civil-, geo-engineering and natural hazards projects. Therefore, the literature on the implementation of new technologies in general in the construction industry was consulted. According to Tripathi et al. (2023), successful implementation of a new technology for construction and asset management involves **good coordination between people, process and technology**. Unsuccessful implementation occurs when the **technology maturity is low** and the **technology is not compatible with existing systems** or when the **people factor is neglected** and there is a lack of end-user input, lack of staff training or lack of management support.

Second, the diffusion of innovation in the natural hazard industry was examined. There is almost no scientific literature on this subject. Thaler et al. (2019) and Li (2017) state that the drivers and barriers of transformation in hazard management and disaster-mitigating innovation are poorly understood. Similar to the AEC industry, a complicating factor in natural hazards and disaster risk science is the **need for multidisciplinary and interdisciplinary integration**. (Cui et al., 2021). The authors conclude that successful implementation of new technologies in the field of national hazards requires **integration of natural science, engineering and social science**.

2.5 Project Success Characteristics

Besides knowing how the diffusion of the InSAR technology into the industry it achieved, is is interesting to know the factors that lead to successful deployment in practical civil-, geo-engineering and natural hazard projects. In order to determine whether a project has been successful, it is necessary to distinguish between two fundamentals for assessing project success, namely success criteria and critical success factors (Lamprou and Vagiona, 2018). Success criteria are measures by which the success or failure of a project is judged, and critical success factors are the inputs that lead directly or indirectly to the success of the project.

However, according to Albert et al. (2017); Davis (2014); Ika (2009); Baccarini (1999); De Wit (1988) the concept of project success is difficult to define, there is no common definition of project success and it cannot be measured objectively. Furthermore, the definition of project success varies from project to project and from phase to phase of the project lifecycle, is context dependent and is based on people's perceptions and personal objectives (Williams et al., 2022; Baccarini, 1999). According to Baker et al. (1997), the definition of project success is that a project is perceived to be an overall success if it meets the **technical specifications and/or the mission to be accomplished**, and if there is a high level of **satisfaction with the project outcome among key people**.

Traditionally project success criteria are **time, cost, and quality** and were first described by Barnes (2006). However, even if a project has met these three traditional measures, it can still be perceived as a failure. Conversely, a project can be considered a success even if two of the three criteria are not met (Baker et al., 1997). Over time, these three criteria have been extended to include **meeting the required expectations of stakeholders** (Albert et al., 2017), **(business) benefit to the customer** (Shenhar et al., 2001), and **achieving the intended purpose** (Sanvido et al., 1992). Criteria such as **safety, sustainability and reliability** (Lester, 2021), depending on the type of industry.

The success factors that contribute in different ways to achieving project success are defined by Pinto and Slevin (1988). Their ten critical success factors are:

1. Clearly defined goals and project mission.
2. Top management support.
3. Clear project schedule and plans.
4. Active listening to all impacted parties.
5. Competent project team members.

6. Availability of the required technology and expertise to accomplish the tasks.
7. Client acceptance.
8. Monitoring and feedback at each project.
9. Adequate communication.
10. Trouble-shooting, i.e., the ability to handle unexpected crises and deviations from plan.

The literature also identifies success factors for the implementation of new technologies, such as (i) management support, (ii) end-user involvement, (iii) a clear project goal, (iv) good communication and feedback from stakeholders, (v) clear responsibilities (Karlsen et al., 2006).

In Chapter 3, the success factors that are specific for an InSAR Implementation project in civil-, geo-engineering and natural hazard projects are investigated, and it is examined when a project is perceived as successful. Chapter 4, 5 and 6, present three practical applications of InSAR and its advantages and disadvantages for these applications.

Chapter 3

InSAR Deployment in the Civil-, Geo-engineering and Natural Hazard Industry – an Interview Study with Engineers from Practice

3.1 Research Objective

Chapter 2 provided a literature study on the practical applications of InSAR, the benefits and challenges of the technique, and an overview of generic project success criteria and factors. Also the theory of diffusion of innovations was discussed to understand how new technologies, of which InSAR is one, spread across industries. The focus of the study in the present chapter is to identify the critical success factors and the obstacles for a successful InSAR implementation in civil-, geo-engineering and natural hazard projects. To answer the first research question, i.e., *what factors influence a successful InSAR deployment in civil engineering, geo-engineering or natural hazard projects?*, a qualitative research approach is chosen. This consists of interviewing experts on this topic, namely individuals who plan, use or have used InSAR in projects and individuals who process SAR data. To our knowledge, this is the first study to systematically explore by interviews the opinions and views of engineers in practice.

3.2 Method

3.2.1 Material and Data Collection

By performing semi-structured one-on-one interviews with InSAR users and InSAR providers we examine how and why InSAR was successfully or unsuccessfully applied in civil-, geo-engineering and natural hazard projects in practice. The format of a semi-structured interview is chosen because it uses a set of predetermined questions, which allows for comparisons between participants, while at the same time, the interviewer remains open to asking other questions and allowing the participants to raise new issues. Semi-structured interviews extend beyond factual information; they aim to uncover participants' perceptions and experiences, providing valuable insights into their experiences (Robson and McCartan, 2002). Through these interviews, participants' perspectives are unveiled, and a thorough understanding of the phenomena is gained.

To find engineers who use InSAR or process the raw data, people from the network of the author were contacted. The selection process for the interviews was done through purposive sampling, which is used to find people who are particularly knowledgeable or experienced with a phenomenon of interest, who are willing to participate, and who can communicate their experiences and opinions (Palinkas et al., 2015).

3.2.2 Sample

In qualitative research, sample sizes are usually smaller than in quantitative studies due to the extensive and meticulous work needed. Sample sizes are not calculated using mathematical rules and probability statistics. Instead, the key to finding when the right number of participants is reaching a saturation point, i.e., the point in the data collection process where further interviews do not provide new insights (Glaser et al., 1968). There is no universal rule to determine the maximum and the minimum number of interviews for qualitative research but typical sample sizes to reach saturation range between 5 and 10 (Hamilton and Finley, 2019) or 6 and 12 (Guest et al., 2006) individuals in key roles. Furthermore, based on a systematic review of 16 studies with interview data, Hennink and Kaiser (2022) show that saturation in these studies was reached at between 9 and 17 interviews. In our study, 9 individuals took part, and no more individuals were added because an adequate level of saturation was reached, i.e. only little new information was obtained in the last three interviews.

Participants' backgrounds are distributed as follows:

- Geomatics engineer with 20 years of working experience in structural and geo-monitoring companies (InSAR user)
- Structural engineer with 25 years of working experience in engineering companies (InSAR user)
- Civil engineer with 16 years of working experience in academia (InSAR user)
- Natural hazard specialist with 30 years of working experience in the railway industry (InSAR user)
- Geotechnical engineer with 30 years of working experience in the geotechnical industry and academia (InSAR user)
- Geotechnical engineer, with 3 years of working experience at an InSAR service provider
- Environmental engineer, with 10 years of working experience at an InSAR service provider
- Electrical engineer, with 30 years of working experience at an InSAR service provider
- Geodetic engineer, with 30 years of working experience at an InSAR service provider

3.2.3 Interview Guide

All interviews were conducted by the author and each interview lasted approximately 45 to 60 minutes. The interviews were held in German, Dutch, or English, depending on the participant's preferred language, and were performed face-to-face in person or face-to-face online. All interviews were audio recorded. Before the interview, the participants were requested to sign a consent form where they were informed that the interview would be recorded, that the data and names would be anonymised, and that the results of the study may be published in an academic journal.

The author developed an interview guide as a base for the interviews. All interviews started with an introduction about the interview process and approximate duration. The interview questions were adapted over time. The following questions were used as a base, however, due to the semi-structured format, the interview sometimes unfolded more like a conversation.

- Do you have an example project of a successful InSAR application? Why was it successful there?

- Do you have an example project of a project where InSAR was not successful? Why was it not successful there?
- In your opinion, what are the influencing factors for the successful use of InSAR in a civil engineering and geo-engineering project or in a project with natural hazards? Please mention technical and social factors.
- In your opinion, what are the main limiting factors for a successful InSAR deployment in a civil engineering and geo-engineering project or in a project with natural hazards? Please mention technical and social factors.
- What are your recommendations for solving these limiting factors?
- Why do potential projects fail to get an InSAR analysis at all?
- Do you know of a project in which InSAR could have been used but was not? Why was it not used?
- What is your experience with nationwide or regional readily available Persistent Scatterer Interferometry (PSI) products?
- What are your expectations of an InSAR product/result in a project?
- How do you experience the cooperation between the engineer working at an InSAR company and the engineer/geologists working in a civil engineering/surveying/geology company? Where are the difficulties in the cooperation?
- What are the differences in the work processes in the different disciplines?
- How would InSAR fit better into your project workflow?
- When is a project successful for you?
- Summarising in keywords, for what type of projects do you see the greatest potential of InSAR?

3.2.4 Data Analyses

First, the interviews were transcribed literally but with omitting noises, such as ‘mmm’ and repetitive words. Then, all words or data that could reveal the interviewee’s identity, the company they work for, and the projects they mentioned were anonymised.

Next, the data was analysed using qualitative content analysis. Qualitative content analysis allows the exploration of patterns across qualitative data and involves identifying key themes in this data. Chunks of text are labelled, known as ‘coding’, to identify similar text in the different transcripts. These codes enable the identification of overarching categories of common information (Braun and Clarke, 2006). With this approach, the data from the interviews becomes visible and comprehensible.

An inductive approach for the qualitative content analysis was used. This means that the codes used to label the data during the coding process are based on the actual content of the data set. The researcher identifies the codes within the data itself, as they emerge (Vears and Gillam, 2022), without trying to fit them into a pre-existing coding frame or the researcher’s preconceptions. Inductive coding is an iterative process. Each transcript is re-read and re-coded a number of times because new aspects will emerge from the data as more transcripts are analysed. This iterative approach is important to avoid missing newly identified codes in the earlier coding rounds.

In the present study, the step-by-step model of qualitative content analysis of Mayring and Fenzl (2019) was used. With this method, the analysis is broken down into individual steps of interpretation. This makes the process comprehensible to others and the results verifiable and transparent. The subsequent steps according to Mayring and Fenzl (2019) are:

1. Determination of the units of analysis.
2. Paraphrasing of content-bearing text passages
3. Generalization of paraphrases below this level of abstraction
4. First reduction through selection (coding)
5. Second reduction (if necessary)
6. Collation of the new statements as a category system
7. Re-testing of the new statements as a category system (iteration)

The units of analysis in step 1 in our research were paragraphs; these paragraphs were summarised in step 2, then in step 3, the summaries were generalised and finally, a code was assigned in step 4. This final code provided sufficient reduction, and therefore, the second reduction in step 5 was not made in the present study. Table 3.2.1 shows an example of steps 1 to 4 for interview sections with participant 9.

Then, all columns with the last reduction from all interviews were put side by side, and double reductions per interviewee were removed. Next, based on all interviews, overarching ‘final codes’, i.e. themes, were identified, according to step 6. As an example, Table 3.2.2 shows the result for one code (theme), i.e. ’communication and aligned expectation'.

Step 7 consists of re-testing and re-reading when new statements appeared in consecutive interviews. This step was performed continuously during the coding of the interviews, and each interview was analysed and re-coded multiple times. In the last step, based on all final codes (themes), four overarching categories were identified, which are:

1. Technical benefits and obstacles
2. Non-technical success factors and obstacles
3. Readily available Persistent Scatterer Interferometry (PSI) products
4. Recommendations

Although it is not necessarily required, a frequency analysis of the occurrence of the different themes can be done (Mayring and Fenzl, 2019). Ideally, there will be a number of instances of a certain theme across the data set, but more instances do not necessarily mean the theme itself is more crucial (Braun and Clarke, 2006). In the literature, there is no fixed number of occurrences of a theme for it to be considered a theme. Furthermore, the importance of a theme does not necessarily depend on quantifiable measures but on whether it reveals important information to answer the overall research question (Braun and Clarke, 2006). In this research, a frequency analysis was performed, and the occurrence of themes among the interviewees was counted (See Section 3.3).

The raw data used in this study consists of about 100 pages of transcribed interview statements. These transcripts and the final coding table are available on request from the 4TU data repository (Reinders, 2024).

Table 3.2.1: Example Part of Interview Analysis of Participant 9.

Interview text	Paraphrasing	Generalisation	Reduction
These are just intrinsic in the method at least until now. So I don't think it's really a realistic expectation in certain cases and it shouldn't or it could also not be necessarily a deal breaker in successful deployment. What needs to be done for a successful deployment is communication before.	InSAR has intrinsic obstacles that yet cannot be overcome. However, this is not necessarily a deal breaker in successful deployment if there is communication before the start of a project.	With prior communication the intrinsic obstacles of InSAR do not necessarily hinder successful deployment.	Prior communication about intrinsic obstacles
And that is in terms of realistic expectations. So if it's clear, if I am an InSAR provider or a researcher or someone who just has technical background and use it in a technical project. So it can be both on the side of the provider or expert people from the side of the project. If it's clear that the method is built this way and these are the results that we can expect and type of errors and type of limitations are clearly explained, I think many of the now limiting factors will be just embedded in the approach. There will be just embedded in a methodology that for example adds some extra check on specific issues like you don't know exactly what is vertical and what is horizontal behavior. Clear expectation is the first point.	As an InSAR provider or expert on the client side, it is crucial to have a clear expectation of the method's results and limitations. The limitations can be embedded in the approach.	Having clear expectation of the method's results and limitations is crucial.	Clear expectations about method
It's the client, but also the expectations need to be clarified, like what are realistic expectation, what are realistic things to expect. This needs to be clarified from the provider point of view.	InSAR provider and client need to clarify their expectations.	InSAR provider and client need to clarify their expectations	Clarifying expectations

Table 3.2.2: Example of final coding. P1 to P9 are abbreviations for participants 1 to 9. The columns contain the reduction of a paragraph of each interview.

P1	P2	P3	P4	P5
-	Good cooperation between InSAR users and provider. No wrong expectations.	Clear explanations and communication	Good communication, expectation management. Client has different expectation of product	Good communication between problem owner and InSAR provider. Aligned expectation

P6	P7	P8	P9	Final code (theme)
Different expectations regarding precision and accuracy between disciplines	False expectations	Aligned expectations	Prior communication about intrinsic obstacles. Clear expectations about the method.	Communication and aligned expectation

3.3 Findings from the Interviews

It is emphasised that the findings are based on the perception and experience of the interviewees and the author's interpretation of what was said in the interviews. In this section the four overarching categories, (1) technical benefits and obstacles, (2) non-technical success factors and obstacles, (3) readily available Persistent Scatterer Interferometry (PSI) products and (4) recommendations are elaborated. Each category contains its themes.

Subsequently, in Section 3.4 the findings from the interviews are compared to the literature study from chapter 2. In Section 3.5 a reflection and discussion is presented. The last Section 3.6 comprises the conclusions of the interview study.

3.3.1 Technical Benefits and Obstacles

In the perception of the interviewees, the following benefits (i.e., themes of this category) exist:

1. The potential for detection of slow displacements and deformation trends (8 participants: 4 InSAR users and 4 InSAR providers).

   Displacements can be detected (i) in wide and remote areas, (ii) in urban areas, (iii) without material and people on site, (iv) for baseline assessment at the start of a project, i.e. to assess the natural ground deformations before any construction activities start, (v) at high precision, (vi) at low cost and (vii) with little time. Also, the weekly SAR acquisitions allow for change detection of displacement trends before any damage or failure occurs.

   'Yes, the benefit is of course that it is area-wide. There is no need for installations or fixed points in landslide areas, whether for reasons of danger or, above all, structural measures. Structural measures are often expensive. That is actually the big advantage, that it covers the whole area, not individual points and you don't actually need to install anything.' (Participant 1, InSAR user).

   'So I think a lot of customers are happy because it allows you to monitor wide areas and also remote locations. For example, I had been recently working on a project and it was located in a really remote location, so they were really happy because it takes a lot of effort and time and money to send people there and do their checks and also this project was really wide. So when it comes to these kind of situations, it's really convenient to have InSAR and I think the customers are also really impressed by the precision of the technique because you can really reach the millimetre precision of the estimates. So that's impressive, I think.' (Participant 4, InSAR provider).

'So I think the real power of InSAR is in the detection. And detection means that we see that something changes and we see it before something happens.' (Participant 8, InSAR provider).

'There are many cases where we were able to see displacement over areas, we see issues really in time before any failure.' (Participant 4, InSAR provider).

2. Retrospective analyses and determination of causality (6 participants: 5 InSAR users and 1 InSAR provider).

   Historical archive InSAR data is available, which enables to analyse deformations of the past. This saves time in the project planning. Also during a monitoring campaign the data does not need to be analysed immediately but can be analysed at various moments at various intervals. Moreover, displacement data is available prior to construction which is useful for insurance companies and other parties in liability claims. Deformation changes that happened in the past might be assigned to a natural event or construction activity that occurred at a certain moment in time. Moreover, also excluding causality is possible.

   'That you have data with which you can look at something retrospectively. You simply don't have that otherwise. That's groundbreaking, it doesn't exist anywhere else. Any terrestrial measurement campaign where you think it's good, it's starting now and depending on the rate of movement, you'll have the first results in five years.' (Participant 2, InSAR user).

   'Suppose they still have to start their normal terrestrial monitoring there, then it takes two years before there are results. So the idea with InSAR, you can look back in time with that, so that just saves a lot in the lead time in a project.' (Participant 5, InSAR user).

   'With InSAR you can show a timeline, which point went down at what time, you can either verify this, assign cause, assign causality, or say no, not at all.' (Participant 2, InSAR user).

   'Excluding causes. You don't necessarily get to the right solution answer at the end but excluding a cause or another will be already useful.' (Participant 9, InSAR user).

3. Optimisation and complementing in-situ monitoring (4 participants: 3 InSAR users and 1 InSAR provider).

   Archived SAR data can be used to target the soil and terrestrial survey investigation more effectively. Also it can be used as a complementary tool to conventional monitoring to measure displacements outside the area covered by surface levelling points.

'I would describe it as successful if a long-term measurement campaign could be optimised to a relevant extent using InSAR, for example number of in-situ measurement points reduced, correct locations selected.' (Participant 3, InSAR user).

'And I know that we are trying to insist on the civil engineering community that InSAR is a very valuable tool, complementing, of course we should say this is complementing in-situ observation.' (Participant 7, InSAR provider).

4. SAR data may be the only data source available (3 participants: 3 InSAR users).

   In some projects, no measurements, such as terrestrial surveying data or ground investigations are available. In those cases, SAR data can be the only source of information.

   'So a network of satellite based measurements is usable because it actually provides extra information where you would have none.' (Participant 9, InSAR user).

   'Reason why I would look at InSAR data is think in general if geotechnical data are scarce. In geotechnical engineering, just try to get a 10-year time series to keep a monitoring system up and running for 10 years. That is difficult and costly.' (Participant 5, InSAR user).

5. InSAR does not require fixed measuring points (1 participant: InSAR user).

   The problem with terrestrial measurements is that the man-made benchmarks must be remeasured in the field if they are moving as well. Although InSAR does not require measured fix points, it requires a network of stable PS. Therefore this benefit only applies in case stable PS can be defined without on-site survey.

   'We have projects in difficult soils where the fixed reference points also have movements. And you have to remeasure them afterwards and equalise the measurement network. And that's where we struggle because the fixed points move.' (Participant 3, InSAR user).

In the perception of the interviewees, the following obstacles (i.e., themes of this category) for using InSAR in their projects exist:

1. The intrinsic obstacles (8 participants: 5 InSAR users and 3 InSAR providers).

   (i) Presence of vegetation and snow, (ii) the large velocity of the displacements, (iii) the unsuitable orientation of the area of interest towards the satellite, (iv) difficulty to detect horizontal movements, (v) erroneous phase ambiguities in case ground displacements are close to or larger than the wrapping threshold $\lambda/4$, (vi) displacements are in line of sight of the satellite, (vii) the limits regarding time and space resolution and also (viii) unavailability of SAR data due to unreliable satellite mission, i.e. satellite or its sensor does not function properly, were pointed out in the interviews.

   'But if you want to monitor really vegetated area, it's not the best technique to go. There's a lot of noise that you have to take into consideration and maybe the results are not that precise or accurate.' (Participant 4, InSAR provider).

   'What might be a disadvantage is that it is not in 3-D but simply in Line of Sight.' (Participant 1, InSAR user).

   'It's not a real time monitoring system, InSAR. So we should recognize this very frankly.' (Participant 7, InSAR provider).

   'And when it comes to InSAR, it's not always possible to kind of filter out the noise from the rest.' (Participant 4, InSAR provider).

   'There is a lot of statistics, a lot of data processing, and it takes a lot of measurement data to find out something that makes sense.' (Participant 2, InSAR user).

   'Then, another key factor is the reliability of the space sector, space segment. Because if you start providing a monitoring project and then for any reasons, unfortunately you have a failure in the satellite sensor. Of course we are not liable for these, responsible for this, but from the point of view of the client you are, you are my interface with the space world.' (Participant 7, InSAR provider).

2. InSAR is an opportunistic method without success guarantee at the start of a project (6 participants: 3 InSAR users and 3 InSAR providers).

   While this is also an intrinsic technical obstacle of the method, this point is mentioned separately because it is one of the main obstacles. The location of the PS cannot be determined in advance. Only after a first SAR analysis, the amount and location of scatters is known.

'So the most important limiting factor of the technology in practical use is the fact that we're dealing with an opportunistic technique where the availability of benchmarks and measurement points both spatially and temporally is not a given from the start. It's dependent on the area that we're looking at. So we cannot guarantee as a provider that we will get sufficient data points, that we will get sufficient measurements, and that the estimates that we were producing in our information products, that they are directly relevant to the problem of the stakeholder.' (Participant 8, InSAR provider).

3. The deformation values derived from the InSAR data and terrestrial measurements are not directly comparable to each other (2 participants: 1 InSAR user and 1 InSAR provider).

   The accuracy and precision of SAR data are different compared to terrestrial measurements. Also, SAR data is obtained in the line-of-sight of the satellite sensor, while terrestrial measurements are done within a local coordinate system. While comparing the absolute values of the different data sources is difficult and sometimes impossible, the deformation trends still can be compared.

   '... it has a different meaning compared to what other kind of ground measurements means with its precision.' (Participant 6, InSAR provider).

4. Precursors are not always identified (1 participant: InSAR provider).

   Although one of the benefits of InSAR is the identification of change detection of displacements, identifying precursors before any damage or failure occurs cannot be guaranteed.

   'There are plenty of successful cases showing that SAR could have shown the precursor. But there is always this big question from the final market: they say, OK, but you said it after it happened. Also, every case is different. The precursors are sometimes visible, sometimes not. So there is no doubt that sometimes collapse are happening quite fast and sometimes it takes time. The precursor, yes, … so it's easy to say you saw it afterwards.' (Participant 6, InSAR provider).

3.3.2 Non-Technical Success Factors and Obstacles

Most of the interviewees mention the following main success factors (SF) and obstacles (O) (i.e. themes of this category) for a successful implementation:

1. (SF) Aligned expectation and good communication are key success factors for an InSAR project (9 participants: 5 InSAR users and 4 InSAR providers).

   Good communication involves (i) engaging with each other, (ii) sharing information, (iii) InSAR engineers being transparent about the obstacles and advantages of InSAR, (iv) clients being clear about their problems, in order that the expectations are aligned.

   (O) Obviously, the opposite, having different expectation of a final product, lack of interaction and communication, are considered obstacles for a successful deployment. Also, a wrong narrative on InSAR products and too positive pitches of InSAR provider are considered an obstacle.

   'The most important things are aligned expectations between the provider and the receiver of the InSAR results.' (Participant 8, InSAR provider).

   'If it's clear that the method is built this way and these are the results that we can expect and type of errors and type of limitation are clearly explained, I think many of the now limiting factors will be just embedded in the approach.' (Participant 9, InSAR user).

   'Mutual understanding is really important.' (Participant 2, InSAR user).

   'Another reason why I think there is a problem currently with the uptake of InSAR, is the narrative that there is only one sort of InSAR data. The InSAR data, I always very much object to this. So this is why I'm talking about the InSAR information product, because you can make from one particular set of raw data, you can make many different products, depending on what your goals are.' (Participant 8, InSAR provider).

   'We have encountered people working in projects and they were like flashed by the pitches of the InSAR provider who was saying we can view all this displacement on all this points with this millimeter accuracy. But then they weren't really able to address questions related to uncertainties for example.' (Participant 9, InSAR user).

2. (SF) Pre-analyses or a step-by-step deployment (6 participants: 5 InSAR users and 1 InSAR providers).

   To know if InSAR is feasible for a project, a first analysis is necessary to assess if the amount, locations and quality of scatterers is sufficient to answer the question of the client. This can be seen as an investment of the InSAR provider or embedded in the project chain and client side. However showing this information can be precarious because a pre-analyses already contains a large amount of information.

'So you have to 1st basically do the analysis and then make a statement on whether it is useful or not.' (Participant 8, InSAR provider).

3. (SF) InSAR results provide additional information (6 participants: 4 InSAR users and 2 InSAR providers).

   SAR data is valuable if it adds new information that was not available with other measurements or if it confirms other measurements. Also SAR data showing almost no displacements or changes is useful and important information.

   'The project is successful if the InSAR data has provided added value in terms of knowledge, regardless of the measurements that may already be made.' (Participant 1, InSAR user).

4. (SF) Having show cases and example projects (5 participants: 3 InSAR users and 2 InSAR providers).

   'When talking to a customer, being able to showcase all the existing applications helps.' (Participant 4, InSAR provider).

5. (O) A different way of thinking and language between the InSAR users of different market sectors and InSAR provider are considered obstacles (5 participants: 1 InSAR users and 4 InSAR providers).

   Due to the different education, background and working environment, civil engineers and SAR engineers have a different way of thinking and language.

   'I had quite often discussion with civil engineers, or I mean people coming from different application field. Sometimes I see we speak a different language.' (Participant 6, InSAR provider).

   'They were not prepared to think in the way that the civil engineer thinks.' (Participant 9, InSAR user).

   'We are struggling to speak the same language as the people we are talking to.' (Participant 7, InSAR provider).

6. (SF) Having knowledge and skilled personnel that can interpret the SAR data for the different market sectors (9 participants: 5 InSAR users and 4 InSAR providers).

Different customers and market sectors have different requirements, that need specific knowledge and skills on the InSAR provider side. On the user side, engineers need to have some basic knowledge of InSAR and other surveying techniques to choose the appropriate monitoring tool for the project. Besides knowledge, awareness is needed about InSAR and its possibilities. Obviously, the opposite, lack of skilled personnel and lack of expertise and unawareness of the technique are obstacles.

'I think on the client side, you have to have someone who has an idea of what InSAR is and can do.' (Participant 5, InSAR user).

'The problem is that the people, our engineers, were really not up to date with the technology.' (Participant 3, InSAR user).

'Gathering actionable intelligence from data that requires skills and education. So on the on the end user side, there are very few people who have that.' (Participant 7, InSAR provider).

'I'd like to address one important point, at least to me, which is the fact that that fortunately or unfortunately InSAR data can be used in many different applications. Probably too many and this is probably part of the reason of the slow uptake of InSAR services. So if you think for a while, you realize that they are very different communities, those people speak different languages.....And this creates the need for a quite large group of people who can address those different market sectors.' (Participant 7, InSAR provider).

'And also on the provider side, we don't train enough people which have the good background, who know something about quality about what kind of conclusions you can relate to a particular result. So the focus is much is way to much on data and too little on skills and knowledge.' (Participant 8, InSAR provider).

'Also trust or knowledge in dealing with this technology, i.e., what it can do and what it can't, there is a lot of education to be done. There is still a lot of uncharted territory and a need for education.' (Participant 1, InSAR user).

7. (O) InSAR is still an unknown technology in the industry (7 participants: 4 InSAR users and 3 InSAR providers).

   In academia, InSAR is mostly known but there is a gap between research in academia and the applications in practice. Many civil engineers in the industry do not know the technique yet or do not know how to use and interprete the data.

   'Now it is still a technology largely unknown.' (Participant 7, InSAR provider).

'I think by no means everyone in our organisation is aware of success factors.' (Participant 5, InSAR user).

'And of course there's a lot of work done by researchers and all the research institutes and other companies, but still there's really active gap in between the research and the applications.' (Participant 4, InSAR provider).

8. (O) High cost of InSAR analyses (6 participants: 3 InSAR users and 3 InSAR providers).

   The price of an InSAR analysis is perceived as high. Even more if commercial satellite images are needed.

   'The biggest reason is above all the price.' (Participant 1, InSAR user).

Few participants mention the following additional success factors (SF) and obstacles (O):

9. (O) The civil engineering community is conservative and sticking to traditional surveying techniques (2 InSAR users and 1 InSAR providers).

   'Railway companies are very focussed on track-laying machines and that is also working. They say that in future the machines themselves will have radar or cameras, and they can also deliver the points. The InSAR provider faces a lot of competition there.' (Participant 3, InSAR user).

   'It is still true and that it's hard to cross the border and enter into the civil engineering the community, for example. They are very conservative.' (Participant 7, InSAR provider).

10. (O) Harsh competition in the InSAR market (2 InSAR providers).

    'And I think from industry, is what you see is all the companies are trying to do their best. And actually, in a way, at the moment, it's kind of race to the bottom, I think. So, you know, there are these companies trying to survive.' (Participant 8, InSAR provider).

11. (O) InSAR is not a mature technique yet and it remains a niche market without big players. The push for InSAR was premature (2 InSAR providers).

    'So it's a niche in remote sensing now.' (Participant 7, InSAR provider).

    'So there is this chasm between early adapters, which are the first ones that start with new technology, and the early majority. This gap needs to be crossed to get further with the adaptation of new technology.' (Participant 8, InSAR provider).

12. (O) The quality of the SAR data when the processing is automated can be

suboptimal (2 InSAR providers).

(SF) The opposite, human evaluation of SAR data, is a success factor.

'If you have to process thousands of SAR scenes over millions of square kilometres, of course, you are not allowed to even think about checking every single time series. So everything becomes more industrial, standardized, and of course the level of quality can go down.' (Participant 7, InSAR provider).

'I think the human intervention in this field is still really important and it's not true that everything can be done automatically.' (Participant 6, InSAR provider).

13. (O) Time constraints and personnel problems (2 participants: 1 InSAR user and 1 InSAR provider).

    'Clients don't have the personnel, they lack people. I mean, everyone is working overloaded. People really have no time to invest in these extra activities. So they say, OK, I pay for it. So I hope to get something that I can use, but if this interaction is not happening, the data won't be useful anymore anyway.' (Participant 6, InSAR provider).

14. (O) Lack of laws, guidelines and standards in the InSAR industry (1 InSAR provider).

    'There is no standard in the way we provide results. Depending on the data provider, depending on the technique, depending on many things somehow....So and then you know, as there are no official rules, everyone can do as they prefer.' (Participant 6, InSAR provider).

15. (O) Tender and proposal regulations (1 InSAR user).

    'We can't say after the process of a pilot that we have now set something up with an InSAR company and then afterwards our purchasing department says, but we need at least 3 offers for this amount. That is a fact. That's another key question. How do you make sure that you get an order afterwards? Procurement law is important.' (Participant 3, InSAR user).

16. (O) Governmental philosophy (1 InSAR provider).

    'It also depends on how the governments in different countries deal with new technology. Whether there is a philosophy to encourage companies to stand on themselves or whether governments want to regulate and subsidise. ' (Participant 8, InSAR provider).

To conclude, InSAR is considered an underrated technique with great potential.

Especially the potential of InSAR for monthly monitoring and change detection of individual assets and large areas is considered unexploited (4 participants: 1 InSAR user and 3 InSAR providers).

> *'I think the potential is very much unexploited.'* (Participant 8, InSAR provider).
>
> *'I think unfortunately it is really an underrated technique and there's a lot of potential and I wouldn't mind seeing it developing further from now in some years because some people just don't get how useful it could be to monitor their assets.'* (Participant 4, InSAR provider).
>
> *'I still think that for monthly monitoring we are underestimating the potential really.'* (Participant 7, InSAR provider).
>
> *'I think there are more opportunities for infrastructure managers to use InSAR measurements...... there's probably a lot more that can be done.'* (Participant 5, InSAR user).

3.3.3 Readily available Persistent Scatterer Interferometry (PSI) products

The interviewees mention the following themes:

1. Nationwide PSI maps are application-agnostic, indicating that they are not optimised for a particular application or location (5 participants: 2 InSAR users and 3 InSAR providers).

   'So it's application-agnostic, and everybody who has a bit of understanding knows that it will be suboptimal for a particular application.' (Participant 8, InSAR provider).

   'They are all based on certain kind of data, so they are mostly based on C-band data which is great for certain applications but it's really not accurate if you are looking at the individual infrastructure. And the level of uncertainty, again everything we mentioned before, where the points are, the density and the accuracy of the measurements itself. They are visualized in a way that can be perceived as misleading, if you don't know exactly what is behind.' (Participant 9, InSAR user).

   'I'm trying also to pass the message about the importance of the documentation stating clearly that this is not InSAR for measuring individual buildings for example. No, it is for wide area.' (Participant 7, InSAR provider).

2. Benefits of PSI maps are large scale information, accessible to many people, base for researcher, starting point for investigations (2 participants: 1 InSAR

user and 1 InSAR providers).

'So they do provide information on a large scale that is really useful to get better insights of phenomena.' (Participant 9, InSAR user).

'Sometimes they are happy with just this screen of a large territory and they stop with the EGMS (European Ground Motion Service).' (Participant 7, InSAR provider).

3. PSI maps create awareness (3 participants: 1 InSAR user and 2 InSAR providers).

   'I think in EGMS could create a decent level of awareness, at least about the technology.' (Participant 7, InSAR provider).

   'It creates awareness, that's a very nice thing of course.' (Participant 8, InSAR provider).

4. Users have little background knowledge of PSI maps (3 participants: 2 InSAR users and 1 InSAR provider).

   'So it can lead sometimes to non-trusting the tools because you find things that you cannot explain just because you are not enough educated or knowledgeable.' (Participant 9, InSAR user).

5. PSI maps contain sensitive data, for example with information of peoples assets (2 participants: 1 InSAR user and 1 InSAR provider).

   'So even when the EGMS show the maps, they could have caused problem to someone.' (Participant 6, InSAR provider).

   'It's also a tricky aspect, especially in residential areas and neighbourhoods, when you can see which places are sliding and which are not. Of course, there is a certain financial risk when such information is included.' (Participant 1, InSAR user).

6. Companies handling PSI maps data are a threat (1 InSAR providers). New companies are emerging that use the freely available PSI products, produce tools to analyse the data and provide results. However this may pose a threat as the PSI data is not always the suitable data for answering a certain problem.

   'So what is a bit concerning me is that now there are a lot of free tools and free application and companies that are basing their business on this data.' (Participant 6, InSAR provider).

3.3.4 Recommendations from the Interviewees

The interviewees provide the following recommendations:

1. Managing expectations (8 participants: 5 InSAR users and 4 InSAR providers).

   InSAR users and InSAR providers should engage and understand project challenges from InSAR user and InSAR provider side, in order to have aligned expectations. This comprises InSAR providers being clear about the technical obstacles and advantages and listening to clients needs. The InSAR users should be willing to share information, be pro-active, and formulate their needs and requirements.

   - Clarity about obstacles and advantages (9 participants: 5 InSAR users and 4 InSAR providers).

     'It's important that the communication to the customer is clear, so you need to properly explain how the technique works and to make clear what the limitations of the technique are because otherwise you may run into the risk of having emerged with too high expectations and then they are disappointed when they get the product because they don't know the limitations of the technique' (Participant 4, InSAR provider).

     'It simply has to be clear what you can and cannot do. You must not raise false expectations.' (Participant 2, InSAR user).

   - Engaging with each other and sharing information (8 participants: 4 InSAR users and 4 InSAR providers).

     'So they (client) need to be kind of willing to share and willing to cooperate....' (Participant 4, InSAR provider).

     'So in other words, the client should be open enough to describe his pain.' (Participant 7, InSAR provider).

     'I think we need to better formulate our requirements to the InSAR provider. Project-specific requirements. Almost like a functional specification.' (Participant 3, InSAR user).

   - Providing consultancy to client (3 InSAR providers).

     'We're not just selling the data. Because if it was just about the data. We wouldn't even run the preprocessing. Let's say it's more about also consultancy.' (Participant 4, InSAR provider).

     'I think we should focus much more on giving an answer to a question.' (Participant 8, InSAR provider).

- Keep explanations about InSAR technique simple (2 InSAR providers).

  ‘Making simple sketches when I explain things. I really try to simplify a lot. .... but it’s the only way to make other people understand.’ (Participant 6, InSAR provider).

- Clients knowing in advance how they will handle SAR results (1 InSAR user).

  ‘If you only have a report with "this comes from InSAR measurement" and that doesn’t fit into the way the organisation works yes, it won’t be a success.’ (Participant 5, InSAR user).

- Explain difference between diagnostics and detection clearly (1 InSAR provider).

  ‘the thing there is, I call it the difference between diagnostics and detection. These are two different totally different things....„in my view, the diagnostic value of InSAR is not so high. The real power of InSAR is in the detection’ (Participant 8, InSAR provider).

- Communicate clearly about European Ground Motion Service (EGMS) as many users have no bckground knowledge about PSI maps (4 participants: 2 InSAR users and 2 InSAR providers).

  ‘There is an expectation from the civil engineers point of view that these PSI maps are the final output. And that they are the best possible outcome that we can get because tens of researcher has worked on that. And that again they will apply to every situation. But they don’t.’ (Participant 9, InSAR user).

2. Building trust in the technology (8 participants: 5 InSAR users and 3 InSAR providers).

   SAR Providers should have a portfolio with example projects, including the benefits and obstacles, to show to clients in order to make the technique more tangible. Also a step-by-step InSAR deployment in projects and validation with conventional monitoring will help gain trust.

   - Providing and developing show cases and example projects (5 participants: 3 InSAR users and 2 InSAR providers) [1].

     ‘It is good to approach the clients with some examples. I’m sure all final users would tell you that that they need some examples even to start

[1] This theme is listed in both the non-technical success factors and the recommendations

talking. Otherwise, everything is very theoretical' (Participant 7, InSAR provider).

'Case studies help us the most in our discussions with customers' (Participant 1, InSAR user).

- Providing pre-analyses or a step-by-step deployment (6 participants: 5 InSAR users and 1 InSAR providers) [2].

  The participants are aware that these are extra cost that need to be seen as an investment of the InSAR provider or embedded in the project chain and client side.

  'Knowing in advance with a quick overview of what could be possible for a specific case might work. I understand it's an investment. So, it's something that might be embedded in the chain of a project investment from the point of view of the provider for example. Or given that it is in any way much cheaper than other kind of monitoring it can be something included in the service as costs. So that I also the preview, in a way, is something that is paid for within the project. .' (Participant 9, InSAR user).

  However showing this information can be precarious because a pre-analyses already contains a large amount of information.

  'It is certainly the case that the guarantee of success is definitely something diffuse that can be intercepted by receiving a stepwise price. First you do a pre-analysis, have a meeting, see if we are going in the right direction, if it delivers what it promises. I think that's certainly a good approach and not a price and then it's top or flop. It's important that you deploy stepwise and involve the customer.....However at the moment when you show this data to the customer he actually already receives a main result. I find this transition tricky.' (Participant 1, InSAR user).

- Start with a pilot project.

  'One should start with a pilot and do on-site measurements together with InSAR measurements to gain trust.' (Participant 3, InSAR user).

- Physical meetings and site visits with project team (3 participants: 2 InSAR users and 1 InSAR providers).

  'Probably it would be necessary not just adding a some activity related to reporting, but also spending sometimes together in the same room. I think

[2] This theme is listed in both the non-technical success factors and the recommendations

in the same room, because even having a call and speaking theoretically, the day after, no one cares. You should be going into the site and try to check the results together. To feel the work activities. Going into the site together, try to check the results with the survey team and somehow put together the information.' (Participant 6, InSAR provider).

- Validation by comparing deformations trends from SAR data with terrestrial measurements (2 InSAR users).

  'They did 'as well as' and then realised that yes, it works. And afterwards you could dismantle the classic measurement and say, yes, that works.' (Participant 3, InSAR user).

  'Just look at what conclusion you draw from terrestrial measurements in relation to subsidence, velocity and what conclusions do you draw from the InSAR measurements? If you then put that side by side, there was a really good agreement. Both terrestrial monitoring and InSAR identified the same structures as suspicious. That was a really convincing story.' (Participant 5, InSAR user).

3. Education (9 participants: 5 InSAR users and 4 InSAR providers).

   This includes raising awareness, providing simple explanations, educating civil engineer about InSAR and InSAR provider gaining knowledge about civil and geotechnical engineering needs.

   'There should be awareness about earth observation, say in general, or at least awareness about the fact that now earth observations satellite can provide very useful information.' (Participant 7, InSAR provider).

   'So when I say mini courses, I can be a bit more specific we start with that. They really go both directions. So it's about civil engineers learning about the technique and pro and cons and limitations because sometimes limitations seeing in the context of how the technique is developed are way more meaningful. So that could be done from the side of the structural engineers. But also providers,they might have some update themselves on the kind of interpretation that are needed from civil engineers.'...So the register or the chartership as it is in the UK, is really good to make sure that more knowledge is uniformly distributed to those who will benefit from it. I don't know an alternative mechanism for places where it's not mandatory, but other than accepting that you need to learn how to use. (Participant9, InSAR user).

   'Teaching how to treat the data, need somehow the right way and you need to adapt the kind of level to who is learning.' (Participant 7, InSAR provider).

4. Clear procedures, tools and guidelines (4 participants: 2 InSAR users and 2 InSAR providers).

    - Dedicated InSAR processing for local projects (2 InSAR providers).

      'In the future I think, having dedicated processes for at least type of projects if it's not the specific project, might be useful.' (Participant 9, InSAR user).

    - Standardization of InSAR processing steps and results.

      'So this is for example one big thing that obviously everyone now there are standardizing somehow the kind of parameters that need to be defined together with the service.' (Participant 6, InSAR provider).

    - Adhere to tender regulations.

      'As a supplier, you also have to be aware that procurement law is very strict and must be adhered to properly. ' (Participant 3, InSAR user).

    - Integration with the customers tool, however this is costly and complicated (1 InSAR user and 1 InSAR provider).

      'Of course, we have the data from others in our portal.... It would certainly be an advantage if InSAR data were also included.... However, if it's only for individual projects, this would almost certainly be too much work for us to integrate. ' (Participant 1, InSAR user).

    - Sufficient preparation time.

      'If you want to do that, you can't do it in a project under time pressure. You have to think very carefully in the project phase about what InSAR brings to the project.' (Participant 3, InSAR user).

5. Appropriate team (4 participants: 2 InSAR users and 2 InSAR providers).

    - Qualified staff.

      'And really to come to a risk assessment you need to have high level experts of the two fields to work together.' (Participant 6, InSAR provider).

      'It also helps, I think, to achieve optimal results, that the person at the InSAR provider doing the interpretation knows very well what it is for.' (Participant 5, InSAR user).

    - InSAR company providing consultancy to client (InSAR user) (3 InSAR providers). This means combining the SAR data with other information to answer the question of the client, instead of only providing SAR data.

'There needs to be some kind of consultant in between client and InSAR provider,who can make the interface between the specialims.' (Participant 2, InSAR user).

- Involve team from start (1 InSAR user).

  'And on the client side, we have to make sure that the right people are involved, that they are aware of the whole process. So not just one person who informs the others and says it's a good thing. I would set up a team.' (Participant 3, InSAR user).

- Company with own SAR division (1 InSAR provider).

  'They could have their own SAR division. I think at this point is the best because then they are people paying to become expert and there is a real collaboration between the SAR division and the civil engineering division.' (Participant 6, InSAR provider).

6. Restrict the cost of InSAR analyses (2 participants: 2 InSAR users).

   - Clarity about cost *'Yes, if the pre-analyses could actually be done cost-effectively, so that the InSAR provider does not have to invest three days to see whether it is possible or not, that would of course be helpful to validate in advance whether it is possible in this case.'* (Participant 1, InSAR user).

   - Reduce costs, for example by using SAR images for multiple projects to reduce costs per project (1 InSAR user).

     'And I think you should look at the whole railway network, not just one project, if you could spread the costs of the images, then there would no longer be such a burden on a single project.' (Participant 3, InSAR user).

3.4 Comparison Literature and Interviews

Sections 3.4.1 to 3.4.4 provide a comparison of the findings of the interviews and the literature study from chapter 2.

3.4.1 Comparison Literature and Interviews on Technical Benefits and Obstacles

The literature and interviews are in agreement concerning the technical benefits. In Table 3.4.1 the literature and interviews are compared. However, a few differences are observed. First, using InSAR for optimising terrestrial monitoring is considered a large benefit by the interviewees but not mentioned in the literature. On the other hand, the literature mentions the use of InSAR for predictive maintenance planning of infrastructure systems, which none of the interviewees mention in such a way. Additionally, one issue with terrestrial measurements is brought up by one interviewee: If the man-made reference points are also moving, they must be regularly re-measured in the field, which can be difficult and time consuming. The interviewee notes that this problem would not occur when using InSAR. Yet, the literature indicates that although InSAR does not require measured fix-points, it requires a network of stable persistent scatterer (PS) (Ferretti et al., 2002).

Regarding the technical obstacles, the findings from the literature and interviews also correspond well. Table 3.4.2 shows the comparison between the literature and interviews. However, there are a few obstacles that are mentioned uniquely in the literature or the interviews. First, the uneven distribution of SAR data around the globe is only mentioned in the literature. All InSAR users that were interviewed were doing projects only in Europe, and therefore, they might not be aware of this obstacle. While the interviewed InSAR providers were doing projects worldwide, they did not mention this obstacle either. Second, the fact that a-priori knowledge is needed to evaluate the SAR data was not mentioned by the interviewees.

Regarding comparing InSAR data and terrestrial measurements, the interviewees mention that those measurements are not directly comparable. However, trends from both data sets can be compared. Yet, in the literature examples are found where not only the displacement trends but also the displacement values of SAR data and terrestrial data are compared directly. These should as such be treated with care.

It is observed that in research papers the focus is often on the potential of the InSAR technology. Moreover, no case studies in which InSAR was unsuccessful are found in the literature. Also, two InSAR users mention that InSAR providers only show success stories and have a too positive narrative about the technique. The interviewees give a more balanced overview than the literature by stating that InSAR is unsuitable for some projects and not always the appropriate tool.

Table 3.4.1: Comparison technical benefits between the literature and interview results.

	Inter-views	Liter-ature
The potential for detection of slow displacements - in wide areas - over remote areas - in urban areas - without material and people on site - for baseline assessment - with high accuracy and at fine spatial resolution - at low cost - with little time - for change detection before failure - to reveal precursors and use as early warning system - outside the area of the conventional surveying benchmarks	x	x
The large historical archive of SAR data for - retrospective analyses - forensic engineering - determination of causality possible	x	x
Optimisation of in-situ monitoring techniques with InSAR	x	-
Complementing in-situ monitoring techniques with InSAR	x	x
SAR only data source available that makes the study of past incidents possible, for which in-situ monitoring data is not available	x	x
Use for predictive maintenance planning of infrastructure systems	-	x

Table 3.4.2: Comparison technical challenges between the literature and interview results.

	Inter-views	Liter-ature
Intrinsic challenges: - It is an opportunistic method. Locations and distribution of monitoring points are unknown in advance - Land use and the presence of vegetation and snow - The maximum detectable deformation depends on the wavelength - Limits regarding time and space resolution. - Unsuitable orientation of the area of interest towards the satellite - Displacements are in the Line of Sight (LoS) of satellite - Phase bias, unwrapping errors - Geometric distortion - Near-polar orbit - The positioning precision of radar scatterers is usually poor - The revisit time of the satellite is to large to perform real-time monitoring - Separating abnormal structural behaviors from noise difficult - Atmospheric disturbances need to be evaluated.	x	x
SAR data availability is unevenly distributed around the globe	-	x
Choosing stable reference points can be difficult and the stability of reference point can be uncertain	-	x
A-priori knowledge necessary	-	x
InSAR data and terrestrial measurements are not directly comparable. However, trends from both data sets can be compared	x	-
Unreliable satellite mission, availability of sufficient SAR images	x	x

3.4.2 Comparison Literature and Interviews on Non-Technical Success Factors and Obstacles

Regarding the non-technical success factors and obstacles, the findings from the interviews give much more insight than the literature. See Table 3.4.3 for a comparison between the literature and interviews. While it seems straightforward that managing expectations and good communication are key success factors, apparently, this is not common practice in all InSAR deployment projects, as misaligned expectations are considered a major obstacle by all interviewees.

A project is considered successful by the interviewees if InSAR adds value in terms of new information. It is evident that this is not mentioned explicitly in the literature as a main success factor. Authors tend to stress the potential of the technology in most papers and new information is always gained from research.

The scientific literature demonstrates applications of InSAR for a wide range of projects and industries. However, no articles mention the problems when supplying different markets with specific needs. All InSAR providers in the interviews clearly state that working with a large range of clients can be challenging as each client has a different way of thinking and speaks a different language. This requires specific knowledge from the InSAR provider. All InSAR users and providers consider knowledge and skills key success factors. It is clearly stated that InSAR engineers should understand clients' problems and that InSAR users must be knowledgeable about satellite geodetic techniques. This is in agreement with the literature where the lack of experienced engineers, both on the users' and providers' side, is mentioned as a key obstacle. In addition, the interviewees reveal also that time constraints in the project planning and lack of staff with enough time to work on the projects are obstacles.

With InSAR users not having sufficient knowledge about the InSAR technique, it is obvious that the interviewees also state that InSAR is still an unknown technology in the civil, geo-engineering and natural hazards industries. Looking at the large number of scientific papers, this seems inconsistent at first glance. However, interviewees also mention that there is a gap between the research in academia and practice. The large amount of research in recent years does not necessarily reach the market sectors. Probably, this is even more difficult in the construction industry as both interviewees and the literature state that the civil engineering community is conservative and reluctant to adopt new technologies.

Also, InSAR must compete with traditional terrestrial surveying methods, which are more established in the industry. Moreover, strict tender regulations are not beneficial for the development of pilots as consecutive assignments for projects may be procured to a different InSAR provider. It is therefore not surprising that the

InSAR providers in the interviews state that InSAR is still an underrated technique, that its potential is not fully exploited and that it is still a niche market.

Despite the harsh competing InSAR market being mentioned as a obstacle by two InSAR providers, the interviewees consider the high cost of an InSAR analysis a major obstacle. The high price of high resolution images is also mentioned in the literature

Table 3.4.3: Comparison non-technical success factors and obstacles, (SF = success factor and O = Obstacle) between the literature and interview results.

	Interviews	Literature
Aligned expectations and good communication (SF)	x	-
Pre-analyses and step-by-step deployment (SF)	x	-
InSAR providing additional information (SF)	x	-
Show cases and examples (SF)	x	-
A different way of thinking between InSAR users and providers (O)	x	-
Knowledge and skilled personnel - Specialised SAR data processing skills (SF) - Adequate personnel (SF) - Team capable of covering multiple expertise (SF) - Users' knowledge of the technique and ability to correctly interpret SAR results and to extract useful information (SF) - Lack of expertise and experienced image interpreters (O) - Inexperienced users (O)	x	x
InSAR unknown technology (O)	x	-
High costs for processing SAR data (O) and high cost for high-resolution imagery (O)	x	x
The civil engineering community is conservative and slow in adopting new technologies (O)	x	x
Harsh competition in the InSAR market (O)	x	-
InSAR not mature, niche market, no big players (O)	x	-
Qualitiy reduction when automation of processing (O)	x	-
Time constraints and personnel problems (O)	x	-
Compare deformations trends from SAR data with terrestrial measurements (SF)	x	-
Lack of laws, guidelines and standards for the quality assessment of the InSAR results and products (O)	x	x
Tender and proposal regulation (O)	x	-
Lack of resources for storage and computation of the data (O)	x	-
Handling and homogenizing huge SAR data amounts (O)	x	-

Both the literature and the interviews recognise that handling a large amount of SAR data may be a obstacle because the automation of the processing of the SAR data can lead to a quality reduction of the result. It is mentioned that human evaluation and knowledge are always needed. Moreover, the lack of standards for quality assessment, regulations and guidelines in the InSAR market is considered a obstacle in both the literature and the interviews. Finally, the literature notes that the availability of sufficient resources for storage and computation of the SAR data can be a challenge, which is not mentioned by interviewees.

The results of this study are also consistent with the literature's criteria for project success, which include time, cost, quality, satisfaction with project results, meeting expectations, customer benefits and achieving the intended purpose.

In the perception of the interviewees, an InSAR project is considered successful if

- *'the SAR data has provided added value in terms of knowledge'* (participant 1, InSAR user), *'the data gives additional insight into the condition of objects'* (participant 5, InSAR user), *'the results are meaningful'* (participant 3, InSAR user).
- *'a long-term in-situ measurement campaign could be optimised '* (participant 2, InSAR user) and *'it can be successfully used for long-term monitoring'* (participant 9, InSAR user).
- *'money was saved because InSAR has replaced some traditional measuring methods.'* (participant 2, InSAR user).
- *'InSAR was able to check displacements in an certain interval and if no in-situ measurement was necessary'* (participant 9, InSAR user), *'displacements are as expected. InSAR is an additional check'* (participant 9, InSAR user) and *' when the displacement estimates match with the actual values of displacement on the field.'* (participant 4, InSAR provider).
- *'it helps to grant safety.'* (participant 4, InSAR provider).
- *'people consider InSAR deployment for a next project and understand the tool.'* (participant 9, InSAR user).

An InSAR project is considered not successful if

- *'high costs have been incurred and InSAR shows no sensitivity to the movements. In other words: If a lot of money has been spent without being able to draw any conclusions.'* (participant 1, InSAR user).
- *'incorrect conclusions are drawn from the InSAR data. For example, if a trend is derived from time series that are too short or from questionable data and it later*

turns out that the actual behaviour was different.' (participant 2, InSAR user).

- *'the promises from the initial proposal are not fulfilled'.* (participant 3, InSAR user).

3.4.3 Comparison Literature and Interviews on Readily available PSI Products

There is little information in the literature about opinions on PSI products, such as PSI maps. Table 3.4.4 shows the comparison between the interviews and the literature. The research papers about PSI maps emphasise the potential of the results for a wide range of users and do not focus on the constraints. While the free availability of such products is also considered a large benefit by many interviewees, the constraints emerge clearly. One major constraint is that these maps are application agnostic, meaning they are sub-optimal for a particular application and local use. The interviewees state that this should be communicated clearly to prevent wrong use and expectations by users who do not know about PSI maps. Moreover, the maps may contain sensitive information but are now available to everyone. The interviewees, however, mention that, despite the constraints, these maps create awareness about the InSAR technology.

Table 3.4.4: Comparison of opinion about PSI products between the literature and interview results.

	Interviews	Literature
Benefits of PSI maps are large scale information, PSI displacement maps accessible to non-expert InSAR users, base for researcher, starting point for investigations	x	x
Nationwide PSI maps agnostic and not suitable for local scale	x	-
PSI maps create awareness	x	-
PSI maps contain sensitive data	x	-
Communicate honestly about PSI maps as users have limited background knowledge	x	-
Companies handling PSI maps data are a threat	x	-

3.4.4 Comparison Literature and Interviews on Recommendations

Regarding the recommendations, the findings from the interviews give much more insight than the literature (Section 2.3.5) and primarily concern the non-technical obstacles. Table 3.4.5 shows the comparison between the interviews and the literature. The most important recommendations are managing expectations, good communication, providing show cases, educating personnel, performing InSAR pre-analyses before deploying it and a step-wise InSAR implementation in projects. The literature also mentions that InSAR users need more knowledge and guidance, that adequate personnel should be involved, that cooperation between InSAR providers and InSAR users should be improved and that example projects should be shared. The interviews and literature note that uniform methods of quality evaluation are necessary.

The interviewees also provide more tangible recommendations on how to realise those recommendations in practice. To improve communication and align the expectation, sharing information openly between InSAR users and InSAR providers, preferably in physical meetings or even on the project site is desired. Also InSAR providers should communicate the challenges of the technology clearly. Education of engineers could be done already at university by including SAR technology in the curriculum of civil engineering and by organising mandatory courses for both users and providers about each others discipline. While the literature recommends to provide user-ready products, this is not mentioned by the interviewees. The interviewees focus more on education. Also from the literature improving computer processing and data storage facilities are recommended. This is not mentioned by the interviewees. See Table 3.4.5.

Next, evaluating the ten critical success factors of Pinto and Slevin (1988) and the additional success factors for the implementation of new technologies (Karlsen et al., 2006) of Section 2.5 we observe, that the interviewees mention most of these factors as well. Aligned expectations and good communication were mentioned by all participants as key success factors. This corresponds well with the following success factors of Pinto and Slevin (1988) *clearly defined goals and project mission*, *active listening to all impacted parties*, and *adequate communication*. This also matches the following success factor of (Karlsen et al., 2006) for the implementation of new technology: *end-user involvement*, *good communication and feedback from involved parties*. Having knowledge and skilled personnel is mentioned by the participants, which corresponds well with success factors *competent project team members* and the *availability of the required technology and expertise to accomplish the tasks*. The participants also mentioned delivering on time within budget, which corresponds well with success factor *clear projects schedule and plans* of Pinto and Slevin (1988) and success factor *a clear project goal* of Karlsen et al. (2006).

The success factor *management support* was not mentioned explicitly by the participants at all. It is obvious that this is not an issue for InSAR providers as providing consultancy and processing SAR data is their business goal. However, also the users did not mention this, despite non of the interviewees being in a top management position. One reason could be that the interview questions did not address this

Table 3.4.5: Comparison of the recommendations between the literature and interview results.

	Interviews	Literature
Manage expectations by		
- communicating the characteristics of SAR data and PSI products clearly, guiding users with no radar experience and explaining the practical impact of different assumptions	x	x
- sharing information	x	-
- engage with each other's problem	x	-
- explaining difference between diagnostics and detection clearly	x	-
Build trust in the technology by		
- show-cases of example projects	x	x
- pre-analyses, step-by-step deployment, pilot project	x	-
- physical meetings and site visit	x	-
- validation of deformations trends from SAR data with terrestrial measurements	x	x
Education and training of		
- end-users to gain understanding of SAR data.	x	x
- SAR providers to gain knowledge about the working fields of end-users	x	-
Clear procedures, tools and guidelines and standard approaches and interpretation criteria for SAR data	x	x
Provide tools for end-users to understand the data	-	x
Dedicated InSAR processing for local projects	x	-
Appropriate team with qualified staff on InSAR users and InSAR providers side	x	x
Restrict the cost of InSAR analyses	x	-
Improve computer processing and data storage facilities	-	x

specifically and the internal organisation of the companies where the interviewees worked, was not a topic in the interview. Investigating if this success factor is indeed also influencing the deployment of InSAR in projects could be a topic for further investigation. Also *trouble-shooting, i.e. the ability to handle unexpected crises and deviations from plan* was not mentioned by the interviewees. We hypothesise that this success factor might be indeed less relevant for InSAR deployment. However, also this could be a topic for further research.

3.5 Discussion and Reflection on the Interviews

The present study aims to find out how InSAR users and InSAR providers perceive the deployment of InSAR in geotechnical, civil engineering and natural hazard projects. To our knowledge, this type of qualitative research with in-depth personal interviews among users and providers has not been performed before, and we believe that the results contribute to a better understanding of users' and providers' experiences. The interviews give valuable insight into their opinions. However, we stress that the interviewees' perceptions of InSAR vary based on their experiences, knowledge of the technology, and the specific applications they encounter in their work. Their statements depend, therefore, on a specific context and cannot necessarily be generalised. Moreover, the somewhat biased sample characteristics can be viewed as constraints of the present study. The participants were selected based on willingness and availability. While searching for participants, some contacted engineers did not want to participate in this study due to various reasons such as company policy or personal motives. In addition, the InSAR users who were willing to participate already had some, mainly positive, experience with InSAR or had some knowledge about the possibilities of this technique. Also we realise that the InSAR providers of this study benefit from a positive opinion of InSAR. We believe that, despite these challenges regarding our participants, the present study's findings do allow a certain degree of generalization.

Based on the interviews, we can extract a few common denominators, which concern the technical benefits. Many of the interviewees consider the ability to provide precise measurements of ground deformation with millimetre to centimetre accuracy over large areas without the need for physical access and the large historical archive, which makes it able to assess deformations of the past, the greatest advantages of the technique.

On the other hand, some of the interviewees' statements regarding the technical challenges cannot be generalised. For example, the interviewees mention the presence of vegetation and snow as major technical obstacles, while in fact, the real challenge is the lack of useful acquisitions or reduced spatial sampling with a certain satellite and wavelength. The wording of the users regarding this obstacle seems to indicate that for a user the cause of the challenge may not always be fully clear. Moreover, some of the technical obstacles mentioned by the interviewees may be solved with, for example, a different type of satellite with a different wavelength or revisit time, a different formulation of the problem of adding information from other data sources. It seems that some of the interviewed InSAR users are not fully aware of this.

We stress that the outcome of an InSAR analysis depends on the object of study. This means that the feasibility varies on the size and spatial extent of the object of study, the surrounding environment, the materials on the ground, the amount of deformation, the temporal stability of the deformations and other influencing factors. All these factors can affect the data quality and coherence. Moreover, InSAR is an opportunistic method and the availability of benchmarks and measurement points both spatially and temporally is not given from the start. Therefore, the technique's success or application possibilities for a particular project cannot be determined with certainty in advance. We believe that this opportunistic nature of the technique and its applicability, being dependent on the object of study, is hampering engineers from understanding InSAR, as these characteristics make InSAR different to traditional monitoring techniques that users are used to. Many users may consider InSAR as another monitoring technique and do not fully realise that InSAR has a different approach and one needs to work with what comes out from the processed SAR data, instead of being able to design a network prior to and for a particular application.

The statements of the interviewees about Persistent Scatterer Interferometry (PSI) products provide information about the perception of these products, which cannot be found in the literature. While these products are considered to create awareness and provide valuable information, their application possibilities and constraints need to be communicated clearly. Especially, as these products are more and more available to a broader public, information regarding the correct use of these products is essential. These interview results can be interesting for future research and actions to raise awareness of the correct use of different PSI products.

We find, based on the interviews, that many users working in civil- and geo-engineering projects still have misconceptions about InSAR. This opinion is also enhanced by the interviewees' own statements. Many mention that InSAR is still an unknown technology in the civil and geotechnical industry, there is a lack of knowledge and awareness and there are too few skilled people to interpret the data correctly. Moreover the interviewees state that users and providers have different expectations of the technique. Finally the different way of thinking and language are mentioned. We believe, that these non-technical obstacles are major barriers for the deployment of InSAR in geotechnical and civil engineering projects.

Finally, an important outcome of the interviews are the recommendations given by the interviewees. This is previously unknown and new information based on experiences in the daily practice of InSAR users and InSAR providers. By combining this with the available literature, a list of hands-on recommendations was provided that can be implemented into practice.

3.6 Conclusion

The interviews give unprecedented information regarding the non-technical key success factors for deploying InSAR in civil-, geo-engineering and natural hazard related projects, which are aligned expectations, good communication, knowledge and skilled people. Moreover, the main limiting factors in a successful application are different expectations about the project and product between InSAR users and InSAR providers, a lack of knowledge of each other's needs, and a shortcoming in skills. It is clear to potential users that InSAR has many benefits in civil- and geo-engineering related projects and for natural hazard evaluation, however the technical obstacles lead to it not being optimal for every application. Also many misconceptions still exist among InSAR users about the technology.

Also, the interviewees provide previously unknown recommendations for improving the deployment of InSAR, such as sharing information between InSAR users and the InSAR provider, preferably in a physical meeting or even on the project site. Also, educating InSAR users and providers, thus creating a mutual understanding of each other's discipline and needs, is a major recommendation. Another main recommendation is that InSAR providers communicate clear and transparently regarding the technical obstacles of InSAR. Also, regarding the use of PSI maps, it is recommended that the obstacles of PSI maps should be communicated clearly, as users of these maps have limited background knowledge on SAR. Developing show cases for potential users, a step-by-step InSAR deployment in a project and providing pre-analyses at low cost are also recommended.

Chapter 4

Operational Framework for Integration of InSAR Monitoring with Geotechnical Design Codes

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4.1 Introduction

Interferometric Synthetic Aperture Radar (InSAR) is a geodetic 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. In geotechnical design codes such as the Eurocode-7 (European Committee for Standardization, 2020) in Europe, the SIA267 Geotechnik code in Switzerland (Schweizerischer Ingenieur- und Architektenverein, 2013) and the Geotechnical Site Characterization Publication No. FHWA NHI-16-072 of the Department of Transportation in the US (US Department of Transportation, 2017) procedures are explained how to choose appropriate methods of soil investigation for specific type of structures. Mapping, remote sensing techniques and monitoring are also mentioned in these codes. These geodetic methods may include terrestrial geodetic techniques, which observe the Earth's surface and its changes with sensors at or near the Earth's surface, as well as space geodetic techniques. These different techniques are not distinguished in the geotechnical design codes and InSAR is not specifically mentioned for geotechnical applications.

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 4.2 offers an overview of the current practice for assessing geohazards. Section 4.3 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 4.4 the framework is applied to an infrastructure retrofitting project.

4.2 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 InSAR within current geotechnical design codes.

4.2.1 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 (Zangerl et al., 2008). 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 geodetic 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 (European Committee for Standardization, 2020). 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 (Mansour et al., 2011; Bru et al., 2018). Moreover, frequent measuring is time consuming, labour intensive and challenging for areas with difficult access (Huang Lin et al., 2019).

4.2.2 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 (Hanssen, 2001). 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 (Reinders et al., 2021; Scoular et al., 2020; Bischoff et al., 2019). Additionally, InSAR was applied to monitor buildings (Venmans et al., 2020; Hoefsloot and Wiersema, 2020; Giardina et al., 2019; Chang and Hanssen, 2015), bridges (Xiong et al., 2021; Cusson et al., 2021; D'Amico et al., 2020; Gagliardi et al., 2020; Hu et al., 2019; Milillo et al., 2019; Peduto et al., 2018; Selvakumaran et al., 2018; Sousa et al., 2014), dams (Milillo et al., 2016a; Sousa et al., 2014; Hanssen and Van Leijen, 2008), levees (van Buuren et al., 2020; Özer et al., 2019), railways (Tosti et al., 2020; Hu et al., 2019; Wang et al., 2018; Qin et al., 2017; Peduto et al., 2017a; Chang et al., 2018,0,0), pipelines (Arsénio et al., 2015), airport runways (Gagliardi et al., 2021) and roads (Bianchini Ciampoli et al., 2020; Yu et al., 2013).

Also, InSAR proved to be capable to measure ground displacements in areas affected by slow-moving landslides (van Natijne et al., 2022a). With this information, inventory maps and landslide hazard assessments were produced (Hormes et al., 2020; Antonielli et al., 2019; Colesanti and Wasowski, 2006; Cascini et al., 2009; Bovenga et al., 2012; Bianchini et al., 2012; Cigna et al., 2013; Herrera et al., 2013; Wasowski and Bovenga, 2014; Béjar-Pizarro et al., 2017; Frattini et al., 2018; Bru et al., 2018; Di Maio et al., 2018; Crosetto et al., 2018; Huang Lin et al., 2019; Wasowski and Pisano, 2020; Xie et al., 2020). InSAR information was used to identify critical sections in roads, affected by slow moving landslides (Nappo et al., 2019; Infante et al., 2018). Finally, historic settlements of the past decades in deltaic areas were measured with InSAR (Wu et al., 2020), and InSAR-based observations of consolidation settlements proved to match well with the results from geotechnical boreholes (Zhang et al., 2019).

4.2.3 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 (European Committee for Standardization, 2020). 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 (see Fig. 4.2.1). As remote sensing covers a wide ranges of techniques such as optical or acoustic measurements, laser, InSAR and other geodetic 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 4.2.1, we show for which type of activities, that are listed in table B.1 of the Eurocode-7, InSAR can be applied for the acquisition of information in geotechnical projects. Table 4.2.1 should be seen as an addition to table B.1 of the Eurocode-7.

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																		

Figure 4.2.1: Table B.1 from Eurocode 7. The row 'Mapping and remote sensing' shows the applicability of remote sensing techniques for the required information.

Table 4.2.1: Activities with InSAR applicability. Adaptation of table B.1. of Eurocode-7.

Geotechnical activities with InSAR applicability
Desk Study history and, past uses of site
Site Inspection – ground features and geomorphology
Assessment of disposition and nature of geotechnical units
Evalation of groundwater conditions
Geotechnical monitoring
Assessment of soil stiffness properties
Determination of soil cyclic response and seismic properties
Detection of presence of voids (natural or man-made)

4.3 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.

4.3.1 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 (Fookes, 1967). 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 (Ward et al., 1991) and leads to a better understanding and planning of the upcoming required site investigation.

According to Eurocode-7, Part 2 (European Committee for Standardization, 2020), the required investigation phases are desk study and site reconnaissance (1a), in-situ testing for 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 Committee for Standardization (2020).

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.

4.3.2 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 (Xie et al., 2020; Infante et al., 2018; Peduto et al., 2017a; Eddies et al., 2018; Couture et al., 2013; Bichler et al., 2004).

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 [1]. Table B.1 of Eurocode 7

[1] CIRIA Report C805 (Mason et al., 2022) was not yet available when publishing this article.

Project phases	1. Pre-construction phase			2. Construction	3. Operation and maintenance
	1a. Conceptual planning and feasibility study	1b. Preliminary design and engineering	1c. Detail 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

Figure 4.3.1: Overview of project phases and site investigation phases that could benefit from InSAR deployment.

(Fig. 4.2.1) does not distinguish between different type of geodetic techniques and their use in different project stages. Fig. 4.3.1 presents an overview of the potential application of InSAR during all five generic project phases, as proposed in this paper. In Sections 4.3.2 to 4.3.2 the value of InSAR combined with the soil investigation per phase is elaborated.

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 (Eddies et al., 2018). 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 (Glossop, 1968).

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 (European Committee for Standardization, 2020) 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. 4.3.2 shows a scheme for implementing InSAR information in the desk study.

Examples of the application of InSAR at stage 1a 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 for example be applied to piezometer data. Given several piezometers, a contour map of groundwater head decline can be made, and InSAR data can be used to estimate the subsidence and verify or extend the contour map (Béjar-Pizarro et al., 2017; Ghazifard et al., 2017). Similarly, by performing settlement back analyses based on InSAR results and the available soil investigation, a settlement model can be obtained (Wu et al., 2020). 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 (Nof et al., 2019; Intrieri et al., 2015). All this information can be integrated in the baseline assessment of a the project.

In the *preliminary* and in the *design 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. 4.3.2 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.

Construction Stage

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

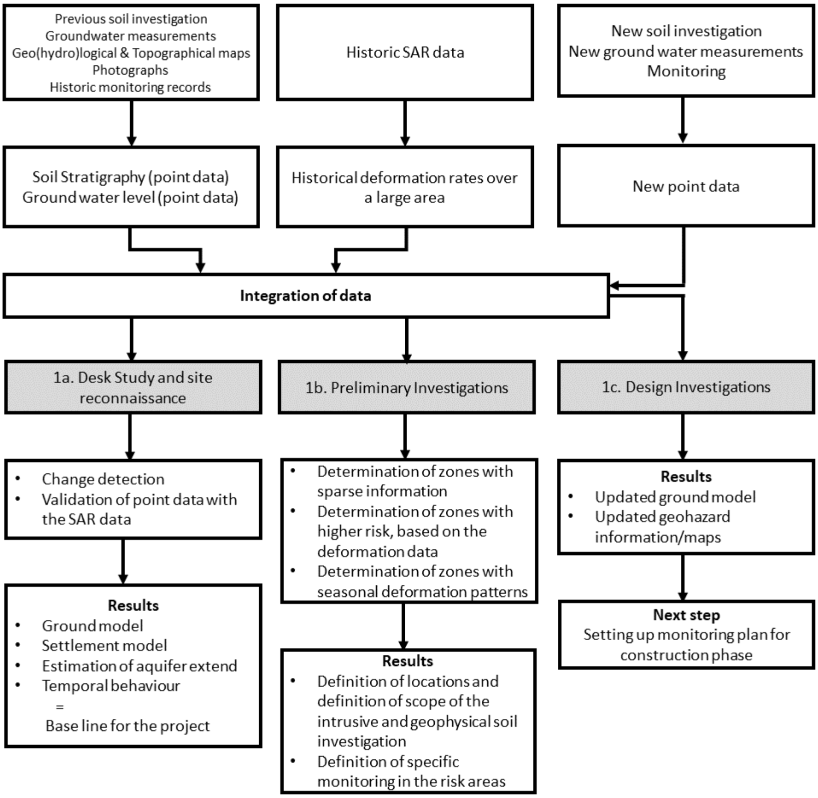


Figure 4.3.2: Integration of InSAR in (i) the desk study phase, in (ii) the preliminary and design soil investigation phase. This shows how InSAR results can be used during the first three phases of a project.

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 (Macchiarulo et al., 2021; Drougkas et al., 2021; Giardina et al., 2019). See Fig. 4.3.3

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 (Czikhardt et al., 2021; Mahapatra et al., 2018). 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.

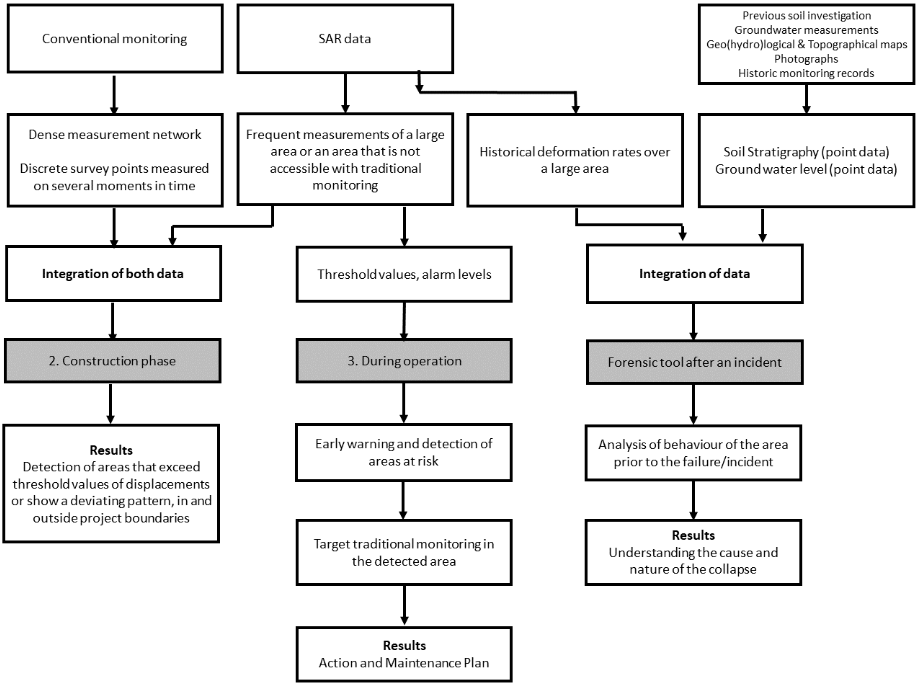


Figure 4.3.3: Integration of InSAR with conventional monitoring during the construction stage and operational stage. Also the use of InSAR as a forensic tool is presented.

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 (Mazzanti, 2017). 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 (Bouali et al., 2016; Ní Bhreasail et al., 2018). 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. 4.3.3. 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 (Grebby et al., 2021; Milillo et al., 2019; Selvakumaran et al., 2018; Sousa and Bastos, 2013), see Fig. 4.3.3.

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.

4.4 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.

4.4.1 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. 4.4.1. 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%.

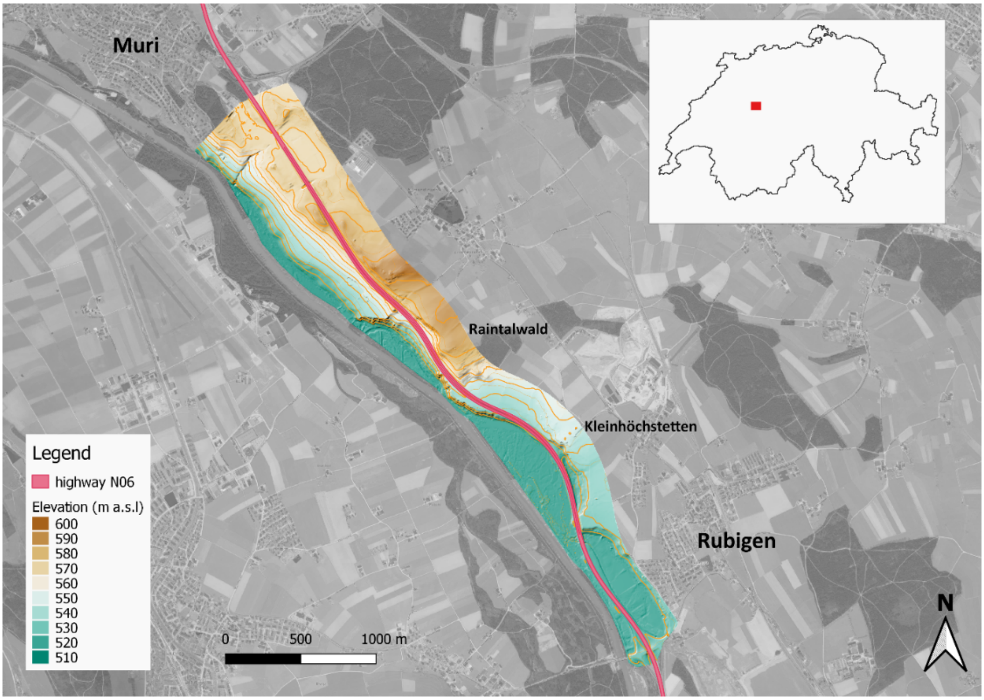


Figure 4.4.1: Location and elevation of highway N06 between Muri and Rubigen, Switzerland.

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 (Kilchenmann, 1973) 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 (Kilchenmann, 1973). This suggests an extremely low to very low velocity, according to the classification by Varnes and Cruden (1996). 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 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.

4.4.2 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 (Bundesamt für Landestopografie swisstopo, 1972; Gruner, 2001). 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

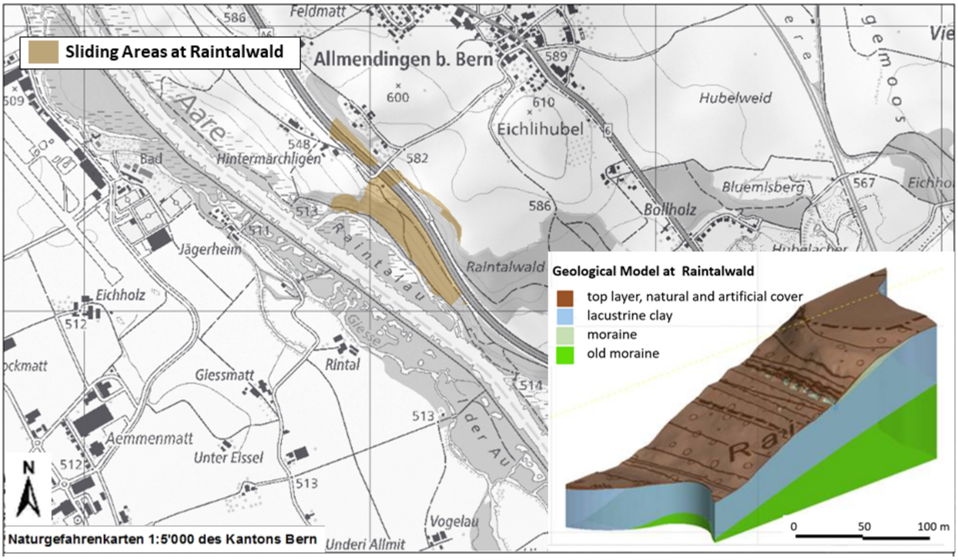


Figure 4.4.2: Geological model of the area of interest Raintalwald with background map of landslide hazards of the Kanton Bern (Amt für Wasser und Abfall des Kantons Bern, 2020).

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 (Seequent, 2020). The model includes underground information from archive boreholes (Amt für Wasser und Abfall des Kantons Bern, 2020) and new drillings, as well as geological maps from the Federal Office of Topography swisstopo (swisstopo, 2022). In addition to lithological information, data on historic and current groundwater levels was also included. A sketch of the model is displayed in Fig. 4.4.2.

4.4.3 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. 4.4.3. The data show a clear seasonal trend. In summer, most of the rain-

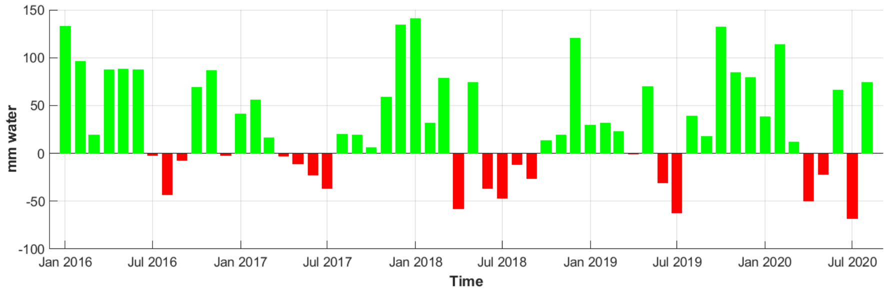


Figure 4.4.3: Water balance Bern for 2016 to 2020 at Meteoschweiz measuring station Zollikofen.

water 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 (Schürch et al., 2010).

4.4.4 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 (Hanssen, 2001), which may be coherent only for a limited subset of the time series (Hu et al., 2019). 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.

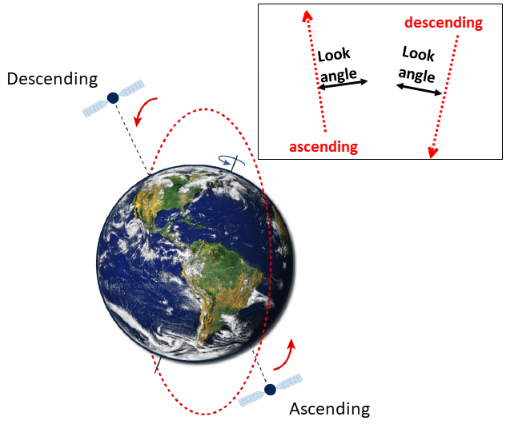


Figure 4.4.4: Graphic representation of descending and ascending orbits.

In this study we used SAR data acquired between 2015 and 2020 from the Sentinel-1 satellite mission (Table 4.4.1). 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. 4.4.4). 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 (Chang et al., 2018). See Fig. 4.4.5 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 (Skygeo, 2020), following methodology from Kampes (2005); Van Leijen (2014) and Hanssen (2001). 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.

Table 4.4.1: Sentinel-1 satellite data.

Orbit	Revisit time (days)	No. of images	Period	Incidence angle θ (°)	Spatial resolution (m)	Band
ASC track 88	6	226	Dec 2015 to June 2020	39.4	13.2 x 3.5	C
ASC track 15	6	205	May 2016 to June 2020	39.4	13.2 x 3.5	C
DSC track 139	6	210	May 2015 to June 2020	39.4	13.2 x 3.5	C
DSC track 66	6	235	May 2016 to June 2020	39.4	13.2 x 3.5	C

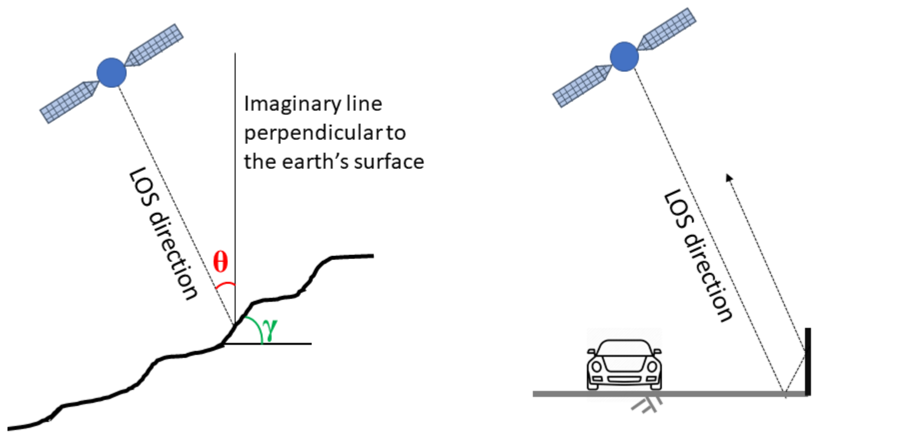


Figure 4.4.5: (Left) Incidence angle θ and slope angle γ. (Right) Double-bounce, or dihedral radar reflection, via the ground and a vertical wall back to the satellite.

4.4.5 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 a (vertical) wall or guardrail, this will result in a 'double-bounce' reflection (Fig. 4.4.5b). In this case, double bounces were stronger for the descending then for the ascending acquisition geometry.

Fig. 4.4.6 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 $\geq$ 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. 4.3.2). To evaluate the regions of interest, cross sections were drawn at these locations in the geological model (see Section 4.4.2) 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. 4.4.7).

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.

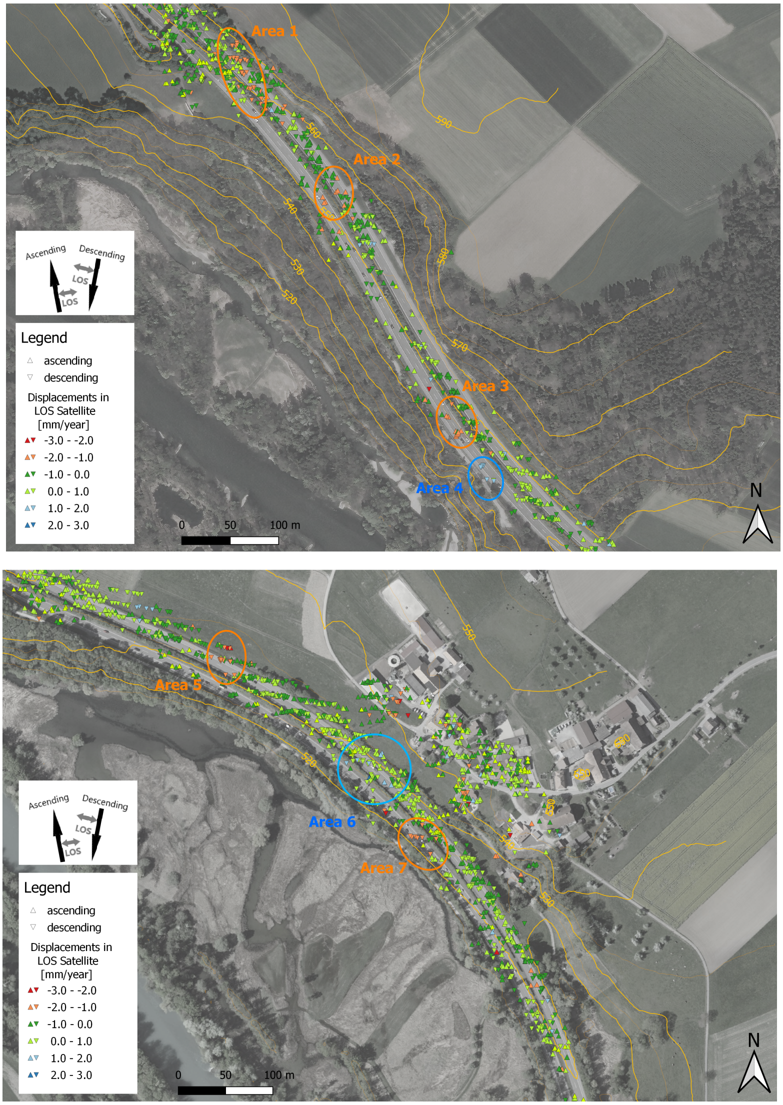


Figure 4.4.6: Displacements in LOS direction from Raintalwald to Brüelmatt/Kleinhöchstetten. Sentinel-1. Positive displacements indicates a movement towards the satellite, negative displacements a movement further away from the satellite.

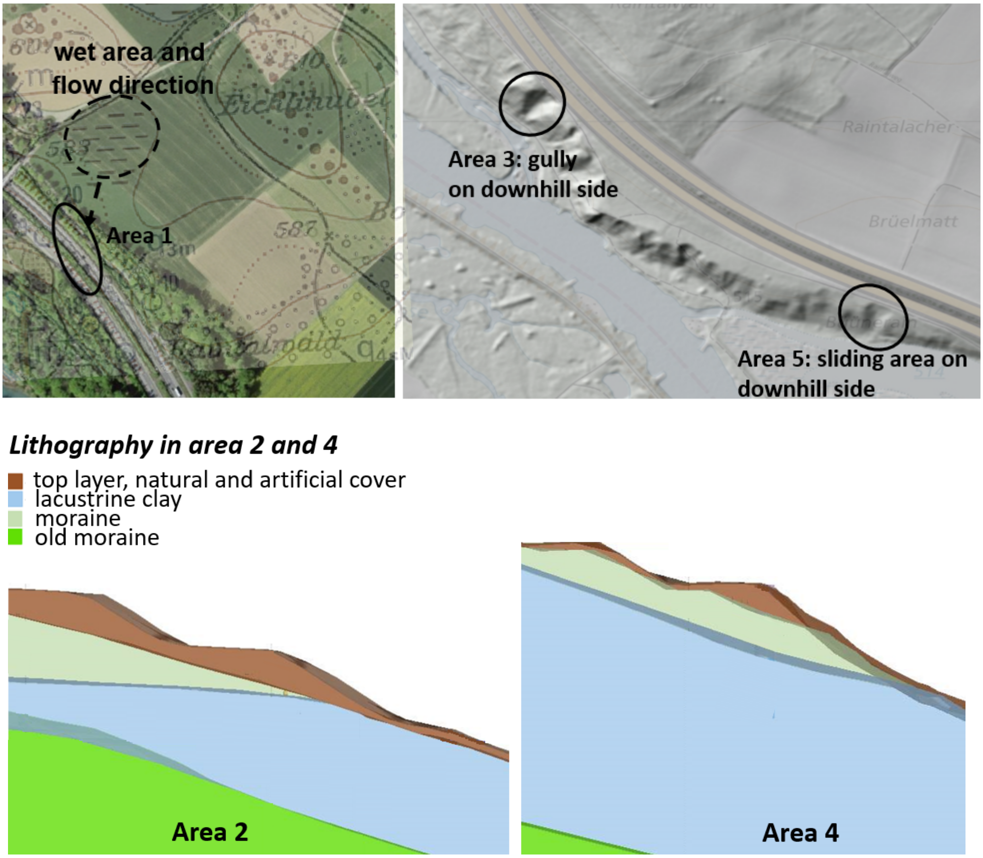


Figure 4.4.7: Details of individually analyzed areas. (Top left) Top view for area 1. (Top right) Top view for area 3 and 5. (Down left) Geological cross section for area 2. (Down right) Geological cross section for area 4.

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. 4.4.8).

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. 4.4.8, 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.

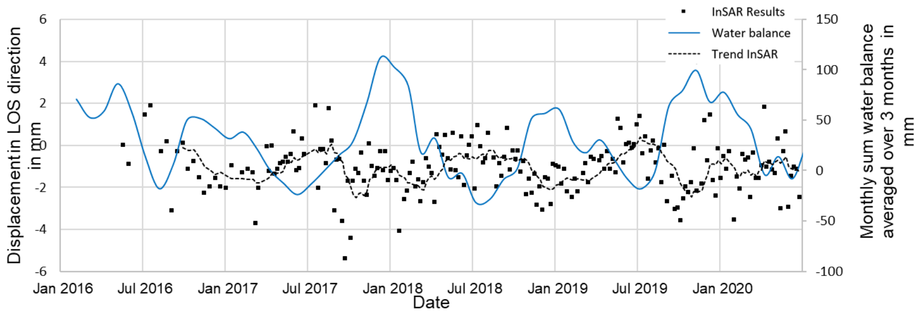


Figure 4.4.8: Example of a seasonal trend in the InSAR estimates in the project area (black dots), and water balance estimates (blue line), from the descending orbit.

4.4.6 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 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.

4.4.7 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 phases.

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.

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.

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.

4.5 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 gengineers, 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 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.

Chapter 5

Augmented InSAR for Deformation Detection in Tunnelling Projects

This chapter has been published under Reinders, K.J., Hanssen, R.F., van Leijen, F.J., Korff, M., 2021. Augmented satellite insar for assessing short-term and long-term surface deformation due to shield tunnelling. Tunnelling and Underground Space Technology 110, 103745.

5.1 Introduction

During the past decades, satellite radar imaging using the Interferometric Synthetic Aperture Radar (InSAR) technique was used to monitor displacements of the land surface (Hanssen, 2001; Özer et al., 2019; Gabriel et al., 1989; Ferretti et al., 2002; Crosetto et al., 2016a). The applicability of InSAR was also demonstrated in some tunnel projects (Bischoff et al., 2019; Giardina et al., 2019; Barla et al., 2016; Schindler et al., 2016; Macdonald et al., 2015; Mark et al., 2012; Schneider et al., 2015). This showed that InSAR can be used for (i) the detection of tunnelling-induced settlements, resulting in localization and timing of the settlement, complemented by (ii) an estimation of the quantitative amount of settlement. Particularly for long-term settlements, occurring years to decades after the construction phase ends (Shirlaw, 1995; Mair, 2008; Wongsaroj et al., 2013), InSAR is probably the only economically feasible monitoring option.

The main limitations of InSAR for tunnelling are imposed by the revisit times of the satellites and the condition of coherence—where reflection characteristics of the geo-objects should remain relatively unaltered over time (Hanssen, 2001). Moreover, due to the fixed wavelength of the radar instrument, abrupt changes in the spatial displacement gradients greater than the *wrapping threshold*—defined as a quarter of the physical radar wavelength in the line-of-sight of the radar—may lead to an under- or overestimation of the deformation signal. As surface settlements that occur during excavation of a shield tunnel typically have a magnitude range of a few millimetres to a few centimetres, which may occur within roughly one week of construction at the location where the tunnel boring machine (TBM) has passed (Broere and Festa, 2017), over a spatial distance of a few tens of meters, such deformation ambiguities cannot be ignored in the InSAR estimates. In this paper we extend this analysis and evaluate if, when, and how InSAR can be used in different stages: (i) prior to the tunnel construction, as a design tool to optimise the monitoring plan, (ii) during construction, as a diagnostic tool to detect surface settlements and (iii) after construction as a forensic tool to evaluate damage as a low-cost monitoring tool and to monitor the long-term settlements. We use the twin shield tunnels of the North/South Metro Line in Amsterdam that were excavated in 2011 and 2012 as a case to demonstrate the applicability. Surface settlements larger than or close to the wrapping threshold occurred during this project.

5.2 Review and Background

This section comprises a short explanation of surface settlements during shield tunneling, the basic concepts of InSAR and the potential of InSAR for tunneling projects.

5.2.1 Surface Settlement Due to Tunnelling

During the excavation of shield tunnels surface settlements may occur due to insufficient support at the face, over-excavation, soil relaxation and inefficient tail void filling (Maidl et al., 2013). In practice, the settlements that occur during construction in cross-sectional direction of the tunnel are often calculated with Peck's formula (Peck, 1969) and are well understood. This empirical formula is based on observations and analyses of a large amount of monitoring data from tunnels and is most commonly used for 2D calculations. The settlement trough that occurs in a cross-section perpendicular to the tunnel axis can be expressed by the following Gaussian curve:

$$S(y) = S_{\max} \exp(-\frac{y^2}{2i^2}) \tag{5.1}$$

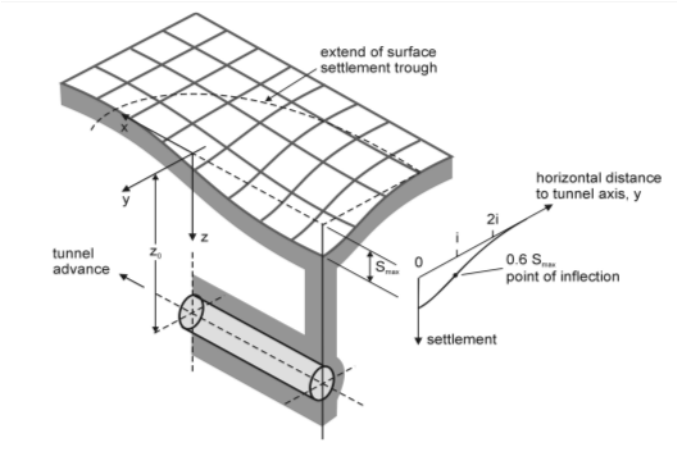


Figure 5.2.1: Three-dimensional representation of surface settlement induced by a tunnel (Attewell et al., 1986).

where $S(y)$ is the settlement at ground level, y is the horizontal distance from the centreline, $i = 0.28z_0 - 0.1$ is the horizontal distance from inflection point to the tunnel centreline for a sandy soil, as a function of the tunnel depth z_0 (O'Reilly and New, 1982), and $S_{\max}$ is the maximum ground settlement at the tunnel centreline. $S_{\max}$ can be expressed as

$$S_{\max} = \frac{c_L \cdot \pi D_0^2/4}{i \cdot \sqrt{2\pi}} \tag{5.2}$$

where the numerator is the product of c_L, the volume loss influence factor—around 0.005 (0.5%) for a slurry machine—and the cross-sectional area of the circular tunnel, scaled by D_0—the outer diameter of the tunnel. The major assumption is that the volume of the settlement trough equals the volume of soil losses around the tunnel. Usually these settlements occur within a length of 40 to 50 m, which corresponds to typically one week of construction (Broere and Festa, 2017). Fig. 5.2.1 shows the development of surface settlement as tunneling progresses.

On the other hand, the long-term settlements of shield tunnels in soft soil conditions are not so well understood and have large uncertainties in their predictions (Mair, 2008; Wongsaroj et al., 2013). These settlements may occur in the years and even decades after construction due to consolidation and creep of clayey soils. Although the magnitude of these settlements can account for 30–90% of the total settlements (Shirlaw, 1995), only a few studies were performed (Stallebrass et al., 1994; Addenbrooke, 1996; Mair, 2008; Shin et al., 2002; Bowers et al., 1996). From these studies it is known that the long-term settlement trough tends to be deeper and wider than the trough that occurs during construction. As traditional monitoring is generally ceased within a year of the end of construction, little data is available on the exact amounts of long-term settlements due to tunnelling in soft soils. This is where InSAR may be of complementary value.

5.2.2 Basic Concepts of InSAR

SAR is a geodetic technique that can measure displacements of the ground or objects on it (Elachi, 1987). It is an imaging radar, mounted on a satellite, that sends pulses of electromagnetic waves to the earth. Part of these pulses reflect back towards the antenna of the satellite. The phase of the incoming signal, which is dependent on the two-way travel time of the signal, is recorded. Table 5.2.1 shows several characteristic elements of current C-band and X-band missions.

Table 5.2.1: Relevant characteristics for current C-band and X-band SAR missions.

Mission	Band	Wave-length (mm)	Wrapping threshold (mm)	Repeat cycle[1] (days)	Revisit time[1,2] (days)
RadarSAT-2	C	56	14	24	6
TerraSAR-X/Tandem-X/Paz	X	31	7.8	11	4
Cosmo-Skymed 1/2/3/4	X	31	7.8	4	2
Sentinel-1 a/b	C	56	14	6	2

The repeat cycle indicates the achievable repeat interval for interferometric combinations. The revisit time indicates how often the area of interest can be imaged, albeit with different viewing geometries.[1)] This is assuming that the satellite is tasked to acquire data over the area of interest.[2)] These values reflect situations for latitudes higher than 45 degrees.

A reflection from the ground may stem from two types of scatterers, i.e. distributed scatterers (DS) and point scatterers (PS). PS are pixels which have one dominant reflecting object within the pixel's footprint that shows constant behaviour over time. DS are pixels which contain multiple objects with a weaker reflection but that also show consistent behaviour over time.

A single phase observation φ_M in one SAR acquisition does not contain interpretable information. However, when obtaining a second phase observation φ_P, at a different location, and subsequently repeating those measurements during a second radar acquisition at the next satellite pass, the double-difference (i.e., spatial and temporal phase difference) $\Delta\varphi_{\text{int}}$ between the two measurements can be determined, i.e. the interferometric phase

$$\Delta\varphi_{\text{int}} = (\varphi_M - \varphi_P)_{t_2} - (\varphi_M - \varphi_P)_{t_1} \tag{5.3}$$

see Fig. 5.2.2. Typically, these differences have a precision in the order of a few millimeters. By calculating the interferometric phase for each successive image, a time series of displacements is obtained. The interpretation of double-difference measurements requires an arbitrary reference point and reference time. The movement of all points within the analysis is relative to this reference point and time. The relation between phase and displacement D is given by

$$\Delta\varphi_{\text{int}} = \frac{2\pi}{\lambda} \cdot 2D = \frac{\pi}{\lambda/4} D \tag{5.4}$$

where $2D$ is the extra two-way distance between satellite and target, and λ is the radar wavelength, which is typically either 31 or 56 mm for X-band and C-band satellites respectively, cf. Table 5.2.1. Thus, a phase change of π radians corresponds with a displacement of $\lambda/4$—a quarter of the physical radar wavelength, in the line of sight direction to the radar.

If a pixel has displaced more than π radians, a multiple of 2π should be added or subtracted from the interferometric phase to get the correct absolute phase change

$$\psi = \Delta\varphi_{\text{int}} + 2\pi k, \quad k \in \mathbb{Z} \tag{5.5}$$

where k is the integer cycle correction, or the phase ambiguity number. This procedure of ambiguity resolution is called phase unwrapping. Erroneous phase ambiguities are easily detectable in case the deformation rates are constant and small. However, if the settlements are close to or larger than the wrapping threshold $\lambda/4$, i.e. 7 or 14 mm, the InSAR result may yield an erroneous ambiguity number. Fig. 5.2.3 shows an example of an InSAR time series. Observation A is positioned around the wrapping threshold and may be estimated with ambiguous phase levels, leading to different (ambiguous) solutions.

To overcome this problem, prior assumptions about the deformation behaviour are required. For example, if we expect that the ground surface will behave similar in the future as in the past, we would select the middle ambiguity level in Fig. 5.2.3. On the other hand, if we expect sudden settlements due to underground tunnelling works, occurring at the time of observation A, the lower ambiguity level seems more likely. And if we would expect heave at the time of observation A, the upper ambiguity level might be the correct choice. This example demonstrates that a-priori knowledge is required to estimate the correct ambiguity level.

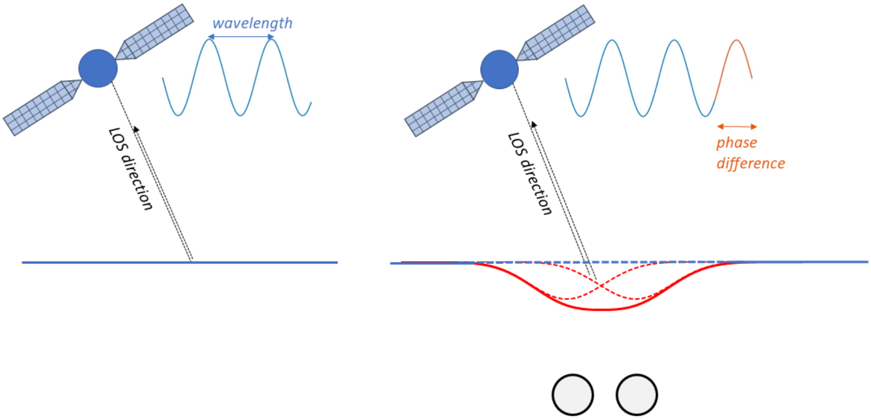


Figure 5.2.2: Two sequential InSAR measurement before and after deformation due to tunnel construction (after Özer et al. (2019)). The LOS is the line of sight direction of the radar signal.

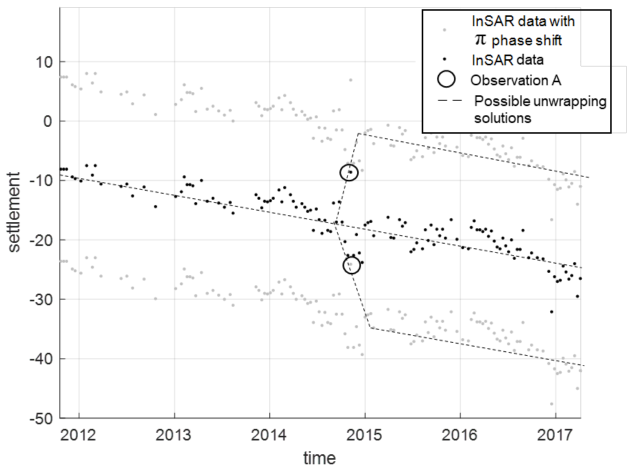


Figure 5.2.3: Potential ambiguity levels, or unwrapping solutions, for an InSAR time series.

5.2.3 Value Assessment of InSAR for Tunneling

To evaluate the potential and overall feasibility of InSAR for tunnelling we can distinguish a specific value before, during, and after construction.

Prior to tunnel construction, InSAR can be used (i) to understand the (undisturbed) stability of the area of interest, by evaluating the archive of satellite data, and (ii) to determine the position and distribution of coherent measurement points, which serves as a design tool to complement these with the in-situ surveying network to be installed.In soft soil areas it is common to find a background settlement in the form of long term subsidence mechanisms. As InSAR data is available since decades, it can reveal these spatial and temporal patterns of ground motion over a wide area, prior to construction. This can be used to find the driving mechanisms behind the observed deformation, which is valuable in the risk assessment and the design of the construction phase. When the influence zone of the tunnel is known, the location, density and quality of coherent InSAR points can be assessed. This analysis can be important for economic reasons, to design the required surveying efforts during and after the construction phase. Apart from a cost-saving driver, inclusion of the information readily available from satellites could lead to optimization of the monitoring plan and improved risk detection thresholds.

During construction, InSAR measurement points can be used complementary to the traditional monitoring, e.g., to assess the displacements of the ground and buildings in an area outside the traditional surface levelling points. This way, the information is used as a diagnostic tool to detect deformations. The value is defined by the range of observable signals, which is case-specific. For a particular situation, potential displacement signals (both intentional as well as unintentional) need to be defined. Ideally, this is done in terms of a model, but also expectations on location, spatial extend, spatial smoothness, temporal extend, temporal smoothness, direction and magnitude are valuable. These so-called signal characteristics can then be evaluated against the spatio-temporal sampling and extend of the InSAR measurements.

Typically, *after* a tunnelling construction project ends, the in-situ monitoring network is discontinued. This means that dynamic effects, i.e. displacements, and settlements on the longer term cannot be observed any more. As the magnitude of such long term settlements can account for 30–90% of the total settlements (Shirlaw, 1995), SAR observations are most like the only source of information. A regular evaluation using InSAR is therefore cost-effective and sufficient. Moreover, the InSAR information can be used as a forensic tool to investigate, post-hoc, the displacements that may have led to observed damage or failure of a construction.

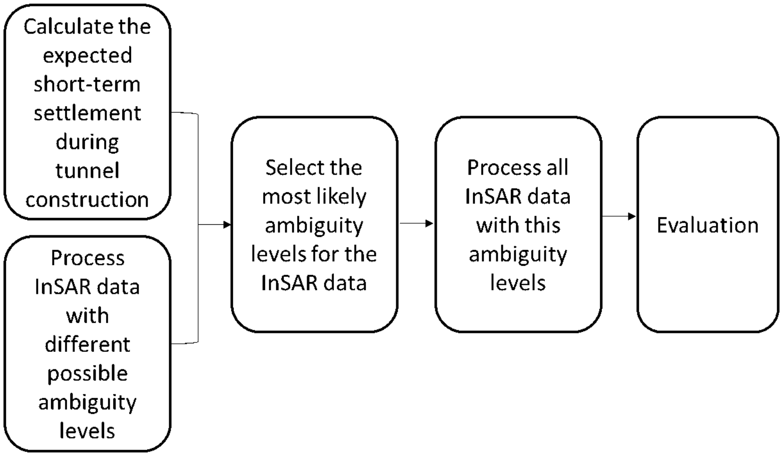


Figure 5.3.1: Flowchart for augmented InSAR data processing prior to construction.

5.3 Method

For this study we designed an augmented InSAR method by combining InSAR with prior expert information, and we evaluate the overall feasibility of InSAR for tunneling by addressing how InSAR can be used prior, during, and after construction.

5.3.1 Prior to Construction

Based on the influence zone of the tunnel we first assess the location, density and quality of coherent InSAR points. An evaluation of the InSAR data prior to construction will yield a preliminary quality assessment of the measurements during construction. In turn, this leads to the definition of detectability thresholds, such as the minimal detectable displacements.

Second, we evaluate with InSAR data the deformation patterns prior to construction. This analyses can reveal phenomena in surface deformation prior to tunnel construction and serve as baseline for the future project.

5.3.2 During Construction

To use InSAR during construction as a diagnostic tool to detect deformations, prior information is needed to select the most probable phase ambiguity level. We use the analytic settlement prediction of (Peck, 1969) as prior information to overcome the problem of ambiguity, following the scheme in Fig. 5.3.1.

Then we process the selected InSAR points with three different ambiguity levels and compare them with the measurement of the surface levelling points.

5.3.3 Assessment of InSAR Data after Construction

Based on the correct ambiguity level that we have chosen with the prior information during construction, we evaluate the long-term deformation trends, in the years after construction, with InSAR data. Second, we investigate if InSAR information can be used as a forensic tool to investigate, post-hoc, the displacements that may have led to observed damage or failure of a construction.

5.4 Study Area: North/South Metro Line, Amsterdam

To evaluate the value of InSAR for a practical situation, we use the case of the shield tunnel of the North/South Metro Line in Amsterdam, which was excavated with a slurry tunnel boring machine. In this section first the location and geology of the study area are described. Second the type of conventional monitoring data and the InSAR data are explained.

5.4.1 Location

In Amsterdam, a new metro line between Scheldeplein and Centraal Station, the so-called North/South Metro Line, was constructed between 2002 and 2018 in soft soil conditions. The 3.8 km long track consists of twin shield tunnels with a diameter of 6.52 m and has three deep intermediate stations: Ceintuurbaan, Vijzelgracht and Rokin. The tunnels were excavated between 2010 and 2012 with a slurry tunnel boring machine. In this research we focus on the part of the line between Scheldestraat and Ceintuurbaan, see Fig. 5.4.1.

In the first part of this trajectory, from Scheldeplein to Cornelis Troostplein, the tubes are located at the same depth next to each other with a spacing of 3.75 m. In the second part, from Cornelis Troostplein to Ceintuurbaan, the tubes are located above each other with 7 m spacing. The depth of the axis along the track varies from 15 to 30 m. The tubes are mostly located in sand or clayey sand. The soil conditions are shown in Fig. 5.4.2 and described in the next section in more detail. Both tubes in this trajectory were drilled from south to north with a slurry shield tunnel boring machine (TBM).

We selected two instrumented cross sections: Churchilllaan in the first part of the trajectory and Van Ostadestraat in the second part of the trajectory, see Fig. 5.4.1. The TBM of the West tunnel passed Churchilllaan on 27-06-2011 and Van Ostadestraat on 01-08-2011. The TBM of the East tunnel passed Churchilllaan on 27-01-2012 and Van Ostadestraat on 26-02-2012. The West tunnel (numbered with [1] in Fig. 5.4.2) was drilled in 2011 and the East tunnel (numbered with [2] in Fig. 5.4.2) in 2012.

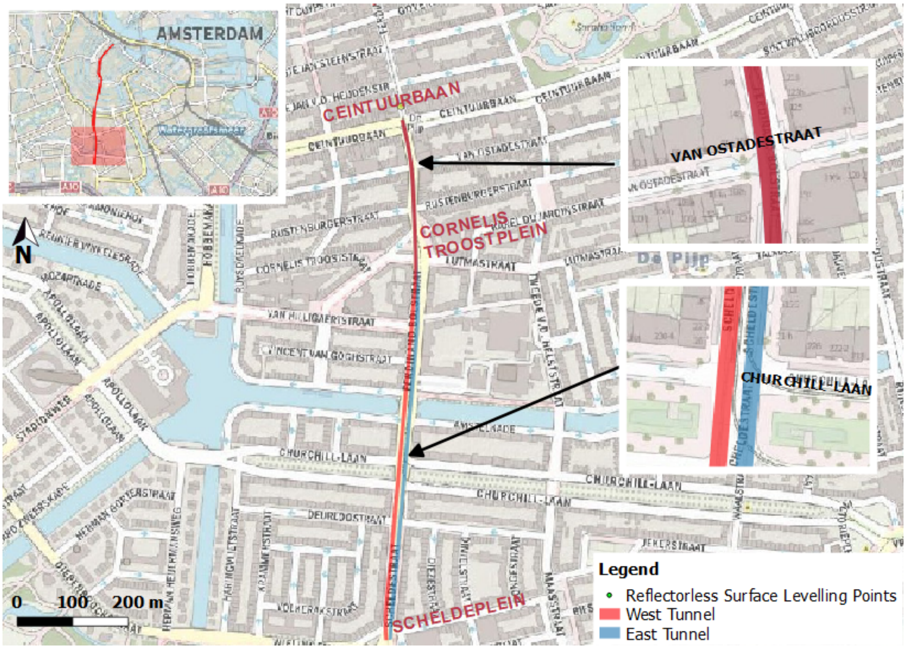
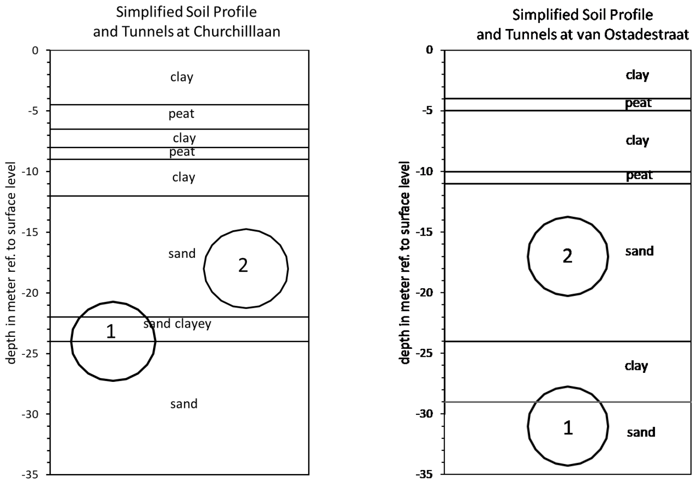
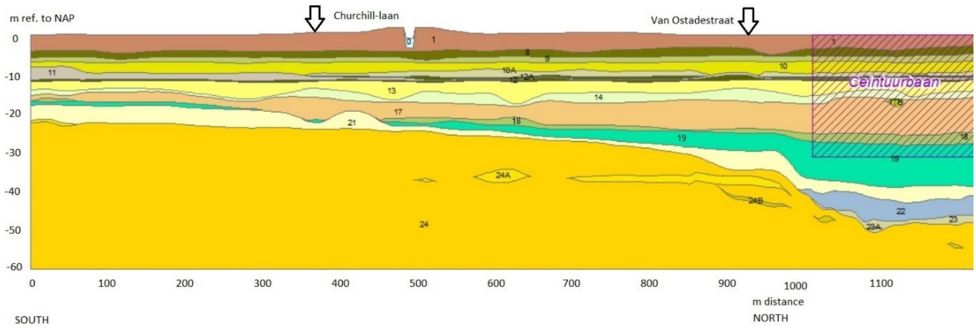


Figure 5.4.1: South part of the track of the North/South Metro Line.



(a) (b)

Figure 5.4.2: a) Simplified soil profile and depth tunnels at Churchilllaan. b) Simplified soil profile and depth tunnels at Van Ostadestraat.



1=sand/clay/peat, 8=peat (Hollandveen), 9=old marine clay, 10=wad deposit (sand), 10a=silt, 11=wad deposit (clay), 12= peat, 12a=peat (basisveen), 13=1st sandlayer, 14=Alleröd deposit (sandy clay), 17= 2nd sand layer, 19= Eem clay, 21=intermediate sand layer, 24=3rd sand layer, 24a=3rd sand layer, 24b=3rd sand layer

Figure 5.4.3: Geotechnical cross section along the south part of the track of the North/South Metro Line, based on (Adviesbureau Noord/Zuidlijn, 2014).

5.4.2 Geology

The geology in the city of Amsterdam consists of a Holocene layer of approximately 10 m to 13 m thickness which consists of clay with peat layers and some sand. The Pleistocene layers, with the first, second and third sand layers, including intermediate clay layers are found below the Holocene to a depth of well over 50 m, see Fig. 5.4.3.

5.4.3 Conventional Monitoring Data

During the construction of the North-South Line, the buildings and surface in the zone of influence were extensively monitored with 74 robotic total stations (Van der Poel et al., 2006; Cook et al., 2007). On the buildings, prisms were installed that were measured by the total stations (Korff et al., 2013). In order to measure the ground settlement, the automatic total stations recorded the vertical heights of points positioned on a virtual horizontal grid without the need for prisms on the surface. This is known as refectorless surface levelling.

In the line of the axis of each tunnel, the surface was measured hourly at one meter intervals. Furthermore, at several locations also points perpendicular to the tunnel axis were measured to obtain a transversal settlement profile. In the detail in Fig. 5.4.1 the reflectorless surface levelling points are shown for the Churchilllaan and Van Ostadestraat.

The monitoring started approximately two months before the TBM passed and ended one month after passing of the TBM. Both the surface and structures in the expected influence zone of the tunnel were extensively monitored. Fig. 5.4.4 shows

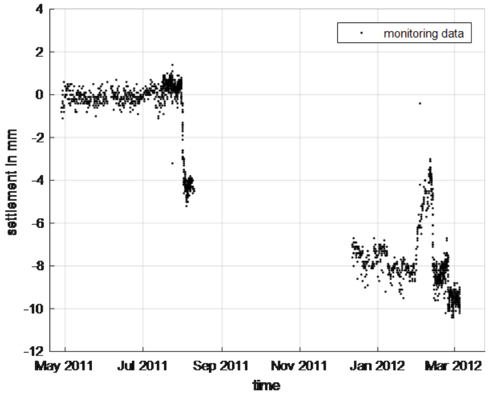


Figure 5.4.4: Example of monitoring of one reflectorless surface levelling point.

an example of a monitoring time series. The data gap shows that monitoring ended after the first tunnel was completed and started again shortly before the second tunnel was constructed. The heave during construction of the second tunnel is explained in Sec. 5.5.3.

The total stations were linked to each other and were checked on a regular basis against a benchmark of a deep datum, positioned outside the tunnel influence zone, on the stable third sand layer (?).

5.4.4 InSAR Data

For the chosen trajectory, we use SAR data acquired between 2009 to 2018 by the TerraSAR-X satellite. Our dataset contained data along the whole tunnel track in a strip of around 100 m wide, i.e. extending approximately 50 m to each side of the tunnels. The data set is acquired from an ascending orbit, where the satellite passes from south to north, and since the antenna is pointing to the right, the radar line of sight direction is roughly west-east. The repeat cycle of the satellite is 11 days and the radar wavelength λ is 31 mm, see Table 5.2.1. The displacements are measured in the line of sight to the satellite, with an incidence angle of 32 degrees with respect to zenith. Therefore, the measurements are sensitive to the projection of the 3D displacement onto the line of sight direction. Here we assume that the horizontal displacements are small and therefore we mapped the measured displacement in the vertical direction. This assumption is common for tunnelling conditions as vertical displacements are expected to be more dominant than horizontal.

We use both distributed scatterers (DS) and persistent scatterers (PS) in our research. Since InSAR data is relative both in time and space, a temporal and spatal 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 the complete dataset over Amsterdam is set to zero. It should be noted that these choices are arbitrary and do not influence the interpretation of the results.

5.5 Data Analysis

In the following section we subsequently analyze the InSAR time series data prior, during, and after construction of the North/South Metro Line.

5.5.1 Assessment of InSAR Data Prior to Construction

First we retrieved the relevant InSAR data is and second we evaluated this data for the period prior to construction.

Retrieving the Relevant InSAR Data

To reveal the patterns in surface ground motion prior to construction, we use the InSAR data in the zone of influence of the tunnel, which extends up to $\sim 2.5i$ m to both sides of the tunnels, depending on the depth and soil type (Cording et al., 1976; Attewell et al., 1986), where i is the distance from the tunnel center line to the point of inflection, see Eq. (6.1). In our case, the tunnel tubes are located at a depth of 18 to 32 m, see Fig. 5.4.2, which results in an influence zone of at most 22 to both sides of the tunnels.

Since the InSAR data processing yields estimates of the elevation of the measurement points, see Hanssen (2001), we distinguish points higher and lower than 3 m from the street level, which are linked to the buildings and the ground surface, respectively. The location precision is at the decimeter level (Dheenathayalan et al., 2016). Fig. 5.5.1a is a top view of Churchilllaan showing the influence zone and the location of the scatterers on the ground. Fig. 5.5.1b shows the location of the scatterers on the buildings. Note, that the results are already projected onto the vertical direction.

Evaluating the Data

First, we assess the location and density of the InSAR points. We observe that the point density at the outer limits of the influence zone is large whereas it is low in the middle of the expected settlement trough. This is due to the (to be expected) loss of coherence in the street, where all kinds of (construction) activities take place. Only at cross sections with other streets the point density is sufficient to detect the settlement trough with InSAR.

(a) low points, on the ground surface.

(b) high points, on the buildings

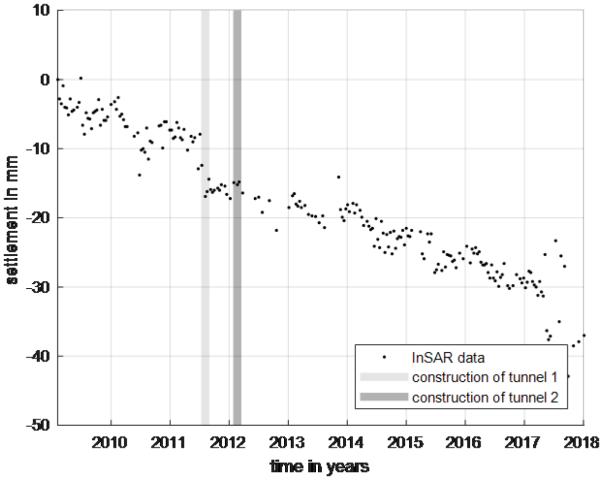
Figure 5.5.1: InSAR points near Churchilllaan. The colored dots indicate the vertical deformation rates in mm/y. The yellow lines indicate the influence zone of the tunnel.

On the other hand, almost all buildings have coherent scatterers, which remain coherent and can therefore be used to monitor the buildings during and after construction, see Secs. 5.5.2 and 5.5.3 respectively. Based on the quality of the points, the minimal detectable deformation (MDD) of each point can be established (Chang et al., 2018).

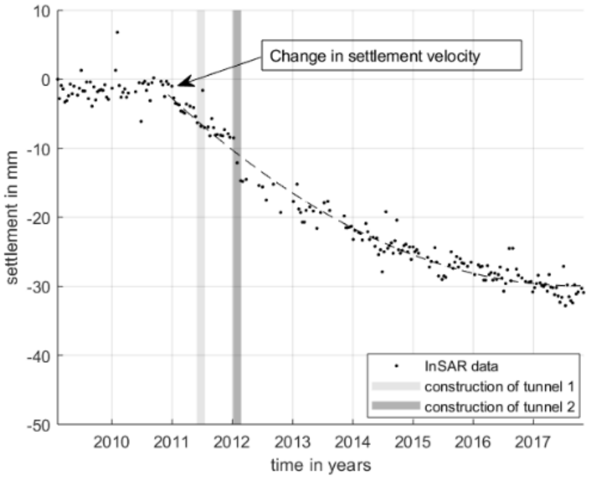
Second, we evaluate the InSAR data prior to construction, based on two selected cross sections. The InSAR data before 2011, i.e. prior to tunnel construction, show different deformation patterns for Churchilllaan and Van Ostadestraat. In particular, whereas at Van Ostadestraat, Fig. 5.5.2a, the settlement remains constant, Churchilllaan shows a significant change in settlement velocity at the end of 2010, which is *before* tunnel boring commenced, see Fig. 5.5.2b.

One of the reasons for the change in settlement velocity at Churchilllaan could be the construction of two vertical shafts of around 30 m deep that will serve as an emergency exit for the tunnels. See Fig. 5.5.3 for the location of the shafts and the location of the InSAR point X from Fig. 5.5.2b. The shafts were excavated *in the wet* in 2010 by pushing prefabricated concrete rings into the ground and excavating within these concrete rings. After complete excavation, the shafts were pumped dry late 2010, which is around 6 months before tunnel 1 was excavated. This corresponds well to the observed change in settlement velocity in the InSAR data, Fig. 5.5.2b. The long-term consequence of the shaft construction can be explained by the drainage effect of the shafts, which act as a vertical well due to the non-zero permeability of the walls. This drainage can cause consolidation of the soil in the years after construction, leading to the observed surface settlements.

We conclude that in our case, the amount of InSAR points was sufficient to reveal spatial and temporal patterns of deformation prior to construction, caused by shaft excavation. This demonstrates that InSAR can be used as a diagnostic tool to detect deformations (or the absense of deformations) before conventional monitoring commences.



(a) Van Ostadestraat



(b) Churchilllaan

Figure 5.5.2: Vertical settlement (mm) of a point at Van Ostadestraat (a) and point X in Fig. 5.5.3 at Churchilllaan (b).

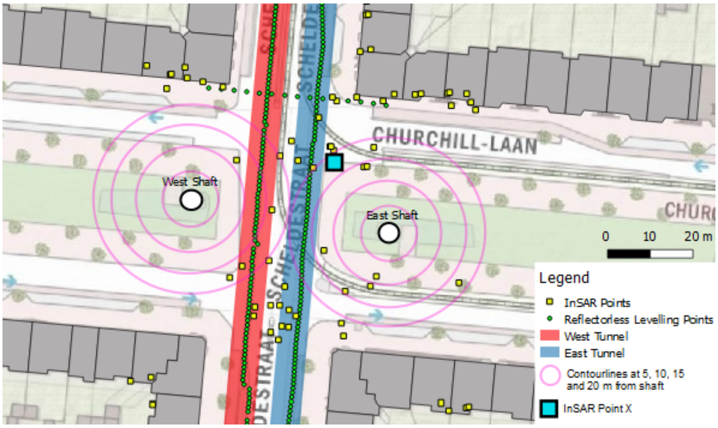


Figure 5.5.3: Location vertical shafts at the Churchilllaan. The point X is indicated with the blue square, and its time series is shown in Fig. 5.5.2.

5.5.2 Assessment of InSAR during Construction

We compute the expected surface settlements *during* construction and use these priors to guide the selection of the correct InSAR ambiguity levels, followed by an evaluation of the results.

InSAR Ambiguity Resolution

The revisit time of SAR satellites is typically once every few days or weeks, see Table 5.2.1. Thus, in case the displacements between two subsequent InSAR acquisitions are larger than the wrapping threshold $\lambda/4$, an erroneous ambiguity level may be estimated, see Sec. 5.2.1. Selection of the correct ambiguity level is only possible given prior information.Here, we use the expected settlement that is calculated before construction as prior information to estimate the most likely ambiguity level.

Based on the soil profile, the depth of the tunnels and the expected a-priori volume loss, the expected settlement trough for both cross sections is calculated following Peck (1969). We assume a typical average volume loss of 0.5% during tunnel construction (Vu et al., 2016) and assume that this value has an uncertainty of 0.25 percentage points, which is regarded as the standard deviation of a normal distribution. For tunnel 1 at Churchilllaan, this results in a settlement of 10 ± 5 mm, see Fig. 5.5.4. Assuming a normal distribution, this implies that the probability of a settlement larger than the wrapping threshold projected onto the vertical, i.e. 9.1 mm, is ~55%, see Fig. 5.5.5.

We use the two points on top of the tunnel axis at Churchilllaan, see Fig. 5.5.6, and process them with the same three different ambiguity levels. Then we compare

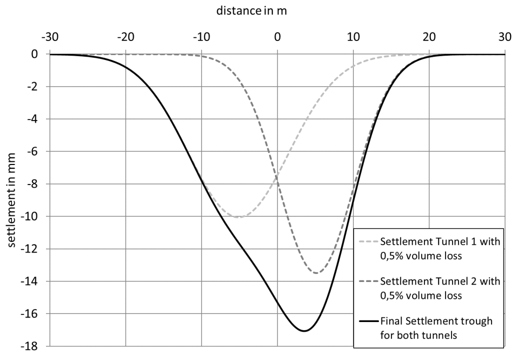


Figure 5.5.4: Settlement trough at Churchilllaan with 0.5% volume loss.

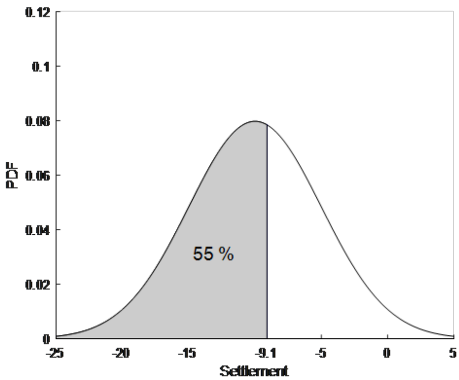


Figure 5.5.5: Probability density function for the maximum settlement of tunnel 1 at Churchilllaan.

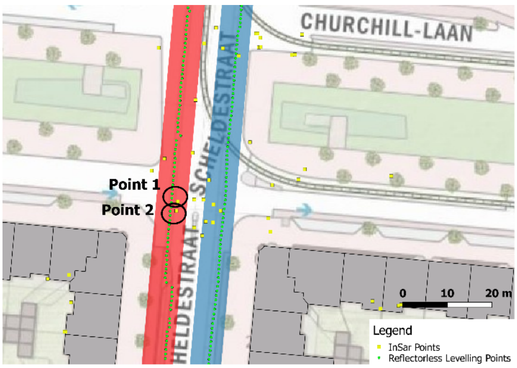


Figure 5.5.6: Surface levelling points and InSAR data points at Churchilllaan.

the ambiguity levels with the expected settlement, see Fig. 5.5.7. The upper ambiguity level would represent heave, which has a probability of 2% based on the settlement calculation, and is hence very unlikely. The lower ambiguity level shows a settlement of more than 20 mm for Churchilllaan which has a probability of less than than 2%. Thus, given this information, the middle ambiguity level, with 8 mm settlement, is considered to be the most likely solution.

Evaluating the Results

Validating the InSAR results (with the selected ambiguity level) with the in-situ monitoring data, see Fig. 5.5.8, shows a good agreement. Thus, when we can expect surface settlements to be close to, or larger than, the wrapping threshold, prior information is essential to select the correct ambiguity level in InSAR data. It is important to stress that these are differential settlements, i.e., they hold for relative displacements between two points at a particular spatial separation.

When the use of an analytic settlement prediction enables the selection of the most probable ambiguity level, we refer to this as an *augmented implementation of InSAR*. Augmented InSAR can be used to evaluate surface settlements at locations were no conventional monitoring is available and it can be used to assess long-term trends, see Sec. 5.5.3.

5.5.3 Assessment of InSAR after Construction

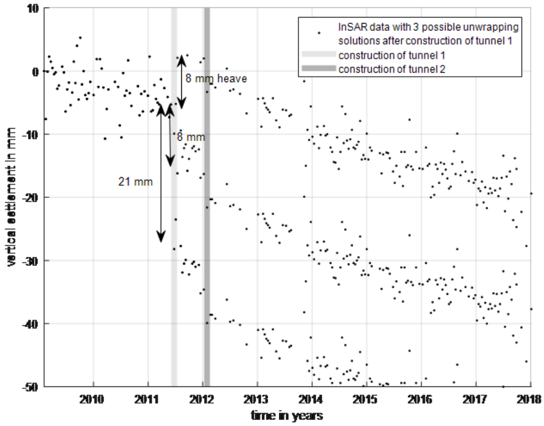
The same InSAR dataset is used to assess the deformation *after* the construction phase. First, the InSAR ambiguity resolution is assessed, followed by an evaluation of the results.

InSAR Ambiguity Resolution

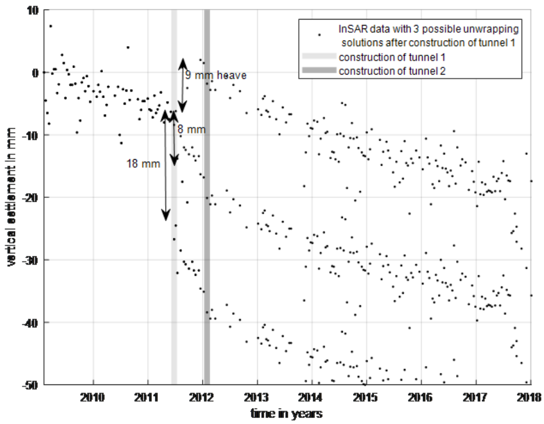
We select three InSAR points perpendicular to the tunnel axis at Churchilllaan and at Van Ostadestraat, see Fig. 5.5.9, and select the chosen ambiguity level of Sec. 5.5.2. Then we compare these solutions with in-situ monitoring data. Figs. 5.5.10 and 5.5.11 confirm that the chosen ambiguity level was correct.

We then include all InSAR points at the cross section of Churchilllaan in our analysis. The dataset now contains 59 points, see Fig. 5.5.12.

We process these points with the selected ambiguity level and approximate the expected curve, see Eq. (6.1), locally with a second-degree polynomial. In Fig. 5.5.13 the settlements at the end of each year, starting in 2009, are plotted against the distance to the tunnel axis.

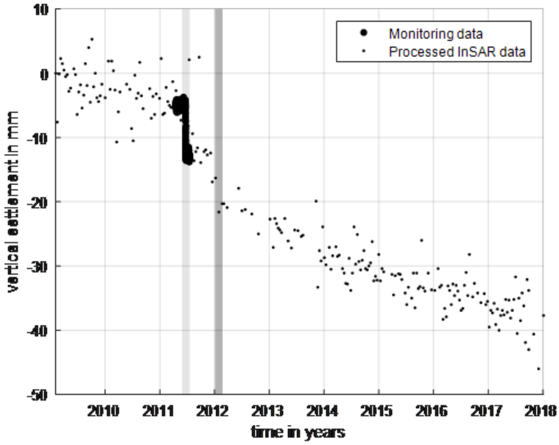


(a) Point 1

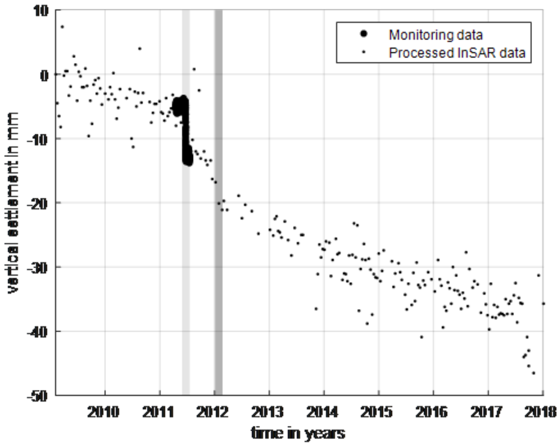


(b) Point 2

Figure 5.5.7: Three different ambiguity levels at Churchilllaan, Point 1 and 2.

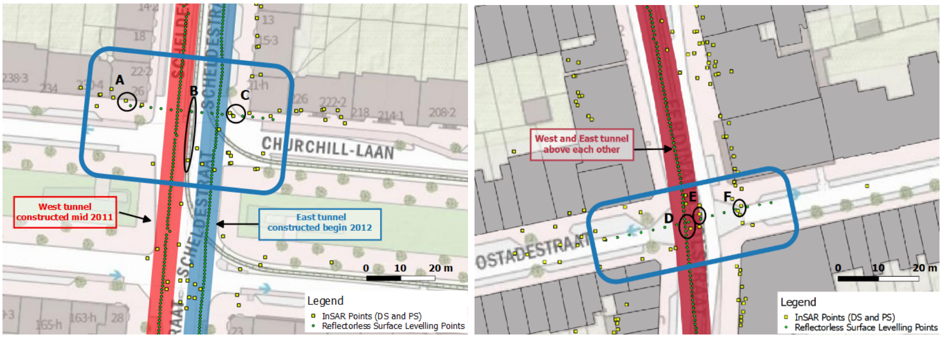


(a) Point 1



(b) Point 2

Figure 5.5.8: Verification of the ambiguity level at Churchilllaan, Point 1 and 2.



(a) (b)

Figure 5.5.9: Location InSAR data and levelling points at Churchilllaan (a) and at Van Ostadestraat (b).

Evaluating the Results

Based on Figs. 5.5.10 and 5.5.13 , we conclude that there is a long-term downward trend and that the InSAR data shows a settlement trough that is shaped like a bowl with the largest depth between the tunnels. Therefore, it seems straightforward to deduce that these long-term settlements are a consequence of the tunnel construction. However, the vertical shafts were already excavated in 2010. Therefore, we expect that this is the most likely cause of the increase in settlement velocity starting from the end of 2010, see Sec. 5.5.1. Thus, Fig. 5.5.10 shows a juxtaposition of settlements due to tunnel construction and settlements due to the vertical shaft excavation. To isolate the long-term effect due to tunnelling only, we also analyze the settlement trough at Van Ostadestraat, where there are no vertical shafts, see Fig. 5.5.14. We observe that once the settlement trough has occurred, it does not become deeper and wider in time, and the trough settles equally. Moreover, Fig. 5.5.15 shows that the settlement trend seems to be linear before and after tunnel construction. We conclude that at the North/South Metro Line, there is no significant long-term effect due to the tunnel construction, and that InSAR is indeed a cost-effective and simple tool to reach this conclusion.

Finally, we also find that the settlement behaviour is not consistent over time. The conventional monitoring data shows heave in February 2012, see Fig. 5.5.16. As we suspect that these deviations may be due to atmospheric events, we use meteorological data from the Royal Netherlands Meteorological Institute (KNMI) and find that there was a frost period in February 2012, see Fig. 5.5.17.

We conclude that frost may have been a reason for the heave. However, as all total stations are linked to each other and to the reference point, it is also possible

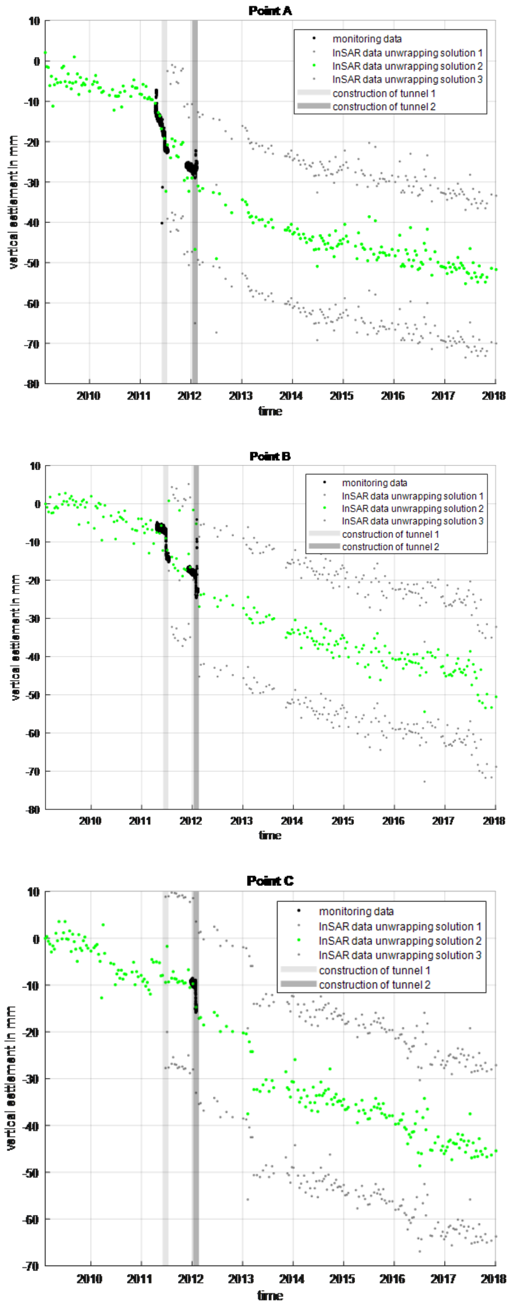
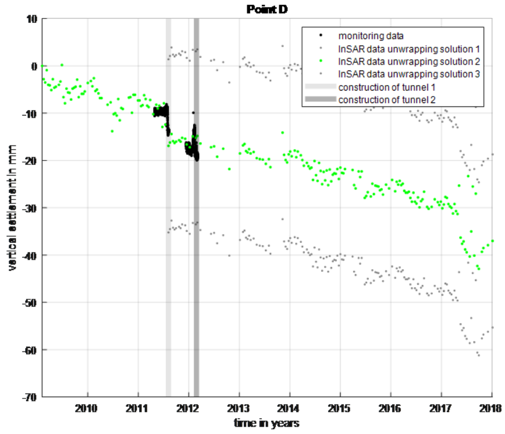
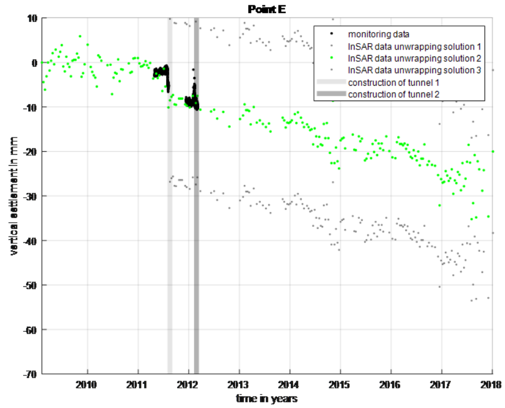


Figure 5.5.10: Comparison InSAR and in-situ data from surface levelling, Points A, B, and C at Churchilllaan.





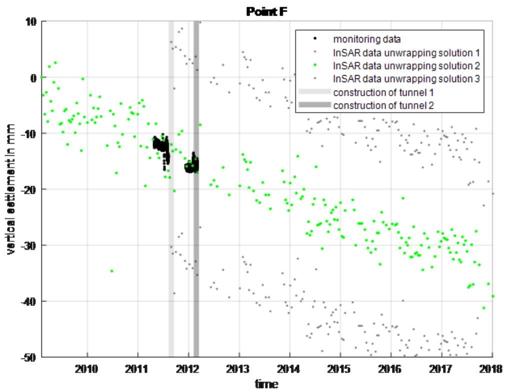


Figure 5.5.11: Comparison InSAR and in-situ data from surface levelling Points D, E and F at Van Ostadestraat.

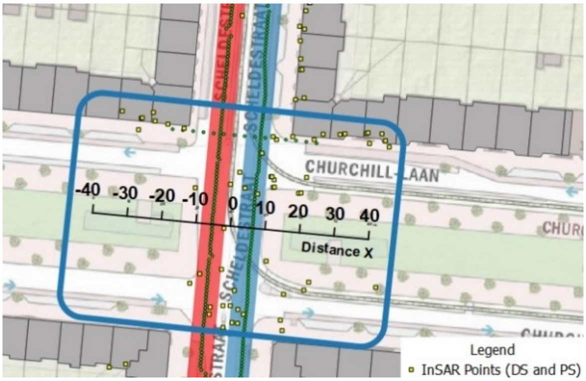


Figure 5.5.12: Selection of InSAR points at Churchilllaan.

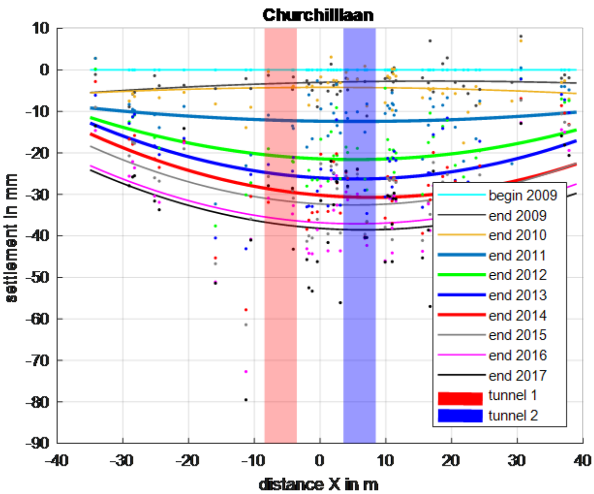


Figure 5.5.13: Vertical settlement of selected InSAR points at Churchilllaan.

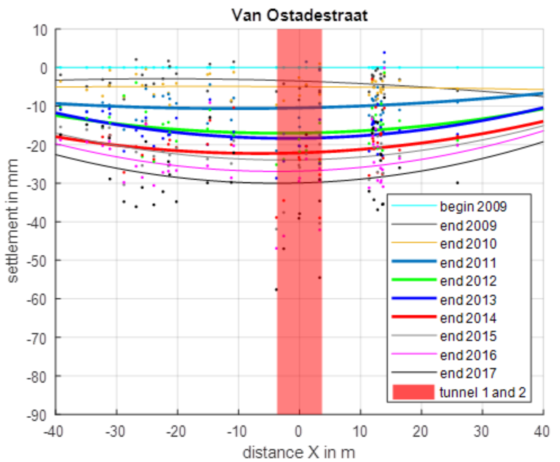


Figure 5.5.14: Vertical settlement of selected InSAR points at Van Ostadestraat.

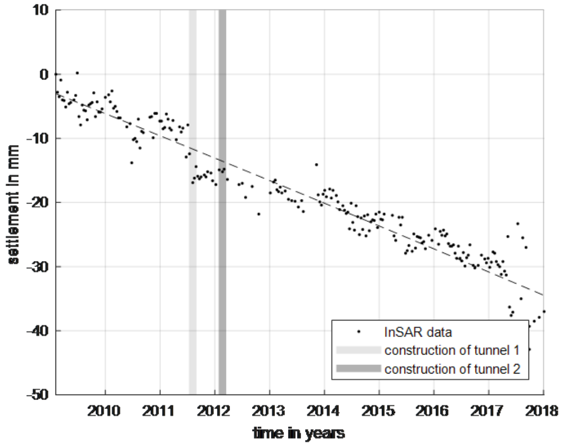


Figure 5.5.15: InSAR point of Fig. 5.5.14 at distance $x = 0$.

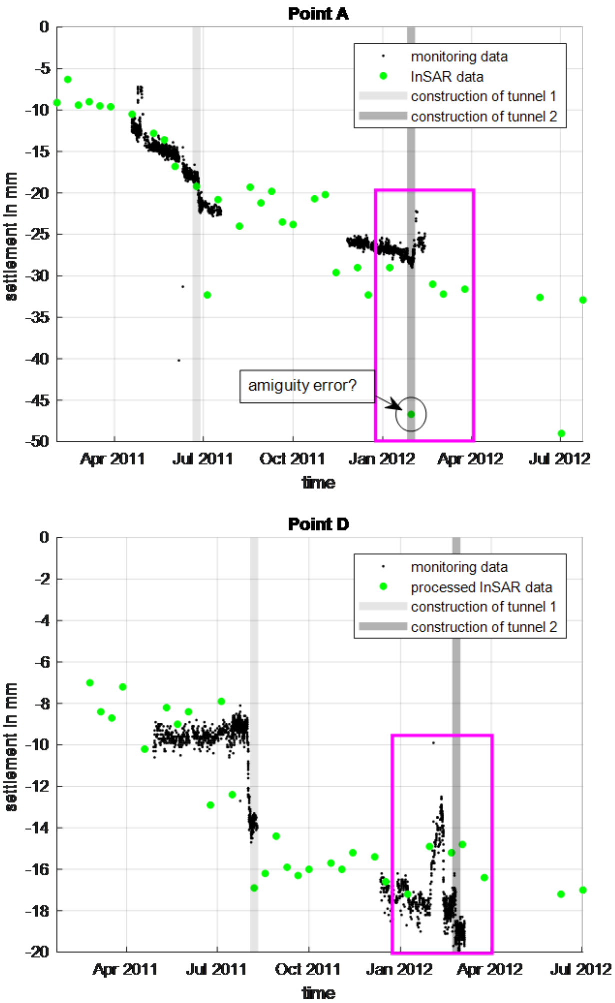


Figure 5.5.16: Detail of points A and D.

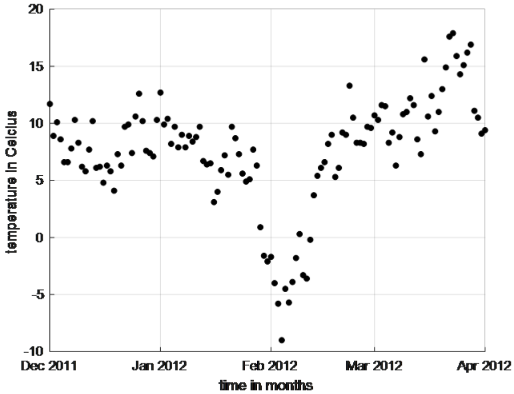


Figure 5.5.17: Temperature in the selected period.

that some disturbance happened to the reference point in that period, which could have led to a measurement anomaly. Based on the available information from the conventional monitoring dataset, we cannot draw a unique conclusion. Using the InSAR data to assess this heave, we did not detect heave in point *A* of Fig. 5.5.11 and 5.5.16, even when considering the possibility of ambiguity errors. However, in point *D* of Fig. 5.5.11 and 5.5.16 the InSAR shows a small heave.

5.6 Discussion

The case of the shield metro tunnel of the North/South Metro Line in Amsterdam shows that the long time period of available SAR data provides unique information about the deformation behaviour prior to construction. The InSAR data reveal that six months prior to the tunnel excavations, an increase in settlement velocity of the surface at Churchilllaan occurred. Additionally, the InSAR data showed that the settlement velocity at this location decreased slowly in time but remained at an increased pace for around six years. Future InSAR measurements will tell if this increased settlement velocity is continuing. We speculate that the reason for this increase in settlement is the pumping that took place at the end of 2010 for the construction of the two vertical 30 m deep exit shafts, resulting in a vertical inward movement of the shaft walls, which caused a surface settlement. Also, in general, shafts (like tunnels) are never completely water tight and act as a big vertical well that drains the surrounding soils. This leads to consolidation during the years after construction, resulting in surface settlements.

5.7 Conclusions

We evaluated if and how InSAR can be used (i) prior to the tunnel construction to optimise the monitoringsplan, (ii) during construction as a diagnostic tool to detect surface settlements and (iii) after construction as a forensic tool and to monitor the long-term settlements. InSAR provides long times series of deformation, and can be used to map deformations in the past, with SAR data archives going back to 1992. Therefore, it is a very useful tool to perform a baseline assessment *prior* to construction in civil engineering projects. Given the repeat time of the satellite and an extra time latency due to processing of the SAR data, SAR data is not suitable as a real-time warning system *during* construction when immediate action, say, within hours, is needed in case of abrupt settlements. However, due to its high spatial resolution and the availability of long time series, it is a valuable complementary source of information to the conventional monitoring. InSAR provides high-precision monitoring of ground movement over a large area without the need to install instruments on the ground. Also, InSAR provides information about settlement patterns prior to construction when the conventional monitoring systems are not installed yet. Finally, InSAR is a useful tool *after* construction to monitor settlements when the conventional monitoring is ceased. It is able to reveal important deformations patters in the years after construction, which will help understand the problem of long-term tunnel settlements better.

Resolving the correct ambiguity level in InSAR data can be challenging, especially in the case of abrupt settlements over short spatial distances with magnitudes close to the wrapping threshold. To retrieve unbiased displacement estimates, prior information regarding the expected settlement is needed. Analytical settlement prediction methods can be used successfully to find the most probable ambiguity level in the InSAR estimates. This way, augmented InSAR can capture the short-term settlements that occur immediately during construction of the shield tunnel. The constraint on the abruptness, steepness, and magnitude of the displacement can be alleviated by having more coherent InSAR scatterers with a shorter repeat cycle. Typically, this favours X-band satellites.

We believe that the proposed methodology to select the most probable ambiguity level can help in the development of a practical tool that is able to quantify and insert the prior information on the displacement dynamics in the InSAR displacement estimation software. And as such, augmented InSAR can be integrated in the monitoring framework of more civil engineering projects.

Chapter 6

Possibilities of Sentinel-1 SAR Data for Deformation Assessment of Alpine Permafrost Areas

This chapter contains the latest revised version of Reinders, Kristina Juliana, et al."Exploring the use of Sentinel-1 to monitor spatial and temporal evolution of permafrost in the Swiss Alps." EGUsphere 2023 (2023): 1-21. It was submitted on 11.07.2024.

6.1 Introduction

Climate change is occurring in alpine regions at a faster pace than elsewhere in the world (IPCC (Intergovernmental Panel on Climate Change), 2018; Goodfellow and Boelhouwers, 2013). In the Austrian and Swiss Alps temperature has increased by 2 °C between the end of the nineteenth and the beginning of the twenty-first century (Auer et al., 2007) and it is predicted that in the Swiss Alps the annual average temperature will rise by an additional 2.1 to 3.7 °C by the middle of the 21st century if global greenhouse gas emissions continue to rise at the current rate (CH2018, 2018). Besides the temperature rise, the number of days with fresh snowfall are expected to decrease (Meteoschweiz, 2022). Measurements show that since the year 2000 ground surface temperatures raised (Etzelmüller et al., 2020) and snow cover, glaciers and permafrost areas declined and it is expected that this decline will continue in almost all regions throughout the 21st century (Hock et al., 2019). Currently, permafrost in the Alps occurs at elevations above 2500 m, but predictions show that the lower permafrost boundary will rise in the 21st century (Magnin et al., 2017).

Increasing evidence is becoming available on the hypothesis that changing alpine permafrost conditions may alter the frequency and magnitude of mass movements, and result in an increase of slope instabilities, rockfalls and debris flow activity, or in the destabilisation of rock glaciers (Baral et al., 2023; Jones et al., 2023; Noetzli and Phillips, 2019; Patton et al., 2019; Krautblatter et al., 2013; Gruber and Haeberli, 2007; Noetzli et al., 2007). Many mountain infrastructures such as cable-cars, railways, avalanche barriers, communication and power lines, as well as mountain cabins that are in high alpine areas, can be affected. The effect of permafrost degradation on infrastructure has been extensively studied (Hjort et al., 2022; Duvillard et al., 2019; Bommer et al., 2010); however, so far most of the works focused on polar regions and only a very limited number of investigations have been carried out in the Alps (Arenson and Jakob, 2017; Duvillard et al., 2015). For the French Alps a risk assessment was performed for many infrastructures located in permafrost areas (Duvillard et al., 2021,0,0). This inventory showed the vulnerability to climate change of structures located in mountain permafrost.

Permafrost in Switzerland covers about 3.5% of the national territory (SLF, 2019) and it is estimated that 15% of mountain railways (cable railways, chair-lifts, ski-lifts) are located in permafrost regions (Keller et al., 1998). As these infrastructures are important for tourism, communication, power supply, and other human activities, it is essential to accurately assess promptly potential signs of instability. Fig. 6.1.1 shows the amount of structures and infrastructures located in zones where permafrost is expected, according to the permafrost and ground ice map of Switzerland (SLF, 2019; Kenner et al., 2019). This includes more than 200 km of cable car lines or ski-lift routes, more than 30 km of roads, ca. 8 km of railways, hundreds of buildings, several important communication antennas, as well as ca. 7 km of snow avalanche barriers. These are critical assets, and the evaluation of their current and future stability is of major importance.

Currently, the most common method to assess the occurrence and the evolution of permafrost is by performing temperature measurements within boreholes. A permafrost monitoring network (PERMOS) for the Swiss Alps runs since the 1990s, including 14 borehole sites (PERMOS, 2023). The active layer thickness is measured in the boreholes and ranges between 1.8 and 13 m in 2021, 2022 and 2023, with an average of 5.7 meters. The measurements in the boreholes started between 1997 and 2020, and the mean increase in active layer thickness in the past 2.5 decades was 15 cm/a. Drilling boreholes and monitoring temperatures in this high Alpine environment can be difficult, labour-intensive and expensive (Noetzli et al., 2021).

The boreholes are often distributed unevenly geographically and biased toward more accessible locations or pre-existing research sites (Hock et al., 2019). Also, if any monitoring is performed on structures and infrastructures, this is mostly executed with ground-based conventional geodetic methods, for which physical access of material and people is required. Like the borehole locations for measuring the permafrost, these in-situ measurements are only local point data.

For more than 30 years, Interferometric Synthetic Aperture Radar (InSAR) has proven to be a valid alternative to monitor ground surface displacements. Persistent Scatterer Interferometry (PSI) is a specific class of InSAR methods and combines multiple images over the same area, resulting in mean surface velocity maps and displacement times series (Hanssen, 2001). InSAR and PSI have been extensively used for monitoring subsidence, landslides, buildings and infrastructure, and successfully used in permafrost areas (Wang et al., 2023; Bertone et al., 2022; Li et al., 2021; Liu et al., 2022; Rouyet et al., 2019; Daout et al., 2017; Abe et al., 2020; Liu et al., 2015; Barboux et al., 2014). An overview of the available literature and the limitations and potential of this technique for these applications is given in (Macchiarulo et al., 2022; Bertone et al., 2022; Reinders et al., 2022; Barboux et al., 2013). Open SAR data from satellite missions such as the ESA Copernicus Sentinel-1 mission have made InSAR and PSI technology even more accessible. This data provides new opportunities for wide-area ground motion detection and monitoring. At regional and national scale publicly available PSI maps are being produced (Crosetto et al., 2020; NCG, 2022; Kanton Wallis, 2022; WSP and Skygeo, 2021; NGU et al., 2018; BGR, 2021; UNIFI, 2022). Also, the European Ground Motion Service provides surface displacements over most of Europe, based on Sentinel-1 SAR data (EGMS, 2022). While all these maps are 'application-agnostic', indicating that they are not optimised for a particular application or location, they can provide valuable insights in different fields of research and technical applications.

In this study we assess the possibilities and limitations of Sentinel-1 PSI data to measure displacements in Alpine permafrost areas and structures and infrastructures therein located. First, we investigate the visibility of Swiss permafrost zones in Sentinel-1 viewing geometries. Second, we examine whether differences in surface displacement trends estimated from the Sentinel-1 can be associated with the known permafrost zones, as mapped in the PGIM. To this end, we focus on Canton Valais, where a regional-scale PSI map is available. Finally, we show some examples of surface displacements around structures and infrastructures located in permafrost and discuss the potential and limitations of monitoring based on Sentinel-1 PSI maps.

6.2 Methods

6.2.1 Nationwide Sentinel-1 Sensitivity Map

The InSAR detection potential of the areas of interest can be evaluated before actual satellite data processing. Combining slopes and aspects derived from the Digital Elevation Model (DEM) with the orbital parameters (incidence angles and the orientation of the zero-Doppler plane towards the satellite) we can determine geometric distortions such as foreshortening, layover, and shadow regions. Moreover, assuming that displacements are occurring entirely along slope, the sensitivity of detection can be computed from the projection of the displacement vector onto the line-of-sight vector (Notti et al., 2014; Chang et al., 2018; van Natijne et al., 2022a; Brouwer and Hanssen, 2023). The R-index, with $R \in [-1, 1]$, (Notti et al., 2014) is a metric that allows combining the visibility of the satellite, i.e., $-1 < R \leq 0$ indicates no visibility, with the sensitivity for detecting down-slope motion, where greater values for R refer to higher sensitivity. Table 6.5.1 gives an indication of the sensitivity to along slope motion.

To compute the R-index, we pre-process the Sentinel-1 data downloaded from the Copernicus Open Access Hub (The European Space Agency, 2022a) per orbital geometry using the ESA SNAP Sentinel-1 toolbox and the Copernicus DEM (The European Space Agency, 2022b). We use data for descending tracks 136, 66, 168, and ascending tracks 88 and 15. See Fig. 6.2.1 for a top-view of the tracks. Table 6.5.2 lists the used Sentinel tracks and the relevant geometry parameters for our Area of Interest (AoI). The azimuth of the zero-Doppler plane, α_d, is defined at a geographic location, in the direction towards the satellite. It is based on the heading of the satellite, correcting for the range-dependent meridian convergence (Brouwer and Hanssen, 2023). We import the results into a geographical information system and create geotiff files containing the shadow and layover mask, the local slope β and aspect α angles, and the incidence angle θ, following Del Soldato et al. (2021).

The R-index for geographic location (ϕ, λ) can be expressed as:

$$R(\phi, \lambda) = \begin{cases} \sin\big(\theta - \beta \cos(\alpha_d - \alpha)\big) & \text{if } S_h = 1 \wedge L = 1 \\ 0 & \text{otherwise,} \end{cases} \tag{6.1}$$

where $S_h \in \{0, 1\}$ and $L \in \{0, 1\}$ are binary indicators for the absence (1) or occurrence (0) of shadow and layover, respectively.

We create one map with the R-index for ascending tracks and one map for descending tracks. In the overlap area we select the track in the far range, i.e., greater incidence angle, because the extent of layover areas is much greater than shadow areas in our analysis. As validation, we repeat the computation with the global sensitivity index for landslide displacements Google Earth Engine tool of van Natijne et al. (2022b) and obtain similar results. Note that a positive R-index condition is necessary but not sufficient, as the occurrence of coherent objects is also highly dependent on land cover and the wavelength of the SAR sensor considered.

6.2.2 Regional PSI Map of Canton Valais

Canton Valais is an administrative subdivision in the southern part of Switzerland. In Valais, the highest mountains of Switzerland are located and the elevation from the lowest valley to the highest top is between 370 m and 4630 m above sea level. The five towns with the largest number of inhabitants are located between 400 and 700 m above sea level and are situated in the Rhone Valley. In the side valleys, the elevation of the villages reaches 1900 m. Due to its geographical location and climatic conditions, Canton Valais is particularly exposed to natural hazards, such as floods, inundations, avalanches, debris flows, rock falls, landslides and forest fires and droughts. Interactive hazard maps are available for the different hazards and over 200 unstable areas are actively monitored (Kanton Wallis, 2023; Crealp, 2024). Since 2003, the canton has been equipped with a remote monitoring network of automated measurement stations, measuring displacements and hydrometeorological data. All monitoring data is integrated in Guardaval, a system for the automatic and continuous retrieval of these measurements, their storage, and their publication via a webviewer. Also more than 40% of the total area classified as permafrost in the permafrost and ground ice map (PGIM) of Switzerland is located in the canton of Valais. This percentage is even higher (50%) if we consider only the ice-poor permafrost, i.e. zone-1 in the PGIM.

Guardaval contains the results of PSI processing based on different SAR satellite sensors and covering the entire Canton Valais showing surface velocity and displacement time series. The data is accessible to selected stakeholders and scientists (Kanton Wallis, 2022). The Sentinel-1 results contain more than 4.5 million Persistent Scatterers (PS) from Sentinel-1 descending track 66, and more than 3.8 million PS from ascending track 88, including line-of-sight mean surface velocities and displacement time series over the period 2015 to 2022. The PS correspond to features on the ground that ideally reflect the radar waves each time the satellite passes over, for example, the roof of a house, a large block, or a cable car mast. Areas with dense vegetation, frequent surface changes or too rapid slope movements can cause phase disturbances in the InSAR signal, and thus measurement inaccuracies or complete loss of information due to decorrelation.

Surface velocities that can be measured depend on the radar wavelength and on the revisit time of the satellite. In the specific case of Sentinel-1, the C-Band sensor with revisit times of 6-days allows to detect movements up to 84 cm/a (Manconi, 2021; Wasowski and Bovenga, 2014). As many rock glaciers may have velocities larger than 100 cm/a, these areas are not suitable for PSI detection with Sentinel-1 and thus do not appear in the PSI data set. Also due to snow cover and associated loss of coherence, winter images were not considered in the PSI processing. Only data between early June and early November are available on the web viewer, with a 6-to-12-day interval. Fig. 6.2.2a shows the number of acquisitions within this seasonal window for both orbits per year for our area of interest. Fig. 6.2.2b shows the number of PS per elevation interval, indicating that most of coherent PS is situated at elevations well above the urban areas. Based on numerous papers over the last 20-25 years, e.g. (Crosetto et al., 2016a; Lanari et al., 2007), the estimated accuracy of the PSI techniques to monitor surface velocity is in the order of 1 mm/a. The geolocation precision of the measurement points is 20 m (Kanton Wallis, 2022).

6.2.3 The Permafrost and Ground Ice Map (PGIM) of Switzerland

Several alpine permafrost maps were published in the last decades. In 2005, the Federal Office for the Environment (FOEN) published a map, showing the potential permafrost distribution in Switzerland (Bundesamt für Umwelt, 2005). Later, the permafrost and ground ice map, called PGIM, was developed by WSL Institute for Snow and Avalanche research SLF (Kenner et al., 2019), see Fig. 6.1.1. PGIM is an indication map for the occurrence of permafrost, based on models that include elevation, potential incoming solar radiation, and the deposition zones of alpine mass wasting processes (Kenner et al., 2019). Data from the current permafrost network (PERMOS) is included, which observes permafrost conditions at 27 sites located between 2200 and 3500 m in the Swiss Alps (PERMOS, 2023).

In the PGIM the total permafrost area is around 1’400 km^2, divided in ice-poor zones (zone-1) and ice-rich zones (zone-2). Zone-1 consist of all areas with modelled negative ground temperatures and a buffer area with ground temperatures ranging between 0 and 1°C. Fig. 6.1.1 these are the permafrost zones from < -3 °C to +1 °C. Zone-2 is generally located at relatively lower altitudes and consists of rock glaciers or ice-rich talus slopes. In the PGIM all areas steeper than 30° were removed in zone-2 because they barely contain ice-rich permafrost (Kenner et al., 2019). All glaciers were excluded in the PGIM and therefore they are also excluded in our analyses.

6.3 Results

6.3.1 Sensitivity to Radar Detection of Permafrost Zones

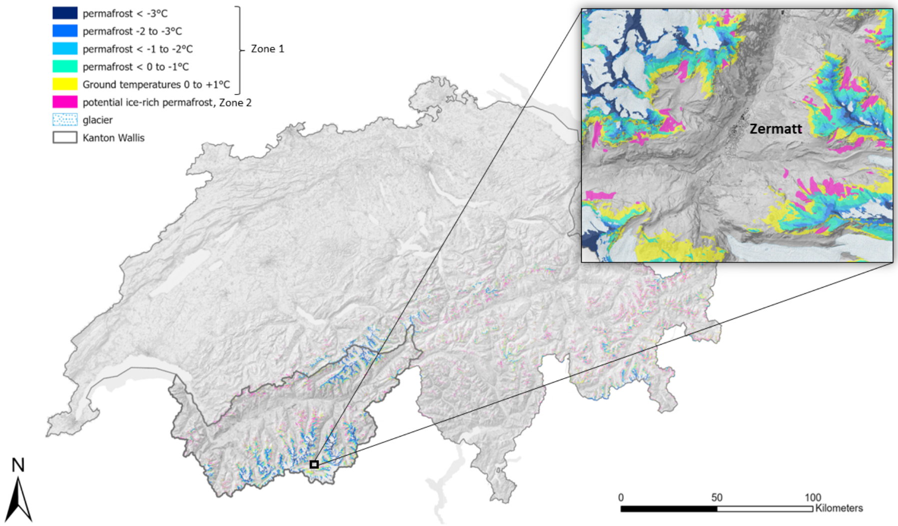
To assess which permafrost zones in the Swiss Alps are sensitive to detection with Sentinel-1, we combine the PGIM with the *R*-index map of Switzerland. This results in a map presenting the sensitivity to Sentinel-1 detection only for the permafrost zones. Fig. 6.3.1 indicates areas with an R-index between 0.5 and 1, which refers to sufficient sensitivity to Sentinel-1 detection for both the ascending and descending orbits for the permafrost zones in Switzerland (see Table 6.5.1 for the *R*-index interpretation).

Table 6.3.1 shows the *R*-index for the different permafrost zones in Switzerland with Sentinel-1. We find that ~92% of the permafrost zones in the PGIM have sufficient sensitivity to radar detection for at least one orbital geometry and ~39% have sufficient sensitivity to radar detection for both ascending and descending orbits.

Next, based on the database of the Topographic Landscape Model (TLM) by swisstopo and the PGIM permafrost map, we identify all structures and infrastructures localised in permafrost areas. We include line infrastructures such as roads, railroads, cable cars, avalanche barriers and structures such as buildings in our inventory (see Figure 6.1.1). Then we combine this information with our *R*-index sensitivity map. The result is an inventory of all structures in the Swiss permafrost areas with sufficient sensitivity to radar detection for at least one orbital geometry (see Table 6.5.3). We find that ~83% of the buildings have sufficient sensitivity to radar detection with descending and ~74% with ascending orbit. As for the avalanche barriers, ~64% have sufficient sensitivity to radar detection with descending and ~53% with ascending orbit. About 95% of the cable cars have sufficient sensitivity to radar detection with descending and ~96% with ascending orbit. All railroads have sufficient sensitivity to radar detection with descending and ~79% with ascending orbit.

Table 6.3.1: R-index of the permafrost zones in Switzerland with Sentinel-1.

R-index value	Area coverage of permafrost zones [%]		
	Descending orbit	Ascending orbit	Combined (descending + ascending)
shadow/layover (R-index=0)	15	16	–
$0 < R$-index ≤ 0.3	4	5	–
$0.3 < R$-index ≤ 0.5	14	16	–
$0.5 < R$-index ≤ 1	68	63	92



Type	Amount in permafrost in Switzerland
Avalanche Barriers	6648 m
Cable Cars (= cable cars, chairlifts, transport cable cars, ski lifts)*	128 items 206 446 m
Roads ⩾ 3 m wide	32 170 m
Railroads (Gornergrat, Allalin underground metro, Bernina)	3 trajectories 8302 m
Buildings (= mountain cabins, restaurants, cable car stations, technical and service buildings, chapels, underground structures)	366 items
Antennas	23 items
Wind Turbine	1 item

* The length is calculated over the permafrost area only

Figure 6.1.1: Permafrost and ground ice map (PGIM), including the amount of affected structures in the table below the figure. Canton Valais is highlighted. The inset shows the area of Zermatt to illustrate the PGIM zones more clearly in detail.

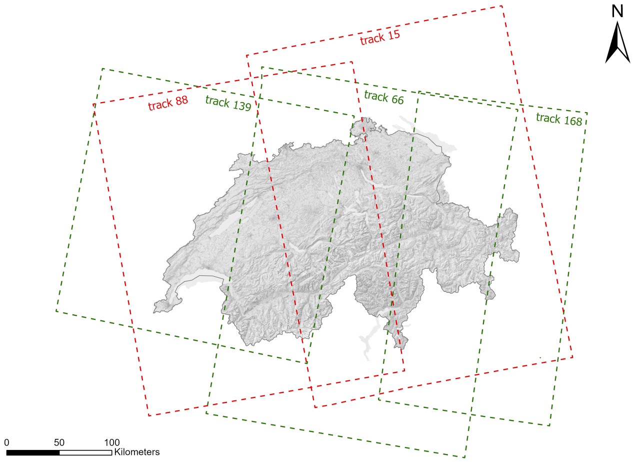
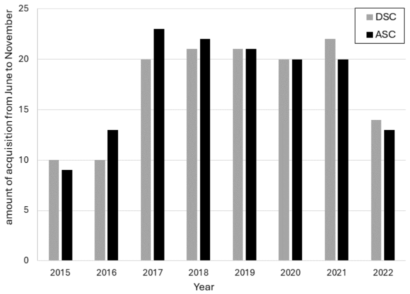
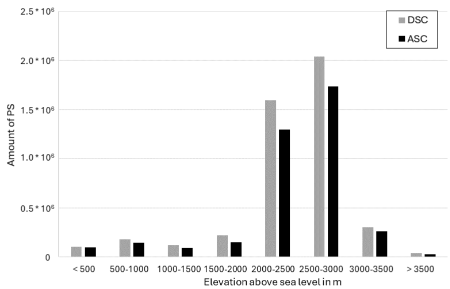


Figure 6.2.1: Top view of the ascending (red) and descending (green) Sentinel-1 images over Switzerland.



(a) Number of acquisitions within the seasonal window.



(b) Number of coherent point scatterers per elevation interval.

Figure 6.2.2: Number of Sentinel acquisitions per year and number of coherent point scatterers per elevation for the PSI map of Canton Valais.

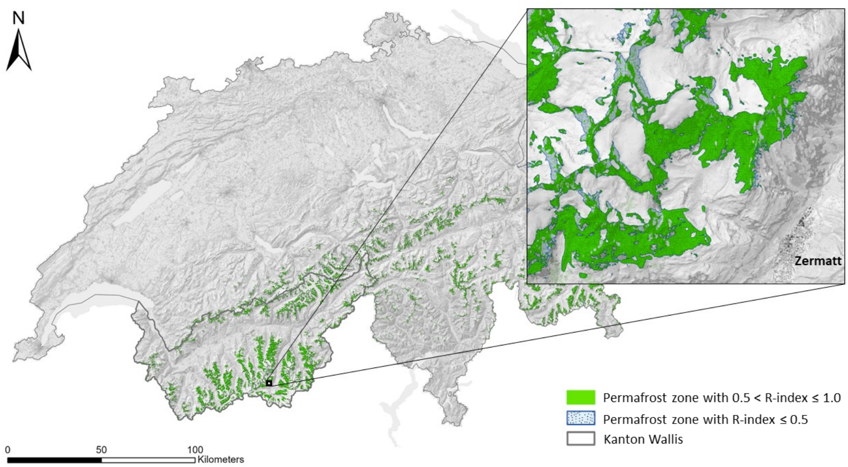


Figure 6.3.1: Permafrost zones according to the PGIM, including the sensitivity. Permafrost areas with R-index values between 0.5 and 1 are green, and permafrost areas with smaller R-index are blue. Ascending and descending orbits are combined.

6.3.2 Comparison Permafrost Zones with Displacement Data from Regional PSI Map of Canton Valais

To assess if any differences in surface velocity between permafrost and no-permafrost zones are present, we combine the PGIM with the Sentinel-1 PSI results of Canton Valais. First, we identify all PS of the descending and ascending orbits in the three zones of the PGIM, i.e. no-permafrost zone, ice-poor permafrost zone (zone-1), and ice-rich permafrost zone (zone-2). 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 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, slope orientation, and incidence angle. For slopes facing east, this will be the opposite. Here we are not interested in the direction of motion but only in their amplitude, thus we consider the absolute velocity values of all displacements to assess the state of activity. Then we calculate the mean, median, and standard deviation of the absolute velocities for all PS in each of the three zones. Table 6.3.2 shows the mean and the standard deviation of the absolute velocity in LOS in mm/a, for all PS in that area over the period of the satellite mission from 2015 until 2022. Fig. 6.3.2 shows a boxplot and a histogram for the absolute values of the displacements of the ascending orbit. In this boxplot the outliers were removed to improve the visibility and clarity of the figure.

Table 6.3.2: Data characteristics of PS map of Valais, with mean and standard deviation of the absolute surface velocities in Line of Sight (LOS) of the satellite.

	#PS*	#PS per 100 × 100 m	Mean velocity [mm/a]	St.dev velocity [mm/a]
Descending track				
No-Permafrost	3 278 000	7	1.7	3.4
Ice-poor permafrost (zone-1)	836 000	13	2.2	3.9
Ice-rich permafrost (zone-2)	496 000	30	3.2	5.7
Ascending track				
No-Permafrost	2 663 000	6	1.5	2.6
Ice-poor permafrost (zone-1)	698 000	11	1.8	3.0
Ice-rich permafrost (zone-2)	474 000	28	2.6	4.3

*The numbers of PS are reported to their nearest 1000.

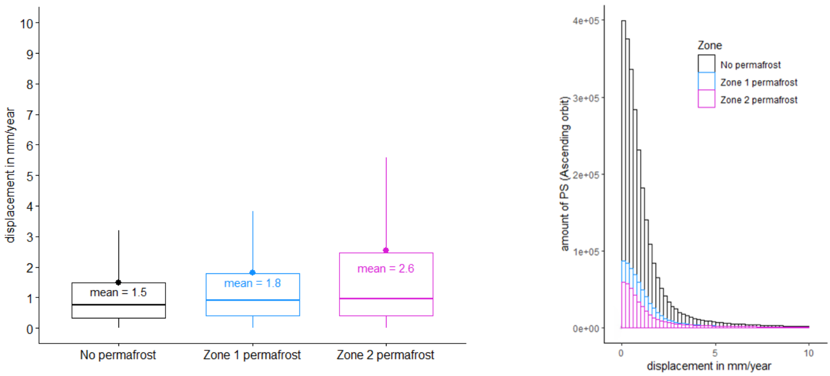


Figure 6.3.2: Boxplot with absolute displacements (left), histogram of absolute displacements (right) for the ascending track, without the outliers.

Next, we compare the mean surface velocities in the three zones using a statistical test. A well-known test to analyse if differences between mean values of populations are statistically significant is the analysis of variance (ANOVA). However, the ANOVA assumes that the data is normally distributed, and absolute velocity values do not follow a normal distribution. Therefore, here we use the Kruskal-Wallis test, which is a non-parametric test, meaning that it assumes no particular distribution of the data. For the analyses we select a 5% confidence level and as null-hypothesis we assume no difference in mean surface velocities between no-permafrost, ice-rich permafrost, and ice-poor permafrost.

The test statistics is H > 10'000 for the ascending and descending orbit. This value is evaluated against the chi-square distribution (Kruskal and Wallis, 1952). H is much larger than the critical chi-square value of 5.991 for 2 degrees of freedom for a 5% significance level. This indicates that the differences in mean surface velocities measured on the three PGIM zones are statistically significant for both the ascending and the descending orbit.

Then we perform a post-hoc test, i.e. the Dunn's test to identify distinct group differences. Our analysis of multiple pairwise-comparison, i.e. (i) no-permafrost versus ice-poor permafrost (zone-1), (ii) no-permafrost versus ice-rich permafrost (zone-2), and (iii) ice-poor permafrost versus ice-rich permafrost, shows that there is a difference between the three zones. Table 6.3.3 shows the results of the Dunn's test and the difference in the means. The result shows that the P-value is $< 2e^{-16}$, which means that the difference in means is statistically significant at the 5% confidence level. This indicates that the differences in displacement rates between the three zones are statistically significant for both the ascending and the descending track. Therefore we reject the null hypothesis and we confirm that there is a significant

Table 6.3.3: Results of Dunn's test pairwise-comparison of the displacements/year (mm/a) in the three zones.

	Difference in Mean [mm/a]	P-value
Descending track		
Ice-poor (zone-1) vs. No-permafrost	0.5	$2e^{-16}$
Ice-rich (zone-2) vs. Ice-poor Permafrost (zone-1)	1.0	$2e^{-16}$
Ice-rich (zone-2) vs. No-permafrost	1.5	$2e^{-16}$
Ascending track		
Ice-poor (zone-1) vs. No-permafrost	0.3	$2e^{-16}$
Ice-rich (zone-2) vs. Ice-poor Permafrost (zone-1)	0.8	$2e^{-16}$
Ice-rich (zone-2) vs. No-permafrost	1.1	$2e^{-16}$

difference between the three groups. Ice-rich permafrost zones (zone-2) have a greater velocity than ice-poor permafrost (zone-1) and no-permafrost zones. Ice-rich permafrost zones show a mean surface velocity of 1.7 to 1.9 times as high as the mean surface velocity in no-permafrost zones. The mean surface velocity in ice-rich permafrost is 1.4 to 1.5 times as high as in ice-poor permafrost. The mean surface velocity in ice-poor permafrost is 1.2 to 1.3 times as high as in no-permafrost zones.

Subsequently, to visualise more clearly that ice-rich permafrost has a higher percentage of PS with high velocity than ice-poor and no permafrost zones, we consider the classes of PS with velocities $\leq$ 5 mm/a, between 5 and 10 mm/a, between 10 and 20 mm/a, between 20 and 40 mm/a and > 40 mm/a in each zone. We normalise the counts dividing each category with the sum of PS in that zone and generate a cumulative frequency plot. Fig. 6.3.3 shows that zone 2 contains a higher percentage of PS with higher surface velocity. In particular, ca. 6% (ascending) and ca. 8% (descending) of absolute velocities in zone 2 are higher than 10 mm/a, while this fraction in no-permafrost is ca. 2% for the ascending orbit and ca. 4% for descending, respectively.

We also perform an additional test to check if the difference in means between the three zones is indeed statistically significant. For this test we randomly sample three sets from the *total population* (i.e. all PS in no-permafrost, ice-poor and ice-rich permafrost) with sample sizes similar to those present in the permafrost zones, i.e three sets of 500.000 points, with unique samples in each set. We repeated the Kruskal-Wallis test and did this analysis 50 times. The result showed that the P-value is greater than 0.05, which means that the difference in means was statistically insignificant. Thus, by random sampling sets of 500.000 PS of the total population,

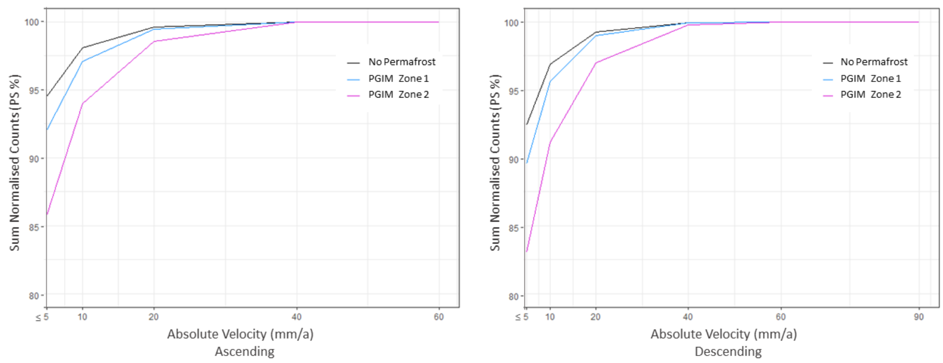


Figure 6.3.3: Cumulative frequency of PS with velocities of ≤ 5 mm/a, between 5 and 10 mm/a, between 10 and 20 mm/a, between 20 and 40 mm/a and between 40 and 60 mm/a, in Line of Sight (LOS) of the satellite.

the means of each set are almost the equal. Table 6.3.4 shows the results of one calculation with three samples of 500.000 points.

Table 6.3.4: Example of a Kruskal-Wallis test with random sampling of PS for the ascending orbit

	#PS	Mean velocity [mm/a]	St.dev velocity [mm/a]
Random Sample 1	500 000	1.66	2.95
Random Sample 2	500 000	1.66	2.95
Random Sample 3	500 000	1.66	2.95
P-value = 0.95 and test statistics H = 0.1			

Finally, to test if the significant difference between no-permafrost, ice-poor, and ice-rich permafrost is merely due to elevation difference, we create a *data set with only PS above 2500 m altitude* in each zone. With this data set, we also perform the Kruskal-Wallis test. The result is shown in Table 6.3.5. Our test statistics is again H > 10'000 for the ascending and descending orbit, which is much larger than the critical chi-square value of 5.991. This indicates that the difference in mean surface velocities measured on the three PGIM zones above 2500 m altitude is statistically significant. This proves that we are not correlating between surface velocity at different heights and the PGIM permafrost conditions.

All the statistical tests performed suggest that the difference in mean surface velocity

Table 6.3.5: PS located in zones with altitude > 2500 m.

	Amount of PS* > 2500 m	Mean velocity [mm/a]	Stand.dev. velocity [mm/a]
Descending track			
No-permafrost	1’264’000	1.9	3.6
Ice-poor permafrost (zone-1)	820’000	2.2	3.9
Ice-rich permafrost (zone-2)	313’000	3.2	5.7
p-value < $2e^{-16}$ and test statistics H > 10’000			
Ascending track			
No-permafrost	1’072’000	1.5	2.7
Ice-poor permafrost (zone-1)	683’000	1.8	3.0
Ice-rich permafrost (zone-2)	292’000	2.8	4.6
p-value < $2e^{-16}$ and test statistics H > 10’000			

*The numbers of PS are reported to their nearest 1000.

between the three PGIM zones is indeed significant. However, as the data set is very large, it has large discriminatory power, which means that the results will be statistically significant in most cases. With a sufficiently large sample, a statistical test will almost always detect a significant difference unless there is no effect at all, i.e. the effect size is exactly zero; however, very small differences, even if significant, are often meaningless. Hence, reporting only the significant P value for an analysis is not sufficient (Sullivan and Feinn, 2012). Unlike significance tests, effect size is independent of sample size and therefore, we complement our analysis with the effect size (Tomczak and Tomczak, 2014). It quantifies differences between the groups and helps decide whether the difference found is meaningful or not (Ellis, 2010). The Kruskal-Wallis test can be complemented with the eta-squared parameter, which ranges from 0 to 1, and is a measure for the effect size. According to the literature, common interpretations of eta-squared values are: between 0.01 and 0.06 is considered small significance, between 0.06 and 0.14 moderate and beyond 0.14 large. However, there is no unambiguous method to determine whether a value for the effect size is of practical importance. Observed effect sizes should be judged within the context of prior relevant research and even small effects might be of practical importance (Cohen, 1988). In our field of research, no comparable statistical studies were performed, and we cannot currently compare our effect size with similar studies. Our results in Table 6.5.4 show that there is a very small effect size between all zones. This means that while the difference in mean surface velocity between the three zones is significant, the magnitude of the differences is small.

6.3.3 Comparison PSI map with PERMOS network measurements

We use geodetic displacement data from the PERMOS network (PERMOS, 2023), acquired by repeated GNSS and total station surveys between 2016 and 2022, and compare it to the Sentinel-1 PSI results. Fig. 6.3.4 shows the Alpage de Mille site, mapped in purple as permafrost PGIM zone-2. This is the only location of the PERMOS measurement field sites where PSI results are available for such a comparison, as all the other locations are not suited for a PSI survey due to slope orientation towards the satellite and too large slope movements. The right side of the figure shows the velocity from the terrestrial geodetic data, projected onto the line-of-sight to the ascending Sentinel orbit. The left figure shows the surface velocity estimated from the PSI maps, in ascending viewing geometry. The PSI maps corroborate the terrestrial results in terms of the location and extent of displacement. At several locations the PSI results are smaller than those of the PERMOS network. The PSI map only contains snow-free images, and the movements between each summer are interpolated. The information by the producer of the map (Kanton Wallis, 2022) does not mention how this interpolation is done. This interpolation can be an over- or underestimation of the yearly trend. Yet, the PSI map has a wider coverage compared to the existing geodetic benchmarks, illustrating the value of the wider coverage of the in-situ measuring results.

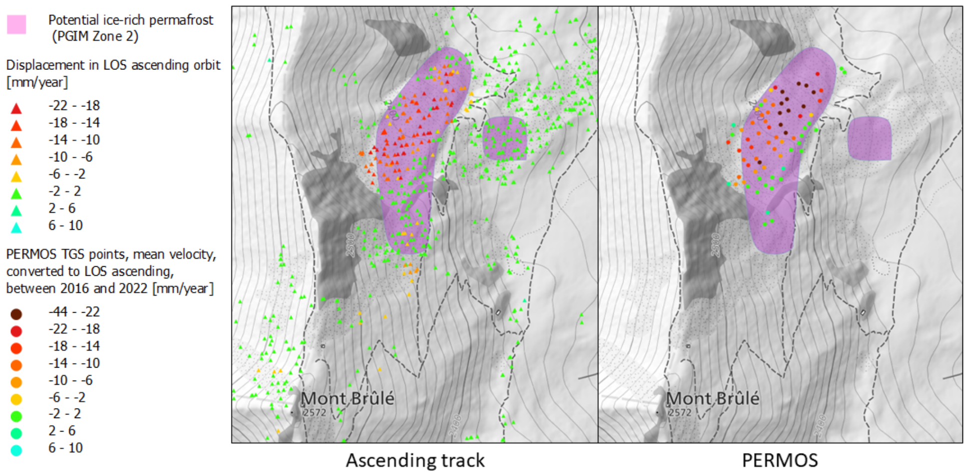


Figure 6.3.4: Local comparison between surface velocities derived from terrestrial observations and projected onto the line-of-sight to the ascending orbit and surface velocities derived from the ascending orbit from the PSI Map.

6.3.4 Assessment of Surface Velocities at Buildings Located in Permafrost Areas

In chapter 6.3.1 we have shown the sensitivity to radar detection for all structures and infrastructures in permafrost in the Swiss Alps. Here we zoom in to Canton Valais and focus only on the buildings. Table 6.3.6 shows the total number of buildings located in permafrost, including the sensitivity to radar detection. The table shows that ~62% of the buildings have sufficient sensitivity to radar detection (i.e., $0.5 < R$-index ≤ 1) for both ascending and descending orbit.

Table 6.3.6: Number of buildings in Permafrost Areas in Canton Valais.

Type	Amount	With $0.5 < R$-index ≤ 1		
		DSC Orbit	ASC Orbit	DSC and ASC
Buildings*	210	183	158	131

**Buildings include Mountain Cabins, Restaurants, Cable Car Stations, Technical and Service Buildings, Chapels, and Underground Structures.*

Then we assess if the buildings with $0.5 < R$-index ≤ 1 contain sufficient PS information in the PSI map of Canton Valais, allowing to accurately monitor their displacement status and evolution over time. We create a buffer of 20 m around each building and count the PS points within the buffer. This buffer was chosen because the geolocation precision of C-Band is 20 m, according to the information provided with PSI map of Valais. Table 6.5.5 shows the number of PS for each buffer area with $0.5 < R$-index ≤ 1. Based on this assessment we find that many areas around structures in permafrost in Valais contain PS.

Next, we analyse the displacement time series of several areas within zone-1 of the PGIM with buildings in detail. We conclude that, although many locations contain sufficient PS per orbit, often no clear assessment about the displacement trends at these locations can be made. Distinguishing between reflections from the ground or from the building and knowing the exact location of a reflection point is not possible in many areas. The spatial resolution, which represents the ability of a radar sensor to identify two closely spaced objects as being separate, of 5 m x 20 m of the Sentinel-1 sensor is inadequate for monitoring relatively small infrastructures. As example we show the analysis of one of the areas we looked at, i.e. Gornergrat, which is a famous touristic location visited by many people every year. The buildings at Gornergrat are located on the north side of a mountain ridge that is running from east to west. The area contains 9 and 19 PS in descending and ascending orbit, respectively. Fig. 6.3.5 shows a photo of the Gornergrat area, the location of the PS and the mean displacement and standard deviation of the displacement time series of the descending and ascending orbits.

The northwards slope of the Gornergrat on which the buildings are located has an unfavourable orientation with respect to the satellites orbits. The ascending satellite passes with heading north-by-west and the viewing direction is east-by-north and the descending satellites passes south-by-west with a west-by-north viewing direction, meaning that displacements parallel to this heading direction are difficult to detect. Although the area contains many PS, no conclusions about the direction and the magnitude of movements can be drawn. There are not enough PS from both the ascending and descending orbits at the same location to decompose the signal in a vertical and horizontal displacement component and the geolocation precision of 20 m does not allow for attributing the radar signal to a single geometric feature, such as the buildings. However, all PS show an increase in dispersion in time, which could be an indication for changing surface conditions in the vicinity of the buildings, and this can be an important information to prioritize additional investigation to evaluate their stability.

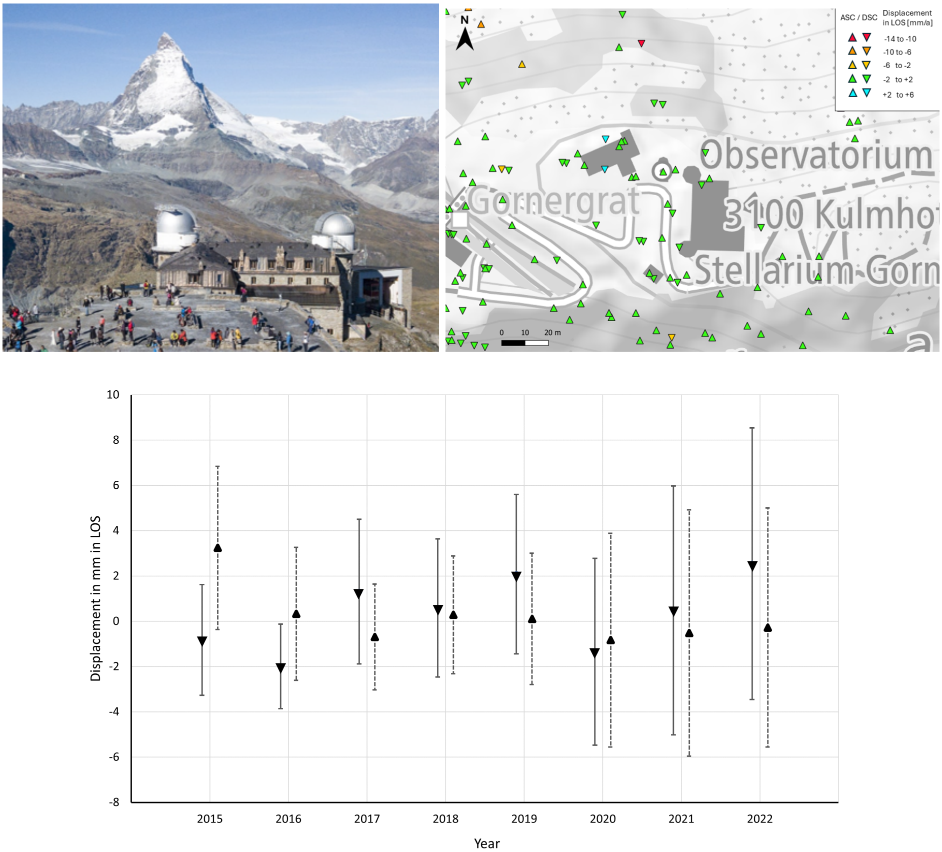


Figure 6.3.5: Photo of the Gornergrat area (Gornergrat Kulm, 2023) (top left), Top view of distribution of PS (top right), mean and standard deviation of displacements, derived from PS from the ascending and the descending orbit (bottom), summer images only. ∇ = descending orbit and Δ = ascending orbit.

6.4 Discussion and Conclusion

In this study, we evaluated the potential and the performance of PSI interferometry based on Sentinel-1 data to monitor surface displacements. We found that 92% of the areas currently labelled as permafrost and the majority of structures and infrastructures satisfy the geometric visibility criteria, combining ascending and descending Sentinel-1 orbits. Second, by exploiting a regional PSI dataset over Canton Valais, we found that mean surface velocities are higher in zones currently labelled as permafrost. The mean surface velocity estimated over ice-rich permafrost zones is 1.7 to 1.9 times as high as the mean surface velocity in no-permafrost zones. In contrast, the mean surface velocity of the ice-poor permafrost zones is only 1.2 to 1.3 times as high as in no-permafrost zones. Most of the papers using standard InSAR in the Swiss Alps have focused on rock glaciers (Bertone et al., 2022; Barboux et al., 2014), and in many cases, the surface velocities derived for rock glaciers are based only on interferograms, thus covering only a relatively short period. Other research addresses the behaviour of rock glaciers and mass movements (Kummert et al., 2021; Lugon and Stoffel, 2010), which encompasses a specific area or phenomenon only. Fast active rock glaciers, which are part of ice-rich permafrost (zone-2), are not included in the PSI map of Canton Valais as they exceed the sensor's maximal detectable displacement per year. We note that even without considering the most active rock glaciers, the mean surface velocities in the PGIM zone-2 are larger than the values measured in other zones. We stress, that larger displacements in the PSI map are not necessarily related to processes occurring in the permafrost active layer. Specific investigations and a thorough knowledge of geomorphology is required to distinguish between permafrost related movements and other processes (RGIK, 2023), which is not the focus of this study.

We emphasise that PSI has intrinsic limitations that might affect the interpretation of surface displacements. All displacements are projected onto the Line of Sight (LoS) of the satellite. To convert these LoS displacement into a downslope and a normal component, PS of an ascending and descending orbit at the same location are necessary (Brouwer and Hanssen, 2024,0). Moreover, the velocities that can be measured depend on the sensor considered and on the revisit time, which means that PSI maps based on C-Band satellite SAR can retrieve very little or no information on relatively fast displacements. In addition, the presence of snow results in the loss of coherence. In this study snow images were removed resulting in a smaller number of useful images per year. Furthermore, the phase aliasing limits and resolving the correct ambiguity level when converting the radar data to displacements can be a constraint (Manconi, 2021; Reinders et al., 2021; Barboux et al., 2015). However, the advent of new SAR satellite missions with different viewing geometries, revisit times or wavelengths, combined with contextual InSAR analysis, will further increase the potential of the technology. Moreover, as terrestrial monitoring data at high elevation is scarce, our study shows that regional PSI can be used as an additional source of information.

Concerning structures and infrastructures, we verify that, although many areas around structures in permafrost in Valais have sufficient sensitivity to Sentinel-1 radar detection, the regional Sentinel-1 based PSI maps are not suitable for monitoring buildings. Moreover, the resolution of C-band data is not sufficient for this purpose and higher resolution SAR data is necessary for structural health monitoring of buildings.

Our research comprises all permafrost areas in the entire Canton Valais for a period of 7 years, i.e. 2015 to 2022. The main result of our research is that areas mapped in PGIM have different ranges of mean surface velocities. To the best of our knowledge, the observation we provide at a regional scale is new and important information that can be the basis for further investigations of the displacement processes in high alpine environments.

6.5 Appendix: Tables and Figures

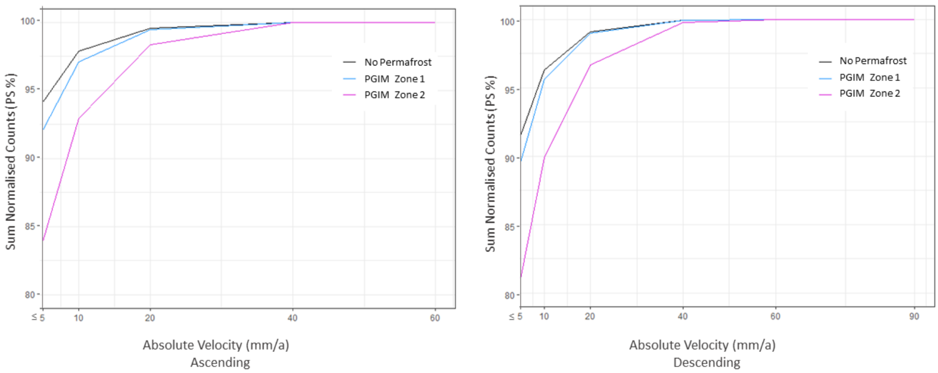


Figure 6.5.1: Cumulative frequency of PS in areas at altitude >2500 m, ascending and descending,in Line of Sight (LOS) of the satellite.

Table 6.5.1: R-index interpretation modified from Notti et al. (2014).

R-index	Sensitivity
$-1 \leq R\text{-index} \leq 0$	No visibility towards satellite due to layover, shadow, or foreshortening
$0 < R\text{-index} \leq 0.3$	very little sensitivity to downslope motion
$0.3 < R\text{-index} \leq 0.5$	moderate sensitivity to downslope motion
$0.5 < R\text{-index} \leq 1$	sufficient sensitivity to downslope motion

Table 6.5.2: Sentinel-1 data covering Switzerland, see Fig. 6.2.1. ZDP is the zero-Doppler plane.

Track		Incidence Angle θ within the AoI [deg]	Azimuth ZDP α_d [deg]
88	ascending	32.4 to 45.9	255.71
15	ascending	37.0 to 44.6	255.87
139	descending	37.0 to 40.8	104.50
66	descending	37.0 to 45.9	104.69
168	descending	39.5 to 45.9	104.49

Table 6.5.3: Amount of structures in permafrost areas in Switzerland with R-index > 0.5.

Type	Amount in Permafrost	With $0.5 < R$-index ≤ 1	
		DSC Orbit	ASC Orbit
Avalanche Barriers	6 648 m	4 232 m	3 531 m
Cable Cars	128	120	123
Cable Car Length*	206 446 m	197 664 m	199 893 m
Roads ($\geqslant$ 3 m wide)	32 170 m	27 367 m	29 686 m
Railroads (Trajectories)	3	3	3
Railroad Length	8 302 m	8 302 m	6 589 m
Buildings	366	307	272
Antennas	23	11	17
Wind Turbine	1	1	1

* The length is calculated over the permafrost area only.

Table 6.5.4: Effect size: eta-squared of Kruskal-Wallis.

	DSC	ASC
Ice-poor permafrost (zone-1) – No-permafrost	0.01	0.004
Ice-rich permafrost (zone-2) – No-permafrost	0.008	0.007
Ice-rich permafrost (zone-2) – Ice-poor permafrost (zone-1)	0.0005	0.002

Table 6.5.5: Number of buildings in Valais with $0.5 < R\text{-index} \leq 1$ *in Permafrost areas, with number of PS within a buffer of 20 m around the building.*

	0 PS	1 to 2 PS	3 to 5 PS	6 to 10 PS	>10 PS
Descending	34	32	35	51	31
Ascending	27	26	35	42	28

Chapter 7

Overall Discussion

In this research the benefits and barriers of using InSAR in civil-, geo-engineering and natural hazards projects were investigated. This discussion focusses on three specific aspects. First, the technical obstacles that were studied in Chapters 4, 5 and 6 are discussed. The second part evaluates the process of diffusion of InSAR in the industry. In the third part a reflection on qualitative versus quantitative research is given.

7.1 Evaluating Advantages and Obstacles of InSAR

In Chapter 5 the potential of InSAR for assessing surface deformation caused by shield tunnelling in an urban environment was discussed. During construction, abrupt settlements can occur over short spatial distances with magnitudes close to the wrapping threshold, making it difficult to resolve the correct ambiguity level in the InSAR data. For this specific application, a methodology has been developed to select the most likely ambiguity level. Resolving the most likely phase ambiguity level can also be challenging in other applications, for example in landslide-prone areas. However, as the application of InSAR will always depend on the local situation in terms of geometry, orientation and other reflective conditions, the effectiveness of the use of InSAR observations should always be evaluated in relation to these local circumstances. The proposed methodology in Chapter 5 uses Peck's formula (Peck, 1969), which he developed to predict settlements caused by shield tunnelling. This formula cannot be applied generically to other projects as ground deformation may have different origins and patterns. This requires different prior information and approaches to unwrap the SAR data correctly.

The same applies to the research on the use of PSI products (see Chapter 6). The potential of freely available Sentinel-1-based Persistent Scatterer Interferometry (PSI) maps for the detection of alpine permafrost in the Swiss Alps has been assessed. The results show that the used PSI map can reveal permafrost areas with different ranges of mean surface velocities. It is emphasised that the study concerns the use of a specific PSI product for a specific application. Other PSI products, areas or applications will require different analyses.

The developed guideline for using InSAR in compliance with the existing geoengineering design codes (see Chapter 4) can probably be used universally, even though this research focuses on Eurocode-7 and infrastructure applications. In other types of projects there is also always a prior, during and after construction or natural hazard event and InSAR can be applied to each phase, with objectives varying over time. The developed guideline contributes to the education of potential InSAR users.

Finally, this research reflects the state of the art at the time of writing. Ongoing research, advances in SAR technology and new satellite missions will lead to the resolution of some of the technical obstacles in the coming years.

7.2 Diffusion of Innovation

This study not only looked at the benefits, success factors, and technical and non-technical obstacles for the use of InSAR in civil-, geo-engineering and natural hazard projects. Also the diffusion of Interferometric Synthetic Aperture Radar (InSAR) technology was assessed. Based on the literature and the interviewees of Chapters 2 and 3, it is observed that InSAR is an underrated technique and it is still in a niche market. Although the demand for InSAR-based solutions in the civil, geotechnical and natural hazard industries is growing, the uptake has been slow. Looking at the adopter categorisation of Rogers and Williams (1983) (see Fig. 2.4.1), and based on the fact that the technology is not yet fully exploited and is growing slowly, it is hypothesised that the diffusion process of InSAR technology is probably still in its beginning, meaning that only the innovators and early adopters are using it. Diffusion is likely to have passed the innovators, but not the early adopters. The InSAR users in this study were individual engineers in companies using the technique for individual projects. We hypothesise that they can be considered early adopters and that the technology has not yet reached the early majority and become a mainstream monitoring method in engineering companies.

Rogers and Williams (1983) defined five main characteristics that potential adopters consider when deciding whether to adopt a new technology. By comparing these characteristics with the results of the interviews, possible explanations for the slow rate of adoption can be found. In table 7.2.1 the characteristics of Rogers and Williams (1983) are repeated and possible explanations for the slow uptake, including recommendations, are given.

Other influencing factors mentioned by Rogers and Williams (1983) are the intensity of the promotion efforts, the right timing and nature of communication channels and whether the adoption decision is taken individually, collectively by consensus, or authoritatively by the state or a company's management. These three factors are not addressed in the interviews and also not further investigated in this research. However, also the nature of the social system is mentioned by Rogers and Williams (1983) as an influencing factor. In this research, the industries involved are the civil-, geo-engineering and natural hazard industry. The literature (Alaloul et al., 2020) states that the architecture, engineering and construction (AEC) industry, which is part of the civil engineering industry, is generally slow to adopt innovations and therefore civil engineers may be reluctant to use InSAR in their projects. The nature of the industry of potential users may be an additional reason for the slow uptake of InSAR.

In addition to the characteristics from Rogers and Williams (1983), other factors that influence the use of InSAR in practice were mentioned in the interviews. One important factor is the fact that different disciplines are involved, who speak different languages and have different educational backgrounds and experiences. In addition, the wide range of potential users can be a challenge for InSAR providers, as many users require a specific project approach tailored to their needs. The price of processing the data can also be perceived as high by users, and the cost of commercial high-resolution SAR images is mentioned as a barrier. The lack of common standards for quality assessment is also noted. Currently, the way InSAR results are presented depends on the InSAR provider and the processing technique of the SAR data. Finally, the technical challenges of the technique may also hinder its diffusion in practice.

Rogers and Williams (1983) also state that adopters need to understand how to use an innovation correctly and that complex innovations require a greater amount of knowledge for their proper adoption than do less complex ideas. While it may be possible to adopt an innovation without basic knowledge, the risk of misusing the new idea is greater. This is also observed in this research. SAR data are used by geo-engineers, asset managers and stakeholders who are unfamiliar with the limitations of the technique. This can lead to misinterpretation of the data and affect the outcome of the analysis. SAR technology requires a high level of knowledge, which makes adoption more difficult. The processing of SAR data requires special skills and users who are able to interpret SAR results correctly.

Finally, this research has shown that there is a need to raise awareness and educate

Table 7.2.1: Explanations for the slow uptake of InSAR.

Characteristics of Rogers and Williams (1983)	Possible explanations, partly based on Section 3.4.2 and 3.4.3	Recommendations based on Section 3.4.4
Relative advantage	Despite the technical advantages of InSAR, such as providing (historical) ground deformations over wide areas at fine spatial resolution, also in remote and areas that are difficult to access without needing persons and equipment on site and in bad weather conditions, InSAR is still a little-used technology in the industry. Especially professionals in the architecture, engineering, and construction (AEC) sector, are not fully aware of its the possibilities and advantages.	Communicate the advantages and obstacles of the technique clearly and share case studies. Also InSAR providers and InSAR users have to be willing to cooperate and engage with each others problems.
Compatibility	The products that are provided by InSAR providers are often not compatible with the tools on the user side.	Provide standardised products and user-friendly platforms that can be combined easily with other geospatial data.
Complexity	Specialised skills are required to process and interpret the data. Also sufficient resources for storage and computation of the SAR data is needed.	Provide educational and training programs for InSAR users and providers. Set up guidelines for users. Ensure adequate SAR data processing and storage facilities.
Triability	Persons without InSAR knowledge cannot process the data themselves.	Perform pre-analyses at low cost, implement step-by-step deployment, start pilot projects.
Observability or Communicability.	The market is still niche, and therefore, the technique might not be very visible in the daily engineering practice among potential users. Moreover, the advantage of the technique is not visible enough.	Readily available PSI products can help to promote the technique. However, the obstacles should be communicated clearly.

potential InSAR users. This confirms the statement of Rogers and Williams (1983) that adopters need to understand how to use an innovation optimally to properly adopt it.

7.3 Reflection on Qualitative versus Quantitative Research

In civil engineering, geo-engineering and natural hazards research, most research is conducted with quantitative data. However, civil- and geo-engineering by default address real problems in human society. Similarly, the work of natural hazards experts is to assess the safety of people. Qualitative research seems obvious when dealing with these real-world problems, as it can provide important insights that cannot be captured by numbers alone. Nevertheless, no qualitative research was found in our literature review, apart from the CIRIA report 805 (Mason et al., 2022). Without judging or trying to explain the reasons for mainly using a quantitative approach in engineering research, one thing can be said: the choice to use a qualitative or quantitative approach should depend on the research subject and research question. Qualitative research cannot be conceived as an alternative to quantitative content analysis and vice versa. Rather, quantitative and qualitative research can be complementary. In engineering, for example, qualitative research should be used to assess the needs and experiences of users and stakeholders, to understand the impact of particular projects on the community concerned and to generate innovative ideas. This type of research is also particularly suited to discovery and exploratory studies. The results can form the basis for further research, which can then be carried out using quantitative methods.

In this research we used the semi-structured interview, a qualitative method of data collection and analysis, to identify benefits, success factors, technical and non-technical obstacles and recommendations for the use of InSAR in practice. The semi-structured interview format is particularly suited to elicit personal perspectives and insights on a given topic that are not captured by other data collection methods. As only quantitative data and case study based literature was available in this area of research, the semi-structured interview provided unprecedented information on the real-life experiences and opinions of InSAR users and providers. In particular, information was gathered on the non-technical factors influencing a deployment in practice, which had not been done before. The semi-structured interviews provided new and valuable insights.

However, gathering data with semi-structured interviews also has some drawbacks. First, the quality of the data obtained depends on the interviewer's skills and experience in conducting interviews and eliciting responses from participants.

There is also the possibility of interviewer bias, which can affect the results. Finally, interviewees' statements depend on their experience, knowledge of the technology and the specific applications they encounter in their work and cannot necessarily be generalised. Therefore, a rigorous qualitative semi-structured interview guide should be developed to increase the neutrality of the studies and the reliability of the findings. In addition, the data should be analysed by more than one researcher to increase objectivity. In this research, the interviews and analyses were carried out by the PhD researcher alone. Although the (co-)promoters also looked at the interview data and carried out spot checks, the analysis of the data by one researcher is a drawback of this study and future research should involve more than one researcher.

Finally, the semi-structured interview may be perceived as a simple method of data collection. However, data collection and analysis is extremely labour intensive and should not be underestimated. In this study, 9 participants were interviewed for approximately one hour each, resulting in an enormous amount of data. Therefore, researchers should be aware that conducting interviews is time consuming and certainly no less work than analysing quantitative data. It should also be emphasised that the aim of semi-structured interviews is not quantitative analysis, but the aim of the interviews is to uncover the views and perceptions of the participants.

Chapter 8

Conclusions and Recommendations

This research investigates the implementation of Interferometric Synthetic Aperture Radar (InSAR) in operational civil-, geo-engineering and natural hazard projects. The first objective of this study was to gain understanding of factors that influence the deployment of InSAR in projects. Then, three specific topics, that were identified in the first part of the study, were selected and investigated in depth. The first topic considered the application of InSAR in relation to the current geotechnical design codes. The second topic examined the practical application possibilities of InSAR in all phases of a tunnelling construction project. The third topic was the usefulness of freely available Sentinel-1-based Persistent Scatterer Interferometry maps for the application of alpine permafrost detection in the Swiss Alps.

8.1 Conclusions

In this section, the conclusions per research question are presented.

1. What factors influence a successful InSAR deployment in civil engineering, geo-engineering or natural hazard projects?

   An extensive literature review and interviews with five InSAR users and four InSAR providers were conducted to assess the technical and non-technical factors that may influence the use of InSAR in civil, geotechnical and natural hazard projects. It was concluded that InSAR has many advantages for civil engineering, geotechnical and natural hazard projects, such as providing accurate deformation point measurements over large areas with fine spatial resolution, even in bad weather and at night, providing data outside the area of conventional survey benchmarks, providing data in remote and difficult to access areas without the need for people and equipment on site, providing historical ground displacement data and for baseline assessments at the start of a project. However, the technology cannot be optimal for every application. There are technical barriers to its use in certain applications: It is an opportunistic method and the locations and distribution of the monitoring points are not known in advance, land use affects the detection of stable reflectors, the range of detectable displacement velocities is limited, unwrapping errors can occur due to phase ambiguity, the displacements are in the line of sight (LoS) of the satellite, geometric distortions can occur, and due to the near-polar orbits of current satellite missions, sensitivity to translational displacements along the north-south direction is limited. With regard to freely available Persistent Scatterer Interferometry (PSI) products, a major limitation is that these maps are application agnostic, i.e. they are sub-optimal for a particular application and local use.

In addition, non-technical factors also influence the application in practice. Some interviewees mention that the civil-, geo-engineering and natural hazards industries still seem to be unfamiliar with the technique. Also, freely available Persistent Scatterer Interferometry (PSI) products are being used by potential InSAR users without knowledge of the limitations. Based on the interview statements and the literature, the following picture emerges: non-technical issues such as aligned expectations, good communication, knowledge of each other's discipline and needs, and skilled people are key success factors for the use of InSAR in projects.

2. How can InSAR be used in a way that is compatible with the existing geo-engineering design codes?

   This question relates to the problem that potential users lack the knowledge of InSAR to use it properly in their projects.

   In the planning phase of new infrastructure or when designing renovation of existing infrastructure, information on existing slope movements or settlements is essential to make informed design decisions. Interferometric Synthetic Aperture Radar (InSAR) can provide insight into the surface movement of an area from historical archives using satellite-based SAR data. Furthermore, InSAR observations can help identify zones of displacement that are greater than the average for an area and can be used to plan future ground investigations 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.

However, the use of InSAR is not yet standard practice in geotechnical projects and no formal guidelines exist on how to use InSAR within a project. This research has demonstrated the application of InSAR during the lifecycle of a civil engineering project, i.e., the pre-construction stage, construction stage and operation and maintenance stage, within the established standard geotechnical design codes, such as the newly published Eurocode-7. An operational framework was developed to combine InSAR with current geotechnical design codes in all project stages and demonstrated that the use of InSAR technology fits well within the required activities.

This framework improves the understanding of InSAR applications in geo-engineering projects among stakeholders such as engineers, contractors, asset managers and planners.

3. How can the ambiguity problem be solved for a real tunnelling project and provide a method to use InSAR effectively for the assessment of ground deformations in similar tunnelling projects?

   This question addresses one of the technical obstacles, i.e. the phase ambiguity, for a specific application.

   Based on a real tunnelling project, it was investigated how InSAR can be used to assess ground deformations prior to, during and after construction.

   Prior to construction InSAR proves to be a very useful tool to perform a baseline assessment. InSAR provides long time series of deformation and can be used to map deformation in the past, with SAR data archives going back to 1992.

   During construction, when immediate action is required in the event of abrupt settlements, SAR data is not suitable as a real-time warning system due to the satellite's repeat time and the additional latency in processing the SAR data. However, due to its high spatial resolution and the availability of long time series, it is a valuable complementary source of information to conventional monitoring. InSAR provides high-precision monitoring of ground movement over large areas without the need to install instruments on the ground.

   After construction InSAR is a useful tool to monitor settlements when the conventional monitoring has ceased. It can reveal important deformation patterns in the years after construction, which will help to better understand the problem of long-term tunnel settlement.

   Resolving the correct ambiguity level in InSAR data can be challenging, especially in the case of abrupt settlements over short spatial distances with magnitudes close to the wrapping threshold. To retrieve unbiased displacement estimates, prior information regarding the expected settlement is needed. Analytical settlement prediction methods can be successfully used to find the most probable ambiguity level in the InSAR estimates. This way, augmented InSAR can capture the short-term settlements that occur immediately during construction of the shield tunnel. The constraint on the abruptness, steepness, and magnitude of the displacement can be alleviated by having more coherent InSAR scatterers with a shorter repeat cycle.

The proposed methodology to select the most probable ambiguity level can help in the development of a practical tool that is able to quantify and insert the prior information on the displacement dynamics in the InSAR displacement estimation software. In this way, augmented InSAR can be integrated into the monitoring framework of more civil engineering projects.

4. What are the possibilities of free available Sentinel-1 based Persistent Scatterer Interferometry (PSI) maps for alpine permafrost detection in the Swiss Alps?

   This question addresses the fact that freely available PSI maps are being used by non-InSAR engineers without knowledge of the correct applications and challenges.

   The potential and the performance of PSI interferometry based on Sentinel-1 data to monitor surface displacements in the Swiss alps was evaluated. It was found that 92% of the areas currently labelled as permafrost and the majority of structures and infrastructures satisfy the geometric visibility criteria, combining ascending and descending Sentinel-1 orbits. Second, by exploiting a regional PSI dataset over Canton Valais, the mean surface velocities appeared to be higher in zones currently labelled as permafrost. The mean surface velocity estimated over ice-rich permafrost zones is 1.7−1.9 times greater compared with no-permafrost zones. In contrast, the mean surface velocity of the ice-poor permafrost zones is only 1.2−1.3 times larger than the no-permafrost zones.

   Concerning structures and infrastructure located in permafrost zones, the study showed that although many areas around structures in the canton Valais have sufficient sensitivity to Sentinel-1 radar detection, the regional Sentinel-1-based PSI maps are not suitable for monitoring buildings. Moreover, the resolution of C-band data is not sufficient for this purpose and higher resolution SAR data is required for structural health monitoring of buildings.

However, as terrestrial monitoring data is scarce at high altitudes, regional PSI can be used as an additional source of information.

8.2 Recommendations for InSAR Deployment

Based on the literature and interviews, recommendations were formulated to improve the use of InSAR in civil-, geo-engineering and natural hazard projects. The most important recommendations are summarised below.

1. Managing expectations. InSAR providers and users need to be willing to work together and engage with each other's problems, communicate well and share information openly. InSAR providers should be transparent about the benefits and challenges of InSAR and clearly explain the difference between diagnostics and detection. Also addressing the specific project context and concerns of the engineers is key. Moreover, the capabilities and challenges of Persistent Scattering Interferometry (PSI) products should be clearly communicated.

2. Building trust. Case studies should be developed to demonstrate how InSAR can be a cost-effective solution for monitoring deformation over large areas compared to traditional methods. Low-cost pre-analyses, step-by-step deployment and pilot projects will help to introduce InSAR gradually into a project and evaluate its capabilities at each stage of the project. In this case, the costs are also spread over the project. In addition, face-to-face meetings or even on-site meetings are recommended.

3. Education. This includes raising awareness, providing simple explanations, educating civil engineers about InSAR and training InSAR providers with knowledge of civil and geotechnical engineering needs. This can be done through post-graduate courses, workshops and InSAR experts explaining the technique to potential users. In addition, engineers could be trained at university level by including SAR technology in the civil engineering curriculum.

4. Clear procedures, tools and guidelines. Standardisation of tools and platforms, uniform methods and standards of SAR products are necessary to assess their quality and reliability. Then, also guidelines for user and ready-to-use SAR products should be developed that are user-friendly and understandable to InSAR users without deep technical expertise in radar processing. Tools that allow the combination of SAR data with other geospatial data can also increase user acceptance.

5. Adequate team. Qualified personnel on both the InSAR user side and the

InSAR provider side are key. Forming a team with qualified personnel from the beginning of the project and allowing sufficient preparation time will contribute to a successful implementation in a project.

6. Restrict the cost. For example by using commercial images for multiple projects and by offering InSAR pre-analyses at low cost.
7. Sufficient computer processing and data storage facilities to handle the increasing amount of data.
8. Produce high-quality and valuable results that are understandable for users in order that these products are useable and useful.

8.3 Recommendations for Further Research

This research required knowledge of different disciplines. First of all, knowledge of civil- and geo-engineering and knowledge about the SAR technology and geodesy. However, this research also involved knowledge from social sciences, such as psychology, business and innovation development. Looking at such a wide research area goes at the expense of in-depth knowledge of each discipline. Therefore, some topics in this research should be evaluated in more depth in the future.

- The diffusion of SAR in the industry should be studied in more detail. The InSAR providers interviewed indicated that the market is still niche and that competition is fierce. However, market share data was not available. It is recommended that in-depth market research be carried out to assess how many companies worldwide are using InSAR and for which projects. Data should also be obtained on the turnover and number of InSAR providers. Also bridging the gap from academia to industry should be studied in more detail. Despite the large amount of articles found (see Chapter 2), it is hypothesised that academic research on InSAR does not necessarily reach the industry.
- Next, five InSAR users and four InSAR providers were interviewed (Chapter 3). To get a broader overview of opinions and to be able to quantify and statistically analyse the responses, a questionnaire could be sent to a larger group of potential InSAR users and InSAR providers. Based on the responses, the interview results can be validated, and the recommendations can be updated. It would also be interesting to repeat the interviews and questionnaires in a few years' time to assess whether the situation has changed.
- The aim of the framework proposed in this research (Chapter 4) is to provide a practical and operational tool that can be used by planners and engineers throughout the lifecycle of an infrastructure project. To date, no information

has been gathered from the industry on the usability of this framework. It is recommended to obtain feedback from InSAR users on the proposed framework and, if necessary, to adapt the framework to improve its use.

- The proposed methodology to select the most probable ambiguity level (Chapter 5) by inserting prior information on the displacement dynamics in the InSAR displacement estimation software should be further evaluated and extended to other types of ground displacement origins.
- In this study, a specific Persistent Scatterer Interferometry (PSI) product was used for the detection of alpine permafrost in the Swiss Alps and the assessment of structures and infrastructure in these areas (Chapter 6). This PSI product was produced using Sentinel-1 data. As the resolution of C-band data is not sufficient for structural health monitoring, it is recommended to assess whether buildings and infrastructure in alpine regions located in areas prone to displacement can be monitored with higher resolution SAR data.

Finally, research is an ongoing process and never finished. Therefore, the list above provides only a small glance on future research ideas.

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Curriculum Vitae

Full name

Kristina Juliana Reinders

Birth

23 February 1979, Vilvoorde, Belgium

Nationality

Dutch and Swiss

Career

2021 – present:	University Bern, student advisor and exam management
2018 – present:	Delft University of Technology, PhD candidate
2021 – 2023:	Skygeo, consultant
2016 – 2020:	Delft University of Technology, lecturer
2007 – 2016:	Fugro GeoServices B.V. , geotechnical engineer and project leader
2006 – 2007:	Voluntary work in rural area in South Africa
2005 – 2006:	Fugro Ingenieursbureau B.V., geotechnical engineer
2004 – 2005:	IMd Raadgevend Ingenieurs, structural engineer

Education

1997 – 2003:	Delft University of Technology, Faculty of Civil Engineering, Master of Science
2000 – 2001:	ETH Zürich, Fakultät Bauingenieurwissenschaften, exchange semester
1985 – 1997:	European School in Brussels, Belgium

Languages

Dutch, first language

German, first language

English, fluent

French, fluent

Publications

Submitted: Reinders, K.J., Verhoeven, G.F., Sartorelli, L., Hanssen, R., Manconi, A., 2023. Exploring the use of Sentinel-1 to monitor spatial and temporal evolution of permafrost in the swiss alps. EGUsphere 2023, 1–21.

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Reinders, K. J., Schoenmaker, B., and Nohl, W. A., 2015. Limit-State Design of a Steel Storage Tank Foundation on a Crushed Rock Ring Based on Proven Soil Strength. Geotechnical Safety and Risk V. IOS Press, 389-393.