MONITORING DEFORMATION OF WATER DEFENSE STRUCTURES USING SATELLITE RADAR INTERFEROMETRY

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Abstract: 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. 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. Monitoring the status of WDS is particularly difficult, partly because of their large extent: 17000 km in the Netherlands. Inspection methods rely largely on expert observers, who perform yearly manual (visual) inspections, a method that has been unchanged since the centuries. Consequently, such observations are infrequent, subjective and qualitative. Here we show that satellite radar interferometry, using a new methodology derived from earlier results on persistent scatterer interferometry, is able to detect more than 90% of the primary water barriers around the main open waters of the Netherlands; the Waddenzee and the IJsselmeer. The results show that it is possible to derive millimeter scale deformation and to assess whether the outer dike structure remains intact after strong storms.

1. 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 (Kabat et al, 2005). 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 (Inspectie Verkeer en Waterstaat, 2006).

Monitoring the status of WDS is particularly difficult, partly because of 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 since the centuries (Rijkswaterstaat, 2001). 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 (Steenbergen et al, 2004). Some of these events will come without any precursory structural change. 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.

2. 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 (Hanssen, 2001). 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 (Ferretti et al., 2001). 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 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 behave coherently. 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 easier. In these cases, it is possible to separate the identification and estimation step, and perform a supervised classification of scatterers with a high likelihood of being coherent. Many water defense systems, 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, this implies that every point is imaged at least four times—two times from adjacent tracks and from ascending and descending orbits. This leads to (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 is highly unlikely helps in this decomposition.

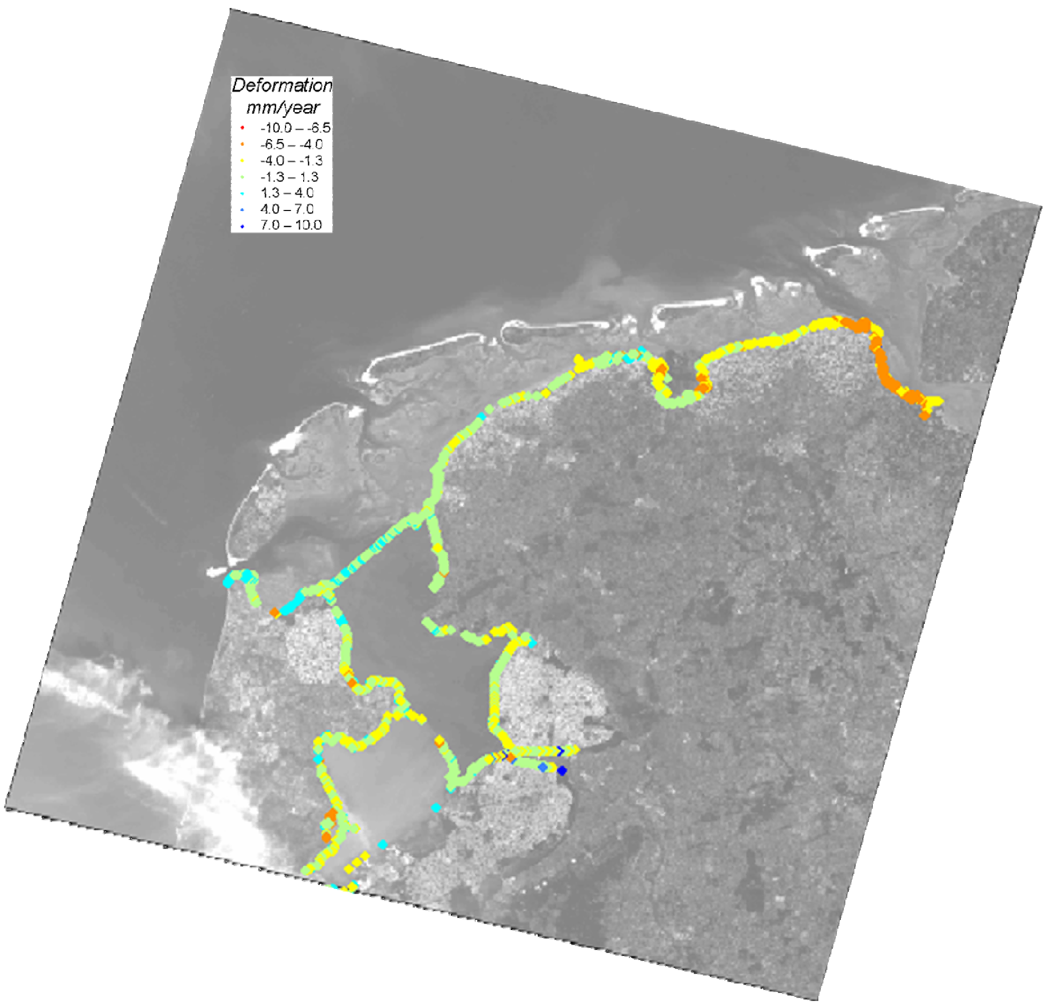

Figure 1 Overview of PSI results over water defence systems based on nine independent radar frame time series.

3. RESULTS

The area analyzed is shown in Figure 1 and covers an area of approximately 300 x 200 km. Nine independent ascending, descending and adjacent radar frames (more than 700 radar acquisitions) have been used to estimate this first result. Datum connection between the 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.

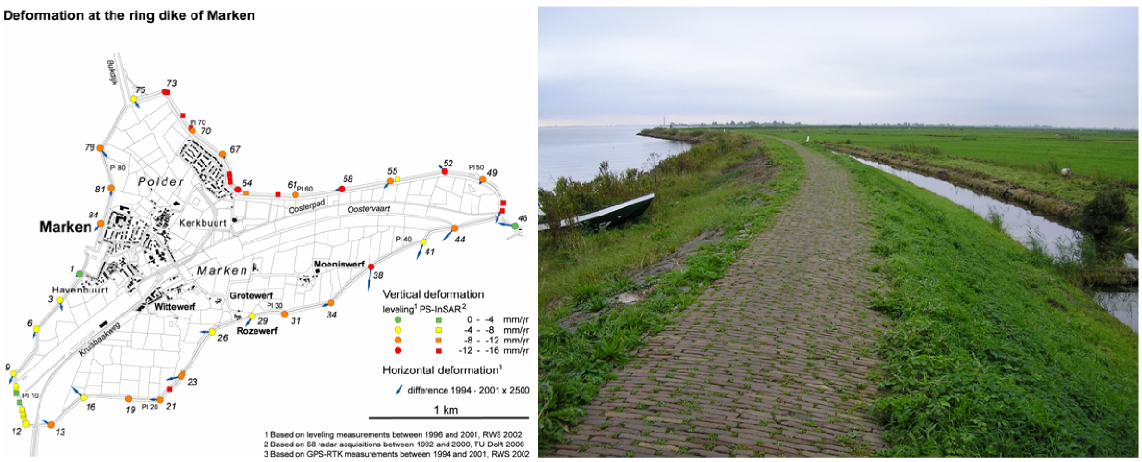

Figure 2 (Left) Leveling, GPS, and PSI measurements over the dike protecting the former island of Marken. (Right) Photograph of the physical appearance of the dike.

Nevertheless, there are some locations which show a significant additional signal. Figure 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 Figure 2 as well. From this photograph it is evident that full coherent coverage of the dike cannot be expected with ERS/Envisat SAR resolutions. Nevertheless, comparison of leveling and PSI displacement rates for nearby points show a strong correlation, see Figure 3.

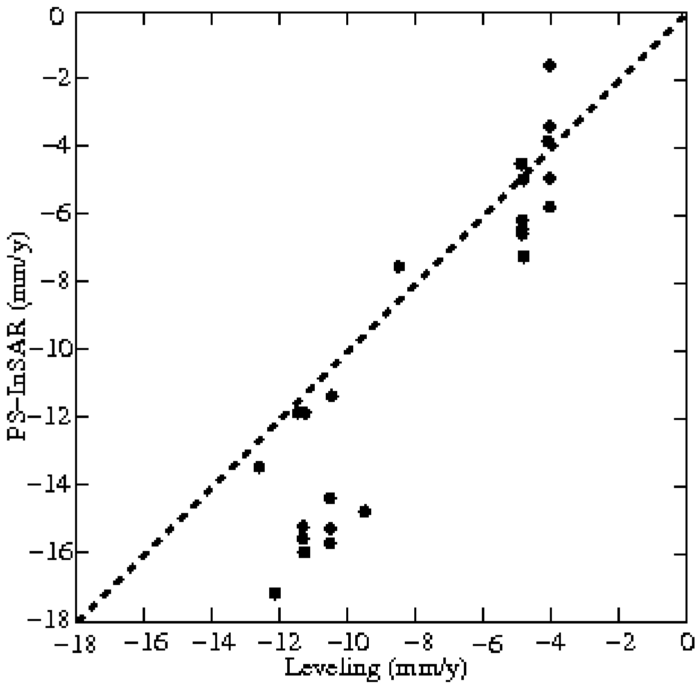

Figure 3 Scatterplot showing displacements observed by leveling versus displacements from persistent scatterer interferometry. Quantization levels of the leveling lead to the columnar appearance.

In Figure 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.

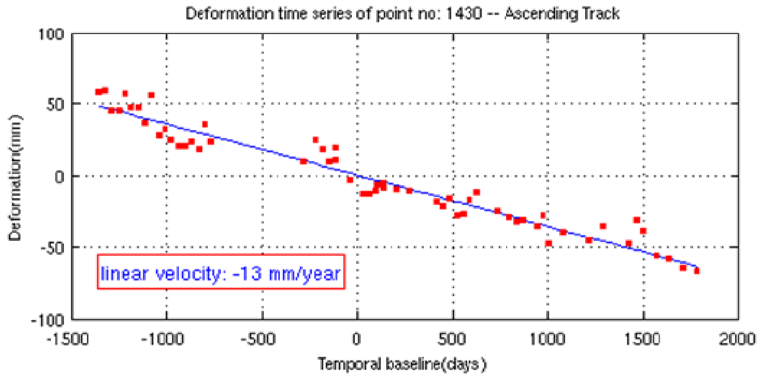

Figure 4 Example of a displacement time series for a persistent scatterer on the north dike of Marken.

4. 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 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.

The situation of the island of Marken is likely due to the superposition of dike segments above 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.

5. 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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