COASTAL AREAS UNDER THE THREAT OF LAND SUBSIDENCE AND FLOODING - THE CASES OF MESSOLONGHI AND AITOLIKON, GREECE

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Introduction

The current study aims to investigate the driving mechanisms of surface deformation occurring in the coastal cities of Messolonghi and Aitolikon in Greece (Figure 1). Low-rate surface displacements have been reported along these sites, often resulting in building damages. Messolonghi occupies a flat lowland and is founded on Quaternary alluvial deposits consisting of fine grain sediments (clays, silts, and sands). Drillings performed in the city of Messolonghi identified organic clay horizons containing a significant amount of plant remains and are characterized as soft to moderately stiff (SPT values 1-14 and compression index of up to 0.42) [1], [2], [3]. The second city, Aitolikon, initially consisted of 4–5 very small islands, which were later connected by fishermen using wooden piles and earth fills. Over the years, continuous fillings were added and the irregularly shaped island of Aitolikon with a 300 m in diameter was created.

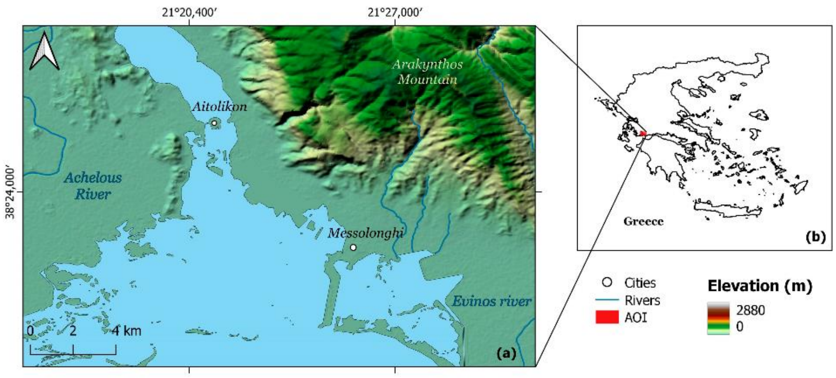

Figure 1. (a) The cities of Messolonghi and Aitolikon & (b) Location of the study area.

Methods

To fully determine the phenomena occurring in these areas, results from the satellite data processing were examined together with geological, geotechnical, hydrogeological, precipitation, sea level rise, and field trip data and thus a more accurate interpretation of the phenomenon was achieved. The parallelized Persistent Scatterers Interferometry PSI (P-PSI) processing chain, developed in the Operational Unit BEYOND Center for EO Research and Satellite Remote Sensing of the National Observatory of Athens (NOA) [4], was implemented in Sentinel-1 SLC images, for a 7-year period, to perform a time-series analysis of the Line of Sight and vertical displacements from both the descending and ascending satellite passes, in the affected areas. The estimated LOS displacements verified the land subsidence phenomena in both sites. The results were correlated with the vertical deformations acquired from the European Ground Motion Service [5].

The effect of global warming and climate change is also evident in Messolonghi and Aitolikon. Both areas have experienced an increased frequency and volume of precipitation, sea level rise as well as floods. The data from the tide gauges of Katakolon and Patras [6], as well as the Representative Concentration Pathway (RCP) [7] and Shared Socioeconomic Pathways (SSP) scenarios [8] were used to estimate the projected sea level rise as well as the areas that will be flooded by 2100. Precipitation data was obtained from the automatic weather stations'

NOANN network of the National Observatory of Athens (NOA) [9] and were statistically processed and analyzed in correlation with the recorded deformations. Finally, Corine's land use map for 2006 [10] and 2018 [11] were used. A correlation between the increase in the area used for residential and commercial purposes in Eastern Messolonghi with the increase in the rate of subsidence in the same part was found.

Results - Conclusion

The recorded subsidence in the east part of Messolonghi indicate a mean rate of −5mm/yr. The estimated subsidence rates increase towards the coastline and numerous buildings are affected. In the city of Aitolikon, maximum deformation values reach a mean rate of −4 mm/yr. The highest deformations are observed in the south part of the Island, where Vaso Katraki Museum is located (mean values of -4.5 mm/year). In the north part of the town, significant damages to buildings have been recorded. In both sites, the main factor contributing to the deformations is the load by external buildings imposed on the normally consolidated clay formations. In Messolonghi, most buildings are constructed with mat foundations, and only a few have spread footings. The difference in the type of foundation is attributed to the improvement of the Greek Code for Seismic Resistant Structures. Moreover, the foundation type also varied based on the nature of the formations encountered during construction. Deformation patterns are manifested primarily in buildings constructed with spread footings. Moreover, due to the constant increase in the sea level and the increased precipitation rates, the groundwater level fluctuates throughout the year, leading to the reactivation of the primary consolidation. Overall, in both sites, the situation is expected to worsen over the next few years because of the gradual subsidence of the sites and the increase in the mean precipitation rates and sea levels caused by climate change.

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EVALUATING THE EFFECTIVENESS OF LANDSLIDE MITIGATION MEASURES USING MCDA METHODS AND SNAP SOFTWARE

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1 Introduction

Landslides can be caused by either natural or anthropogenic factors, such as road construction. On the other hand, human actions such as mitigation measures can also stabilize a slope, preventing a landslide. Multi-Criteria Decision Analysis (MCDA) methods and Geographical Information Systems (GIS) are widely applied for conducting the Landslide Susceptibility Assessment (LSA) of an area. In this process, the mitigation measures are usually not taken into consideration or are notably underestimated (Nefros and Loupasakis, 2022), as there is high uncertainty regarding their effectiveness (Kamal et al., 2023). Remote Sensing techniques, such as Persistent Scatterer Interferometry (PSI), are widely used for monitoring ground movements, providing evidence even for slow-moving landslides. Thus, PSI and GIS can be used to update the LSA of the Area of Interest (AOI) by incorporating the effective stabilization measures taken after the initial assessment. The main objective of this study is to highlight the potential of using MCDA methods with GIS and remote sensing techniques to provide an up-to-date LSA. Critical regions of the road network of Chania, a regional unit (RU) in Crete Island, Southern Greece, were examined as a case study area.

2 Data and Methods

During this study, the Analytical Hierarchy Process (AHP) was applied to the Chania RU. Experts were used to evaluate the most critical landslide causal factors along with their contribution–weight. The SentiNel Application Platform (SNAP), an open-source tool that enables Persistent Scatterer Interferometry (PSI) analysis through the extension of Stanford Method of Persistent Scatterer (StaMPS) software package (Foumelis et al., 2018), was used to analyze Sentinel-1 images and provide evidence about terrain movements in critical regions in the AOI. These regions of the road network were primarily affected by recent extreme precipitation events occured in February 2019, and mitigation measures had been established by civil protection authorities.

3 Results

First, the AHP was applied and the LSA for Chania RU was conducted. Subsequently, the most critical regions of the Chania RU road network were identified. Using SNAP software, PS time series were examined before and after the application of the mitigation measures. In regions where the velocities of the PS movements were below the threshold of 2 mm/year, it was indicated that the applied mitigation measures were effective and the slope was stabilized (Figure 1). Consequently, the susceptibility map was relatively updated for these regions.

Fig.1. PS velocities of the examined area

4 Conclusion

As was revealed, human activities can considerably affect the landslide susceptibility of a region. In this direction, GIS and Remote Sensing techniques can contribute to updating the LSA by providing valuable information about the effectiveness of the mitigation measures already applied and identifying the newly most susceptible regions, where mitigation measures are insufficient and urgent actions must be adopted by authorities. Thus, LSA emerges as a dynamic process that needs to be regularly updated.

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EXPERIMENTAL METHOD FOR TESTING THIXOTROPIC PROPERTIES OF SOILS

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Introduction

Currently, there is no reliable and commonly used method of detecting thixotropic characteristics in soil samples. The complexity of soil behaviour under various loading and environmental conditions further complicates the development of such methods. Disturbing a thixotropic structure of soil causes it to change its plasticity index and in extreme cases leads to soil liquefaction. Thixotropic plasticization can be induced by various dynamic actions. For instance, vibrations emitted by tracked vehicles, conveyor belts, and heavy machinery during construction activities can alter the soil structure. Furthermore, pile driving and drilling operations, particularly impact drilling, exert significant stress on the soil, exacerbating the risk of plasticization. These activities generate complications such as unexpected settlements or shifts in foundation stability, leading to additional costs and delays in construction projects.

Methods

To develop a methodology for determining thixotropic properties, soil samples were collected for subsequent testing. The samples were taken from locations with previously encountered cases of thixotropic soils exhibiting varying intensities of these properties. Several soil characteristics were identified and measured, including natural water content, bulk density, plastic limit, liquid limit, and the grain size analysis. Once collected, the soil samples underwent comprehensive laboratory analysis to identify and measure several critical soil characteristics. First, the natural water content of each sample was determined. This measurement is crucial because the amount of water present in the soil directly affects its thixotropic properties [Ren et al. 2021]. Water content influences the plasticity of the soil and its ability to change state under applied stress.

Determining bulk density, which is the mass of soil per unit volume, helped assess the the compaction level of the soil. This property is important because it affects the strength and behavior of the soil under load [Bao et al. 2019]. Higher bulk density typically indicates a more compact and less porous soil structure, which may affect its ability to exhibit thixotropic behavior.

In addition to bulk density, the plastic limit of the soil was tested. The plastic limit is the minimum water content at which the soil transitions from a semi-solid state to a plastic state. This parameter is vital for understanding the consistency of the soil and its potential to become more pliable when water content is present. Similarly, the liquid limit of the soil was determined. The liquid limit represents the maximum water content at which the soil changes from a plastic state to a liquid state. This measurement is important for identifying the point at which the soil begins to exhibit fluid-like properties, which is a key aspect of thixotropy [Monge et al. 1998].

Furthermore, grain size analysis was performed. This involved examining the mineral composition and particle size distribution, including the proportions of sand, silt, and clay. The fraction composition affects the mechanical and hydraulic properties of the soil, influencing its behavior under various environmental conditions [Zhang et al. 2017, Wang et al. 2021].

By investigating these parameters, a comprehensive understanding of the physical characteristics of the soil that contribute to its thixotropic properties was achieved. This detailed analysis provided the foundation for developing a robust methodology to assess the risk of thixotropy in different field conditions. Such a methodology is essential for geotechnical engineering and geological risk management, enabling better prediction and mitigation of thixotropic soil behavior in construction and land development projects.

Simultaneously, work was undertaken on the construction of a device that would enable the determination of thixotropic properties of the soil. This device has the ability to apply vibrations of

various frequencies and amplitudes in such a way as to best simulate the actual factors causing the soil to liquefy under the influence of vibrations. The soil sample for testing is prepared in such a way as to reproduce the density and natural water content occurring in-situ at the place of sampling.
The methodology being developed is intended to ensure the possibility of measuring the amount of liquefaction immediately after the sample is subjected to vibrations.

Results

The expected results anticipate the creation of an apparatus that enables the study of thixotropic soils under conditions similar to natural ones. The main objective of this apparatus is to achieve correlation between laboratory results.

Conclusion

There is still no methodology that simultaneously determines the properties of thixotropic soils. However, by creating an apparatus that induces soil liquefaction, this goal seems increasingly feasible and achievable.
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OPTIMIZING URBAN MANAGEMENT, PLANNING, AND RESILIENCE THROUGH AN ENGINEERING GEOLOGICAL DATABASE: THESSALONIKI'S EXPERIENCE

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Introduction

The research introduces an advanced engineering geological database, based on the Tunnel Information and Analysis System-TIAS (AGS, 1999; Marinos et al., 2013), a pivotal tool for managing extensive geological and engineering geological data. Derived from hundreds of boreholes and numerous geotechnical investigations, the database facilitates the engineering geological assessment and classification within Thessaloniki's urban area in northern Greece. The focus is on the Quaternary and Neogene age sediments and fill deposits, aiming to mitigate geological uncertainties and geotechnical challenges for safe urban planning. The study underscores the importance of big data management in understanding geological heterogeneity, subsurface variations, engineering geological conditions, geological hazards, and early-stage infrastructure design considerations.

Methods

The research integrates various software, scientific tools and coding techniques to analyze, correlate, and present data. Key outputs include detailed thematic maps, statistical plots, two-dimensional and three-dimensional models, and an updated engineering geological map of the Thessaloniki basin (Figure 1). These outputs provide insights into the spatial distribution of geological formations, physical and mechanical parameters, as well as the redefinition of geological contacts (Kokkala and Marinos, 2022).

Results

The research results propose new, precise ranges of values, detailed by depth and region, for physical, mechanical and hydraulic parameters of the geomaterials examined. Furthermore, examples of specific database applications are created, with emphasis on the investigation and assessment of the engineering geological evaluation based on geohazards (liquefaction and settlement) and type of engineering project (urban tunneling and construction of major foundations).

Conclusion

This research transforms primary data into critical insights, emerging as an essential tool for both researchers and practitioners in the realm of geohazard mitigation and urban planning. It showcases the significant benefits of advanced methodological approaches in enriching the understanding and management of geological and engineering geological data, fostering improved strategies for urban protection and infrastructure design.

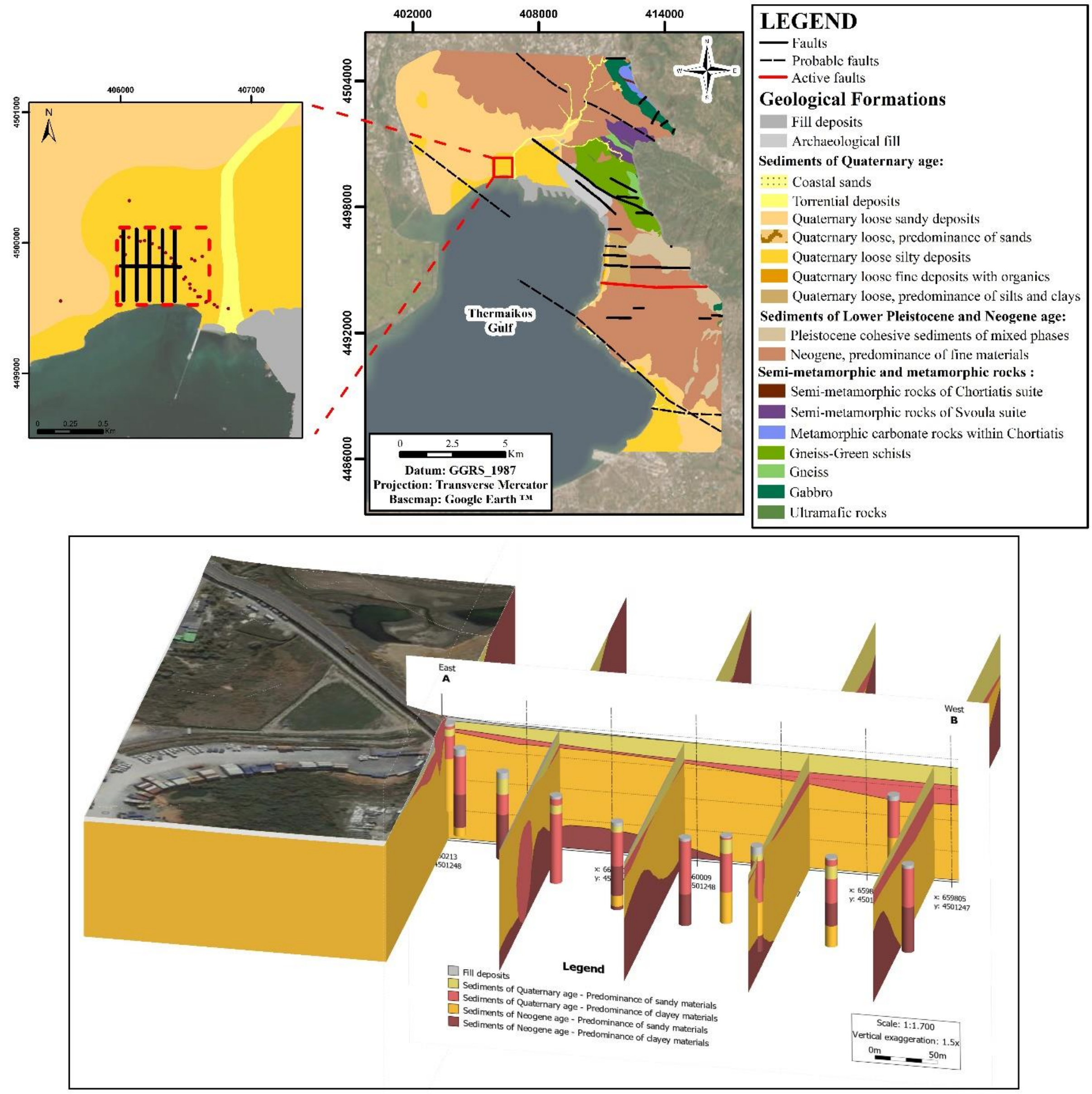

Figure 1. Updated engineering geological map of Thessaloniki city accompanied by a 3D geological model of a specific area (modified by the authors from Rozos et al. 1998).

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FORMATION OF TALUS DEPOSITS IN SOFT ROCK MASS AND ITS IMPACT TO INFRASTRUCTURE: SOME EXAMPLES OF LOW COST MITIGATION MEASURES

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Introduction

The weathering of flysch rock masses which consist mainly of soft rock causes significant erosion of the surface of cuts and slopes (Vlastelica et all, 2018a), as well as it is one of key factors of successive shallow landslides and repeating rockfalls which are generated from harder layers due to differential erosion (Miščević and Vlastelica, 2014). Detached and eroded material is usually deposited at the bottom of the slope where it forms a talus that occupies useful space (Figure 1).

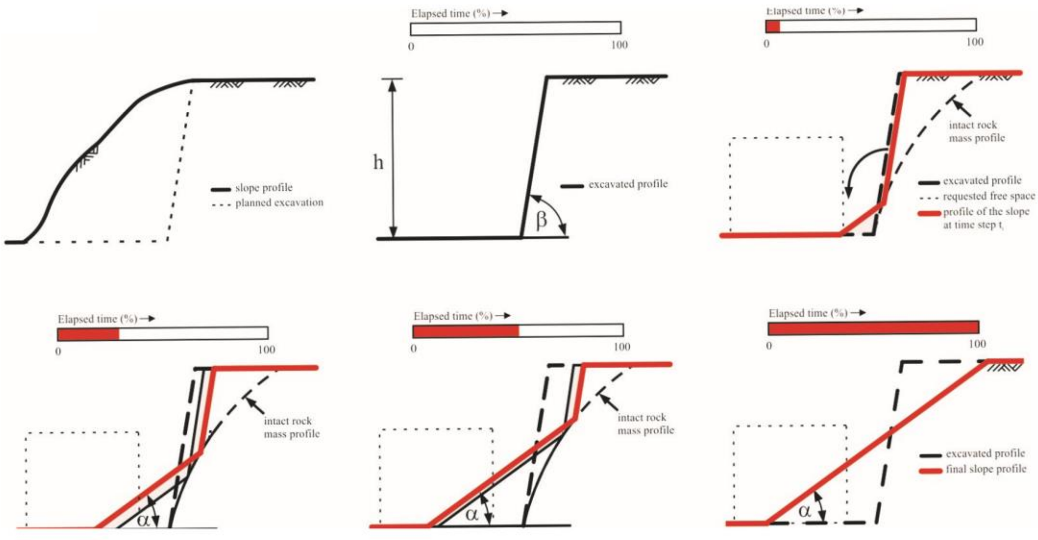

Figure 1. Formation of a steep slope from the initial time to its final transformation. Jelušič et all (2024)

If the talus material is just removed, the weathering and erosion process is further accelerated, leading to possible collapse of the whole slope. The usability of the area in front of the slope is most often required due to necessary infrastructure, buildings, or other reasons. Therefore, if the weathered material is not removed and the slope should not move too far away from the initial wall, a barrier in the form of a retaining wall must be constructed to limit the area in which the slope material is deposited.

Some of the typical low cost mitigation measures which can be used to form the barrier are: reinforced concrete wall, gabion gravity retaining wall and geosynthetic reinforced soil wall (Figure 2). These solutions are presented in detail in Jelušič et all (2024), are compared under functional, cost and environmental aspects (Vlastelica et all, 2016; Vlastelica et all, 2018b).

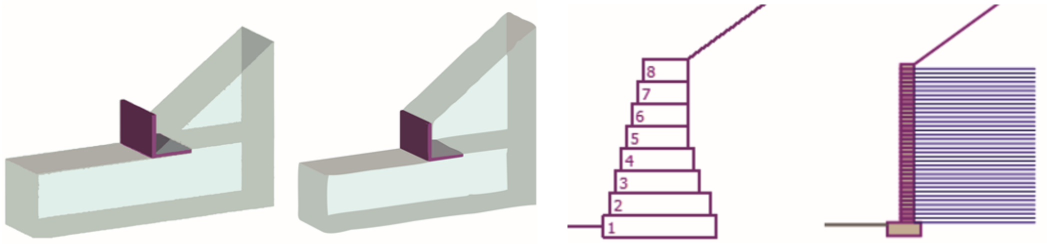

Figure 2. The retaining wall subjected to earth pressure, as a result of scree accumulation. Jelušič et all (2024)

Methods

The time dependent accumulation of scree behind the retaining wall is used as input for dimensioning of the retaining wall. The retaining wall must be verified in accordance with Eurocode standards (EN 1997-1) therefore the five main conditions were defined in the form of five geotechnical constraints: Condition 1: bearing capacity failure; Condition 2: position of resultant (eccentricity); Condition 3: sliding failure; Condition 4: wall overturning; Condition 5: global stability analysis. Each retaining wall is subjected to earth pressure, as a result of the scree accumulation, as shown in Figure 2. It should be noted that each retaining wall is analyzed separately at any selected time *t*. (Jelušič et all, 2016)

A simple analytical model (Jelušič and Žlender, 2020) for a retaining wall is used, that takes into account the position, time, and inclination of the retaining wall (Jelušič et all, 2024). The result of the analysis is the position and geometry of the retaining wall, which should be optimal from various points of view, such as technical, functional, cost or environmental aspects. All walls are dimensioned to optimize costs.

Discussion and conclusion

Permanent solutions that achieve high level of safety (such as complete slope stabilization i.e. with geotechnical anchors or nails) is not affordable for most users, or there is not sufficient amount of funds to cover all endangered areas. Therefore, to use some low cost mitigation measures and recommendations that would reduce damage to infrastructure and reduce the risks of using the space is better than not to use any at all. The added value of low cost mitigation measures is the use of the benefits of the natural process. The previously eroded - softer material can be used to reduce damage to the retaining walls or barriers or reduce the need for it, and the use of construction activities can be highly reduced (reduced material transport, thus the reduced CO_2 footprint).

It should be noted that in cases when low cost mitigation measures are applied, the whole area of the slope which corresponds to final slope profile (from the barier to the top of the slope in lower right profile on Figure 1) has to be inaccessible for people (or used only at their own risk) because of constant danger of potential rockfalls and landslides.

In highly urbanized area it is not acceptable to leave this kind of slopes unattained. It can lead to infrastructure damage and it can be hazardous for people, especially in cases when there are houses or infrastructure on the top of the slope. In this cases more elaborate and permanent measures should be used. Slope transformation is not limited only to change of the slope profile, also the mechanical properties of the material (rock mass) itself are degraded. This should also be taken into account for any future usage of the slope area.

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INIO – A GLOBAL INSAR SERVICE, PROVIDING GEOTECHNICAL ANALYSIS FROM SPACE

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Introduction

Synthetic Aperture Radar Interferometry (InSAR) is a technique that enables observations of ground motion from space with millimeter-scale precision. The Norwegian Geotechnical Institute (NGI) and Kongsberg Satellite Services (KSAT) launched a designated and scalable commercial InSAR service, Inio, in 2024. This comprehensive land monitoring service is unique, combining extensive expertise within earth observation and geotechnical engineering. It ensures maximum benefits from land monitoring while saving costs and mitigating risk via assessments of ground stability and risk.

Infrastructure like bridges, roads, railroads, tunnelling, hydro dams and mine tailings, can be monitored to detect geohazards such as creep and subsidence, to track ground movements, evaluate project impacts and help monitor risk to operations as well as surrounding areas. Subsiding cities, or geological and natural hazards affecting populations, can be continuously monitored and assess risks to the built environment.

Methods

Differential InSAR (D-InSAR) is a class of advanced, multi-temporal microwave remote sensing techniques that are used to determine relative surface deformations in the line-of-sight (LOS) direction of a sensor, by extracting the phase difference from pairs of SAR images of the same area acquired at different points in time. There are several unique algorithms that fall under the differential InSAR umbrella; each with certain advantages and disadvantages, depending on the application. A key aspect of InSAR processing is to identify pixels that provide a stable and coherent backscatter over the entire measurement period. Non-coherent pixels, e.g. affected by vegetation, are masked out. Coherent scatterers are divided into point-scatterers (PS), where a single point-like object is responsible for most of the backscatter within the pixel, and distributed scatterers (DS), where the backscatter is evenly distributed from within across the whole pixel. While PS are most common in urban areas, rural areas are mostly covered by DS. Many processing techniques focus on either PS or DS, however, combined PS-DS processing approaches have been developed as well (see e.g. Raspini et al 2022).

An increasing number of SAR satellites, both public and commercial, provide a constantly growing archive of data for InSAR analyses, which allows for detailed deformation analyses on almost every place on earth. Capturing data for many years into the past, in some places going back to the beginning of the 1990s, provides a unique opportunity to map structural integrity of important infrastructure over long periods of time. The large footprint of the SAR images enables the tracking of spatial variations in ground movement over many kilometers.

Results

For the last few decades, InSAR has been applied to challenging often remote environments, or hard to monitor. Inio has been focused on both stability of the ground and the stability of industry operations and enhancing societal safety (see Figure 1). Past projects included applications in the areas of tailings dams, tunneling, urban infrastructure, landslides, Carbon capture and storage (CCS) and ground water pumping induced subsidence (see, e.g., Vöge et al 2012, Vöge et al 2015, and Vöge et al 2022).

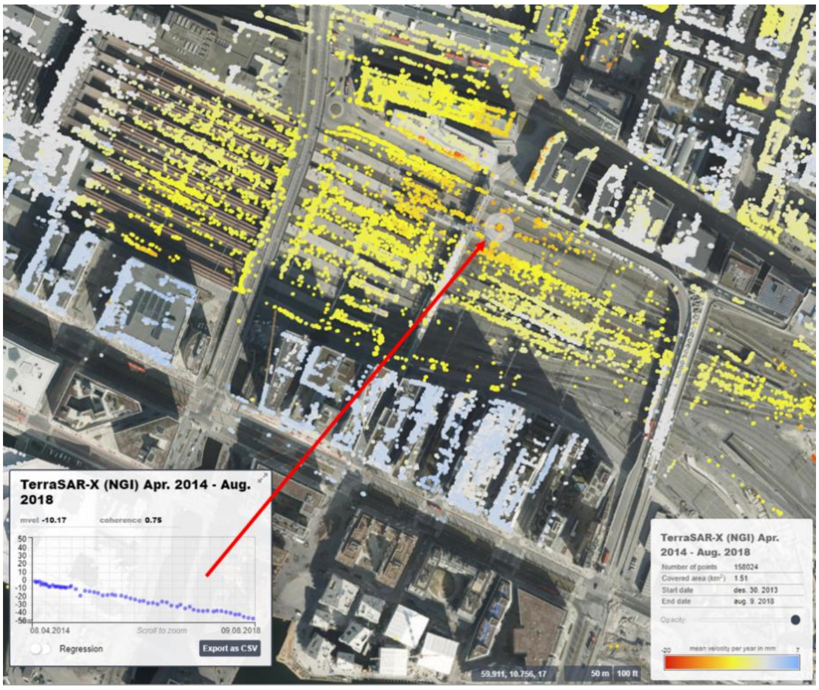

Figure 1: Example of InSAR measurements over the track area of Oslo Central Station. Color-coded measurement points show the mean ground velocity between Apr. 2014 and August 2018. The time-series shows the displacement history for the same period. The data was processed from a TerraSAR-X image stack in staring spotlight mode (resolution <1m) using a Permanent Scatterer algorithm. (see https://insarkart.ngi.no/malte/oslospublic)

Another example is the time-series analyses performed over the Feijão Mine tailings dam in Brazil, with line-of-sight displacements averaged over time, issuing a velocity map for the period May 2015-January 2019 just before the failure on 25 January 2019. In the centre of the dam face, a small part appeared to show an increased downward movement on 17 December 2018. This acceleration could indicate a possible precursor of the upcoming failure. The mean velocity at this smaller part was -9.93 mm/year.

Conclusion

The use of InSAR is on a rapid increase along with elevated access to satellite data and stakeholder awareness of the technology. Industries and communities all over the world are facing challenging conditions for operations and installations as well as rapid environmental change. InSAR has large untapped potential to help cost-effectively map deformation and prioritize stabilization measures and maintenance to mitigate risk at places. Inio is enabling maximum use and benefit of InSAR worldwide.

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