Monitoring water defense structures using radar interferometry

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***Abstract*— Monitoring the safety of water defense systems is crucial for life in low-lying countries such as the Netherlands. Conventional monitoring of structures such as dams and dikes is often limited to visual inspection, with additional in situ measurements if deemed necessary. Here we show that advanced satellite radar technology can be used to obtain weekly updates on dike stability for a significant part of all dikes in the Netherlands. Applying a supervised classification of potential coherent scatterers, it is possible to provide a dense sampling of line structures such as water defense systems. Such observations can be used to assess structural stability of the water defense systems, leading to improved hazard assessment in relation to flooding risk. This may have a significant impact on safety assessment and hazard mitigation in the Netherlands.**

I. INTRODUCTION

The majority of the Dutch population is living on land reclaimed from the sea, below the high water levels of the sea, large rivers and lakes. Seventy percent of the gross national product is earned in these vulnerable areas[3]. Therefore, the safety of the water defense systems (WDS) is of paramount importance to sustain Dutch society. Failure can have catastrophic humanitarian and socio-economic consequences.

The primary water defense systems form a protection against flooding from the sea, the main rivers, and the large lakes, for which failure would have dramatic consequences In autumn 2006, the inspection authority in the Netherlands concluded that 24% of these primary water defense systems does not satisfy the legally adopted standards, and that for another 33% the status of the WDS is not known [6].

Monitoring the status of WDS is particularly difficult, partly because of the their large extent: the Netherlands has 17000 km, of which 4300 km are primary, of WDS.

The inspection methods rely largely on expert observers, who perform yearly manual (visual) inspections, a method that has been unchanged for centuries [4]. Consequently, such observations are infrequent, subjective and qualitative. Moreover, even expert observers cannot see the minute changes in the dike volume that may eventually lead to failure, making their observations not precise enough.

Apart from evident system failure modes such as overtopping during extremely high water events, structural failure is of great concern. Failure of earthworks can be due to many different causes such as sliding slopes, loss of bearing capacity, hydraulic loading, or structural weakening due to draining [5]. Some of these events will come without any precursory structural changes. However, other failure modes will be preceded by slow and minute structural or geometric changes, which can be potentially measured as displacements. It is for the latter situation that satellite InSAR based methods have enormous potential, due to their frequent revisits, wide areal coverage, and high precision displacement monitoring.

II. PROCESSING APPROACH

A wide class of interferometric SAR processing methodologies can be characterized as time series SAR interferometry, using many or all of the available radar acquisitions [2]. Perhaps the most effective subclass of these methods is referred to as persistent scatterer interferometry (PSI), due to its ability to work with single pixels or scatterers as a function of time [1]. PSI methods attempt to solve two problems simultaneously. First, they need to identify coherent scatterers, whose phase history is dominated by the geometry between satellite and scatterer, rather than physical changes within the scatterers' resolution cell. Second, for scatterers deemed coherent, various parameters need to be reliably estimated, such as their relative geometric height, their displacement behavior in time, atmospheric delay factors, and integer phase ambiguities.

The main problem in PSI is that identification and estimation usually need to be performed in concert, as it is not known beforehand which of the millions of observations will have coherent characteristics. Inevitably, this will result in errors. We distinguish type-I errors—coherent scatterers which are not identified as being coherent—and type-II errors, which are incoherent scatterers which are erroneously not rejected (false detections). In most PSI approaches, such errors are practically unavoidable, due to the wide spatial extent, the huge number of observations, and the impossibility to check every possible pair (arc) of points due to numerical constraints. Therefore, type-I errors will lead to undetected points.

For line infrastructure, such as roads, railways, and dikes, dams or other water defense systems the situation is more favorable. In these cases, it is possible to separate the identification and the estimation step, and perform a supervised classification of scatterers with a high likelihood of being coherent. As the coherence likelihood on these constructions is much higher than the surrounding contiguous area, we optimize the algorithm by performing more elaborate testing procedures for these structures. Many water defense systems,

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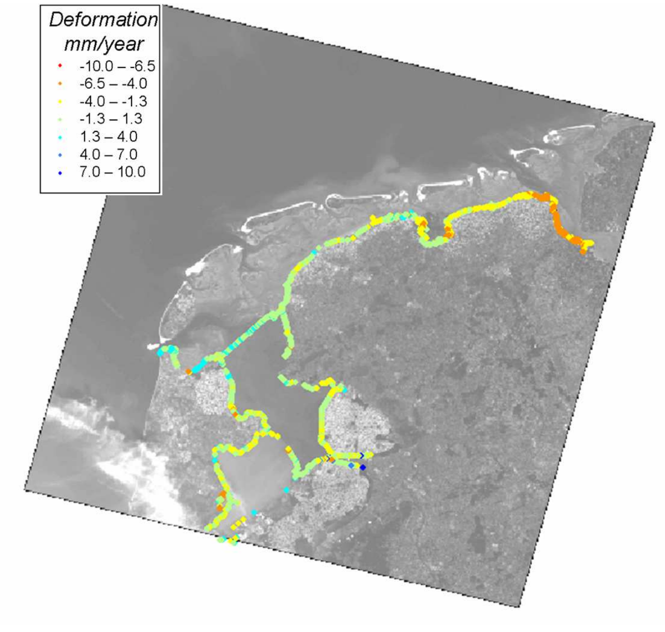

Fig. 1. Overview of PSI results over water defense systems based on 9 independent radar frame time series over the Netherlands.

especially the primary systems, are protected against wave attack by revetments, mostly rock fill and slopes covered with stones. These conditions ensure coherent behavior for radar observations, sometimes with extra conditions for maximum allowable incidence and squint angles. At the land-side, WDS usually have a vegetated (grass) cover, where the vegetation roots provide extra protection against sliding. From a radar perspective, this means that the water-side of dikes and dams is expected to be long-term coherent, and a potential coherent (persistent) scatterer, whereas the land side is likely to decorrelate within days.

The successful inference of displacement parameters from the complex radar backscatter is dependent on many factors, such as the orientation and slope of the dike, the radar look direction and the amount of acquisitions available from a single track. For this reason we apply all available acquisitions over the area of interest. For latitudes of the Netherlands, i.e. ∼52°, this implies that every point is imaged at least four times—two times from adjacent tracks and both from ascending and descending orbits. This results in (i) a higher likelihood of finding coherent combinations, leading to improved PS density along the dike, (ii) higher reliability based on cross validation possibilities, and (iii) the opportunity to decompose the deformation vector in a vertical component and a component tangential to the slope. The fact that displacement along the dike orientation, i.e. *lateral* displacement, is highly unlikely helps to constrain this decomposition.

III. RESULTS

The area analyzed is shown in fig. 1 and covers an area of approximately 300×200 km. Nine independent ascending, descending and adjacent radar frames (more than 700 radar acquisitions) have been used to estimate this first result. Coherent scatterers along the WDS have been identified based on the algorithms described in the previous section. Parameter estimation includes the topographic height differences between scatterers, the contribution of the atmospheric delay, displacements, and phase ambiguities. Under the null hypothesis, steady-state (linear) displacement is assumed as a function of time. The null hypothesis is important only for phase ambiguity estimation, as the estimation problem is in principle underdetermined. After successful phase ambiguity estimation, indicated by its initial *success rate*, arbitrary displacement behavior can be derived, as long as it has some degree of temporal smoothness. In the figures, steady state deformation rates are depicted for convenience, but every point has a complete time series of displacement estimates.

Datum connection between separate frames is performed in a least-squares sense, correcting for a bias and a trend. The resulting persistent scatterer displacement rates are visualized against the backdrop of a Landsat image of the Netherlands. The main variations in displacement rates are due to the withdrawal of natural gas and solution salt mining.

Nevertheless, there are some locations which show a significant additional signal. Fig. 2 shows the former island of Marken, situated north of Amsterdam. Currently, the island is connected to the mainland with a dedicated dam. The physical appearance of the dikes protecting Marken is shown in fig. 2 as well. From this photograph it is evident that full coherent coverage of the dike cannot be expected with low bandwidth sensors such as ERS and Envisat, as SAR resolutions are too poor, especially in range direction. Consequently, north-south oriented line structures are sampled best due to the high azimuth resolution. Nevertheless, comparison of leveling and PSI displacement rates for nearby points show a significant correlation, see fig. 3. Note that in this case, the discretization level of the available leveling data limits the comparison. significantly.

In fig. 4 an example for a time series of one of the PSI points of Marken is shown. The deformation rate of 13 mm/y has lead to a maximum subsidence of more than 10 cm in the evaluated time interval of 10 years. Deviations of the displacements relative to the steady state hypothesis seem to be correlated in time, which suggests seasonal dynamics juxtaposed on the overall subsidence.

IV. DISCUSSION

From the results presented above it is clear that for more than 90% of the primary water defense systems around the Waddenzee and IJsselmeer coherent reflections are received, which provide useful complementary information for operational dike monitoring. Nevertheless, there are several open questions, regarding the signature of the effective scatterers, and the relation to potential dike failure modes. An important remark can be made on the information content of resolution cells over dikes that do not contain a coherent scatterer. Considering that dike segments are rather homogeneous in the

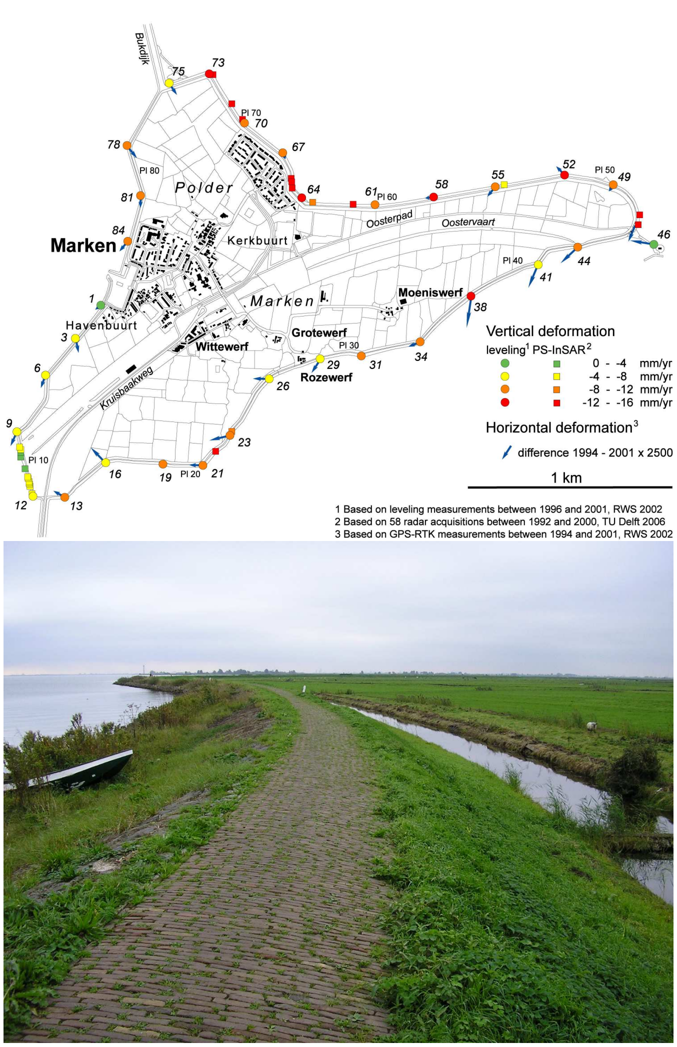

Fig. 2. Top: Leveling, GPS, and PSI measurements over the dike protecting the former island of Marken. Bottom: photograph of the physical appearance of the dike.

Netherlands, the main reason for a time-incoherent resolution cell is a major disturbance somewhere in the evaluated time interval. As such, the absence of coherent scatterers is perhaps a strong source of information of disruption. For all presented cases, these first results suggest an indicator function, directing water management experts to visit a certain location for in situ inspection. An automated mutation signalling procedure is possible.

The situation of the island of Marken is likely due to the superposition of dike segments above shallow peat layers. Due to the mass of the earthworks, the lower peat layers compact, leading to subsidence of the dikes relative to the shallower land area. The dikes of the island have been erected centuries ago, and therefore this process is bound to continue. Revetment and increasing the heights of the dikes will unevitably lead to further compaction.

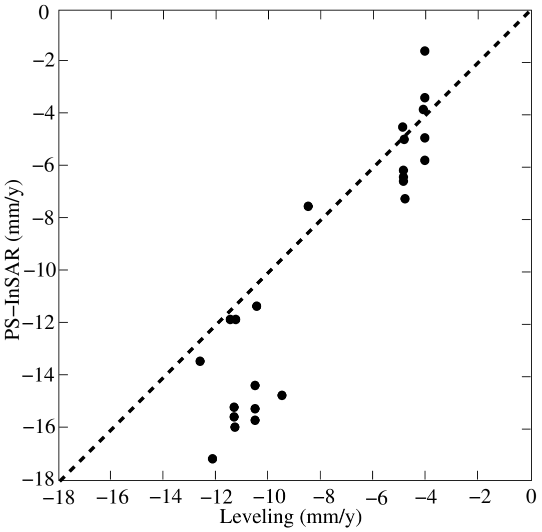

Fig. 3. Scatterplot showing displacements observed by leveling versus displacements from persistent scatterer interferometry. Quantization levels of the leveling results lead to columnar appearance.

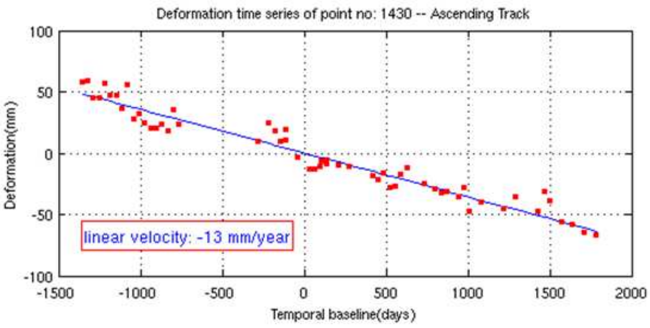

Fig. 4. Example of a displacement time series for a persistent scatterer on the north dike of Marken.

V. CONCLUSIONS

It has been shown that persistent scatterer interferometry, applying a supervised classification of potential coherent scatterers, is able to provide a dense sampling of line structures such as water defense systems. Such observations can be used to assess structural stability of the water defense systems, leading to improved hazard assessment in relation to flooding risk.

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