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Satellite radar obse for large infrast works: A case study on T

Abstract

A very large infrastructural work is being undertaken in Delft. A tunnel is going to be constructed to replace the current rail viaduct. As in any large infrastructural work, the monitoring of the land deformations during the period of the tunnel's construction is highly essential. In this project, one study was performed to analyse the feasibility of PSInSAR as an independent technique for monitoring of land subsidence.

The driving mechanisms for deformation were studied to find out the relations among them. Soil geophysics, hydrology, infrastructures and thermal expansion were studied in relation with deformation. Besides these, the traditional deformation monitoring methods were also studied, since they are the competitors of this technique. LiDAR, photogrammetry, tachymetry, levelling and GPS were considered in this study for the comparison with radar. The major attention has been given in this study to assessment of the geolocalisation quality of PSInSAR observations.

We have found that the accuracy and point density of PSInSAR is sufficient for deformation monitoring. While its repeat interval might not be able to detect quick failure mechanisms, other techniques have proven to be excellent complements for this deficiency. Radar measurements are also good for validation in other fields, showing that they correlate well with thermal expansion and soil mechanics theory. Further work should be directed to improving geolocalisation and deformation models.

Keywords
PSInSAR
Radar
Deformation
Monitoring
Spoorzone Delft

1. INTRODUCTION

The Netherlands have one of the highest population densities in the world, which creates a constant need to improve the transportation infrastructure in the country. Currently, a very large infrastructural work is being undertaken in Delft known as Spoorzone Delft (figure 1). The most significant part of this project is a four track railway tunnel, which will replace an existing two track viaduct. There are many concerns with its construction in a highly populated area near the historic centre of the city. Tunnel building is difficult in the area, because of the presence of ancient building foundations, combined with soft unconsolidated soils and the large impact of groundwater pressure fluctuations. Proper monitoring is crucial to detect any situation that may arise, and prevent a catastrophic event. PSInSAR is a technology which has the potential to become a watchman for large projects such as this one. Radar is virtually always

FIGURE 1. Overview of a part of Spoorzone

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available, day and night and in all weather conditions; it is also powerfully precise, with millimetre accuracy. The objective of this project is to determine the feasibility of a satellite radar based monitoring system for large scale infrastructural public works, with the Delft train tunnel as a case study. Currently, the conventional geodetic techniques (e.g. levelling) are involved in large infrastructure projects, but the use of other independent techniques may yield great advantages. For instance, it can check the correctness of the data obtained by construction companies, providing confidence to the community with a second set of impartial measurements.

2. THEORETICAL RESEARCH

2.1 DRIVING MECHANISMS

Delft is an old city with a long building history. Depending on the age of a construction, a corresponding foundation can be expected (i.e. shallow wooden beams or deep concrete piles). From stiffness theory, it is expected that the buildings with shallow wooden piles will be vulnerable to changes in the stress level caused by the tunnel's construction, resulting in deformation. On the other hand, buildings with deep concrete piles are founded on a stable sand layer and will likely not be affected significantly. Soil subsidence often increases with time, even under a constant load. This phenomenon is called creep, and peat and clay are the best examples of materials which exhibit this behaviour. It causes structures founded on soft soils to show ever increasing settlement. For buildings, such settlements are particularly damaging, especially when not uniform. This may lead to cracks in buildings. Meanwhile, other materials (e.g. sand or rock) show practically no creep, except at very high stress levels. The soil in Delft is mostly composed of clay, sand and peat, which causes an ever increasing subsidence in Delft.

From previous research, it is known that there exists a high correlation between groundwater level and surface deformation. A better understanding of this relationship will help manage groundwater and analyse deformations. DSM Gist plays an important role in this because this company is extracting great amounts of groundwater which has direct influences on the groundwater level. Surface deformation is also dependent on subsurface soil composition, with peat being significantly more sensitive for compaction than other materials. Since it is composed of organic material, it oxides when in contact with air, reducing in volume and producing subsidence. On those depths, where groundwater fluctuates, peat will come in contact with air.

2.2 RADAR METHOD

Synthetic Aperture Radar (SAR) is a remote sensing technique that can image the terrain and by transmitting a radar wave from an airborne or spaceborne platform and receiving its reflection from the ground (backscattering). It can image at any time of the day or the night, regardless of sun illumination and weather condition.

When the amplitude of the radar complex waveform is discarded, the technique is known as Radar Interferometry or Interferometric SAR. It is based on the subtraction of phases between two or more radar acquisitions over the same area. The capability of reaching mm level accuracy when measuring range differences in this way, along with the repetition in the satellite orbits form the basis for the monitoring of ground deformation.

Many long-term monitoring campaigns are performed in regions with excessive vegetation, snow cover, flooding, or man-induced earth movement, as is the case of the construction work being carried out in the Delft Spoorzone. All of these phenomena can degrade traditional InSAR capabilities, since success with interferometry relies on the ability to observe coherent phase measurements from scene to scene. One solution to overcome limitations of conventional InSAR is the use of Persistent Scattering Interferometric InSAR (PSInSAR). This technique uses the same technology as traditional InSAR, but takes an additional advantage of point targets, the so-called Persistent Scatterers (PS). PS present stable reflectivity properties and coherent phase measurments over time. A persistent scatterer is much larger than the radar wavelength, but small enough not to be influenced by geometric decorrelation.

2.3 DATA LINEAGE

Along this synthesis project, crucial radar data have been provided by DLR through the satellite TerraSAR-X, launched on June 15th 2007. Operating in the X-band (wavelength of 31 mm and frequency of 9:6 GHz), achieves high resolution (3 metre in StripMap mode) from a polar orbit at 514 km altitude. TerraSAR-X, delivers an ascending and a descending radar image of Delft every eleven days and has been doing so since April 8, 2009, for the purpose of our project. It looks at a 30 kilometre wide area around Delft, with an incidence angle of 22.5 – 25.5° for the descending view and 38.0 – 40.5° for the ascending one.

The data acquired in this way has been processed by TU Delft and the outcomes have been delivered to the Geomatics Synthesis Project team to be analysed. From these data, deformation maps (figure 2) and height maps have been obtained. Time series showing the relative motion of each point have also been extracted from the datasets.

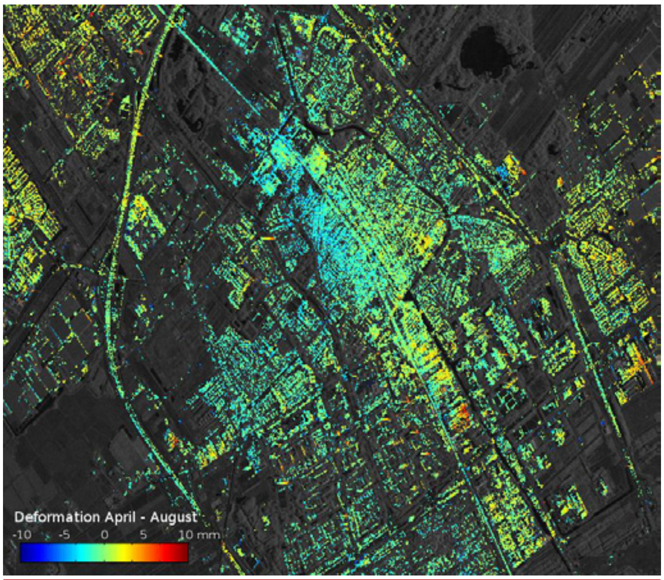

FIGURE 2. One of the outcomes of PSInSAR is a map displaying the deformation from April to August 2009 of PSs relative to a reference surface

2.4 QUALITY OF OBSERVATIONS

Opposed to a human eye, which is capable of distinguishing objects located at various angles, radar can only distinguish between objects placed at different distances from it (figure 3). Analysis of PSI results requires a visualisation tool, which allows combining radar observations and external data into a common reference system. This combination leads to the possibility of interpreting PS data with reference to physical ground features, and hence, provides an idea of the reasons for the subsidence.

2.5 OTHER METHODS FOR MONITORING

The monitoring of the Delft train tunnel involves mainly tachymetry, but also terrestrial laser scanning (phoenixstraat) and inclinometers are used. In the Delft case study area, prisms are mounted on

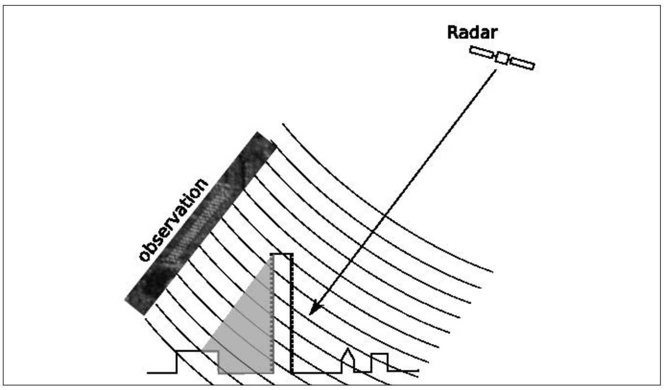

FIGURE 3. The way radar observes distance

buildings in order to make the measurements with the tachymeter faster and to have the ability for continuous monitoring of the deformation. So far, no monitoring technique has succeeded in being low cost, accurate, having a high point density and that has been fast in area coverage. All currently used techniques for deformation monitoring have their strengths and limitations. It has been found that only methods operating at ground level are capable so far, in monitoring deformations for infrastructural works like Spoorzone. This includes levelling, tachymetry, close range photogrammetry and terrestrial laserscanning. The latter two are considered to be suitable to complement PSInSAR.

3. DETAILED ANALYSIS

3.1 GEOLOCALISATION

To relate the PS points to real objects, the points are loaded in a GIS system and compared to reference data. For this we have used the excellent AHN2, a very accurate height model of the Netherlands, and GBKN, the Dutch big scale base map. After geometrical transformations the majority of PS can be located with an error of less than 3 m, horizontally as well as in height.

To get more insight into the position of points observed by radar relative to the actual location, cross sections of the AHN2 profile were overlaid with PS.

Since the InSAR technique is capable only of measuring path differences in its Line of Sight direction, in order to properly decompose the displacement into horizontal and vertical components, measurements taken from two directions (ascending and descending interferograms) should be combined. Radar observations from TerraSAR-X in different orbit directions result in two kinds of independent measurements. The location of scattering points representing the same physical object in both datasets, would stand as a sign of a reliable measurement and a strength on the technique. There is an example where points from both orbits prove to belong to a same building, by presenting the same deformation trend and very close geolocalization.

3.2 THERMAL EXPANSION

Thermal expansion is a tendency of a material to change its size in response to a change in temperature. As a rule of thumb, we can expect that a 10° rise in temperature will cause a 10 m tall building to expand 1mm upwards. This expansion occurs both vertically and horizontally, but while the former is relatively easy to account for, the latter depends heavily on the internal structure of a building and is therefore omitted from this report.

Vertical thermal expansion is very predictable for early morning acquisitions, but unpredictable in the afternoon, due to certain factors like uneven heating in households. After the analysis it was concluded that highly coherent points are most strongly correlated with thermal expansion. Furthermore, the mean thermal expansion coefficient for buildings in Delft is found to be $12E{-}6K^{-1}$. It has been concluded that it would be much better to apply the thermal expansion correction before fitting a deformation model and calculating the corresponding ensemble coherence in the PSInSAR process. The correlation between thermal expansion and radar measured deformation for points over 17 m over the ground in the descending orbit is shown in figure 4.

There is an example where points from both orbits prove to belong to a same building, by presenting the same deformation trend and very close geolocalization.

3.3 FLUCTUATIONS IN GROUND WATER LEVELS

There is a direct relation between groundwater level and surface deformation. However, because of the unavailability of groundwater level data over the same time span as the radar deformation measurements, the analysis of such influence has been performed with predicted groundwater levels. After the study, no clear correlation could be found between deformation and changes in groundwater level. It can be concluded that this analysis may only be helpful, if actual groundwater level measurements are considered.

3.4 SOIL SUBSIDENCE

PS points were classiffied using a soil map of Delft. From statistics calculated for each soil class, it was possible to conclude that the layers containing clay had a high deformation rate, while sand had a small deformation rate. It was concluded that the deformation measured with PSInSAR was consistent with the soil mechanics theory.

FIGURE 4. Correlation between thermal expansion and radar measured deformation for points over 17 meters over the ground in the descending orbit

3.5 PSINSAR AND THE DELFT TRAIN TUNNEL

A network relating the future tunnel to all surrounding points is created to monitor the relative movement between the surrounding points and the tunnel. Only the zone with a short angle to the underground infrastructure is likely to be significantly affected by the construction of the tunel.

The minimum displacement detected with PSInSAR depends on the selected direction. The so-called Minimum Detectable Bias (MDB), is found to be 1 mm in the line of sight of the satellite. For a point on the horizontal plane, 1.6 mm east-west in the ascending orbit and 2.5 mm to in descending orbit. The MDB ranges from 1 mm to 2.5 mm in the vertical direction.

4. BUSINESS ANALYSIS

The business potential of this method has been studied as well, where the organisational, financial and legal aspects of the project have been analysed. Three developed business models, connected with TU Delft, have been defined:

- model A: meant for research only; this is the model in which this project was operated,
- model B: where the research is funded by TU Delft, and the product is sold through a related intermediary company,
- model C: where the project team will reach the clients and sell the products.

The financial analysis of the Model B is made. The project with an eight member team with the facilities expenses, costs approximately 260.000 euros. The financial advantage of this model is that the data acquisition is for scientific use, hence it is derived without any cost.

The accessibility of the data, the intellectual property rights and the personal data protection should be taken into account obeying European directives. Contracts should be signed to address all legal points such as usage of data for business purposes, its publishing on the web and the warning of detected deformations.

5. RESULTS, CONCLUSIONS AND RECOMMENDATIONS

5.1 RESULTS

The project has several results. The most important is that deformations can be detected with millimetre accuracy, which is satisfactory for deformation monitoring. It is seen that the point density can easily exceed 5.000 per km^2 . The precision for relative position and height is better than 3 metres. Further it is required to offset the thermal expansion since thermal expansion can be in range of centimetres. The minimum detectable bias in the horizontal plane ranges from 1.6 mm east for the ascending orbit and 2.6 mm west for the descending orbit. The minimum detectable bias in the vertical direction ranges from 1.1 to 25 mm. Terrestrial Lidar or close range photogrammetry is recommended as a complement to PSInSAR for deformation monitoring.

5.2 CONCLUSIONS

The main conclusion of this project is that it is possible to monitor the Spoorzone Delft with millimetre accuracy. In case a building will tilt, it is possible to measure it with several millidegrees accurate. Further it can be concluded that the accuracy of the localisation of the points is not homogeneous. Overall points are within 3 metres accurate, while locally accuracies of about 1 metre can be achieved. Due to the property of every material to change its size in accordance with temperature, buildings expand significantly when they get warmer. The difference between a cold winter night and a warm summer day can be theoretically of 3 centimetre for the highest buildings in Delft. In order to measure proper deformation of the ground under a building, it is necessary to account for this event. PSInSAR really stands out in having a large comparable covered area over time with a very high accuracy. Still, it may be useful to use a complementary technique, especially for faster repeat rates and more control over the observed points. For this, close range photogrammetry and terrestrial Lidar could be considered, and it may be attractive to use a more proven technique such as tachymetry.

5.3 RECOMMENDATIONS

It is recommended that Spoorzone Delft will be monitored by PSInSAR. TU Delft should continue further research on the PSInSAR technique. In the upcoming years a quick improvement can be expected. This research should include the following things. The geolocalisation of the points could be more accurate. Further a possibility for obtaining a better deformation model than the linear one used in this research, and finding a better filtering method. For monitoring large infrastructural works smaller than 10 km^2 , it is recommended to switch from the radar operational mode StripMap to Spotlight to reach a higher PS density. Groundwater level measurements should be obtained from the same time span as radar acquisitions, and for those depths, where groundwater fluctuates, it will be useful to analyse soil types. Further, the possibility of using thermal expansion offsets before any estimation based on radar data should be researched. Additionally, the foundation types of buildings could be obtained in order to do a spatial analysis on the relation between foundation type and deformations.

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