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# Building damage related to Amsterdam subway; comparison of traditional monitoring with satellite monitoring results

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**Abstract:** This paper describes the evaluation of the monitoring data obtained from the construction of the North/South Line, a new subway line crossing the historic center of Amsterdam. During construction of the line (2003-2014), building deformations were monitored with Robotic Total Stations and with Precise leveling. This paper describes a summary of the results of the building deformations and corresponding damage due to the construction of three of the deep underground stations. Furthermore, a study was performed to investigate the possibilities to determine the potential for building damage with radar satellite monitoring. A comparison is made between different measurement methods and recommendations are given.

## 1 INTRODUCTION

The use of satellite monitoring is a potential additional tool for risk management related to underground construction and the corresponding damage assessments that have to be made. So far, many examples of the use of satellite monitoring exist, often for large scale or more regional topics, such as subsidence or settlements of levees, pipelines etc. The use of satellite monitoring for the assessment of individual buildings is rather new (see for example [1]). Since in some cases, monitoring of individual buildings is either (unintentionally) not present (at the time necessary) or unfeasible, the potential use of satellite monitoring is investigated.

This paper describes the evaluation of the monitoring data obtained from the construction of the North/South Line, a new subway line crossing the historic center of Amsterdam in the Netherlands. Before and during construction of the line, between 2003 and 2014, building deformations were monitored with Robotic Total Stations and with Precise leveling. A comparison is made between the precise leveling, the robotic total station and the satellite monitoring data.

## 1.1 Construction of the North South Line subway in Amsterdam

The construction of the line started in 2003 with preparation works for the stations. Tunnelling commenced in 2009 and finished in 2011. The three inner city stations have been structurally finished in 2014. A cross section of the Ceintuurbaan Station is shown in Figure 1 on the left, with a picture of a relevant building alongside the station on the right.

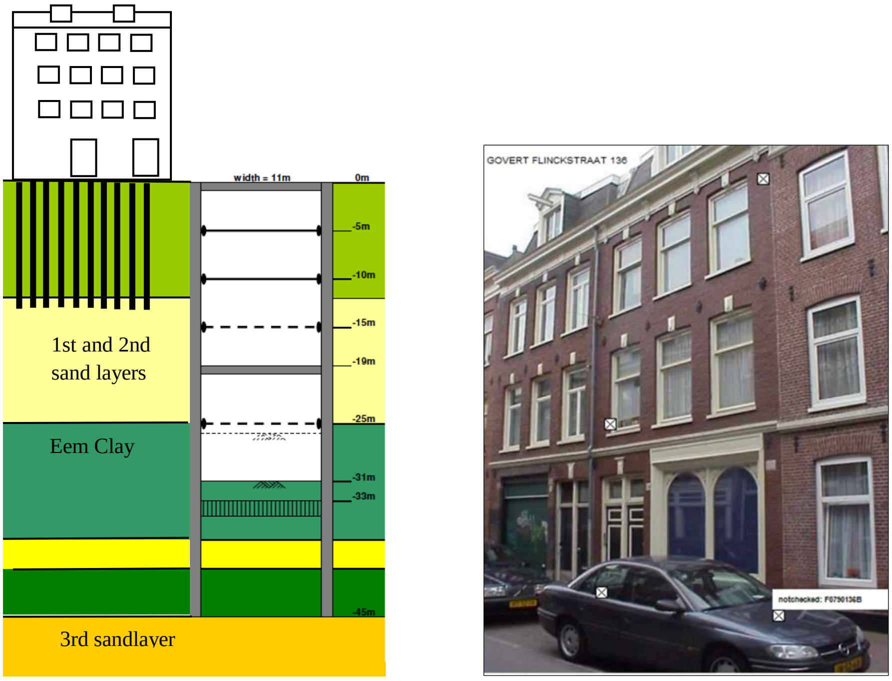

Figure 1 Cross section of Ceintuurbaan Station (left) and picture of Govert Flickstraat 136 (right). Squares with crosses are measurement locations (first and second floor prism locations and lowest level manual measurement bolts.

The soil stratigraphy in the historic centre of Amsterdam consists mainly of soft clay, peat and sand deposits of Holocene and Pleistocene age, underlain by a stiff, lightly over-consolidated clay, the Eem Clay. Ground level is around NAP +1.0m (NAP is Dutch Reference Level). The three stations have been built top-down to a depth of about 26-31 m below surface level, with 1.2m thick diaphragm walls extending to approximately 45m below surface level. Construction details, information about the buildings and dates of the different construction activities can be found in [2]. Most buildings in the historic centre of Amsterdam are built with masonry walls, wooden floors and timber pile foundations, with piles driven to the 1$^{st}$ Sand Layer at about 12m below the surface level (see Figure 1). More recent buildings with 1-4 storeys are built with concrete walls and floors and prefabricated concrete or steel piles. Some older buildings have a basement at half depth, with a raised ground floor level.

## 1.2 Project monitoring equipment and set-up

In order to determine the displacements of the historic structures along the deep stations, an extensive, mostly automatic monitoring system was installed in the city center from the year 2000 onwards. This included 74 robotic total stations (“RTS”) that monitored more than 1700 prisms on the buildings. Each robotic total station monitors about 50 to 100 prisms. The displacement of the prisms is measured in three directions (x, y and z). Measurements made with the RTS are related to other RTS locations outside the zone of influence. Prisms are located on the fronts and the sides of the buildings, usually with a minimum of 4 prisms per building. Precise levelling points referenced to the stable 3rd Sand Layer outside the zone of influence are measured at intervals of 6-12 months.

In order to handle the large amount of monitoring data, a Geographical Information System (GIS) has been developed to store, analyse, structure and visualise the data used and provide rapid reaction opportunities. For each building within the zone of influence, numerous facts are stored such as the condition of the foundation, photographs of the original condition with prism locations, ownership details and details of the structure’s use. Details of the monitoring system, its accuracy and the GIS system can be found in [3], [4], [5], [6].

## 1.3 Satellite data back ground

The Interferometric Synthetic Aperture radar (InSAR) is a group of remote sensing techniques based on the analysis of multiple images acquired by satellite-based radar sensors (Synthetic Aperture Radar - SAR) that orbit the earth at circa 800km altitude. By analyzing the differences between consecutive images, the InSAR methods enable the detection of displacements with millimeter accuracy. In this study, we used the PS-InSAR technique [7], [8]. Hard and relatively static structures, such as buildings, are good radar reflectors and are relatively easy to monitor from space using the PS-InSAR technique. Figure 2 shows the principles of the InSAR measurements. The displacement of a building is determined by analyzing the corrected phase change of the SAR signal that is reflected back to the satellite along its Line of Sight. Since the wavelength is exactly known, the phase change of the reflected signal – after correcting for sources of noise such as atmosphere disturbances – is a direct measure of the deformation of the structure.

The Persistent Scatterers (PS) are strongly reflecting objects for which the spectral response does not change significantly at different SAR acquisitions (stable temporal electromagnetic response). The PS generally correspond well to elements such as manufactured structures (buildings, monuments, streets, railway lines, antennas, metallic structures, etc.) or hard natural elements (rocky outcrops, debris accumulations, etc.). Information that is gathered from the PS include ground target position (latitude/North, longitude/East, altitude in m) and a displacement time series - differential displacement measurement along the satellite LOS direction, see Figure 2.

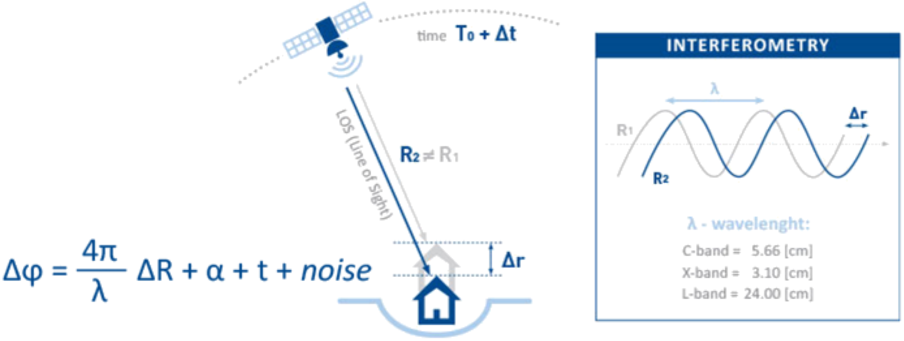

Figure 2 Principles of the InSAR measurement. The displacement is determined along the Line of Sight where the variation of the interferometric phase (Δφ) is determined for each location of the satellite at a given time [8].

For this study, data from the TerraSAR-X constellation are used, which delivers very high resolution SAR data in the X band, i.e with a 3 cm wavelength. This data is available over the area of interest since 2009 at an acquisition frequency of 1 image every 11 days. The data was processed using SkyGeo's commercial Antares software package.

## 2 MONITORING DATA

For one specific building in a street (Govert Flickstraat) perpendicular to Ceintuurbaan Station, the different measurement types have been compared. Figure 3 shows the cross section perpendicular of the station and Figure 1 shows the building of interest.

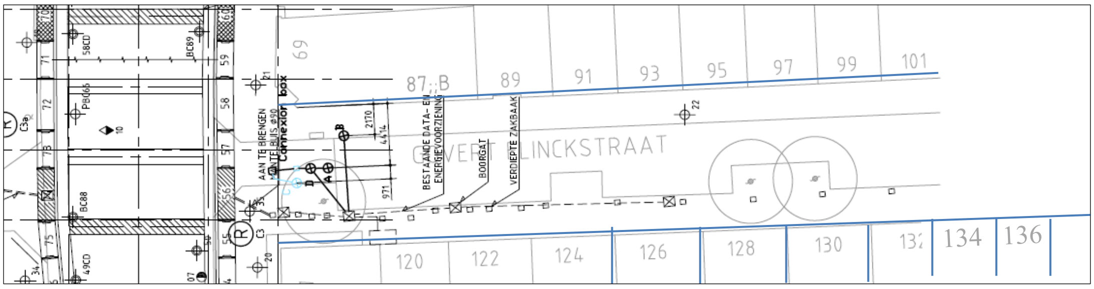

Figure 3 Cross section perpendicular of Ceintuurbaan Station

Satellite data were derived for this specific building and for the neighboring buildings, see Figure 5. Results of all the monitoring systems are shown in Figure 6. All the monitoring data is collected between 2009 (January) and 2013 (December).

Figure 5 PS-InSAR reflection points on buildings, building 136 highlighted. The colour of the points indicate the linear deformation rate. Green is less than 2 mm/year, yellow is less than 4 mm/year.

## 3 COMPARISON

Over this longer period, the manual measurements have shown very consistent results (see [2]). The automatic building monitoring system with prisms has a much higher measuring rate with which it was even possible to show temperature effects [9] and detailed information about the relationship between the construction process and the settlements (also shown in [2]). Due to the nature of this system, the reference of the prisms was a 'floating' average of the total stations in the area outside the zone of influence of the excavation works. This means that by definition there is a difference between the manual and the automatic measurements, because the whole city of Amsterdam is slowly sinking by deep ground water lowering in the polders areas. Therefore the total station measurements will underestimate the vertical deformation compared to the manual leveling. The InSAR-derived settlements have the advantage that the 30x50 km satellite images allow referencing the settlements of the building under investigation to any stable location inside the greater city of Amsterdam.

The prism measurements and the satellite derived settlements show about the same amount of scatter (in 136A larger scatter in the satellite based settlements, in 136B larger in the prism settlement). The measurement frequency of the satellite system (once every 11 days) is enough for the long term analysis as it is made here. For day to day risk control (for buildings closer to the excavation) a more frequent system is still necessary.

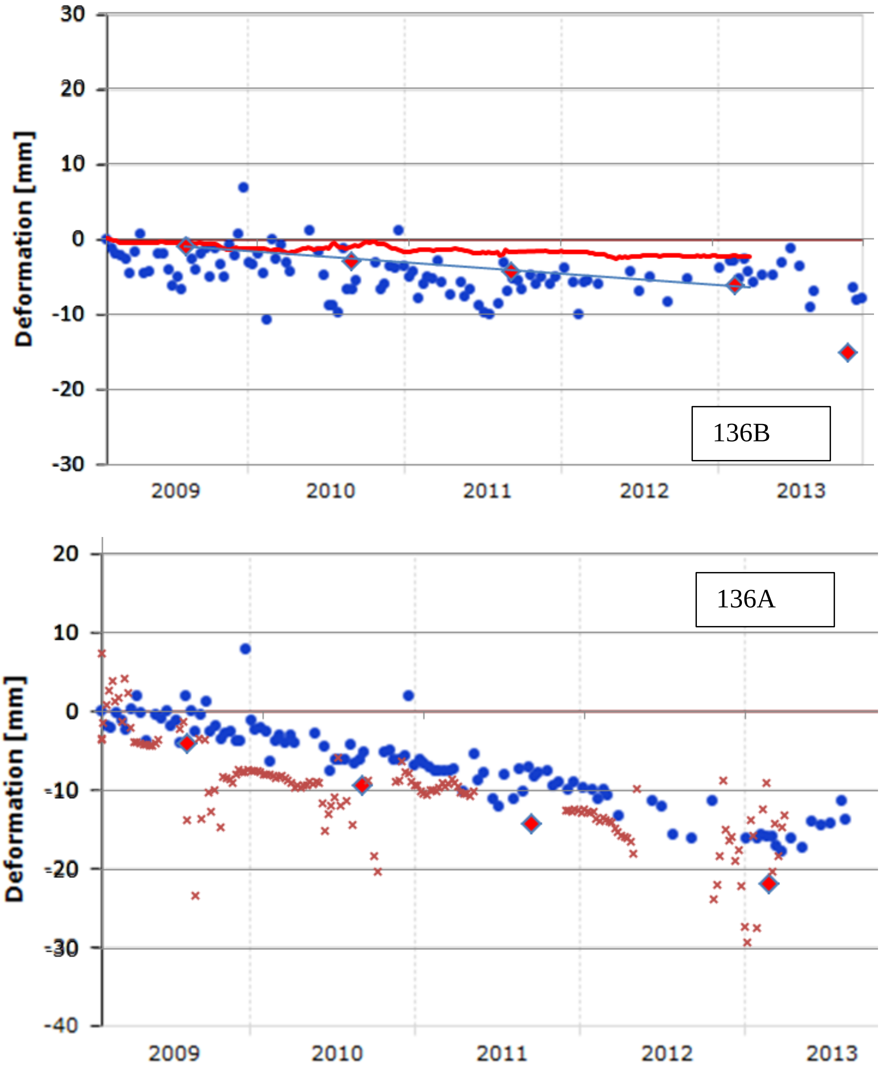

Figure 6 Comparison of prism, manual and satellite monitoring points. Prism data in red crosses, manual points in red diamonds and satellite in blue dots. Building 136 is positioned about 50 m away from the excavation.

## 4 OUTLOOK TO BUILDING DAMAGE

To really assess building damage from just satellite monitoring is still rather a challenge, but with increasing accuracy of the data the possibilities have increased significantly over the last few years. As an example of a way forward, the results are shown from another case where satellite data are used without comparison with manual measurements. In three cities in The Netherlands, a large number of buildings (over 300!) have been surveyed for damage as visible from street view. From these houses, also the satellite data have been assessed for potential indicators of building damage. The difficulty with the latter is that many points reflect on the structures, but a 3D image of the deformation is not easily obtained. As a first step, a virtual cross section is made perpendicular to the street the houses are built along. The deformation of this cross section is assessed from the satellite data and subsequently several damage indicators are used to compare with the surveyed damage. In [10] an analysis is made of the analysis of building damage derived from the absolute settlement difference over a building (A). Two potentially more advanced damage indicators have also been used (B) and (C). See Figure 7.

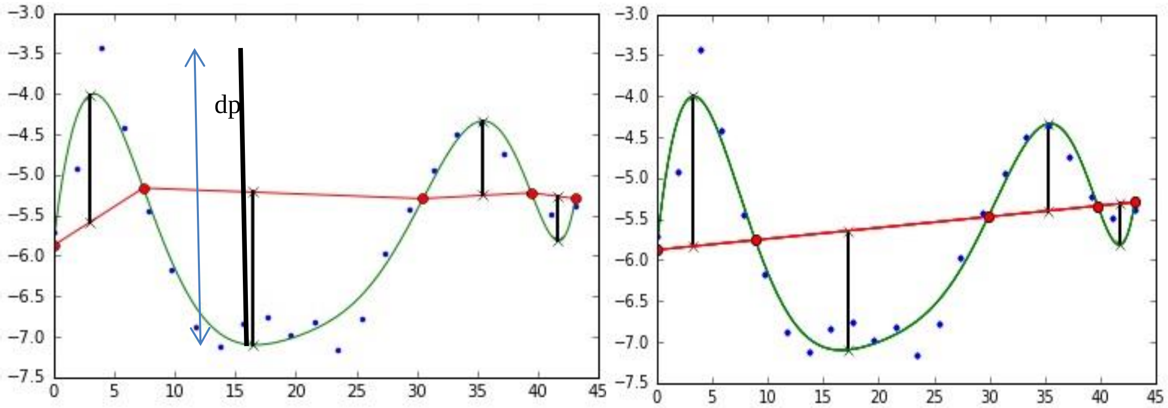

Figure 7 Principles of damage indicators A, B and C. With A is the maximum difference in settlement along the cross section (dp, left figure), B is the ‘deflection ratio’ measured using the connecting line between the first and last measurement point, ‘$\Delta_1/L_1$’ in left figure and C is the true deflection ratio as defined by [11], ‘$\Delta_2/L_2$’ on the right.

All three approaches are shown in Figure 7 for one example building of 44 m length. Figure 8 shows the results of the analysis comparing each of the approaches with the surveyed damage. It is noticed that the surveyed damage fits best (lowest standard deviation, largest difference between the categories) with the most simple damage indicator (A). The most advanced and theoretically most sound indicator (C) at this moment proves to cause much more scatter than the simpler approach. Using approach B, similar results are obtained as with approach C. Full analysis of the causes of this finding is still underway studying cases with manual as well as satellite data and preferably more detailed damage surveys (inside and outside) of the buildings. For now, the conclusion is that use of satellite data for damage assessment is possible if simple approaches are taken. Generalization of these findings needs to take place.

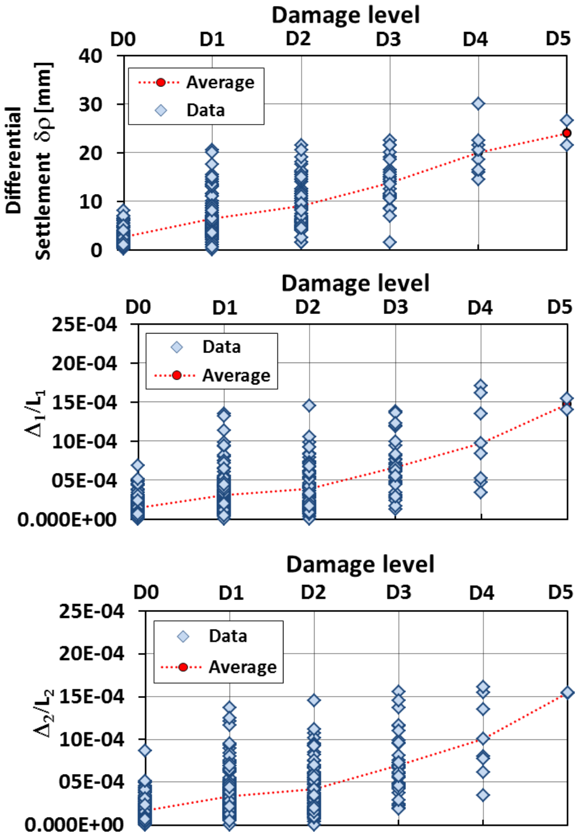

Figure 8 Comparison of surveyed damage with damage indicators A, B and C.

## 5 CONCLUSIONS

PS InSAR measurements show promising results for both the derivation of building settlements over a longer period of time as well as for the assessment of building damage. Especially the latter is a rather new application that with the improvement of the analysis methods and the resolution of the satellite measurements over the last few years has become possible. Use of satellite data for damage assessment of a large number of buildings from the presented study works best if simple damage indicators, in this case the absolute settlement difference, are taken. It is expected that improvements can be made in the analysis methods and the validation of the results with more detailed damage assessment data of a smaller number of more extensively surveyed data.

## 6 ACKNOWLEDGEMENTS

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