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Potential of InSAR for Structural Health Monitoring of Flood Protection Systems

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ABSTRACT: Extreme weather events that cause flooding endanger people, economic goods, and the environment. Flood protection systems, such as dams, dikes, and levees, defend these valuable assets and therefore their structural health should be monitored. The goal of this project is to investigate the potential of Interferometric Synthetic Aperture Radar (InSAR) satellites for the monitoring of dams and dikes. The ability to monitor flood protection systems depends on the availability of a sufficient number of measurement points. This is influenced by several factors, such as the type of the scanned surface area (e.g. vegetation cover, concrete), the orientation of the dike with respect to the satellite's orbit, the temporal and spatial resolution of the SAR sensor, and the period for which the European Ground Motion Service (EGMS) provides the data. It is also of interest to study the differences between persistent scatterers and distributed scatterers. Furthermore, the correlation between surface subsidence detected by InSAR and the changes in water level, which pinpoint flood events, is also investigated. The use of Corner Reflectors or satellites with higher spatial resolution, are also some of the aspects to be explored in the next steps to investigate how to maximize the potential of InSAR satellites for the monitoring of flood protection systems.

KEYWORDS: InSAR, Structural Health Monitoring, Flood Protection, Dike, Levee, Earth dam

1 INTRODUCTION

1.1 Motivation

The occurrence and intensity of flooding constantly increases due to climate change and more frequent heavy rainfall events. Urban areas, often located near rivers, are threatened in particular by this natural hazard. Therefore, sustainable natural hazard management and structural health monitoring is essential to protect human lives, and their environment. Since the catastrophic floods of 2002 in Austria, a shift towards integrated flood risk management has been observed. In this context, the flood protection measures are complemented by the assessment and monitoring of existing protection structures such as dikes and levees.

Currently the condition of flood protection structures is mostly monitored by means of "close-up inspection" or by conducting geodetic surveys with theodolites along the dams. Only in rare exceptional cases are fully automated total stations with installed prisms or locally referenced Global Navigation Satellite System (GNSS) sensors permanently installed. Initial investigations into the use of drones for surveying dams have also revealed various limitations, turning these methods uneconomical.

The aim of the project "Flood protection monitoring via satellites" (HoSMoS) is to investigate the potential of structural health monitoring by means of satellites for flood protection systems. Based on multitemporal Interferometric Synthetic Aperture Radar (InSAR), long-term deformations on the earth's surface can be monitored under certain conditions [1]. The special feature of this indirect monitoring method is not only the fact that no additional sensors need to be attached to the structure, but depending on the mission, it can also offer the unique possibility to analyze data retrospectively, e.g. Sentinel-1 data goes back to the year 2015. The accuracies currently achieved with InSAR are sufficient for monitoring trends of mass movements or glacier retreat, for example. There are promising results for the use of this technology in the monitoring of bridges, where the accuracy can be increased significantly by compensating for environmental conditions [2].

The innovation of the HoSMoS project consists of investigating the fundamental applicability of the InSAR technology for flood protection. The aim is to investigate whether monitoring by satellites is possible in principle under the special circumstances that typically prevail at such structures. For example, the influence of natural vegetation, construction materials, the presence of roads and paths and the orientation of linear structures on the satellite monitoring are to be investigated. The accuracy achievable with advanced differential InSAR (DInSAR) products provided by the European Ground Motion Services (EGMS) [3] is to be compared with the requirements for monitoring. Seasonal effects and relevant environmental conditions that require compensation are to be identified.

Remote sensing by satellites promises a great potential for the monitoring of flood protection systems. It would enable the simultaneous monitoring of deformations for many different structures in a large territory, with a higher temporal and spatial resolution than is currently possible. Long-term trends may be recognized through the retrospective evaluation of deformations. The definition of warning thresholds would allow the rapid, systematic identification of potentially critical areas and sections that require closer monitoring or inspection.

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1.2 Remote sensing with InSAR

The publication of the first differential interferogram related to an earthquake in the United States in the 1990s marked the beginning of exploiting DInSAR to observe surface deformation [4]. Since then, the technique has undergone significant advances, including the development of more refined approaches such as Persistent Scatterer Interferometry (PSI) [5], [6].

The key idea of DInSAR is to combine the phase of at least two SAR images of the same area of interest (AoI) taken at different times and slightly different geometry in an interferometric manner to form an interferogram. The interferometric phase needs to be corrected for the phase contribution induced by the topography of the illuminated scene to extract information on the ground surface displacement that occurred between image acquisitions [1], [4]

SAR images from the Sentinel-1 satellites commissioned by the European Space Agency (ESA), can be processed with InSAR technology to produce displacement maps. They orbit the Earth at an altitude of 693 km, whereby the points on the Earth's surface are flown over in an approximately synchronous polar orbit in two orbital directions, once from south to north (ascending orbit) and once from north to south (descending orbit). The SAR images are taken in a skewed Line of Sight (LOS) with respect to the Earth's surface, see Figure 1, left. The return time to the same orbit is 12 days [2], [7]. Originally, Sentinel-1A and 1B satellites were used together, which doubled the temporal resolution. Unfortunately, satellite 1B has been out of service since December 2021 due to a solar storm. However, Sentinel-1C has been successfully deployed end of 2024 as a replacement.

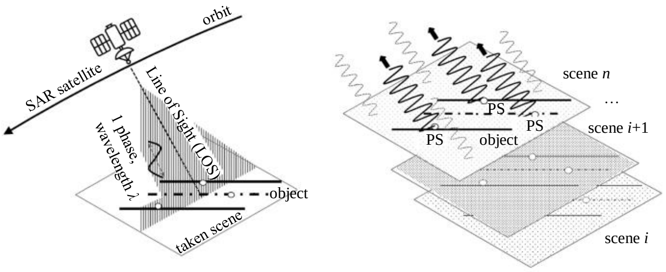

Figure 1. Left figure: The deformation measurement of the Earth‘s surface is recorded in so-called scenes during overflight; the direction of measurement is right-looking in the direction of flight of the satellite (= Line of Sight, LOS); right figure: Coherent reflectors (Persistent Scatterers, PS) of the recorded pixels are used as reference values and differential displacements are observed after approx. *n* recordings and analyzed, source: [8].

The basic idea of advanced DInSAR techniques, such as Persistent Scatterer Interferometry (PSI) is to identify pixels with low noise in a time series of differential interferograms. Relevant information about the observed deformation of the ground surface is then extracted from the backscattered radar signal of only these pixels, also referred to as Persistent Scatterer (PS). The backscattered signal of these pixels is characterized by the response of a single reflector in the corresponding ground resolution cell, which remains stable over time, as illustrated in Figure 1, right. The radar signal reflected from the Earth's surface is detected, and the relative phase change of the PS pixels in between image acquisitions can be determined using interference, with the wavelength of $\lambda = 54$ mm in the case of Sentine-1 operating in C-band, see Figure 1 right. Displacement rates in the range of a fraction of the wavelength λ can be derived based on the comparison of the phase values of corresponding pixels from different consecutive differential interferograms [5], [6], [8]. With Sentinel-1, the images are taken at a time interval Δt of 6 or 12 days [8]. In principle, no additional man-made reflector is required on site; instead, the already present natural and man-made scatterers can be used, which provide a coherent signal for at least approx. 20 to 25 images. Sentinel-1 satellites acquire SAR images of the Earth's surface in a 5x20 m ground resolution cell (Figure 1, left), which slightly limits the spatial resolution. Other satellites, such as TerraSAR-X, can also resolve ground cells down to 1.0 m in High Resolution Spotlight mode. The accuracy of the information obtained from Sentinel-1 data can be further increased by additionally attaching man-made Corner Reflectors (CR) to the Area of Interest (AoI). The CRs also be utilized in landscapes without already established PS for better object assignment [2].

Within the scope of this paper and the HoSMoS project, the focus is on the analysis of ground motion data provided by the EGMS. The EGMS generates fully processed PSI datasets based on Sentinel-1 SAR images for all European Countries supporting the Copernicus Initiative. The datasets are updated yearly using all Sentinel-1 data acquired in the past five years [3], [8].

2 MONITORING OF FLOOD PROTECTION SYSTEMS

2.1 Overview of satellite-based monitoring in flood protection

Before the potential of satellite-based monitoring of flood protection systems is analyzed, a brief overview of previous research on the topic is given. Comprehensive work was conducted within SAFELevee project organized by the Dutch Research Council (NWO) between 2014 and 2019, focusing on better understanding of the behavior patterns and situations that can lead to a failure of the flood protection structures, establishing an International Levee Performance Database [9], [10]. In this context, InSAR was investigated for the purpose of documenting surface deformations of flood protection systems in the Netherlands as a function of hydrodynamic loading and examine these deformations in relation to failure mechanisms [10]. In addition, the application of PSI was evaluated in several case studies in the Netherlands using SAR data from the high-resolution satellite TerraSAR-X, the medium-resolution satellites ERS-1/2 and Envisat, and the surface deformations were documented [11]. The analysis of the case studies showed that it was possible to document surface deformation with sufficient spatial coverage in all cases. The accuracy of the values depends on the orientation of the flood protection system and its slope. Based on the given temporal sampling rate, the authors see the potential for applying PSI for flood protection not in the area of real-time monitoring, but in an early warning system that indicates unusual deformation behavior.

The evaluation of images of Delft from TerraSAR-X in [12] showed that not only the density of the selected Persistent Scatterer (PS) pixels is sufficient to document surface

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deformations, but also that the comparatively narrow temporal sampling rate can be used to observe the expansion and contraction of the flood protection barriers. In addition, it was shown that this short-term deformation pattern correlates with metrological data.

Further studies focused on the flood protection systems along the Mississippi River in the United States. A fully polarimetric L-band SAR mounted on an airplane and the X-band SAR satellite, TerraSAR-X, was investigated in [13] in order to show that weak points can be identified by means of analyzing the backscatter responses of the different polarizations and texture features. The same L-band SAR airborne system was also used in [14] and [15] to examine dike in California for subsidence and seepage in the Sacramento-San Joaquin Delta and the lower Mississippi River. Moreover, the polarimetric SAR (POLSAR) technique was used to detect seepage from multi-polarization images [14].

2.2 Conventional monitoring methods in flood protection

To analyze the potential of satellite monitoring methods, it is essential to create a base line for comparison. With this in mind, the currently available methods of monitoring flood protection systems were collected and are briefly systematically analyzed.

2.2.1 Geodetic surveying

The most commonly used method of monitoring is traditional geodetic surveying. In this process, selected points on the structure are marked and measured at regular intervals (e.g. monthly or yearly) using a theodolite. The accuracy of this method is approximately ± 1 mm [16].

2.2.2 Hydrostatic settlement cells

A very precise option for monitoring settlements is offered by hydrostatic settlement cells [17]. The principle of this device is based on liquid-level that consists of connected tubes filled with liquid causing liquid-level heigh difference or pressure differences (when using electronic liquid-level). The difference between two or more measurement points can be determined even over large distance.

2.2.3 Magnetic settlement tubes

Another solution for monitoring settlement is provided by magnetic settlement tubes, which allow the simultaneous monitoring of numerous vertically distributed measuring points located inside a dam [18], [19]. For this purpose, a tube is installed in the structure, with magnets placed on the bottom and in the wall at the locations, which are to be measured. A probe equipped with a reed switch is pulled up through the pipe in a controlled manner, starting from the bottom, and is activated each time it reaches a magnet, so that its relative height with respect to the bottom can be measured. The measurement accuracy is approximately ± 3-5 mm [20].

2.2.4 Inclinometers

Inclinometers can also provide valuable information about geometric changes in a dam [17]. Inclinometers or tilt sensors measure the angular rotation related to the direction of the gravitational force. In principle, inclinometers can be designed for single-axis or for dual-axis measurements. There is a wide variety of different operating principles for inclinometers. The simplest inclinometers use a solid-state pendulum, the deflection of which can be measured either by inductance or by a potentiometer [21].

2.2.5 Piezometers

Piezometers can be used to determine the water or earth pressure inside an earthfill dam, but they must be placed at the intended location already during construction [16], [22]. Tensiometers can also be used for continuous measurement of soil moisture in dams [23].

2.2.6 Electrical resistivity tomography

Electrical resistivity tomography (ERT) is a geoelectric method for imaging subsurface structures based on measurements of electrical resistivity at the surface or through electrodes in one or more boreholes. Possible applications of ERT on dams include: the localization of cracks, animal burrows, seepage points and leaks, the monitoring of water saturation, and the determination of geometric dimensions and internal properties [24], [25]. The measurements require extensive preparation and are very expensive. However, ERT also allows automated continuous monitoring of entire dam sections [26].

2.2.7 *Fiber optic sensors*

Fiber optic sensors (FOS) make it possible to measure physical quantities of the external world such as temperature, strain, vibration, magnetic field, etc. along the sensor fiber [27]. In the case of earth dams, they can be used primarily to detect seepage points by measuring the resulting temperature differences [28], [29].

2.2.8 Acoustic emissions sensors

Acoustic waves in a test object can be detected by piezoelectric sensors that convert surface displacements (or vibrations) caused by the acoustic emission into electrical signals. This technology can also be used to monitor piping causing seepage failure in dams and dikes [30].

2.2.9 GNSS

A second option for satellite-based monitoring of settlements in addition to InSAR is GNSS (Global Navigational Satellite System). The main difference to the InSAR technology is that a receiving device of the GNSS signal must be positioned on the structure to carry out measurements. In order to achieve greater accuracy, an additional reference station is required, the exact location of which is usually determined by classical surveying methods. The main advantage over InSAR is that not only long-term deformations but also dynamic processes can be observed. The two satellite technologies can also be combined. As an example, global positioning system was employed for monitoring of river embankment in [31].

2.2.10 *Terrestrial laser scanning and Photogrammetry*

Another alternative for capturing the geometry of flood protection structures is Terrestrial Laser Scanning (TLS), also referred to as terrestrial topographic Light Detection and Ranging (LiDAR). A TLS device scans its surrounding by means emitting light pulses in raster-like fashion. The distance between the scanner and the object is recorded and, depending on the scanning mode, one or two angles are recorded between the light and the vertical and horizontal axes. The scanning device can also be mounted on Unmanned Aerial Vehicles

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(UAVs), i.e. aircraft that can operate autonomously or remotely and do not need to carry a human crew. When the UAV is expanded to form a complete system with recording technology, a control unit, a communication method, etc., it is referred to as an unmanned aerial system (UAS). Among UAS, drones are the most common because they can fly in confined spaces and are able to hover and take off and land vertically [32]. Drones can be equipped with various types of sensors, such as cameras [33] or LiDAR [34]. A study on the achievable accuracy for an earth fill dam showed an accuracy of approximately 1-2 cm for TLS and 2-4 cm for drone-based photogrammetry [35].

2.3 Comparison of monitoring methods in flood protection

The satellite monitoring of flood protection is now compared to the conventional methods described above in order to highlight the potential of the latter. In this context, important aspects are not only the spatial (density of measurement points) and the temporal resolution (measuring frequency), but also the accuracy of the measurement as well as required effort in terms of working hours and costs needed for carrying out a measurement and installation of the monitoring system.

Geodetic surveying requires significant effort due to the need of trained personnel to carry out measurements and operate a theodolite in the field. Another consequence of the *modus operandi* of this method is that the spatial and temporal resolution is low. This is noticeable particularly for large structures where scanning the surface's structure with InSAR has significant advantage.

Hose leveling system installation requires more planning and some kind of intervention into the structure as the theodolite surveying method. The very high effort needed to set up the measuring system is compensated with very high measurement accuracy and very high temporal resolution since the measurements can be automatized without the necessity of human supervision. As regards spatial resolution, the installation of this system is limited to a number of measurement cells and length that is bonded to a particular structure.

Electromagnetic settlement tubes require similar effort for setting up the measurement system as the hose leveling, needing a dedicated sensor for one measurement point. The advantage of this measurement system is high level of accuracy. The spatial and temporal resolution are average when compared to other methods.

One receiver device per measurement point is also required when using GNSS. If higher precision measurements are required, an additional reference station has to be in place, making the required effort very high and offering low spatial resolution. On the other hand, displacement monitoring with GNSS provides very high temporal resolution when compared to InSAR measurements.

Laser scanning offers very high spatial resolution stemming from the principle of this method when many measurement points around the TSL device are acquired. However, when aerial vehicles are used to increase scanned area in shorter time the accuracy of this method is compromised. Similar to the geodetic surveying, the measurements have low temporal resolution due to the trained labor that is necessary each time a measurement is taken.

Monitoring inclination is unique in measuring angular changes rather than displacements, which provide a slightly different viewpoint on the health status of the flood protection structure, that is obtained from InSAR data. The inclinometers also provide very high temporal resolution since the device is permanently located at the measurement point. However, the fact that one measurement device is needed for one measurement point limits the spatial resolution and increases the required effort for installation of the measurement system.

Water or soil pressure measurements by means of piezometer sensors share the same levels of temporal and spatial resolution as with the inclinometers. The accuracy of this method is high, although the effort required to employ this method is also high since they have to be installed during construction of the dam. The advantage of using this measurement technique is that it offers information that cannot be directly obtained from any InSAR measurements.

Another technique that provides unique insight into health status of a flood protecting structure in comparison to SAR satellites is electrical resistivity tomography (ERT). However, it is very expensive to carry out ERT measurements, which require elaborate preparation. In comparison to other measurement techniques, ERT provides good accuracy and average spatial resolution, but low temporal resolution.

An excellent spatial and temporal resolution with high accuracy is provided by fiber optic sensors. However, in comparison to SAR satellites the installation of the fiber requires rather high amount of effort.

Similarly demanding on effort is acoustic emission method. This measurement technique also allows for high temporal resolution, but rather low spatial resolution and an average accuracy in comparison to the InSAR measurements.

The comparison of InSAR and other monitoring methods for flood protection systems in terms of effort for the operator of the infrastructure, accuracy, spatial and temporal resolution is summarized in Table 1.

3 RESULTS

Satellite based monitoring is particularly suitable for types of failure that develop over a longer time period and affect medium or large areas, such as subsidence, tilting or sliding. The accuracies and repeat-pass periods achievable through InSAR measurements are sufficient for monitoring these types of failure and the low cost compared to other monitoring methods makes this method particularly attractive. However, the question that arises based on the basic evaluation is whether and under what conditions a sufficient number of natural reflection points are available on dikes and other flood protection structures to carry out meaningful satellite monitoring.

In the present project analyses are carried out to answer this question, mostly based on selected representative AoIs, but in some cases also considering all flood protection systems in Lower Austria region along Danube River. Occasionally comparable systems abroad, where more suitable data is already available, are analyzed. The various investigations are explained individually and thematically separated below, and the results of each are briefly presented.

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Table 1. Comparison of monitoring methods for flood protection systems in terms of measured property, effort, accuracy, measurement point density, and frequency

Method	**Measured property**	**Effort required**	**Accuracy**	**Spatial resolution**	**Temporal resolution**
InSAR	Displacement	Low	High	Medium-low	Medium
Geodetic surveying	Displacement	High	Very high (±1 mm)	Low	Low
Hose levelling	Displacement	Very high	Very high (±1 mm)	Low	Very high
Electromagnetic settlement tubes	Displacement	Very high	High (±3-5 mm)	Medium	Medium
GNSS	Displacement	Very high	High	Low	Very high
TLS / LiDAR	Displacement	High	Medium-high	Very high	Low
Inclinometers	Inclination	High	High	Low	Very high
Piezometers	Pressure	High	High	Low	Very high
ERT	Damaged area	High	Medium	Medium	Low
Fiber optic sensors	Temperature	High	High	Very high	Very high
Acoustic Emission	Flow	High	Medium	Low	Very high

3.1 Point density depending on surface type and orientation

The flood protection structures in the Lower Austria region were divided into eight surface type categories based on characteristic locations, or structures in which they are integrated or surrounded. The typical surface types are the following:

- highways and roads,
- buildings (e.g. a house on a dam),
- green areas with asphalt paths,
- green areas with gravel paths,
- green areas without gravel,
- residential areas,
- foreign objects (e.g. electrical poles),
- miscellaneous (everything that does not fit above).

It is noteworthy that majority of the investigated dikes are situated in green areas, amounting to 60 %. The second and third most common surface type groups are highways with roads, and residential areas representing 22 % and 10 % of all analyzed dikes, see Figure 2.

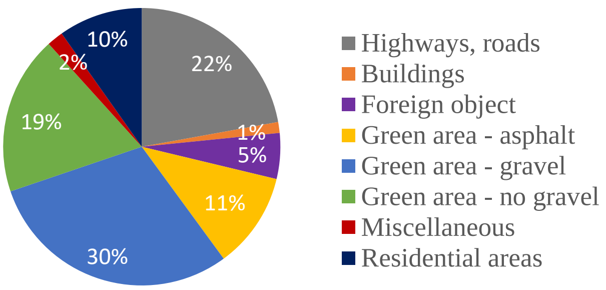

Figure 2. Distribution of surface types on or in the immediate vicinity of the investigated flood protection structures.

Orientation is a characteristic aspect of a flood protection structure since its length is usually significantly longer than the other two dimensions. The orientations of the 155 km of investigated dikes in Lower Austria along the Danube River were analyzed with respect to the cardinal directions. The results show that the dikes are predominantly aligned with the Danube River as evidenced by 43 % of the total dike length being oriented in the east-west direction, which matches the river's course in this region. In contrast, the shortest dike orientation of is north-south, accounting for only 18 km or 12 % of the total analyzed length, see Figure 3.

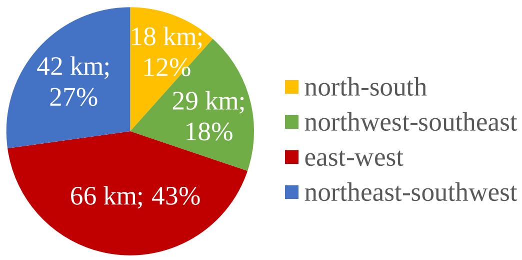

Figure 3. Orientation distribution of the 155 km-long flood protection structures in the investigated area with respect to cardinal directions.

Since the LOS direction of the SAR satellite is related to the cardinal direction, the number of available points also depends on the orientation of the observed object, such as dike. Based on the analysis of the investigated dikes, most of the PS points are obtained for dikes that are oriented in north-south direction for all surface types except highways and roads, as can be seen in Figure 4. Therefore, the number of points in the other directions are shown in relation to this most favorable orientation. Exceptionally high numbers of points are also obtained for all cardinal directions in highways and roads and residential areas. An important finding is that in case of all types of green areas the number of reflection points drops significantly for unfavorable orientations. Particular low number of points is obtained for east-west and northwest-southeast directions, see Figure 4.
The results of the analysis regarding reflection point density with respect to the surface type are unfavorable for the investigated flood protection structures. The green areas, where the most dike sections belong to, have the smallest point density per 100 m. On the other hand, the surface types with the highest density are buildings, residential areas, and highway and roads as can be seen in Figure 5.

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The number of available reflection points depend also on the date release of the postprocessed InSAR database. The EGMS database, used in this study, contains three different releases varying in the different time periods (epochs), 2015-2021, 2018-2022, and 2019-2023. Except for the newest data release in “highways and roads” surface type, the number of available measurements points slightly increases with later release time, see Figure 5. This is probably caused by better and more efficient data processing algorithms.

3.2 Comparison of persistent and distributed scatterers

Having a high number of reliable reflection points on the object or in the AoI is crucial for drawing reliable conclusions on the state of the flood protection structure. The potentially higher density of reflection points provided by additional distributed scatterers (DS) was examined, in order to investigate if their inclusion could remedy the situation regarding scarcity of reflection points in green areas and unfavorable orientation of the investigated objects when using PS.

In contrast to PS pixels, DS pixels do not stand out due to a high coherence over a long period. They rather often exhibit a moderate coherence but show a statistically similar behavior as their neighboring pixels, since they often belong to the same object. This statistical similarity can be exploited to improve the signal-to-noise ratio of DS pixels by spatially averaging them. Thus, allowing a joint processing of DS and PS pixels. While PS pixels are often associated with point-wise bright scatters, such as dihedral or trihedral reflectors on buildings or naturally occurring boulders, DS pixels are often found in desert-like areas, areas covered by debris, and on non-cultivated land with short vegetation. [5], [36].

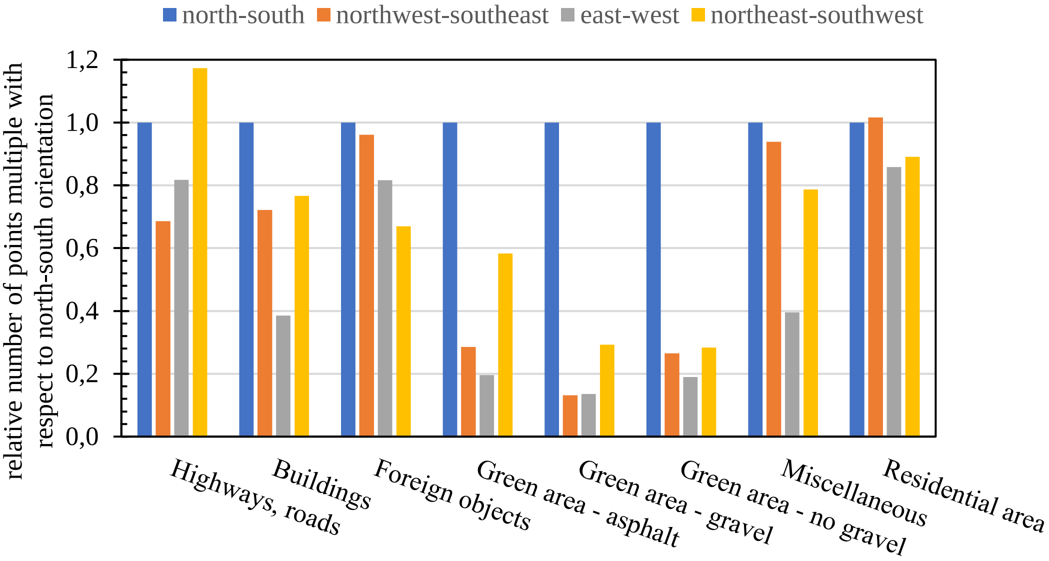

Figure 4. Relative number of points for different surface types with respect to the north-south orientation.

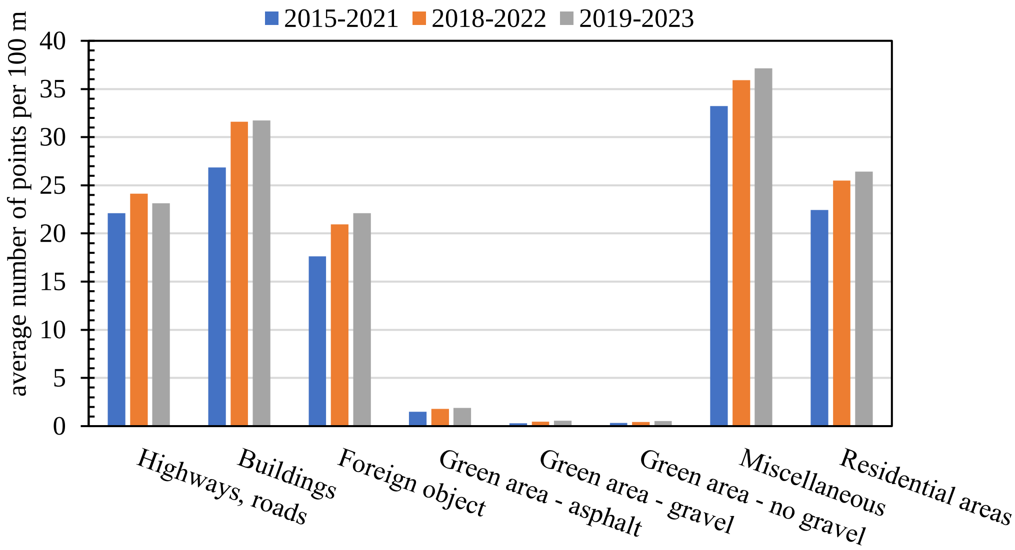

Figure 5. Comparison of the point density for different EGMS database releases and surface types on or in the immediate vicinity of the investigated flood protection structures.

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The EGMS data are processed by four consortia using slightly different algorithms. While only the PS points are evaluated in Austria, the DS are also processed in Spain and France, among other countries. Since these are particularly suitable for non-urban areas, it was verified within the project whether a significantly higher number of data points along the dikes can be expected with a joint PS and DS processing.
For this purpose, a dike section in France, approximately 30 km long, was selected and examined. This is located on the La Loire River between Orleans and Jargeau. Analogous to the investigations on the Danube River, all points within 20 m of the dam crest, as illustrated in Figure 6, were considered and statistically evaluated. It was found that the DS points account for only 4.5% of all available points. The added value of such data processing is therefore not very high. A small part of this section with a particularly high density of PS and DS points was discovered and examined more closely. This section is almost free of vegetation, the surroundings are flat and treeless. The embankment section consists of coarse gravel and has a slope of approx. 20° to 30° and is seen from both orbit directions, the orientation is NW-SE. These findings are well in line with the observations obtained in the Vienna and lower Austria area.

3.3 Correlation of water level with InSAR measurement

As an example of the potential of using InSAR for flood protection structures in Vienna region was showcased for a lock in Greifenstein during high water periods. The object of interest was the end part of a pier of a lock. Here, three reflection points obtained from EGMS data for a period between the beginning of 2018 and the end of 2022 were analyzed and compared with water level measurement stations in Bärnsdorf and Nussdorf. The data from water level measurement stations shows periodical increases of water level in the Danube River depending on the seasons. In the available time period four prominent peaks marking extraordinary high-water level are visible on 30.05.2019, 04.02.2020, 05.08.2020, and on 19.07.2021. Analysis of the InSAR data revealed a settlement of approximately 8 mm (shown in red) at one reflection point and 12 mm (shown in light and dark green) at the other two points, at the beginning of 2020, see Figure 7 for a visual representation of the mean values and standard deviations. When compared to the water level during this period (shown in blue), it seems plausible that this change was related to the high-water level event on February 4th, 2020.
However, this showcase analyzed a rather local effect. Interesting results may be obtained after the analysis of the floodings in September 2024 in central Europe, once the EGMS data for this period becomes available.

4 DISCUSSION – FUTURE OUTLOOK

Corner reflectors provide a possibility to introduce a stable measurement point in areas or on structures that are absent of any reflective elements for L, S, C, or X-band waves. The corner reflectors can be also used as a reference to the other natural reflectors, to which they can be related to. The disadvantage of the corner reflectors is that they require additional effort for installation. On the other hand, the installation is easy, there is no need for maintenance, and the service life is long. The benefit of a corner reflector is that it provides a stable reflection point.
The use of low-cost corner reflectors suited for dikes has been investigated and will also be a focus of future research. To this date, two couples of concrete corners with edge length of 40 cm were installed on a dike along the Danube River. Each couple was oriented in opposite directions so that the corner reflectors face directly to the LOS of the Sentinel-1 satellite descending and ascending flight trajectory, see Figure 8. Thin aluminum plates were glued onto the inner surfaces of one couple of the concrete corner reflectors as shown in Figure 8 a). The other couple of concrete corner reflectors was left untreated, see Figure 8 b). The two couples of low-cost concrete corner reflectors do not reflect enough signal back to the InSAR Sentinel-1A satellite and there would likely be no PS points corresponding to these four corner reflectors in the Sentinel-1 dataset. The reason for this may be small reflective surface or slightly obtuse angle between two neighboring inner surfaces.
In addition to the experimental concrete corner reflectors, a standard double-headed corner reflector, shown in Figure 8 c), was installed near a dike next to the Danube River as a reference. The standardized corner reflector works as expected and a new measurement point is recorded by Sentinel-1A and is likely to appear in the EGMS dataset. This will be used as a reference measurement point in the future research.
As already mentioned, the choice of the SAR sensor also influences the monitoring results that can be achieved on the AoI. In addition to the theoretical maximum value of displacement rate, factors such as spatial resolution also play an important role. There are currently at least six SAR satellite missions (e.g. Sentinel-1, RADARSAT, PALSAR-2, TerraSAR-X, COSMO-SkyMed, SAOCOM) that generate SAR images capable of interferometry and at least two other missions (e.g. NASA-ISRO, ROSE-L) that are currently being implemented. The missions differ greatly in the wavelength used, the achievable spatial resolutions, the temporal sampling rate, as well as the general availability and the underlying data policy. In addition, commercial micro-satellite providers (e.g. ICEYE and Capella Space) are also striving for InSAR capability. Hence, it can be assumed that, as already shown in some studies [11], based on multi-resolution, multi-temporal and multi-frequency approaches the combination of InSAR measurements from different SAR constellations will significantly increase the added value of this measurement method.
Next research step is an analysis of the areas in lower Austria and in Vienna region flooded in September 2024. In comparison to correlation of the water level with the settlement of the pier, this research will exploit the full potential of InSAR that is particularly suitable for examining of middle to large areas.

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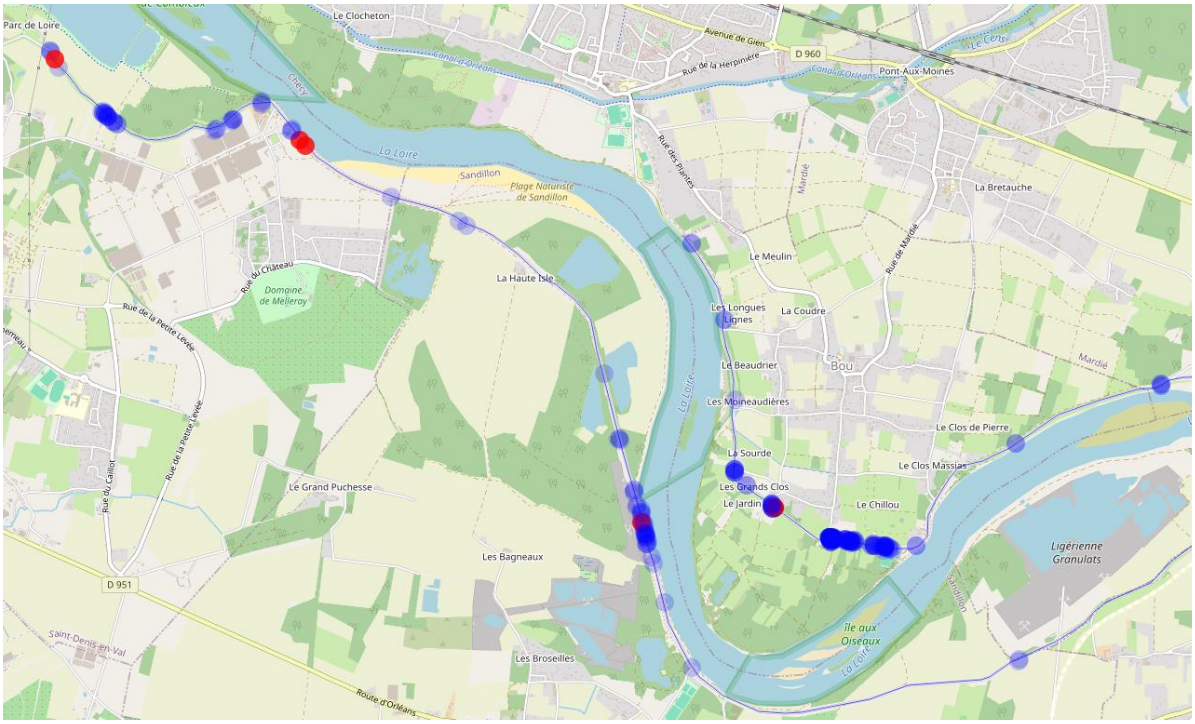

Figure 6. Overview of PS (blue) and DS (red) points along the embankment of the La Loire, France (thin blue solid line).

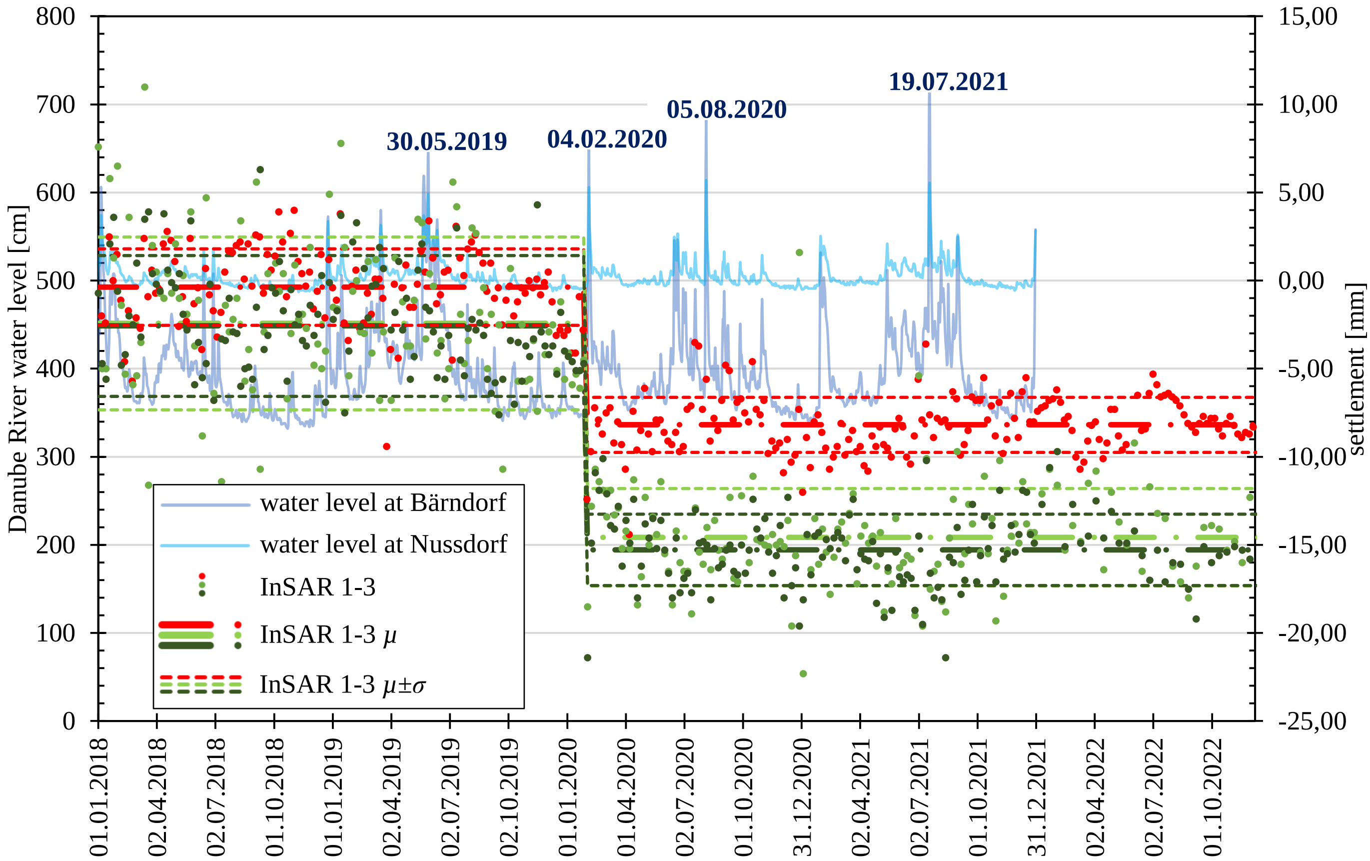

Figure 7. Settlement records from the EGMS database for three points (marked by red, light and dark green points, referring to the right vertical axis) at the endpoint of a river lock pier in Greifenstein, compared with water levels in the Danube River, as measured at stations in Bärnsdorf and Nussdorf (light and dark blue solid curves, referring to the left vertical axis), plotted as a function of time. The settlement mean trend lines, μ, are indicated by bold dash-dotted lines and their standard deviations, σ, are plotted by thin dashed lines. The dates in blue font near the water level peaks mark high-water events.

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a) b) c)

Figure 8. Corner reflectors installed on the dike at the Danube River: a) cement corner reflectors with aluminum sheets, b) plain cement experimental corner reflectors, and c) standard double-headed corner reflector.

5 CONCLUSION

The present paper provides a brief overview of the potentials of InSAR monitoring of flood protection structures comparing it to conventional monitoring methods. In this context, the EGMS data provide high accuracy of displacement measurements with low required effort. However, the temporal and spatial resolution is limited.

The temporal resolution is dependent on the number of satellites and their repeat-pass periods. Since the return time of the Sentinel-1A to the same orbit is 12 days, the resulting EGMS data is suitable for monitoring slowly occurring changes. With the successful launch of Sentinel-1C in December 2024, the temporal resolution will double in the future. The spatial resolution can be increased by using commercial SAR satellites, which, however, increases required costs effort.

The spatial resolution of the Sentinel-1 satellites, with respect to the measurement point availability, was extensively investigated in this study. The EGMS database was used to examine several aspects of the measurement point availability in selected AoIs. First investigated aspect was number of obtained reflection points based on surface type and orientation. Green areas with gravel, asphalt, and no-gravel which constitute 60% of dike length in the investigated area (Figure 2), have the lowest point density out of all considered surface types (Figure 5). The number of available points is also dependent on orientation of the observed object. In this context, the most points in investigated AoIs are obtained for objects oriented in north-south (Figure 4). Unfortunately, 43 % of dikes in the investigated area along the Danube River are oriented to east-west direction (Figure 3).

The number of available reflection points also depends on the database release. EGMS provide access to three databases of InSAR measurement points, 2015-2021, 2018-2022, and 2019-2023. With the exception of highways and roads the newer the database, the more available points there are for each surface type category (Figure 5).

Since most of the dikes are located in green areas and the distributed scatterers are known to be more suitable for natural landscape, the potential use of DS was examined. To this end, the PS and DS were extracted from EGMS database for approximately 30 km dike section. This analysis showed that only 4.5 % of all available points are DS (Figure 6), rendering usability of the DS points rather low.

The settlement at a pier of a ship lock could be linked with high probability the flood of the Danube River. This case study showcased the potential of InSAR utilizing Sentinel-1 satellites for monitoring the condition of flood protection structures along the Danube River in the aftermath of flood events.

InSAR is an excellent method to monitor surface displacements of large areas in all-weather conditions, providing useful insights on the structural health of infrastructure assets. This study shows the potential of this method for monitoring dikes along Danube River, but also highlights the limitations, stemming from the low number of available reflection points. Therefore, future research will focus on increasing the number of available reflection points, by employing low-cost, highly-available corner reflectors, and investigating the availability of InSAR data from other existing or upcoming InSAR satellite missions.

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REFERENCES

[1] R. Bamler und P. Hartl, „Synthetic aperture radar interferometry“, *Inverse Problems*, vol. 14, no. 4, pp. R1, 1998, doi: https://doi.org/10.1088/0266-5611/14/4/001.

[2] A. Vorwagner, M. Kwapisz, P. Leopold, M. Ralbovsky, K. H. Gutjahr, und T. Moser, „Verformungsmonitoring von Brücken mittels berührungsloser Satellitenradarmessungen“, *Beton- und Stahlbetonbau*, vol. 119, no. 9, pp. 636–647, 2024, doi: https://doi.org/10.1002/best.202400017.

[3] M. Costantini *u. a.*, „EGMS: Europe-Wide Ground Motion Monitoring based on Full Resolution Insar Processing of All Sentinel-1 Acquisitions“, in *IGARSS 2022 - 2022 IEEE International Geoscience and Remote Sensing Symposium*, 2022, pp. 5093–5096. doi: https://doi.org/10.1109/IGARSS46834.2022.9884966.

[4] D. Massonnet *u. a.*, „The displacement field of the Landers earthquake mapped by radar interferometry“, *Nature*, vol. 364, no. 6433, pp. 138–142, 1993, doi: https://doi.org/10.1038/364138a0.

[5] A. Ferretti, C. M. Prati, und F. Rocca, „Permanent scatterers in SAR interferometry“, *IEEE Transactions on Geoscience and Remote Sensing*, vol. 39, no. 1, pp. 8–20, 2002, doi: https://doi.org/10.1109/36.898661.

[6] A. Hooper, H. Zebker, P. Segall, und B. Kampes, „A new method for measuring deformation on volcanoes and other natural terrains using

InSAR persistent scatterers“, *Geophysical Research Letters*, vol. 31, no. 23, 2004, doi: https://doi.org/10.1029/2004GL021737.

[7] P. Potin *u. a.*, „Copernicus Sentinel-1 Constellation Mission Operations Status“, in *IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium*, IEEE, 2019, pp. 5385–5388. doi: https://doi.org/10.1109/IGARSS.2019.8898949.

[8] A. Hooper, P. Segall, und H. Zebker, „Persistent scatterer interferometric synthetic aperture radar for crustal deformation analysis, with application to Volcán Alcedo, Galápagos“, *Journal of Geophysical Research: Solid Earth*, vol. 112, no. B7, 2007, doi: https://doi.org/10.1029/2006JB004763.

[9] „SAFELevee project“, TU Delft. Accessed: March 25, 2025. [Online]. Available: https://www.tudelft.nl/citg/over-faculteit/afdelingen/hydraulic-engineering/sections/hydraulic-structures-and-flood-risk/research/safelevee-project

[10] I. E. Özer, M. van Damme, T. Schweckendiek, und S. N. Jonkman, „On the importance of analyzing flood defense failures“, *E3S Web Conf.*, vol. 7, pp. 03013, 2016, doi: https://doi.org/10.1051/e3sconf/20160703013.

[11] I. E. Özer, F. J. van Leijen, S. N. Jonkman, und R. F. Hanssen, „Applicability of satellite radar imaging to monitor the conditions of levees“, *Journal of Flood Risk Management*, vol. 12, no. S2, pp. e12509, 2019, doi: https://doi.org/10.1111/jfr3.12509.

[12] I. E. Özer, S. J. H. Rikkert, F. J. van Leijen, S. N. Jonkman, und R. F. Hanssen, „Sub-seasonal Levee Deformation Observed Using Satellite Radar Interferometry to Enhance Flood Protection“, *Sci Rep*, vol. 9, no. 1, pp. 2646, 2019, doi: https://doi.org/10.1038/s41598-019-39474-x.

[13] J. V. Aanstoos *u. a.*, „Earthen levee monitoring with Synthetic Aperture Radar“, in *2011 IEEE Applied Imagery Pattern Recognition Workshop (AIPR)*, 2011, pp. 1–6. doi: https://doi.org/10.1109/AIPR.2011.6176370.

[14] C. E. Jones, G. Bawden, S. Deverel, J. Dudas, S. Hensley, und S.-H. Yun, „Study of movement and seepage along levees using DINSAR and the airborne UAVSAR instrument“, in *SAR Image Analysis, Modeling, and Techniques XII*, SPIE, 2012, pp. 76–83. doi: https://doi.org/10.1117/12.976885.

[15] K. An, C. Jones, D. Bekaert, und V. Bennett, „Radar interferometry offers new monitoring approach for critical flood control infrastructure“, Accessed: March 25, 2025. [Online]. Available: https://www.authorea.com/users/543806/articles/601411-radar-interferometry-offers-new-monitoring-approach-for-critical-flood-control-infrastructure

[16] J. Luo, Q. Zhang, L. Li, und W. Xiang, „Monitoring and characterizing the deformation of an earth dam in Guangxi Province, China“, *Engineering Geology*, vol. 248, pp. 50–60, 2019, doi: https://doi.org/10.1016/j.enggeo.2018.11.007.

[17] R. Sukkarak, P. Jongpradist, und P. Pramthawee, „A modified valley shape factor for the estimation of rockfill dam settlement“, *Computers and Geotechnics*, vol. 108, pp. 244–256, 2019, doi: https://doi.org/10.1016/j.compgeo.2019.01.001.

[18] B. Beiranvand, T. Rajaee, und M. Komasi, „Spatiotemporal clustering of dam settlement monitoring using instrumentation data (case study: Eyvashan Earth Dam)“, *Results in Engineering*, vol. 22, pp. 102014, 2024, doi: https://doi.org/10.1016/j.rineng.2024.102014.

[19] Y. Li, K. Min, Y. Zhang, und L. Wen, „Prediction of the failure point settlement in rockfill dams based on spatial-temporal data and multiple-monitoring-point models“, *Engineering Structures*, vol. 243, pp. 112658, 2021, doi: https://doi.org/10.1016/j.engstruct.2021.112658.

[20] rst instruments, „Magnetic Settlement Systems“. 2025. Accessed: March 26, 2025. [Online]. Available: https://rstinstruments.com/wp-content/uploads/Magnetic-Settlement-Systems-SSB0001-2.pdf

[21] Q. Han und C. Chen, „Research on Tilt Sensor Technology“, in *2008 IEEE International Symposium on Knowledge Acquisition and Modeling Workshop*, 2008, pp. 786–789. doi: https://doi.org/10.1109/KAMW.2008.4810608.

[22] I. Balan, D. Topa, C. Flaviana, I. Balan, und C. Loredana, „Numerical analysis of pore water pressure changes of an earth dam and monitoring of vertical deformations Case study – Plopi Dam IASI County“, 2023. [Online]. Available: https://repository.iuls.ro/xmlui/handle/20.500.12811/4026

[23] Z. Illés und Ö. Antal, „Installation of a flood protection embankment’s monitoring system“, gehalten auf der 11th International Symposium on Field Monitoring in Geomechanics, London, 2022, pp. 1–9.

[24] C. Comina, F. Vagnon, A. Arato, F. Fantini, und M. Naldi, „A new electric streamer for the characterization of river embankments“, *Engineering Geology*, vol. 276, pp. 105770, 2020, doi: https://doi.org/10.1016/j.enggeo.2020.105770.

[25] R. Norooz, A. Nivorlis, P.-I. Olsson, T. Günther, C. Bernstone, und T. Dahlin, „Monitoring of Älvkarleby test embankment dam using 3D electrical resistivity tomography for detection of internal defects“, *Journal of Civil Structural Health Monitoring*, vol. 14, no. 5, pp. 1275–1294, 2024, doi: https://doi.org/10.1007/s13349-024-00785-x.

[26] G. Jones, P. Sentenac, und M. Zielinski, „Desiccation cracking detection using 2-D and 3-D Electrical Resistivity Tomography: Validation on a flood embankment“, *Journal of Applied Geophysics*, vol. 106, pp. 196–211, 2014, doi: https://doi.org/10.1016/j.jappgeo.2014.04.018.

[27] J. Li und M. Zhang, „Physics and applications of Raman distributed optical fiber sensing“, *Light: Science & Applications*, vol. 11, no. 1, 2022, doi: https://doi.org/10.1038/s41377-022-00811-x.

[28] H. Su, S. Tian, Y. Kang, W. Xie, und J. Chen, „Monitoring water seepage velocity in dikes using distributed optical fiber temperature sensors“, *Automation in Construction*, vol. 76, pp. 71–84, 2017, doi: https://doi.org/10.1016/j.autcon.2017.01.013.

[29] H. Li und M. Yang, „Application Study of Distributed Optical Fiber Seepage Monitoring Technology on Embankment Engineering“, *Applied Sciences*, vol. 14, no. 13, pp. 5362, 2024, doi: https://doi.org/10.3390/app14135362.

[30] P. Ming, J. Lu, X. Cai, M. Liu, und X. Chen, „Experimental Study on Monitoring of Dike Piping Process Based on Acoustic Emission Technology“, *Journal of Nondestructive Evaluation*, vol. 40, no. 1, pp. 23, 2021, doi: https://doi.org/10.1007/s10921-021-00752-2.

[31] Q. Zhao, K. Li, P. Cao, Y. Liu, Y. Pang, und J. Liu, „A Study on the Influence of Double Tunnel Excavations on the Settlement Deformation of Flood Control Dikes“, *Sustainability*, vol. 15, no. 16, pp. 12461, 2023, doi: https://doi.org/10.3390/su151612461.

[32] A. A. Ab Rahman *u. a.*, „Applications of Drones in Emerging Economies: A case study of Malaysia“, in *2019 6th International Conference on Space Science and Communication (IconSpace)*, 2019, pp. 35–40. doi: https://doi.org/10.1109/IconSpace.2019.8905962.

[33] G. Morgenthal, V. Rodehorst, N. Hallermann, P. Debus, und C. Benz, *Bauwerksprüfung gemäß DIN 1076 – Unterstützung durch (halb-) automatisierte Bildauswertung durch UAV (Unmanned Aerial Vehicles – Unbemannte Fluggeräte)*. in Berichte der Bundesanstalt für Straßenwesen, no. B 171. 2021. Accessed: March 25, 2025. [Online]. Available: https://bast.opus.hbz-nrw.de/frontdoor/index/index/docId/2551

[34] D. Roca, J. Armesto, S. Lagüela, und L. Díaz-Vilariño, „Lidar-equipped UAV for building information modelling“, in *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Copernicus GmbH, 2014, pp. 523–527. doi: https://doi.org/10.5194/isprsarchives-XL-5-523-2014.

[35] D. Bolkas, M. O’Banion, J. Laughlin, und J. Prickett, „Monitoring of a rockfill embankment dam using TLS and sUAS point clouds“, *Journal of Applied Geodesy*, 2024, doi: https://doi.org/10.1515/jag-2023-0038.

[36] A. Ferretti, A. Fumagalli, F. Novali, C. Prati, F. Rocca, und A. Rucci, „A New Algorithm for Processing Interferometric Data-Stacks: SqueeSAR“, *IEEE Transactions on Geoscience and Remote Sensing*, vol. 49, no. 9, pp. 3460–3470, 2011, doi: https://doi.org/10.1109/TGRS.2011.2124465.