The paper was published in the proceedings of the 11th International Symposium on Field Monitoring in Geomechanics and was edited by Dr. Andrew M. Ridley. The symposium was held in London, United Kingdom, 4-7 September 2022.

Condition assessment of levees and embankments via satellite radar interferometry

Skevi PERDIKOU[1], Dimitris KOUHARTSIOUK[1]

[1]Geofem Ltd., Nicosia, Cyprus
Corresponding author: Skevi Perdikou (skevi.perdikou@geofem.com)

Abstract

Levees are critical systems providing protection to human life and properties against flooding which can cause severe effects on the economy, the environment and society. Climate change with extreme weather conditions and sea level rise, rapid economic and demographic growth and land subsidence increase the impact of levee failure. In Europe, millions are at risk of flooding, with the associated economic impact reaching over 2 trillion Euro. Monitoring the condition of levees is vital for ensuring they remain fit for purpose. Conventional methods for levee monitoring comprise mainly visual inspection, which is time consuming, subjective, and expensive. Surveys showed that in some cases, the failure of levees occurred at sections which were considered as safe by conventional levee assessments. This paper presents the application of multitemporal satellite radar analyses for monitoring the displacement of levees and assessing their soil moisture condition. Sentinel-1 C-band satellite radar data have been used for a case study along the levee network of The Netherlands. Monitoring of the displacement and soil moisture changes in levees - two of the most important parameters for assessing their condition - can be used as a decision-making tool for efficient levee asset management, allowing more timely and cost-effective maintenance interventions.

Keywords: Flood Defense, Satellite Radar, D-InSAR, Soil Moisture

1. Introduction

Areas around the globe are exposed to a risk of flooding, more so in the face of extreme weather events and climate change. The failure of flood protection systems, such as water barriers and levees, results in major economic, social, and environmental losses and even loss of lives, with the integrity of these systems being critical for millions of people globally. For this purpose, flood defense infrastructure, and in particular aging structures, require monitoring in an efficient and cost-effective way. Knowing if, where, and when a failure will occur is a crucial issue to consider when it comes to safety. In this study, we demonstrate the use of satellite radar for addressing the challenge of monitoring the deformation rate of sections of the Dutch levee network as well as for obtaining the soil moisture condition of the ground surface which could help in the assessment of the condition of levees.

2. Study Area

Netherlands has over 3500 km primary flood defences and about 5 times as large and as long regional flood defence systems (EUCOLD Working Group on Levees and Flood Defences, 2018). The study area (2000km^2) is located in the Provinces of Zeeland and South Holland (Zuid-Holland) in the south-west of Netherlands (Figure 1), covering part of the cities of Rotterdam and Delft including the river delta of the two major rivers Rhine and Meuse. The area is located in a temperate oceanic climate region (Cfb Köppen-Geiger Climate Classification) and receives sufficient solar heat and persistent rainfall throughout the year (Beck et al., 2018). The annual mean temperature ranges between 5◦C and 20◦C. The annual mean precipitation is approximately 1000 mm, most of which occurs between August and December (Attema & Lenderink, 2014). According to the spatial pattern of precipitation in 30 years of climatology, the area is experiencing amongst the highest rainfall in the country. The aspect of rainfall is particularly important as it affects water and pore pressure exerted on the levee structures, which we are considering in this analysis with the examination of radar response to changes in soil moisture.

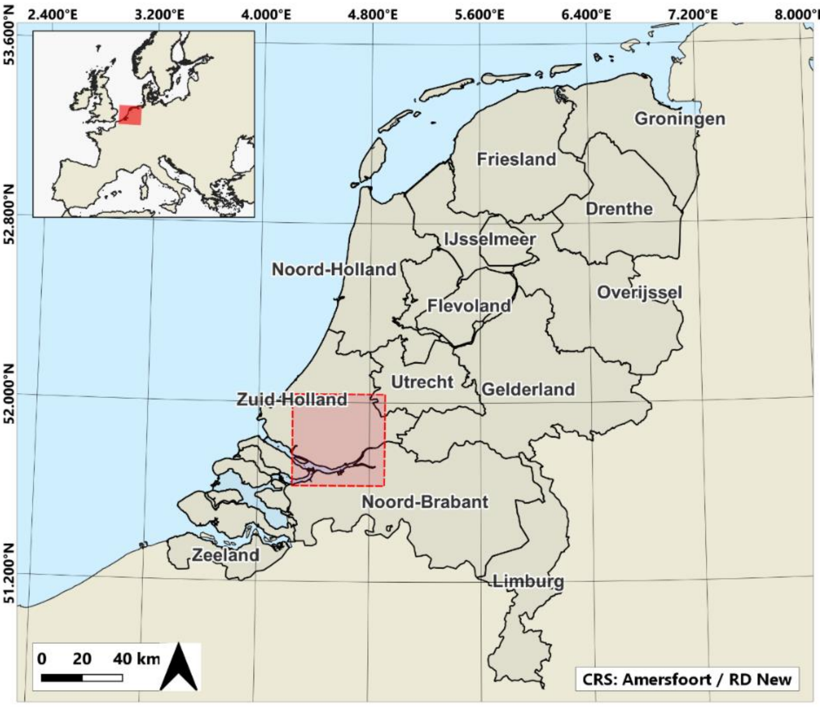

Figure 1: Study area (shown in red).

3. Basics of satellite radar & SAR

Space-borne / satellite radar systems emit electromagnetic radiation in the form of radar microwaves towards the earth surface and receive the returning radar backscatter with the help of antennas. There are different types of satellite radar systems with the main systems being altimeters, scatterometers and Synthetic Aperture Radar or *SAR* systems. The term "aperture" describes the antenna on-board a SAR system that is used to transmit and receive radar waves. To achieve adequate spatial resolution, a large antenna is required which would not be practical to carry on a satellite. Instead, a sequence of acquisitions from a shorter antenna is used as the satellite moves, simulating the acquisition of a larger antenna, thus the term "Synthetic". SAR systems have gained increasing popularity over the last decade with applications in the construction, infrastructure monitoring, mining and oil and gas sectors.

3.1 Measurement of displacement

In a two-way arrangement of transmission and reflection, the phase (ϕ) component of a radar wave represents the distance (range) from the radar antenna to an object or target (Figure 2). The application or process of measuring the phase difference or phase shift of radar waves over time between different satellite passes is known as Differential SAR Interferometry or *D-InSAR*. In the case of satellite *D-InSAR*, the measured phase difference is analogous to various components as described by the equation:

$$\Delta\varphi = \Delta\varphi_{flat} + \Delta\varphi_{elevation} + \Delta\varphi_{displacement} + \Delta\varphi_{atmosphere} + \Delta\varphi_{noise}$$

To determine the interferometric phase difference that corresponds to ground motion/displacement, therefore, requires the isolation of each phase component and its subsequent removal from the difference. An important component of this procedure requires the use of a digital elevation model (*DEM*) for the removal of the topographic / elevation effect and phase component corresponding to flat earth in a process known as "flattening". The application of *D-InSAR* between successive observations (images acquired at different times) is known as multi-pass or multi-temporal interferometry or *MTI* which enables the retrospective measurement of the temporal profile of displacement over longer time scales.

Further processing for removal of residual topographic phase errors, atmospheric phase effects and phase noise (temporal or geometric decorrelation) enables the determination of the displacement along the satellite's Line-of-Sight (*LOS*). As a final step in the interferometric extraction process, the conversion of phase difference to displacement is fractionally analogous to the radar frequency / wavelength and yields the so-called interferogram, a two-dimensional representation of the phase difference. In recent years, there has been an increase in the use of this technique for monitoring civil engineering and infrastructure assets either on its own or as a supplementary to conventional methods (Biondi et al. 2020; Macchiarulo et al. 2021).

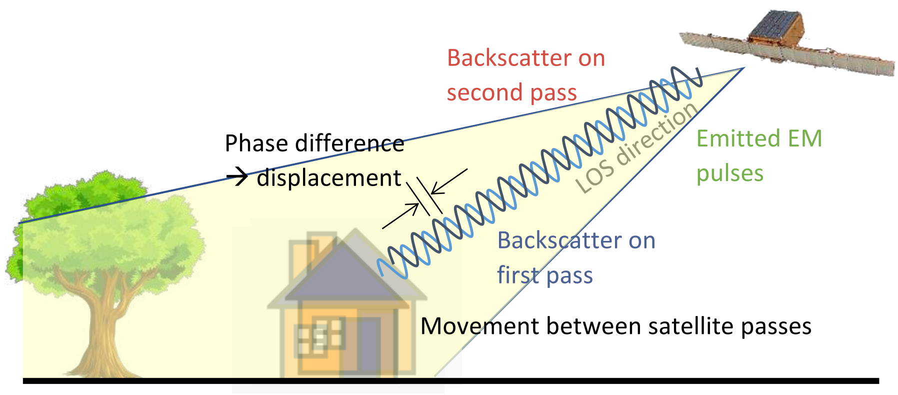

Figure 2: Representation of SAR operation as part of D-InSAR for the measurement of surface deformation.

3.2 Measurement of surface moisture

Soil moisture is an important factor of levee stability as it affects the stability of a slope and determines the swelling potential of expansive clays, often the case of underlying geology of levee networks. However, the measurement of soil moisture over large areas is limited by cost, involving in-situ data collection and installation of sensors. SAR can aid in this via the analysis of the amplitude of radar waves for the measurement of surficial soil moisture. The amplitude component of a reflected / scattered radar wave represents the intensity of the signal and can reveal information regarding the geometric characteristics of a target or object and its dielectric characteristics. In the case of the ground surface, changes in the dielectric properties including the presence of water molecules can be measured using radar, including soil moisture. The analysis of the radar amplitude helps to identify locations of elevated values of backscattering, which are partially associated with the surface soil moisture which when combined with the low vegetation (wetlands) causes the so-called "double bounce" scattering which also explains the observed peak in amplitude (Brisco, 2015). Other factors such as the presence of vegetation, the ground surface roughness and the satellite incidence angle can also affect the backscattering. Determining the contribution of the aforementioned factor to backscatter is often a complicated task. The relationship between these factors to backscatter is explained by backscattering models (Ulaby et al., 1982) which are also used to determine surface soil moisture via model inversion. In this study we are assuming that surface roughness remains unchanged between observations and that vegetation over the sampling sites is limited (bare soil sites considered). In the case of bare soil conditions, the soil scattering is represented as a function of surface roughness and soil moisture. Therefore, assuming that surface roughness particularly in the case of levee slopes remains relatively constant over time, the temporal change in bare soil scattering only reflects the change of soil moisture with time for a site.

4. Methodology

4.1 Persistent Scatterer Interferometry

For the determination of the displacements along the levee system in the study area, the multi temporal interferometric (MTI) technique of Persistent Scatterers (PS) analysis was applied (Ferretti et al., 2001; Crosetto et al., 2016). The principle behind the analysis of PSs, is the detection of targets so called persistent or permanent scatterers on the earth surface that exhibit consistent signal scattering characteristics, i.e., strong temporal scattering. Such persistent scatterers can be either natural or artificial objects. The analysis of PS targets is based on the creation of interferometric pairs between a primary reference image and secondary images of the dataset for the construction of interferograms, subject to a set of geometric and temporal criteria (position and time-difference between acquisitions). The displacement is determined for each of the detected PS targets for each radar image within the dataset and it measured in mm. For measuring the deformation of the levee network, a total of 81 Copernicus Sentinel-1 satellite images were used, covering the period between May 2017 and January 2020. The configuration of the image interferometric pairs is shown in Figure 3 (geometric and temporal criteria). The PS processing was done with the use of the software ENVI SARscape.

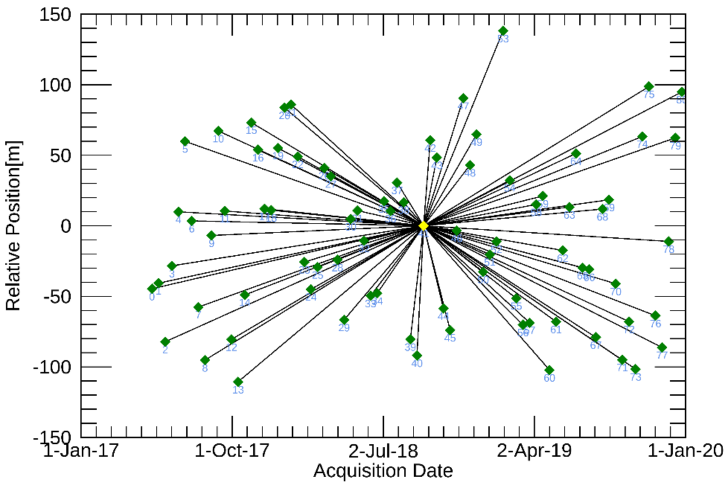

Figure 3: Time-position plot for the interferometric pairs used in the PS analysis. Reference scene is shown in yellow, secondary scenes are shown in green.

4.2 Soil moisture – backscatter analysis

The secondary aim of the study was the analysis of the relationship between the radar backscatter and soil moisture. For this purpose, the temporal profile of surface soil moisture (up to 5cm) covering the period February 2017 to July 2019 was supplied by a station (@ 51°56'6.45"N, 4°47'23.99"E) located within the area of interest from the GROW citizens' observatory network which forms part of the International Soil Moisture Network (ISMN) (https://ismn.geo.tuwien.ac.at/en/). The station is located on average 20km away from the sampled sites. The ISMN is an international cooperation to establish and maintain a global in-situ soil moisture database. This database is an essential means for validating and improving global satellite products, and land surface, climate, and hydrological models. The temporal resolution of the acquired in-situ surface soil moisture data is 15 minutes. Single-polarization scenes from the Sentinel-1 satellite constellation over the same period were acquired which were geometrically and radiometrically calibrated for the extraction of the backscattered signal in decibel (db) values. Site A (Figure 4) was used as sampling location for the analysis with a total of 125 samples acquired. A spatiotemporal filtering method was then applied to match the station data to the data of the nearest satellite acquisition date and time. Given the assumption that surface roughness remains unchanged over the sampled sites, for the purposes of analysis bare soil scattering and surface soil moisture we have employed linear regression analysis. The analysis which also aimed at predicting soil moisture values was based on a machine learning algorithm for supervised learning in which sampled values for backscatter (db) and surface soil moisture were split into training and testing datasets in an analogy of 80/20 percent (100/25 samples).

5. Results & Discussion

5.1 Displacement

The analysis of PS targets has resulted in the identification of a large number of scatterers (approximately 158,000) over the study area with a good density coverage of the levee network (Figure 4). A number of locations along the levee network exhibiting deformation corresponding to over 25mm in LOS displacement have been identified (sites A, B, C and D depicted in Figure 5). An analysis of past optical imagery has revealed construction works at all 4 sites during the period of 2017 to 2019 which could account for the high values of displacement.

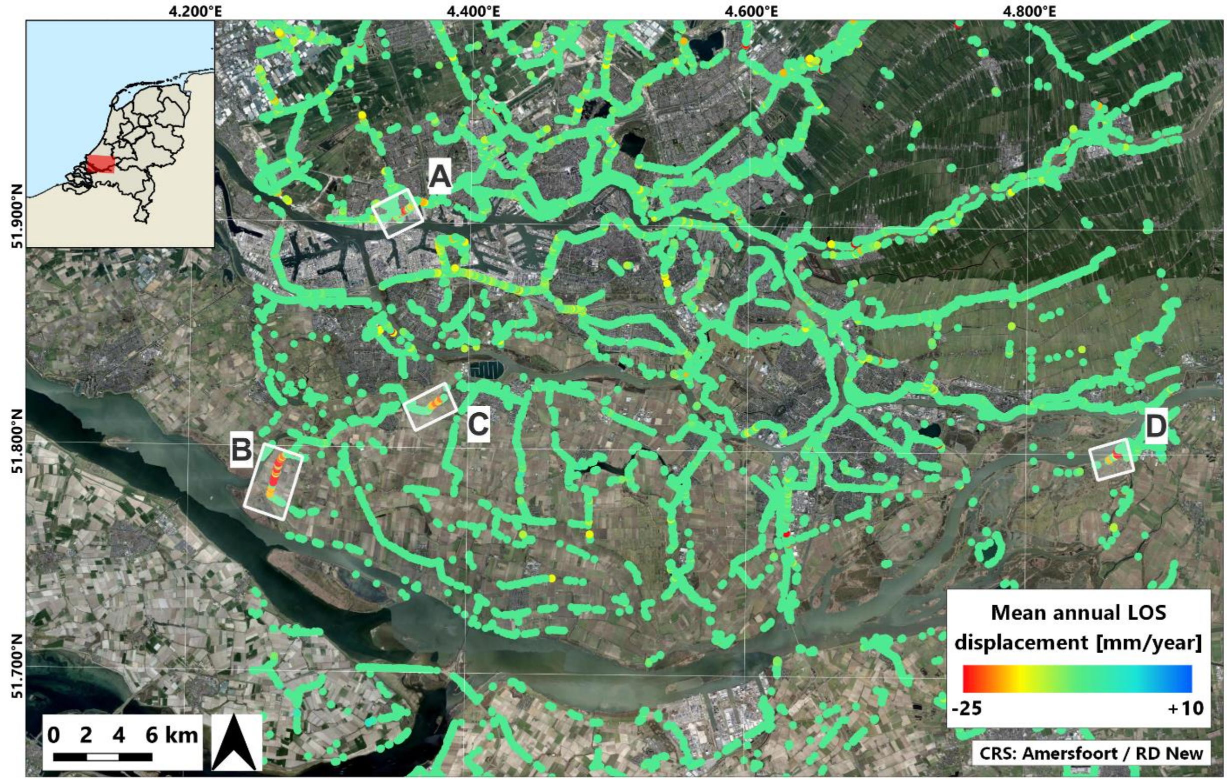

Figure 4: The spatial coverage of PS targets mapped over the levee network. Sites A,B,C and D also shown.

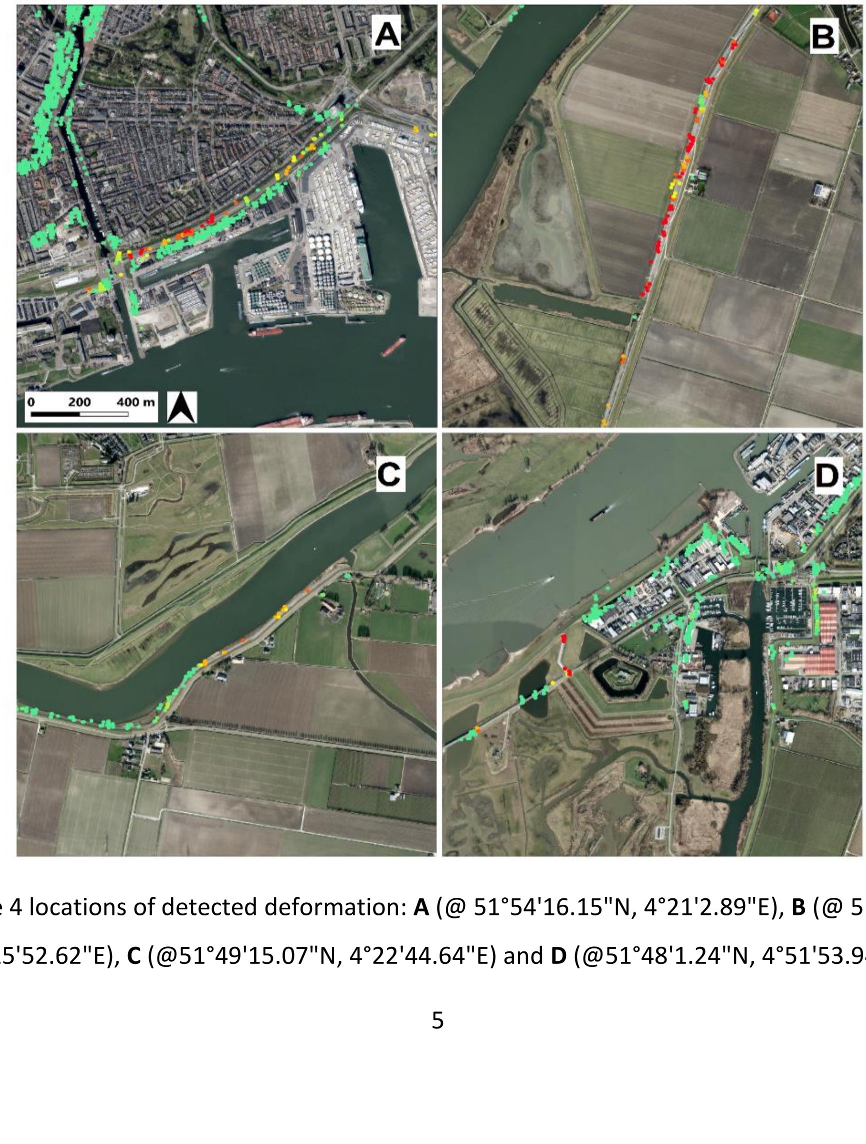

Figure 5: The 4 locations of detected deformation: **A** (@ 51°54'16.15"N, 4°21'2.89"E), **B** (@ 51°47'30.32"N, 4°15'52.62"E), **C** (@51°49'15.07"N, 4°22'44.64"E) and **D** (@51°48'1.24"N, 4°51'53.94"E)

The temporal profile of the displacements for a set of points located within sites A, B, C and D are shown in Figure 6. It is apparent that point A1 (site A) exhibits the highest displacements exceeding 60mm over the 19-month period while the rest of the selected points exhibit displacements of around 40mm over the same period.

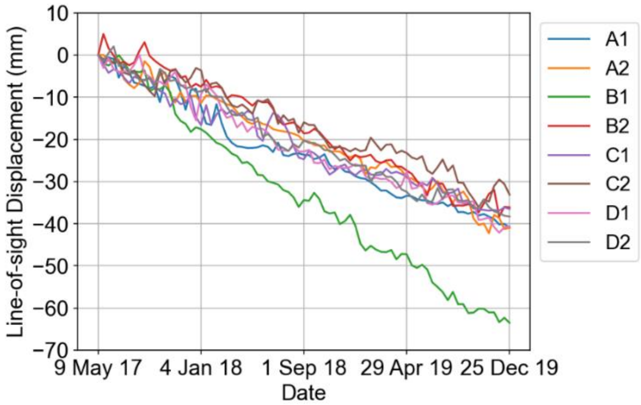

Figure 6: The temporal LOS displacement profile for each of the 8 points within sites A,B,C and D.

5.2 Soil moisture

The soil moisture data extracted from the in-situ sensor of the ISMN were filtered to match the time of the satellite image acquisitions. The satellite data over the same or nearby locations and similar characteristics (e.g. bare soil) to the in-situ sensor locations were extracted with values in decibels. The compared outputs show a good agreement between the satellite backscattering and the in-situ soil moisture sensor with increasing backscatter coinciding with increasing soil moisture content (positive covariance) (Figure 7). Indeed, the correlation between the temporal profile of backscatter is also reflected in the linear regression scatter diagram (Figure 7). The confidence interval of the prediction is clearly lower for lower soil moisture values. The overall coefficient of determination of the model was 0.4 (R^2) between the predicted and testing datasets. Further analysis is required to increase the prediction power of the model.

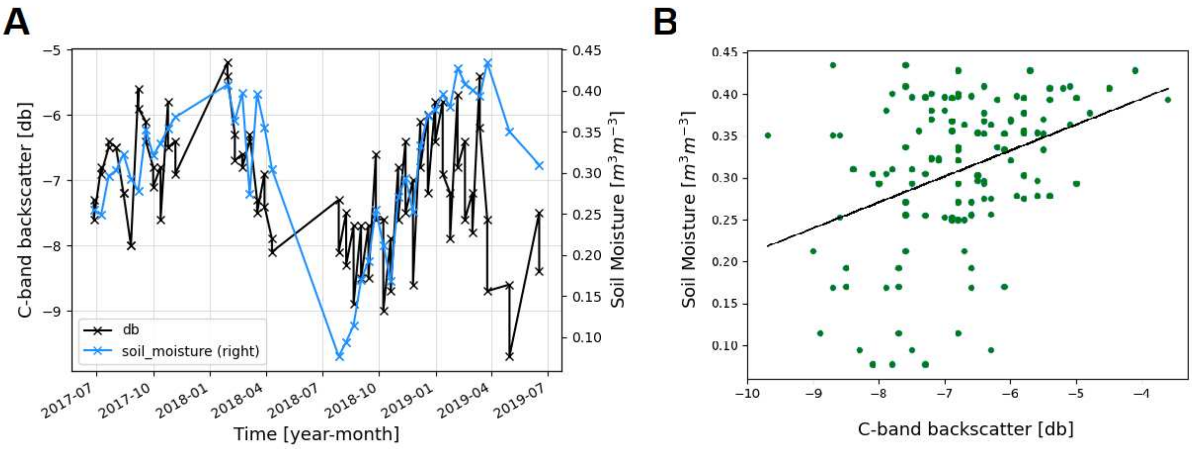

Figure 7: Temporal profile of backscatter (db) and corresponding surface soil moisture over site A (A). Predicted relationship between soil moisture and backscatter (db) via linear regression analysis.

For increasing the accuracy of the prediction model, a much larger dataset is required at different locations of similar surface characteristics to calibrate the satellite radar backscattering response relationship. In addition, the effect of other contributing factors to backscatter such as vegetation canopy and the incidence angle of the antenna will also need to be considered.

6. Conclusions

This paper presents the results of an assessment of the condition of levees via satellite radar analysis. Displacement measurements and soil moisture include two of the most important parameters for assessing the condition of ground structures as they can reveal information on excessive settlements and or associated poor seepage conditions. For the determination of displacements, the PS technique was used on a Sentinel-1 dataset covering the period between May 2017 and January 2020. The results showed a clear identification of sites exhibiting high displacements with some exceeding 60mm over the study period, which could be attributed to settlements following construction. For the determination of the surface soil moisture condition, the satellite radar amplitude data were extracted over the same period as the in-situ soil moisture sensor data. This was performed in an automated fashion for isolating the values associated spatiotemporally between the sensor and the satellite. Results showed good agreement between them with increasing backscattering signal for increasing soil moisture content. The output and more particularly the calculated correlation between backscatter and surface soil moisture over bare soil conditions is potentially very important as calibration of the satellite radar backscattering via in-situ sensor measurements can provide wide coverage of satellite derived soil moisture measurements over large areas. This will enable the estimation of the soil moisture by the use of satellite derived means. The process of deriving surface soil moisture is still a complicated task and effects of land coverage, surface roughness and satellite specific parameters will also need to be accounted for to enable the development of a soil moisture algorithm. Further work is underway for this, also including a larger dataset, expected to further improve the correlation. This will enable the measurement of satellite-based soil moisture which combined with the displacement measurements via satellite data, can provide a robust solution for ground structures assessment and especially for levee safety.

Acknowledgements

This work was co-funded by the European Union – NextGenerationEU and the Republic of Cyprus through the Research and Innovation Foundation (Project no.: INNOVATE/0719/0048).

References

Attema, J. A., & Lenderink, G. (2014). The influence of the North Sea on coastal precipitation in the Netherlands in the present-day and future climate. *Climate dynamics*. 42(1-2), 505-519.

Beck, H., Zimmermann, N., McVicar, T. et al. (2018) Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Sci Data* 5, 180214. https://doi.org/10.1038/sdata.2018.214

Biondi, F., Addabbo, P., Ullo, S. L., Clemente, C., & Orlando, D. (2020). Perspectives on the structural health monitoring of bridges by synthetic aperture radar. *Remote Sensing*. 12(23), 3852.

Brisco, B. (2015). Mapping and monitoring surface water and wetlands with synthetic aperture radar. *Remote Sensing of Wetlands: Applications and Advances*. 119-136.

Crosetto, M., Monserrat, O., Cuevas-González, M., Devanthéry, N., & Crippa, B. (2016). Persistent scatterer interferometry: a review. *ISPRS J. Photogramm. Remote Sens.,* 115, 78-89. Doi: 10.1016/j.isprsjprs.2015.10.001

EUCOLD Working Group on Levees and Flood Defences. (2018). European and US Levees and Flood Defences: Characteristics, Risks and Governance, ISBN 979-10-96371-08-2.

Ferretti, A., Prati, C., & Rocca, F. (2001). Permanent scatterers in SAR interferometry. *IEEE Trans. Geosci. Remote Sens*. 39, 8-20. doi: 10.1109/36.898661.

Macchiarulo, V., Milillo, P., Blenkinsopp, C., Reale, C., & Giardina, G. (2021). Multi-Temporal InSAR for transport infrastructure monitoring: Recent trends and challenges. *In Proceedings of the Institution of Civil Engineers-Bridge Engineering*. 1-50. Thomas Telford Ltd.

Ulaby, F. T., Kouyate, F., Fung, A. K., & Sieber, A. J. (1982). A backscatter model for a randomly perturbed periodic surface. *IEEE Transactions on Geoscience and Remote Sensing*, (4), 518-528.