MONITORING FOUNDATIONS

Master's thesis

By

J. P. Verbeek

4141326

in partial fulfilment of the requirements for the degree of

Master of Science
in Civil Engineering

at the Delft University of Technology

9-5-2019

Preface

In this report the subject and the problem definition of my Master's thesis project will be described. Initial background information about wooden pile foundations and shallow foundations will be given. Furthermore the research questions and the approach on how to solve these questions will be discussed combined with the result. The thesis is written in partial fulfilment of the requirements for the Master degree Building Engineering of Civil Engineering at the TU Delft. From May 2018 to April 2019 I was working on researching and writing this Master's thesis.

I would like to thank the members of the committee; J.W.G. van de Kuilen, H.R. Schipper, W.F. Gard, D. A. de Jong, A. P. Heddes and J.L. Coenders for their useful feedback and guidance along the road. Also I would like to thank Fugro for providing the resources and knowledge to be able to do this research and SkyGeo for providing the data necessary to do the analyses. Moreover, I would like to thank KCAF for giving me access to their sensor data gathered during the first phase of their research.

Enjoy reading my thesis.

Joost Verbeek

Amsterdam, 15-04-2019

Abstract

It is estimated that about 400.000 houses in the Netherlands – both shallow and wooden pile foundations – could be facing problems with their foundations. Although, house owners are becoming increasingly aware of the fact that problems (and thereby costs) can be prevented if remedial measures are taken in time. Monitoring of the foundation can possibly give insights in the remaining capacity of the foundation.

In this thesis, research is performed into monitoring of foundations. The main research question is: Which methods can be used to monitor a foundation and to what extent are these useful and adequate? To answer this question, five different monitoring methods have been investigated: InSAR (Interferometric Synthetic-Aperture Radar), measurement bolts, a subsidence sensor, a groundwater level sensor and a tilt sensor. Other methods have not been considered and are beyond the scope of this research.

First, InSAR data has been compared to subsidence data gathered by measurement bolts in two different cases, one in Zaandam (Netherlands) and Amsterdam (Netherlands). Measurement bolts are used as golden standard in this comparison. The comparison of measurement bolts with INSAR data resulted in a maximum error margin of ± 0,86 mm/year for Case Study Block A and ± 1,31 mm/year for all measurements for the testcase in the Case Study Block B within a 95% confidence interval.

Secondly, the measurement bolts method has been qualitatively compared to InSAR data. Also, the pros and cons have been discussed. Measurement bolts have a better precision (0,3-0,5 mm) than InSAR data (2-3 mm) for individual measurements. Possible errors that can influence the accuracy of this method are: personal errors, instrumental errors and natural errors. InSAR and measurement bolts both have their strengths and weaknesses. Prescreening is an easier application for InSAR but highly accurate measurements in a specific location is more reliable if measurement bolts are used. In a way, these methods complement each other rather than measuring the same way.

The datasets collected by the subsidence, groundwater level and tilt sensors is made available for this research project by KennisCentrum Aanpak Funderingsproblematiek (KCAF) which is an independent knowledge and network organization funded by the government of the Netherlands. Generally, several factors can add noise to the signal. It is unknown if the signal of the sensors is calibrated to measure the right quantity.

This research project has shown that the data showed a similar trend of the groundwater level as local monitoring wells. Therefore, it can be concluded that the sensors are adequate to measure the groundwater level if they are calibrated and referenced to NAP. Moreover, the groundwater level sensor can possibly be used to measure how long dry periods are and how much wood is exposed to air, in order apply measures well in time.

Tilt sensors are currently not used for monitoring of foundations. The factors that can be considered when a tilt sensor is used to monitor a foundation are investigated with a literature study and with expert opinion. As the results show the measured rotation can be related to the stiffness of the wall where the sensor is mounted on.

As for all sensors, it has to be made sure if they are calibrated to actually measure what they observe. Further research could usefully explore how viable a system of sensors is. In general, classification or a prediction of the remaining service life of a foundation can be challenging. Further research might explore how useful it is when big dataset are combined to be able to give better judgement.

Table of Content

1. Introduction

1.1 Problem definition

Nowadays, house owners are often unaware in what condition their foundation is. It is estimated that about 400.000 houses in the Netherlands – both shallow and wooden pile foundations – could be facing problems with their foundations. (KCAF, 2018).

Categorization of the condition of foundations is done by the use of the traffic light colours: Green, Orange and Red. Code Green represents the cases in good condition. These foundations do not need to be checked again for the coming 25 years if the boundary conditions remain unchanged. Code Red represents the cases where immediate action is required. In these cases the foundation does not meet the requirements or does not have sufficient load bearing capacity left. Code Orange represents the cases which are difficult to assess and therefore require special attention. These foundations have a predicted lifespan ranging from 5 to 25 years during which the foundation continues to function, without any need for remedial measures. This range is very wide and it is unknown when these "Code Orange" foundations become critical. A solution could be to observe the situation for alterations indicating a problem.

In this research project, tracking of the parameters: subsidence, groundwater level and tilt of a house or block is referred as *monitoring*. To get more insight in the current state of a foundation, research and categorization is done based on a protocol called "Richtlijn Houten paalfunderingen onder gebouwen" (F3O & SBRCURnet, 2016). This investigation protocol is described in section 2.4. Also, there is a protocol for shallow foundations, called "F3O Richtlijn onderzoek en beoordeling van funderingen op staal" (F3O, 2014). This protocol will not be further elaborated because it is partly the same as the one described in section 2.4.

F3O-Protocols are there to help the experts judge if certain parameters have become critical. Subsidence in foundations is normal. For instance, pile foundations in Amsterdam have a normal subsidence on average of 0,5 to 1,5 mm/year and in Rotterdam of 1,0 to 2,0 mm/year. If higher values are occurring, this can become alarming. The real problem lies in sagging differences and large subsidence. These can cause damage to the structure (see picture below).

Figure 1 Cracks in the façade caused by settlement. (source: kcaf.nl)

However, house owners are becoming increasingly aware of the fact that a lot of problems (and thereby costs) can be prevented if remedial measures are taken in time. When there is uncertainty about the condition of a foundation, foundation research can reveal the current condition and the rate of deterioration. Given the deterioration rate, a time interval can be established on when a new check-up needs to be done. However, monitoring can possibly give insights in the remaining capacity of the foundation. Potentially, it can indicate if and when immediate action is required. The picture below shows one of the many problems wooden foundation piles can face.

Figure 2 Broken wooden foundation piles (source: Fugro)

Once a foundation research has been executed and the foundation condition is classified as mediocre, it raises questions. How long can the foundation service without a check-up or remedial measures? A lot of methods can be used to monitor a foundation. This Master's thesis will look into a few of these methods. Combining methods into a system can potentially provide a powerful tool to keep track of the parameters around a foundation. Moreover, it can verify the outcome of a foundation research. There is currently no real-time monitoring system designed for this purpose. It will be financially beneficial if foundation repair can be postponed but at the same time guarantee that remedial measures will be taken just in time to prevent severe damage. Real-time data can possibly help to show when and where action is required.

1.2 Research objective

The aim of this Master's thesis is to investigate five different possibilities to reliably monitor a foundation including: InSAR (Interferometric Synthetic Aperture Radar) data, measurement bolts, a subsidence sensor, a groundwater level sensor and a tilt sensor. The sensors have been investigated to be able to help an ongoing experimental research called "Code Oranje" by KennisCentrum Aanpak Funderingsproblematiek (KCAF) on sensor data. InSAR data has been investigated because it could be relevant for foundation monitoring and measurement bolts have been investigated because they are frequently used for foundation monitoring in current practice. Other methods are not considered and are beyond the scope of this research. The question to what extent these methods are useful and adequate to monitor a foundation will be elaborated in the next paragraph. With data measured by a monitoring system, experts can keep track of changes regarding the foundation. Moreover, an alerting function in such a system would allow to apply remedial measures just in time. Possibly this can reduce uncertainty of the service life of Code Oranje foundations. On a higher level, the monitoring system can function to map risk areas. This can possibly save time and money when larger areas need to be investigated for foundation issues.

1.3 Research questions

In this section the main research question and the sub questions will be presented and discussed. The main question of this research is:

Which methods can be used to monitor a foundation and to what extent are these useful and adequate?

To address this broad question, five sub questions are devised, which will comprise the methods studied.

1. To what extent is InSAR data useful and adequate to monitor a foundation and what are the advantages and disadvantages?
2. To what extent are measurement bolts useful to monitor a foundation and what are the advantages and disadvantages?
3. What factors can influence the data measured by subsidence sensors?
4. To what extent are groundwater level sensors useful and adequate to monitor a foundation?
5. What factors can be considered when a tilt sensor is used to monitor a foundation?

New methods are used to measure subsidence, groundwater level and rotation and therefore the reliability has to be determined. Reliability can mainly be determined by the accuracy of a measurement method.

1.4 Data sources

In this section the source of the data collected by each of the five monitoring instruments (InSAR, measurement bolts, subsidence sensor, groundwater level sensor and tilt sensor) will be discussed.

The InSAR data has been made available for this research project by SkyGeo. The satellite data contains subsidence measurements of Case Study Block A in the period from February 5, 2009 to October 2017 and Case Study Block B from February 5, 2009 to January 5, 2018. SkyGeo has the copyright.

Two datasets are collected by measurement bolts. One dataset contains subsidence measurements of Case Study Block A in the period from September 19, 1986 to August 2, 2017 which is made available for this research project by Fugro Geoservices b.v. The second dataset contains subsidence measurements of Case Study Block B in the period from August 15, 1993 to June 1, 2018 retrieved from City Data Amsterdam which is an open source platform (Amsterdam, 2018).

The three datasets comprising the subsidence, groundwater level and tilt sensors are made available for this research project by KennisCentrum Aanpak Funderingsproblematiek (KCAF) which is an independent knowledge and network organization funded by the government of the Netherlands.

KCAF aims to prevent problems with foundations and foundation failures. This organization tries to connect the municipality, owners, foundation consultants and foundation repair contractors to get the most optimal approach to deal with foundation problems. They are committed to solve the consequences of foundation problems and they are looking how to improve the situation around damaged foundations; also they inform owners to be aware of all the consequences of these issues. They give courses and lectures to raise awareness around this topic.

The datasets are part of the first stage of a pilot project called Code Oranje. During this project, KCAF is designing a system of sensors to monitor the foundation of a building block. Sensors are used to automatically generate data of the groundwater level, deformation, subsidence. The first stage of Code Oranje consists of testing the initial set of installed sensors.

All datasets collected by the sensors are located in the Case Study Block C (Rotterdam, the Netherlands). The first data set contains subsidence measurements in the period from March 21, 2017 to September 26, 2017. The second data set contains groundwater level measurements in the period from March 22, 2017 to September 26, 2017. The third data set contains rotation measurements in the period from March 21, 2017 to September 26, 2017.

1.5 Report structure

This report consist of five main parts. The first part is this introduction followed by the theoretical framework (chapter 2) and the third part consists of the methodology (chapter 3). The fourth part consists of the results and findings (chapter 4) and the last part the analyses and conclusions (chapter 5 and 6). Every measurement method will have a separate track following this structure.

2. Theoretical Framework

This chapter will give an overview of the background information gathered in a literature study by the author. This includes an explanation of the risks regarding a wooden pile foundation. Moreover the foundation inspection protocol will be explained. Finally, the theory behind InSAR will be given.

2.1 Dutch soil structure

A lot of areas in the Netherlands have a weak top layer especially in the western parts. Figure 3 shows an abstract overview of the upper soil types in the Netherlands.

Figure 3 Overview soil types in the Netherlands. Source: (Ritzema)

As the figure shows, a big part of the Netherlands is covered with weak soils like clay, peat and loam. In those areas the load-bearing layers like dense sand layers are located below the surface.

2.2 History of foundations in the Netherlands

People used to build wooden houses with shallow foundations and because these houses were so lightweight this gave no problems. But as the time went by the need grew for a stronger material like stone to build castles and churches. This new building material resulted in heavier buildings, so a foundation with more bearing capacity was needed. During the 17th century until halfway the 20th century a lot houses were built with a wooden pile foundation and many houses are still standing. Until this day it is estimated that 25 million wooden piles in the Netherlands have a load bearing function. 12,5 Million of these piles are used for buildings and the rest is used for hydraulic structures like quay walls. (Klaassen, Nelemans, & den Nijs, 2013) This is not without problems. Bacterial decay is a concern for wooden piles and due to water drainage, the wooden piles have to cope with fungus attack. These events lead to a lower load bearing capacity and eventually failure.

Later, between 1870 and 1970, 750.000 houses with wooden pile foundations were built, mainly around cities like Amsterdam, Rotterdam, Zaandam and Haarlem. One-third of these houses (250.000) will have foundation problems in the next 15 years, because they are located in peat and clay areas (see picture below).

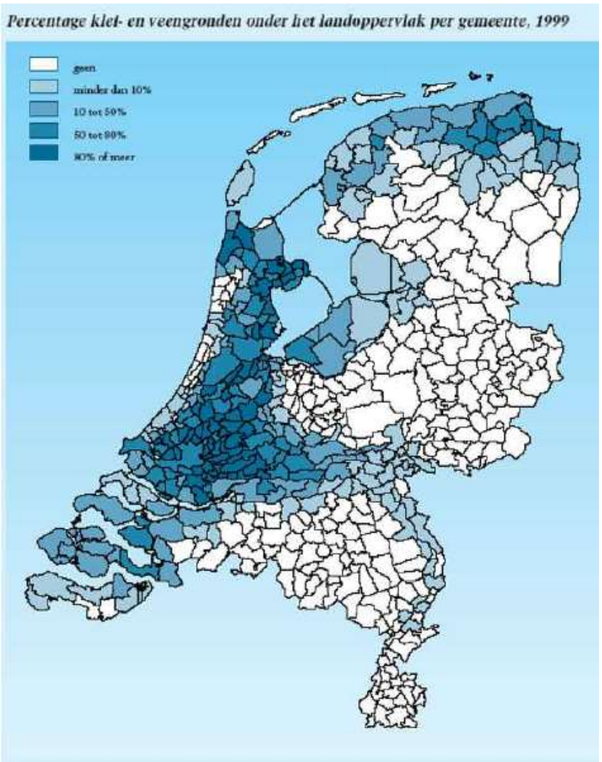


Figure 4 Percentage peat and clay areas under top layer per municipality, 1999

If no action will be taken, the number of houses with foundation problems will increase. Not only houses with wooden pile foundations are at risk but shallow foundations as well. There are around 300.000 houses on shallow foundations, and half of these houses will have foundation problems in the next 15 years (KCAF, 2018).

In the Netherlands, mainly two types of pile foundations for houses are present. The first method is the Rotterdam foundation. A single row of piles was placed below the load bearing walls of a house. This method was mainly used in Rotterdam and its surroundings. The second method is the Amsterdam foundation. In this method two rows of piles with a wooden beam (in Dutch: 'kesp') on top were placed below the load bearing walls. The additional row of piles was used to increase the capacity of the foundation. This method is mainly used in Amsterdam but occurs in different cities as well, for instance Zaandam and Haarlem. The picture below shows the two pile foundations schematically.

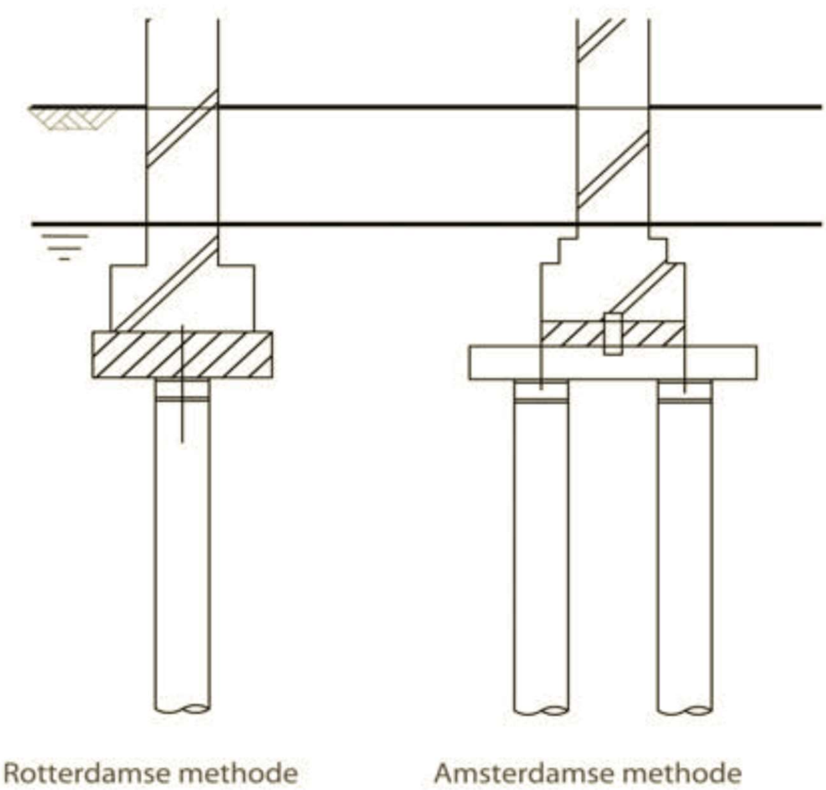


Figure 5 Pile foundations occurring in the Netherlands

People used to put piles in the ground to reach the dense sand layers. Depending on the depth of the dense sand layer and availability of the wood species, usually pine or spruce was chosen (Lange, 2011). Only relatively short piles are available in pinewood. In the region of

Zaanstad, pine was often chosen as wood species. Here, around 7-10 meter below NAP, a dense sand layer is present see CPT 1 (Cone penetration test) below.

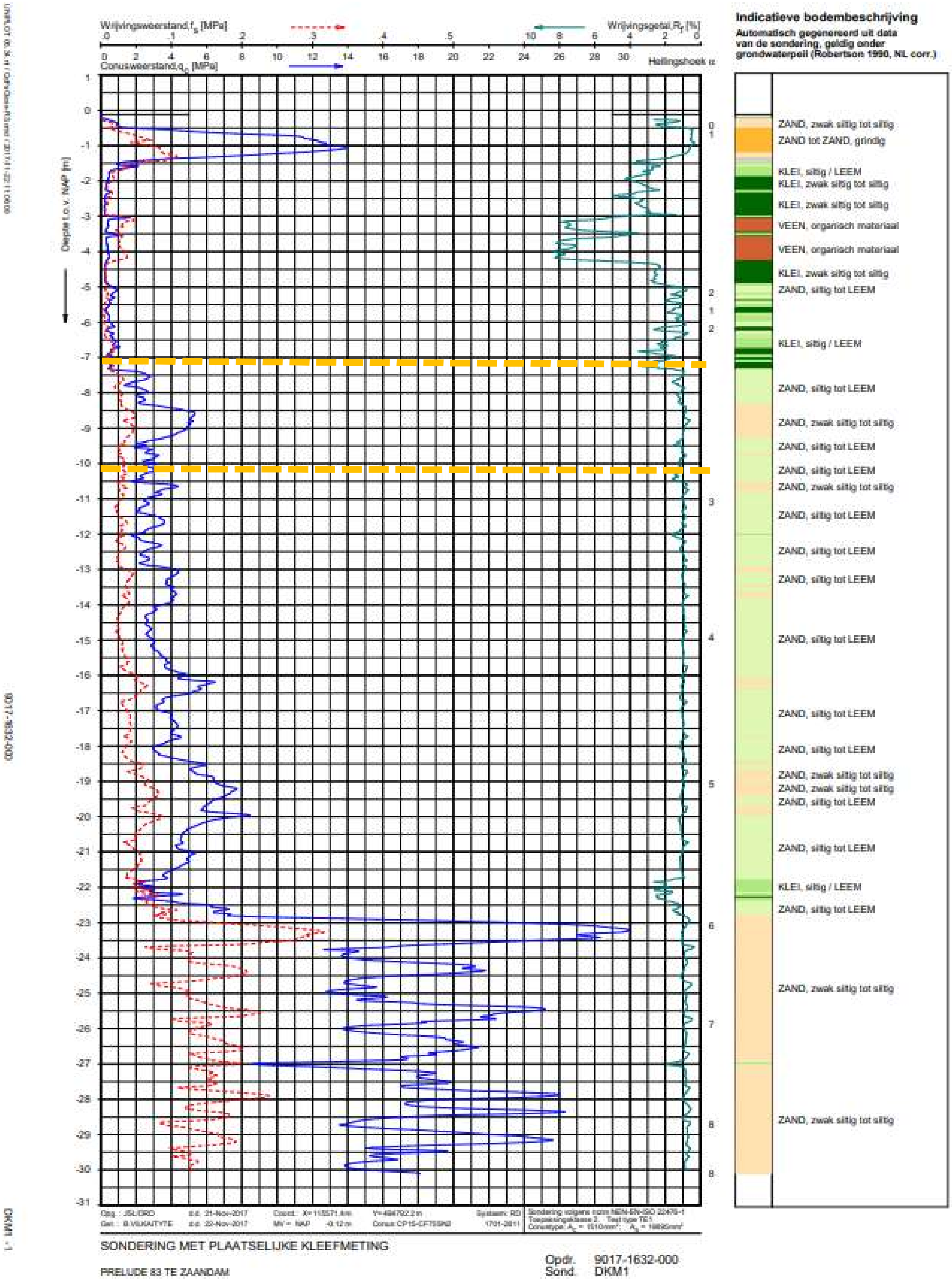


Figure 6 CPT 1 Prelude, Zaandam (source: Fugro)

The top layer consists of sand raisings (0 to -1,5 m NAP) followed by a mixed layer of peat and clay (-1,5 to -7,5 m NAP). In the region of Amsterdam the dense sand layers start at a depth of 12-14 meters below NAP, see CPT 2 below.

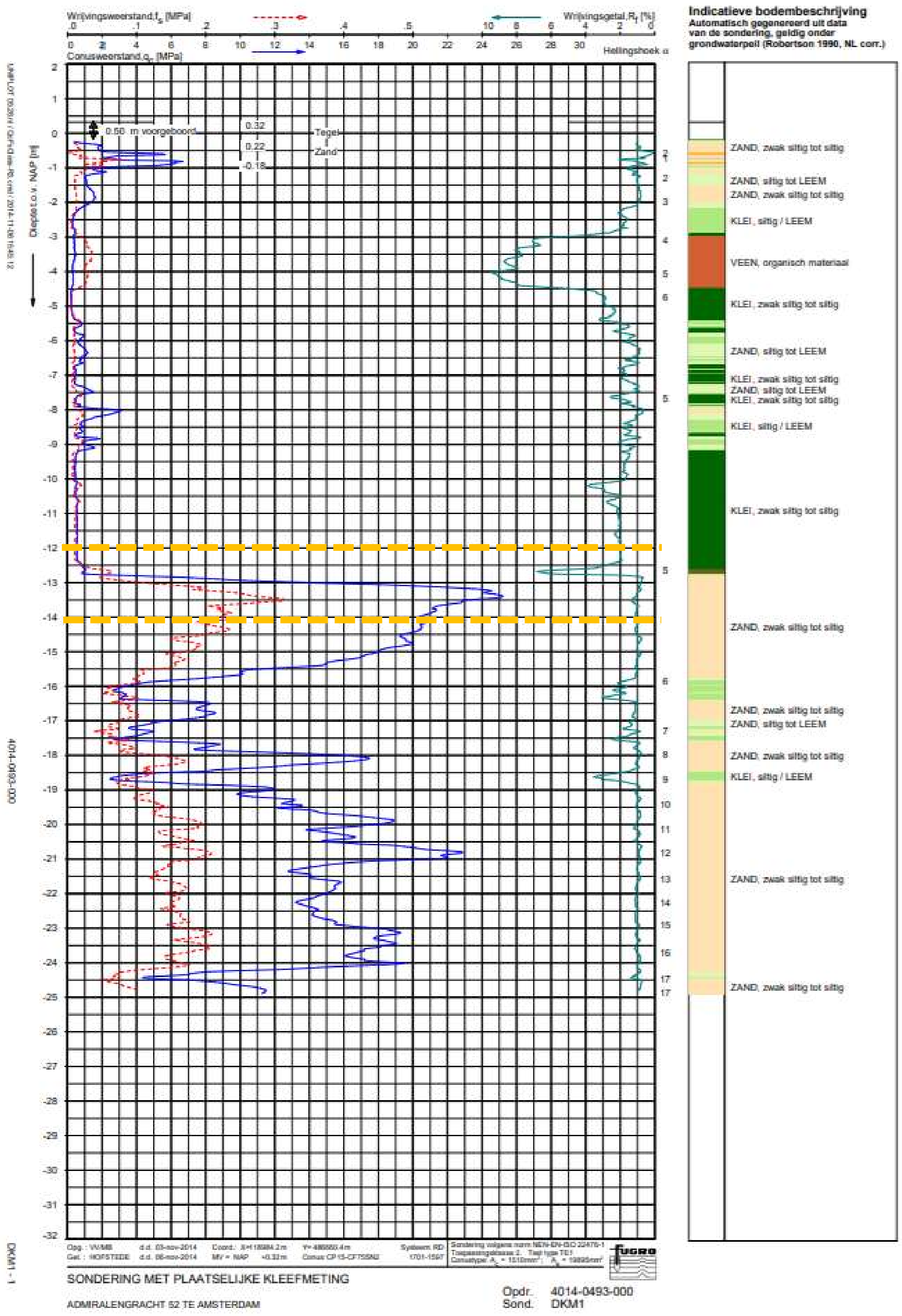


Figure 7 CPT 2 Admiralengracht, Amsterdam (source: Fugro)

Although wooden pile foundations are still in use, nowadays concrete or steel is mostly used as material for foundation piles. Sometimes concrete was used in combination with wooden pile foundations, the top of the pile had to be driven below the groundwater table to deny the fungus attack, see picture below.

Figure 8 Fungus attack on wooden pile (source: Platform Fundering)

Wooden piles are tapered, lengths of 15 to 18 meters are common in the region of Rotterdam. The diameter on the head of the pile is 260 to 280 mm and the 130 to 150 mm on the tip of the pile. Although these measurements are easy to use, in practice the perimeter of the pile is used: For instance, 0,85/0,45 m. The tapered shape has a positive effect on the skin friction, the friction component is reduced by the angle of the pile, see Figure 9 below. Unfortunately in practice α is smaller than 1° which is not sufficiently significant to reduce the *negative skin friction*. This phenomenon will be elaborated in 2.3.3. (Tol, 2006)

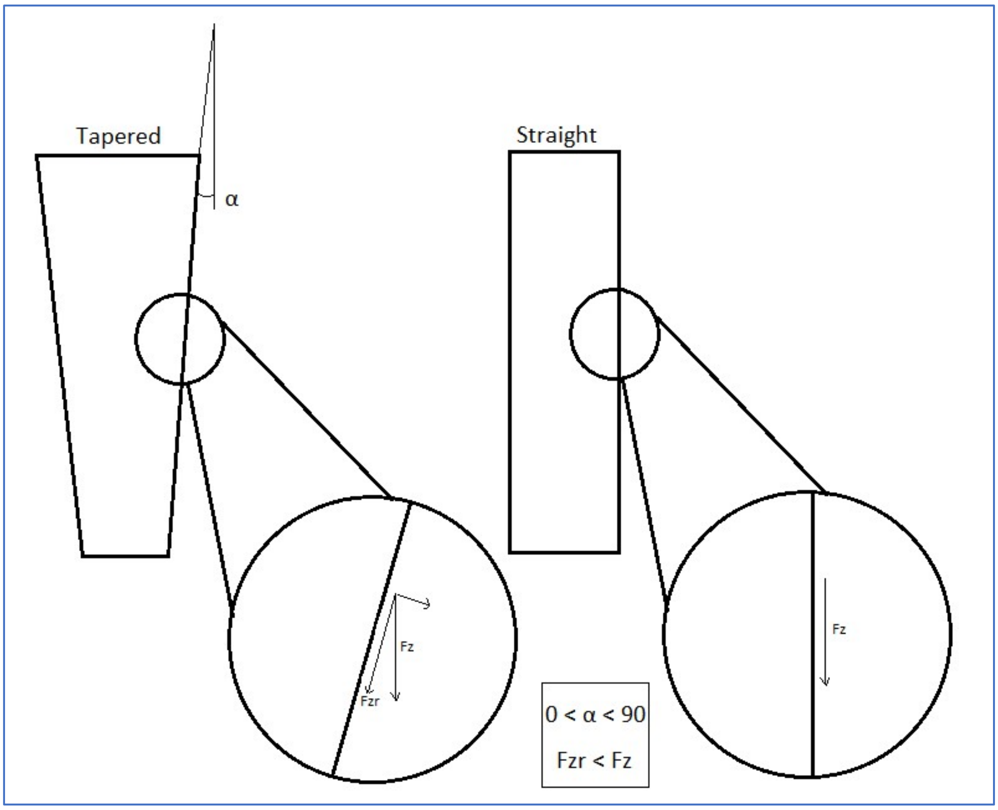


Figure 9 Less negative skin friction due to tapered shape

2.3 Foundation risks

Historically, timber has been a plentiful, locally available resource in many areas. Historic buildings in the Netherlands are built on pine and spruce wood that originated from different regions: Pine originated mainly from the Netherlands but also from Finland and Sweden. Spruce was either imported from southern Germany or, in the mid-17th century, from Norway. Especially in the 17th century, a lot of softwood and oak were transported to the Netherlands. (Sass-Klaassen, Vernimmen, & Baittinger, 2007)

Although timber piles are cheaper than concrete and steel piles, it should be clear that wood is not suitable for heavier loads. Also, there are several problems that can affect a wooden foundation:

1. The foundation can rot due to a fungus attack.
2. The foundation quality can decline due to bacteria.
3. The foundation can subside due to negative skin friction.
4. Due to construction errors, for example, insufficient piles, overloading, application of poor wood quality or insufficient depth (Klaassen R. K., 2012).

In the following subparagraphs the previous risks will be elaborated on and how they relate to the parameters groundwater level, rotation and subsidence.

2.3.1 Wood rot

Wooden foundations generally perform well under anoxic conditions. If the upper part of the wooden foundation construction is getting above the ground-water level, oxygen supply through air will allow wood degrading fungi to be active. The velocity and intensity of the decay is determined by the duration of exposure of the foundation timber, the amount of timber or part of the pile exposure to air, the wood species and the water-holding capacity of the soil. These factors can be measured by monitoring together with the information about the soil structure from a CPT and the wood species.

It is estimated that the maximum degradation velocity of soft-rot fungi that attack water-saturated wood from outer part towards the inside of the pile is approximately 10 mm/year, whereas brown- and white-rot fungi which attack drier wood act much faster by penetrating with a maximum of 100 mm/year radially into the pile. See the graph below. This graph shows the progress once the soft rot is active. If the cumulative time of exposure to air is more than 2 years, there is a possibility that wood degrading fungi is active in “grenen spint” and 4 years for “vuren”.

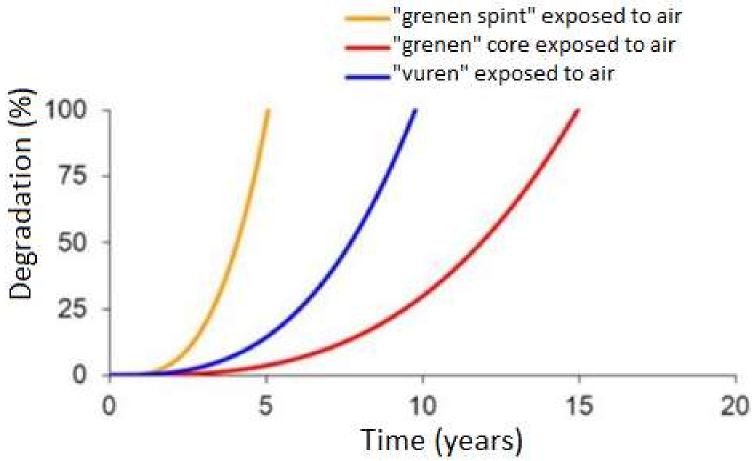


Figure 10 Wood decay by soft rot (Source: SHR)

A decrease in groundwater table often occurs when the Water Boards are forced to lower the groundwater table, because otherwise houses will be flooded. The western part of the Netherlands exists of a patchwork of polders, each with its own pumping system and specific street- and groundwater level. For security reasons it is asked that the lowest groundwater table should be at least 0,5 m above the upper part of the wooden foundation parts.

However, differences between the street level and the upper parts of the foundation are sometimes marginal which means that the ground water table has to be adjusted within a range of 0,2 m. A critically low groundwater level can also appear locally because of broken sewerage systems that act as drainage as they are situated below the groundwater level. The local government is responsible for the sewerage. Other causes of local low groundwater levels are evaporating trees (in spring and summer) or building pits (Klaassen R. K., 2015).

2.3.2 Bacterial decay

Until the eighties of the last century it was believed that no decay was possible when wood was stored under water. Colonisation by bacteria of pounded wood was not considered as wood decay. Bacteria were thought to cause an increased permeability by attacking the pit membrane but were not considered as wood degraders. Only in the beginning of the 1980ies proved that bacteria are able to degrade the woody cell wall. Wood degrading bacteria live in consortia of several species and are common in a wide varieties of soil types. Their decay velocity is typically slow but as they do not need oxygen they are active in environments that are unfavourable for fungi. Bacterial wood degradation is a long-term process. It proceeds much slower than fungal attack. In contrast to fungal decay where the activity is mainly influenced by the environment (availability of oxygen), the activity of wood-degrading bacteria is related to wood quality (permeability); round wood timbers often have sharp boundaries between permeable and nonpermeable structures, i.e. sapwood and heartwood. If such a boundary is reached by the wood degrading bacteria, their activity drops considerably (Klaassen R. K., 2015).

Since the colonisation of bacteria is not affected by groundwater, this phenomena cannot be observed by monitoring of the groundwater level. The load bearing capacity of the piles is slowly decaying when bacteria are present. The subsidence behaviour of a pile with bacteria decay are characterised by an exponential increase of subsidence in a relative short period (less a year) when an affected pile is close to failure. Especially, thin pinewood piles can only begin to show subsidence just before failure (Heddes A. , 2014). In cities like Haarlem and Zaandam this is a serious problem.

2.3.3 Negative skin friction

Usually piles are driven through soft top layers where the head of the piles are placed in a load-bearing layer which can carry the pile loads almost without settlement. The soft top layers exert a negatively directed frictional force on the pile shaft if they are subjected to sagging, when they are loaded by sand raisings (Figure 11).

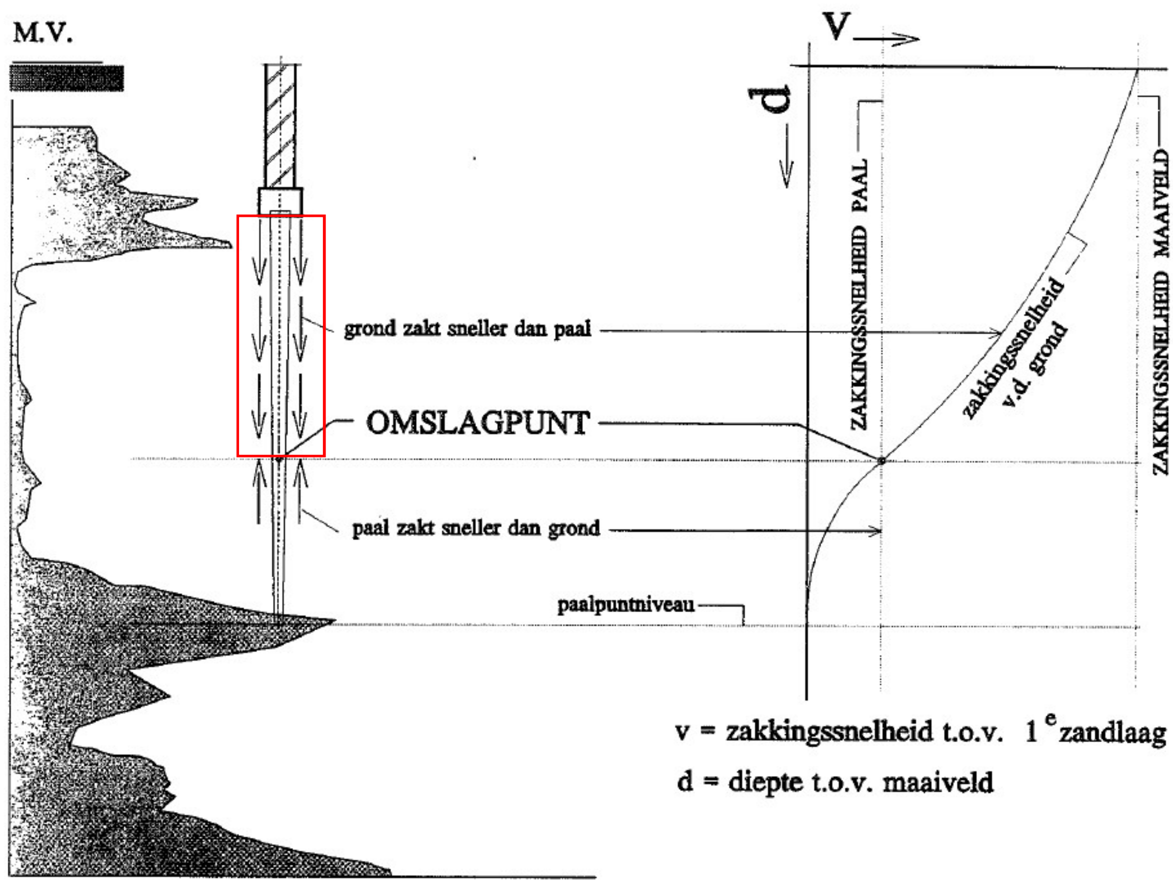


Figure 11 Negative skin friction (Bruine de Bruin, 1997)

This additional load can rise to very high values, even to the same order of magnitude as the load on the pile head. It is therefore necessary to consider the possible load caused by negative skin friction.

In the early 30's no one considered the additional load caused by negative skin friction. During that time the first cases of negative skin friction came to the light. This phenomena caused a lot of wooden piles to be overloaded which resulted in extra settlements. In cities like Amsterdam and Rotterdam this an actual problem (Tol, 2006).

The behaviour of a foundation affected by negative skin friction can be observed with subsidence monitoring. In comparison with normal ground level subsidence, an increased subsidence speed can be observed. Although this is not always a clear relation. Normal subsidence is between 0,5-2 mm/year depending on the region. In particular cases, the foundation can transform in a hybrid foundation and start to behave more like a shallow foundation instead of a pile foundation. The loads are partially distributed to the soil directly below the walls. These foundations are susceptible of faster subsidence caused by a lower groundwater table. When the pore pressure reduces the effective stress on the soil increases, this leads to an increasing total stress on the soil. Ultimately, this forces the loads to be carried by the piles again, only now those are located deeper into the soil because they continued to subside as a result of the negative skin friction (Verruijt & Broere, 2012).

2.3.4 Construction errors

In Rotterdam, the soil in areas with buildings has been raised with 4 meter thick sand layer. Surface level is around -2 m NAP and a thick layer of clay and peat starts at -7 m NAP until a depth of -16 m NAP followed by a dense Pleistocene sand layer with cones resistances between 10 to 30 MPa. See Figure 12 below for a representative CPT (Cone penetration test) in the Elektroweg in Rotterdam (29-02-2012).

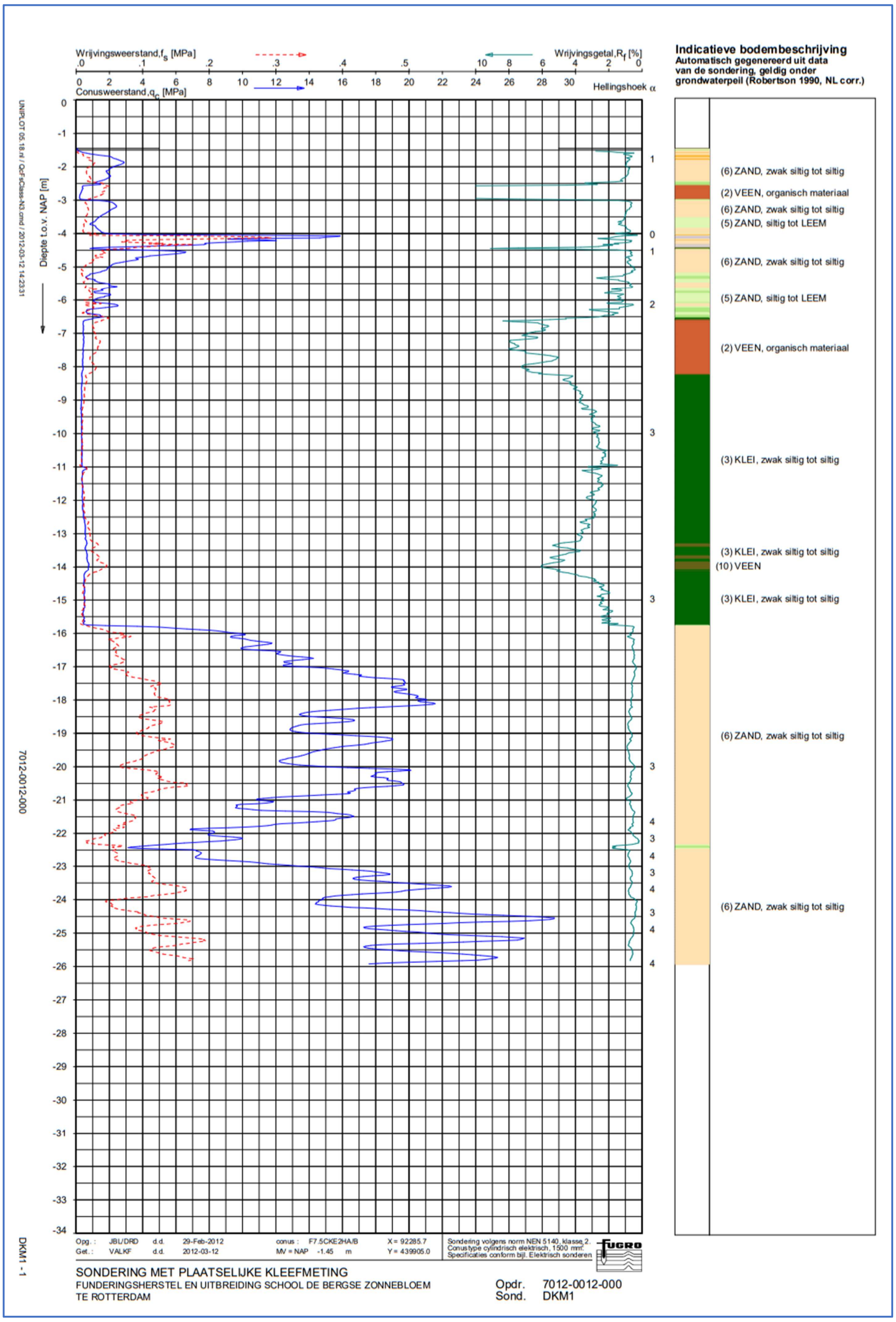


Figure 12 CPT in Elektroweg, Rotterdam (source: Fugro)

Due to this soil profile usually pile foundations were used. Wooden piles with a maximum length of 16 meters were common. Unfortunately, sometimes they did not reach until the sand layer. This was due to the methods they used. The amount of hits to drive a pile into the ground compared with the distance it travelled determined if the pile reached the sand layer. Nowadays, the cone penetration test is used, but before the 1950s this method - to determine the soil properties at a very accurate level and the corresponding design calculations by Koppejan - still has not been developed (De Reister, 1971). If a pile is driven into the ground with an angle other than 90 degrees it can result in the occurrence of mechanisms because of a different distribution of the loads in the foundation which can exceed the maximum capacity.

Another construction error is, usage of too few piles, resulting in overloading. Moreover, inaccurate placement of piles can result in a lower capacity of the foundation. Construction errors are very specific for each and every case. The increase in subsidence of such cases can be monitored by subsidence monitoring. Also tilt monitoring can possibly show where these errors are located.

2.4 Foundation research protocol

This chapter will give an overview of the currently used foundation inspection protocol which is currently based on the “Richtlijn houten paalfunderingen onder gebouwen” (F3O & SBRCURnet, 2016). The inspection methods and measurements will be discussed.

2.4.1 Archival research

The first part of a foundation inspection is an archival research. During this process historical information is gathered. In the table below the minimum required information of an archival research is listed and the goal of this information.

Required information	**Goal information**
Construction date and drawings of building	Building age and layout
Initial construction level of ground floor	Ability to compare to current level
Wood dimensions "langshout" and "kespen"	Determine strength of foundation elements
Historical soil information (raisings)	Additional (eccentric) loading on foundation
Historical groundwater level	Ability to compare to current groundwater level
Construction information: Stability elements	Distribution of loads in the building into the foundation
Construction repairs or adjustments	Change in distribution of loads
Shared building elements	Distribution of loads in the building into the foundation
Results of past inspections and researches	Ability to keep track of earlier discovered foundation issues

2.4.2 Visual inspections

After an initial archival research, a visual inspection of the inside and the outside of the building follows. This consists of a photo report of the defects that show reduced capacity of the foundation. This can be cracks or bulging of the wall. Connections with parts constructed in later stages have to be checked as well. The inside inspection has to preferably take place at the ground floor or if possible in the basement. The outside inspection has to pay attention to the masonry, the connection to adjacent houses and the slanting of window and door frames.

2.4.3 Skew measurements

Three types of skew measurements have to be executed. In the table below an overview of the measurements in this section is given.

Measurement type	**Description**	**Purpose**	**Accuracy**
Level measurement for masonry	Measuring façade elements laid out horizontally by means of levelling	Determine the deformations of the premises	± 2,5 mm
Level measurement for floor	Measurement of the height of the original floor compared with the height during construction	Determine the deformation of walls connected with the foundation	± 10 mm
Skew measurement	Measurement of the skewness on facade	Determine rotation of the building	± 10 mm or ± 0,072°

To execute a skew measurement the device used has to have a precision of at least ± 10 mm. Since this depends on the height of the façade, an indication of the rotational precision for a 8 m height façade is given below.

$$\tan^{-1}(0{,}01/8) = 0{,}072°$$

Results of the measurement will be classified by the following table. (F3O & SBRCURnet, 2016)

Rotation	Damage	Classification
< 1:300	None	Nothing
1:300 tot 1:200	Architecturally	Small
1:200 tot 1:100	Architecturally	Moderate
1:100 tot 1:75	Structurally	Large
> 1:75	Structurally	Very Large

Table 1 Rotation classification

2.4.4 Height and subsidence measurements

In order to link the current and historical construction level a vertical measurement of the top of the ground floor has to be done. Usually the construction level is determined and indicated in the building plan relative to NAP. The accuracy of this type of measurement is ± 5 mm.

The subsidence per year ("Nauwkeurigheidswaterpassing") will be determined by a measurement of a fixed point relative to a reference point on a nearby building which is considered not to be subjected to subsidence. In practice even reference points are subjected to subsidence which causes some NAP reference points to subside faster than others. In the Netherlands, this can differ -4 to +2 cm over 50 km. This is noticeable in large-scale surveying projects, especially in case of satellite positioning for the purpose of altitude measurements. This phenomena is caused by of the soil movement and old errors in the primary NAP network. (Brand, 2004)

The interval advised in the protocol is 3 – 6 months if an instable situation is expected. The classification of the "Nauwkeurigheidswaterpassing" is according to the table below. The accuracy of this method need to be ± 0,5 mm.

Subsidence [mm/year]	Classification
< 0,5	Nothing
0,5 - 2	Small
2 - 3	Moderate
3 - 4	Large
> 4	Very Large

Table 2 Subsidence classification

When the data of a "Nauwkeurigheidswaterpassing" is analysed, attention should be paid when the subsidence is small, this might fall in error margin.

2.4.5 Surroundings

The surroundings are part of a foundation research and have to be visually inspected. Anything in the surroundings that can negatively influence the quality of the foundation has to be documented. Examples of such factors are adjacent new buildings, raising of the street level, building pits, subsidence of the premises related to the street and surface water levels.

2.4.6 Groundwater level measurement

The groundwater level has to be measured to determine the coverage of the foundation piles. If foundation piles are exposed to oxygen for a long time, there is risk of the occurrence of fungus attack. The accuracy of this type of measurement is 10 mm and the water coverage is classified in the following table.

Groundwater coverage	Classification
> 200 mm	Sufficient
50-200 mm	Small
< 50 mm	Insufficient

Table 3 Groundwater coverage classification

Groundwater measurements of local monitoring wells cannot be used without further interpretation unless the well is located close to the location of the inspection. The groundwater level has too much variation in small areas because it depends on factors like sewer systems, surface water and soil structures which can have a high variety.

2.4.7 Foundation inspection

The next phase in a foundation research project is the inspection. Based on the acquired knowledge described in Section 2.4.1 until 2.4.6, inspection pits are being dug. The protocol prescribes two inspection pits for building blocks until five houses and three inspection pits for more than five houses but this can deviate based on earlier research.

Once the foundation construction is revealed the quality can be determined. The dimensions of the foundation have to be reported, this includes the pile, brickwork and concrete girder. The effective diameter of the piles will be determined by a penetration test where a hammer hits the wooden pile with a certain force and subsequently the penetration depth is measured. With this information the remaining load bearing capacity can be determined.

2.4.8 Foundation assessment

The goal of the foundation assessment is to assess the current quality and the future life span of the foundation. This assessment is based on the factors described in the previous sub-paragraphs and the stability and load bearing capacity of the foundation. Next, an expert's analysis is necessary for assessing the foundation and the mutual coherence of the research components. Factors influencing this are usually because the result can have great consequences for the parties involved. Experts at Fugro emphasize this and are really careful when giving a classification to a foundation.

2.5 InSAR technical information

To understand how InSAR (Interferometric Synthetic Aperture Radar) technology works, this Section describes the basics (SkyGeo, 2018).

Active satellites mounted with a radar system are able to send out a radar signal to the surface of the earth which is reflected and captured by a sensor as an image containing the phase and the amplitude. The phase is the fraction of a complete wavelength reaching the sensor on a scale from 0 to 2π and can be coded by a colour. The amplitude is the strength of the signal. See Figure below.

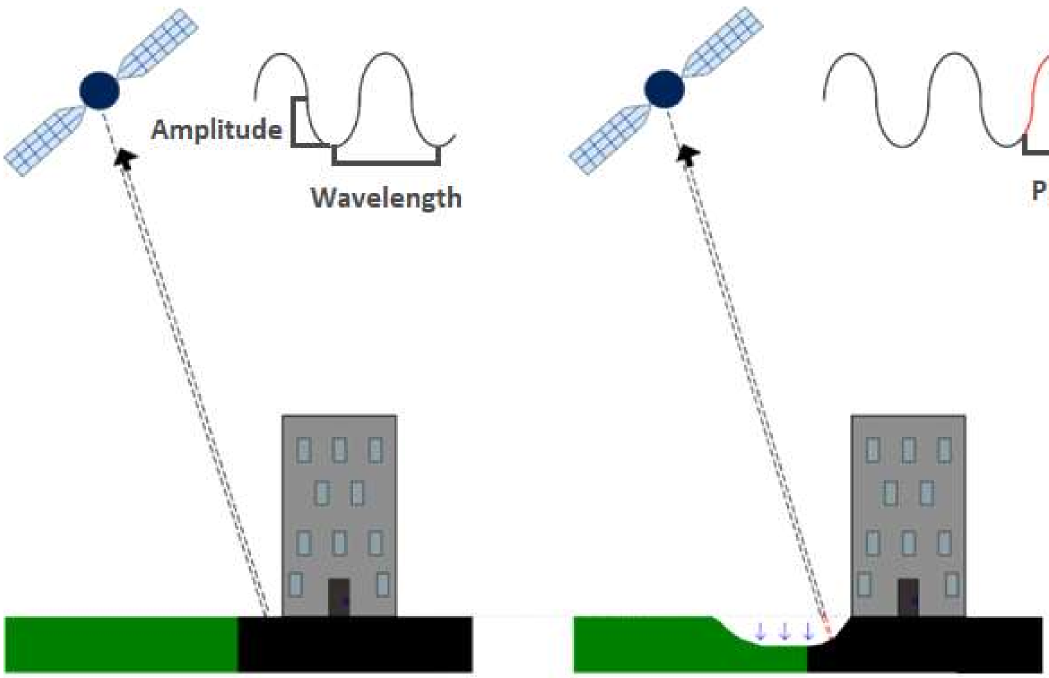


Figure 13 Radar signal before and after subsidence.

To measure deformation with this radar signal, two images containing the phase can be subtracted. The resulting image is called interferogram (see the Figure below).

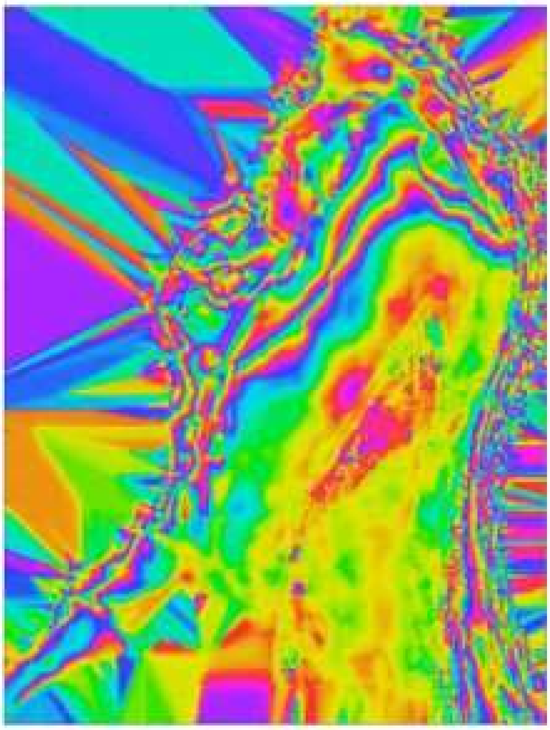


Figure 14 Example interferogram

With the wavelength known in millimetre the deformation can be derived. This process is called “unwrapping”. Unfortunately, not every surface on earth reflects a strong signal. Every pixel in the satellite’s image gives a certain reflection. If the reflection stays constant over time, it is called a “persistent scatter” (PS). Usually these pixels are found on man-made structures. Objects that have the same reflection every time can be related in the satellite’s images. This is even possible on sub-pixel level. In this way the exact same object is measured when the satellite revisits the location. If the algorithm is not sure about the consistency of the reflection, it discards the measurement. This explains why not every point on the map is measured.

The reference point for InSAR data is generally placed at a location that is stable. Stable points have no deformation although the earth’s surface is not exactly a static object but a collection of tectonic plates moving and bumping. Therefor measurements should always be interpreted relative to each other. Example given by SkyGeo: “If the reference point is subsiding, all stable points will appear to ascend. On the other hand, if such an effect is not visible in the deformation map, the reference point was probably well chosen.”

The resolution determines how good the quality of the measurements are. The higher the resolution the more accurate the measurements are. When the size of the pixel is smaller, there is less room for noise. Deformation of buildings requires a high resolution because the order of magnitude of the subsidence is usually very small (e.g. 0,5-3 mm/year) and the absolute position is more precise. The error margin for the absolute position is given below.

	X,Y	**Z**
Standard resolution	2-3 m	2 – 2,5 m
High resolution	1-2 m	1-1,5 m

When individual measurements are plotted on subsiding buildings, linear trends can be found but also quadratic or seasonal trends are common. The individual precision and velocity precision according to SkyGeo is given in the following table.

	Individual measurement precision	**Deformation velocity precision**
Standard resolution	6-8 mm	1-2 mm/year
High resolution	2-3 mm	<1 mm/year

As mentioned earlier, for building movement only high resolution can be used. The precision of standard resolution is not adequate because the average subsidence velocity is within the error margin. In cases that large deformations are found, it can be helpful to refer to ERS satelite data with standard resolution to find more information on the history of the deformations before 2007, which is not available from the newer satellites.

Satellite characteristics

The radar satellites used for InSAR orbit the earth at 500-800 km altitude. They scan the earth’s surface in strips along their path. The time it takes for a satellite to circle around the earth is depending on the satellite. The table below shows the cycle time, from which period they started measuring and the corresponding resolution.

Satellite	Time period	Repeat cycle (days)	Resolution
Sentinel-1	2014-now	12	Standard
TerraSAR-X	2007-now	11	High
COSMO-SkyMed	2007-now	16	High
RadarSat-2	2007-now	24	Standard
ALOS	2006-2011	46	Medium

Envisat	2003-2010	35	Standard
ERS	1992-2001	35	Standard

High/low separation

In order to separate measurement points on buildings and ground level, the algorithm compares the data with a Digital Terrain Model (DTM). Classification is done according to the following distribution: High points are bigger than (DTM height + X), X = 2 m for high resolution satellites and X = 3 m for standard resolution. Low points are between (DTM height – Y) and (DTM height + X). Points below (DTM height – Y) are discarded. Y = 10 m for all satellites. The picture below shows the distribution.

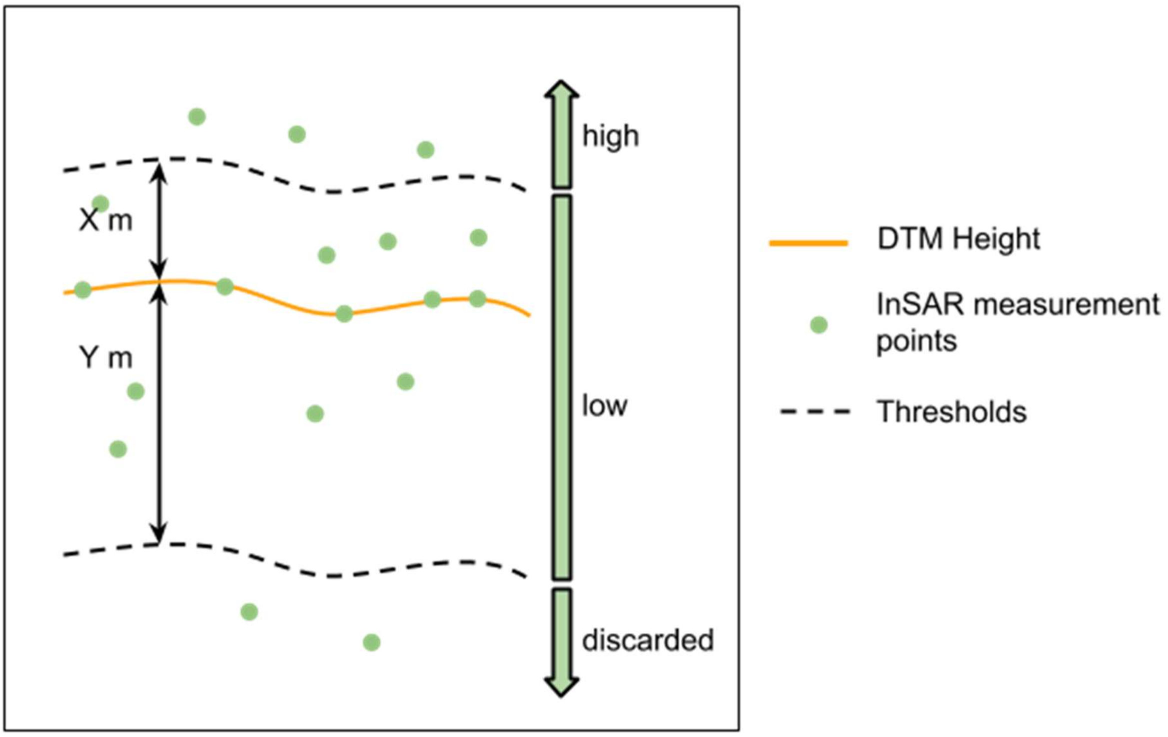


Figure 15 High-low point distribution

Data reliability

The deformation is derived by means of the phase difference. It is important to note that a finite number of phase measurements can be recorded (from 0 to 2π). If a point has changed by one complete wavelength, the phase difference can be interpreted as no change at all, since only the last wavelength of the signal is recorded. In other words, the interpretation can be off by (± **x** * 2π) with **x** ∈ ℕ. This phenomena is called a “unwrapping error”. This can give a deviation in the trendline. See the example below.

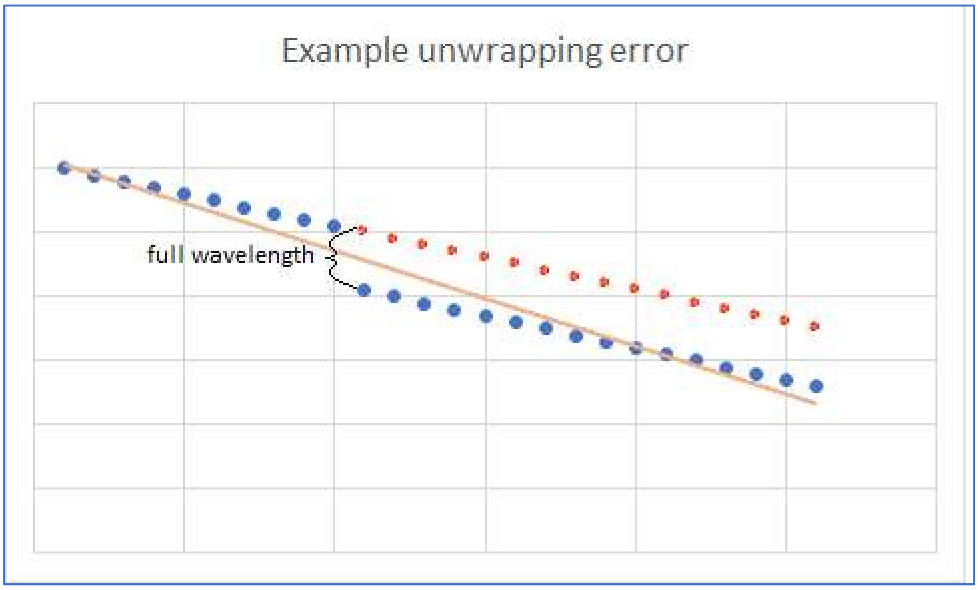


Figure 16 Example Unwrapping error

The data shows a clear trend but because of the unwrapping error the trendline may deviate. These errors have an order of magnitude of the wavelength of the radar signal. For instance the TerraSAR-X satellite can detect deformations up until ± 15 mm per 11 days.

In order to get the right interpretation to derive the actual deformation, the algorithm finds correlations in time and space. These correlations can be linear, quadratic or seasonal. According to SkyGeo this prevents unwrapping errors at least 99.0% of the time (SkyGeo, 2018).

An earlier study (Peduto, et al., 2016), in which results of damage surveys and InSAR data were compared, revealed that InSAR techniques has a potential in monitoring and could facilitate the selection of the most suitable interventions aimed at mitigating the damage effects of differential settlements.

2.6 Machine learning

When monitoring a foundation new technologies can be used to analyse data measured by the different methods. Data can be combined and analysed by "machine learning".

"We are entering the era of big data. This deluge of data calls for automated methods of data analysis, which is what machine learning provides. In particular, we define machine learning as a set of methods that can automatically detect patterns in data, and then use the uncovered patterns to predict future data, or to perform other kinds of decision making under uncertainty (such as planning how to collect more data)" (Murphy, 2012).

The application of machine learning can be particularly useful in the field of monitoring where big data sets are being analysed. Machine learning can possibly connect patterns in data, acquired by new methods like sensor data, to actual foundation risks. Experts think that machine learning might be a tool to analyze data in order to create a reliable alerting function for these monitoring systems.

3. Methodology

In this chapter the methodology, used per measurement method, will be elaborated.

3.1 Methodology: InSAR data

A comparison between InSAR data and the measurement bolts has been made in Case Study Block A (Krommenie, the Netherlands). This street has been carefully chosen because measurement bolts data has been collected for a long period (1986-2017). Subsidence speeds vary from close to 0 mm/year up to 15 mm/year. The InSAR data is filtered and edited by SkyGeo. In this period, the satellite was able to make a point-set of 216 observations per point. Details of the InSAR data set can be found in Appendix A.1. Together with the locations of the measurement bolts, a comparison has been done with the closest point approach. Below a map is shown where InSAR points are generated and measurement bolts ("meetboutjes") is manually added.

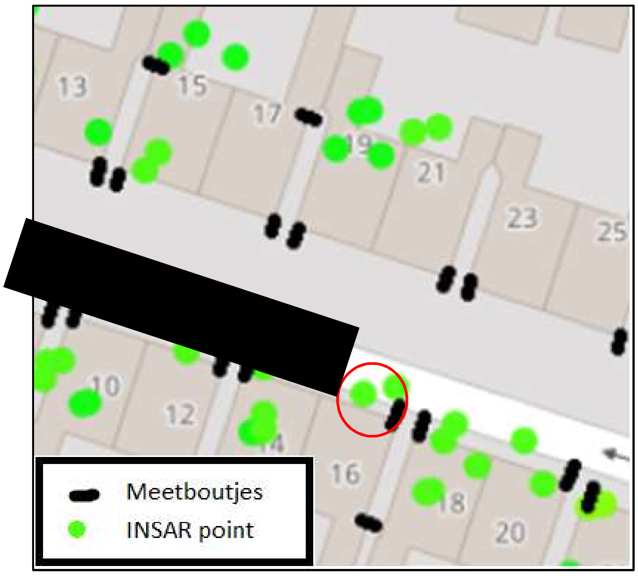


Figure 17 Map InSAR points with location measurement bolts

As an example, the red circle in the above figure represents one comparison. The rules used to find the closest point are given below.

- A measurement bolt and InSAR point need to be on the same house.
- All InSAR points used have an estimated height above 2 meters to filter out the points on ground level. The points remaining are assumed to be on the roof.
- If two InSAR points are equally distant from a measurement bolt, the InSAR point with the estimated height closest to the building height is chosen.

- If two measurement bolts are equally distant from one InSAR point, the average values of the measurement bolts will be compared.
- If there is no InSAR point in a range of approximately 5 meters of the measurement bolt, it will not be considered.

Once a comparison is found, the data is collected in an Excel sheet. Both InSAR and measurement bolts data are drawn in a graph where trendlines are plotted. Below the graph of measurement bolt number 93 is given. An example of a comparison is explained.

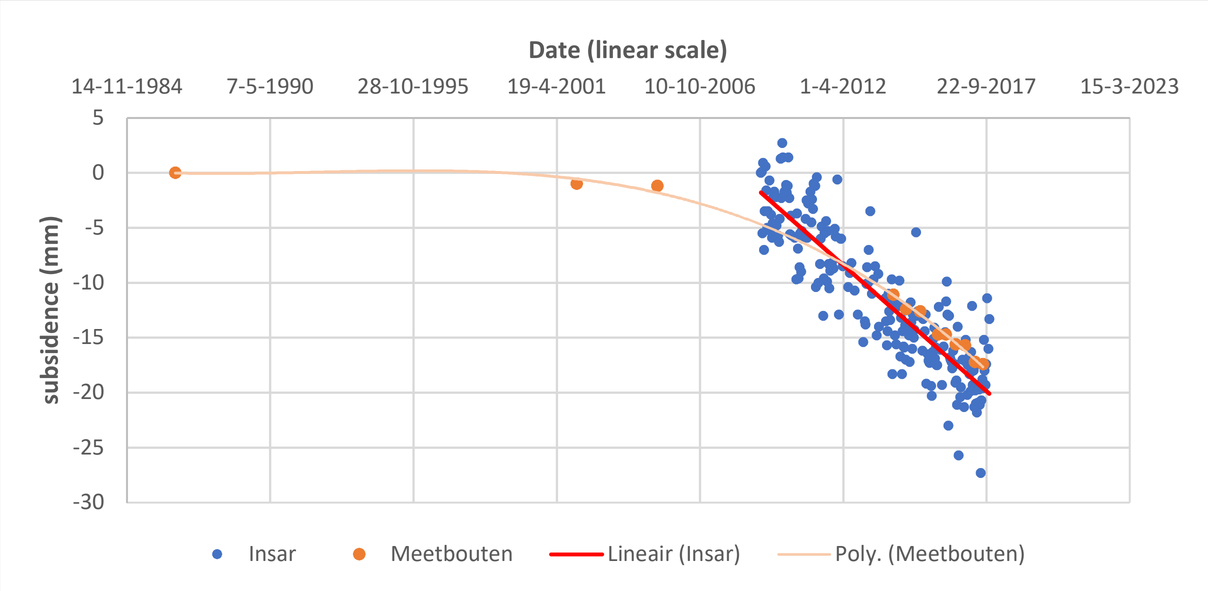


Figure 18 Measurement bolt 93 with added trendlines.

The InSAR trendline is linear and a third degree polynomial trendline is chosen for the measurement bolts. The best overlap can be found in the period 28-2-2014 to 2-8-2017 approximately 3,5 years. In this period the measurement bolts are measured 9 times so this period is chosen for comparison. A subsidence speed in mm/year can be derived from both methods InSAR and measurement bolts in this period. The difference in these values is calculated and analysed with statistical tests to determine to extent of absolute agreement of measurement bolts and InSAR data. The Bland-Altman plot will be used to visually show the absolute agreement between these methods.

"The Bland-Altman plot, or difference plot, is a graphical method to compare two measurements techniques. In this graphical method the differences (or alternatively the ratios) between the two techniques are plotted against the averages of the two techniques. Alternatively the differences can be plotted against one of the two methods, if this method is a reference or "gold standard" method." (MEDCALC, 2018)

In this case the gold standard method will be used since measurement bolts method proved itself to be highly accurate. An consistent measurement accuracy of ± 0,3-0,5 mm is achieved by Fugro.

The second statistical test is the ICC (Interclass Correlation Coefficient). This test calculates to what extent two methods to measure the same thing (subsidence speed in this case) on a scale from 0,0 to 1,0. The model that is used in this test is called Two-way mixed. In this case there are two fixed raters, each subject is measured by the two raters. Only the absolute agreement will be considered because systematic errors are unwanted. For this test, SPSS v24 software will be used.

Also, a second project has been analyzed. This is Case Study Block B in Amsterdam because plenty of measurement bolt data is available. See the figure of the location below.

Figure 19 Measurement bolts Case Study Block B Source: Gemeente Amsterdam

Gemeente Amsterdam provides a lot of data for these two building blocks. It is open-source (Amsterdam, 2018). The measuring period of the measurement bolts ranges from around 2000 to 2018 but for some of the measurement bolts only from 2014 to 2018 the data should cover at least more than 3 years.

The InSAR data is filtered and edited by SkyGeo. In this period the satellite was able to make a point-set of 219 observations per point. Details of the InSAR data set can be found in Appendix A.1. Together with the locations of the measurement bolts (Figure 19) a comparison can be done with the closest point approach. The rules allowing a comparison are slightly different from Case Study Block A project because less data points are available.

- A measurement bolt and InSAR point **do not need** to be on the same house.
- All InSAR points used have an estimated height above 2 meters to filter out the points on ground level. The points remaining are assumed to be on the roof.
- If two InSAR points are equally distant from a measurement bolt, the InSAR point with the estimated height closest to the building height is chosen.
- If two measurement bolts are equally distant from one InSAR point, the measurement bolt with the longest measuring period will be compared. If those are the same, the average of the measurement bolts will be used.
- If there is no InSAR point in a range of approximately 8 meters of the measurement bolt, it will not be considered.

Once a comparison is found, the data is collected in an Excel sheet. Both InSAR and measurement bolts data are drawn in a graph where trendlines are plotted. Below the graph of measurement bolt number 10381285 with the closest InSAR data point is given. An example of a comparison is explained.

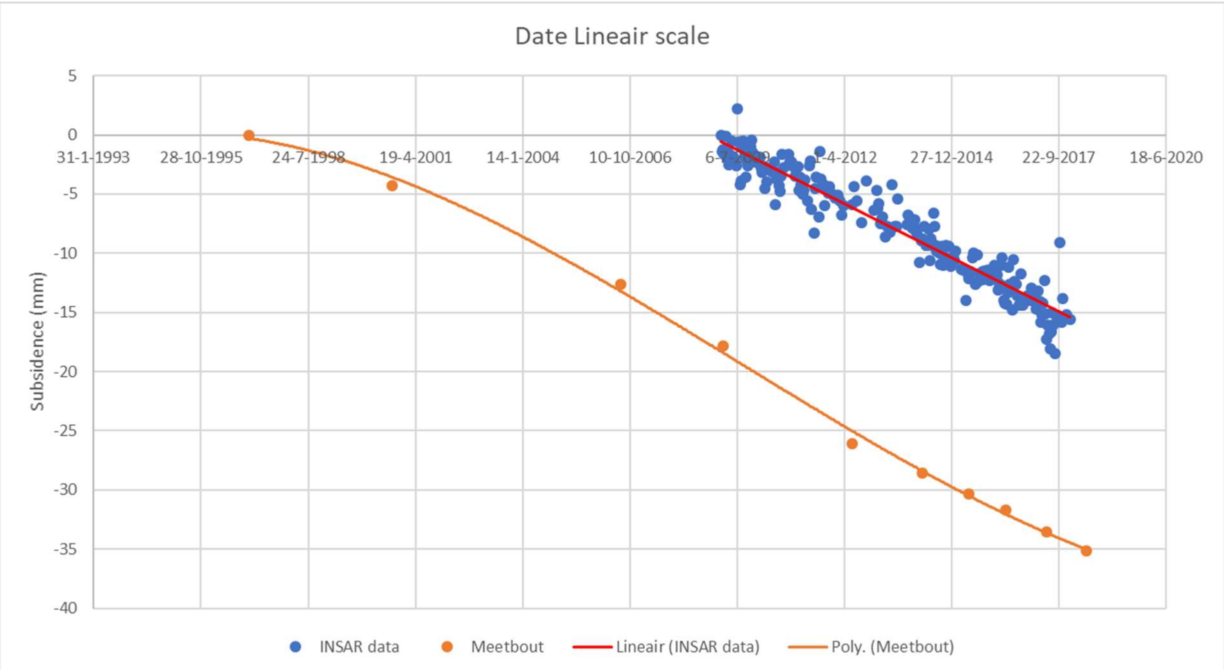


Figure 20 Measurement bolt 10381285 with added trendlines

The InSAR trendline is linear and a third degree polynomial trendline is chosen for the measurement bolts. The best overlap can be found in the period from 2009 to 2018 approximately 9 years. In this period the measurement bolts are measured 7 times so this period is chosen for comparison. Again the difference in these values is calculated and analysed with statistical tests; the Bland-Altman plot and ICC-value just like Case Study Block A project.

3.2 Methodology: Measurement bolts

Since measurement bolts are already well known, a literature study has been done to determine the accuracy of the measurement bolts and an qualitative analysis has been made of the pros and cons. This has been elaborated in Appendix A.2.

3.3 Methodology: Subsidence sensor

An error margin analysis has been performed for the current setup of the subsidence sensor. This is a quantitative analysis where factors that possibly have an influence on the accuracy of the measurements are being considered. By employing qualitative modes of enquiry, there was attempted to illuminate the possible methods that can be used to interpret the data measured by the subsidence sensors located in the Case Study Block C, Rotterdam. Since no measurement bolts data is available in Case Study Block C, a level measurement for masonry will be compared to the data. A level measurement for masonry is the integral of the subsidence speeds assuming the masonry was levelled during construction. Extrapolation of the subsidence speeds found in the data can be misleading if the actual subsidence is lower than the error margin. A literature study has been done to determine how the current setup of the subsidence sensor can add to a monitoring system. This has been elaborated in Appendix A.3.1

3.4 Methodology: Groundwater level sensor

An error margin analysis has been done for the current setup of the groundwater level sensor in the Case Study Block C (Rotterdam). This is a quantitative analysis where factors that possibly have an influence on the accuracy of the measurements are being considered. Moreover, a comparison has been done of the data collected by the sensor with the data collected by local monitoring wells in Case Study Block C, Rotterdam.

3.5 Methodology: Tilt sensor

An error margin analysis has been done for the current setup in Case Study Block C (Rotterdam) of the tilt sensor. This is a quantitative analysis where factors that possibly have an influence on the accuracy of the measurements are being considered. A literature study has been done how tilt sensors can be used to monitor a foundation and what factors need to be considered before installing a tilt sensor. This has been elaborated in Appendix A.3.4.

4. Results

The results will be presented in this chapter. First the findings of the groundwater level, subsidence and tilt sensors – used in Case Study Block C as part of Code Oranje – are given. Thereafter the results of the comparison of InSAR data with measurement bolts will be presented.

4.1 Results: InSAR data and measurement bolts comparison results

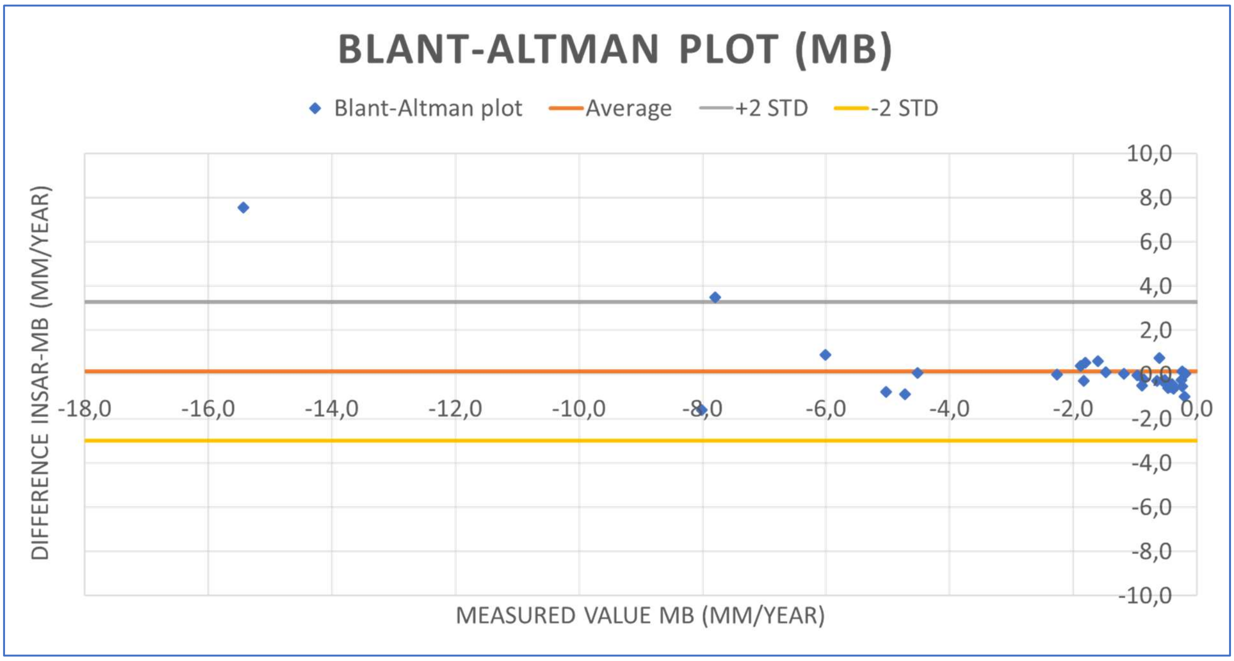
Case Study Block A, *Krommenie*

First the results of the project in Case Study Block A in Krommenie will be discussed.

Two statistical tests have been performed: The Blant-Altman plot and the Interclass Correlation Coefficient (described in 3.1).

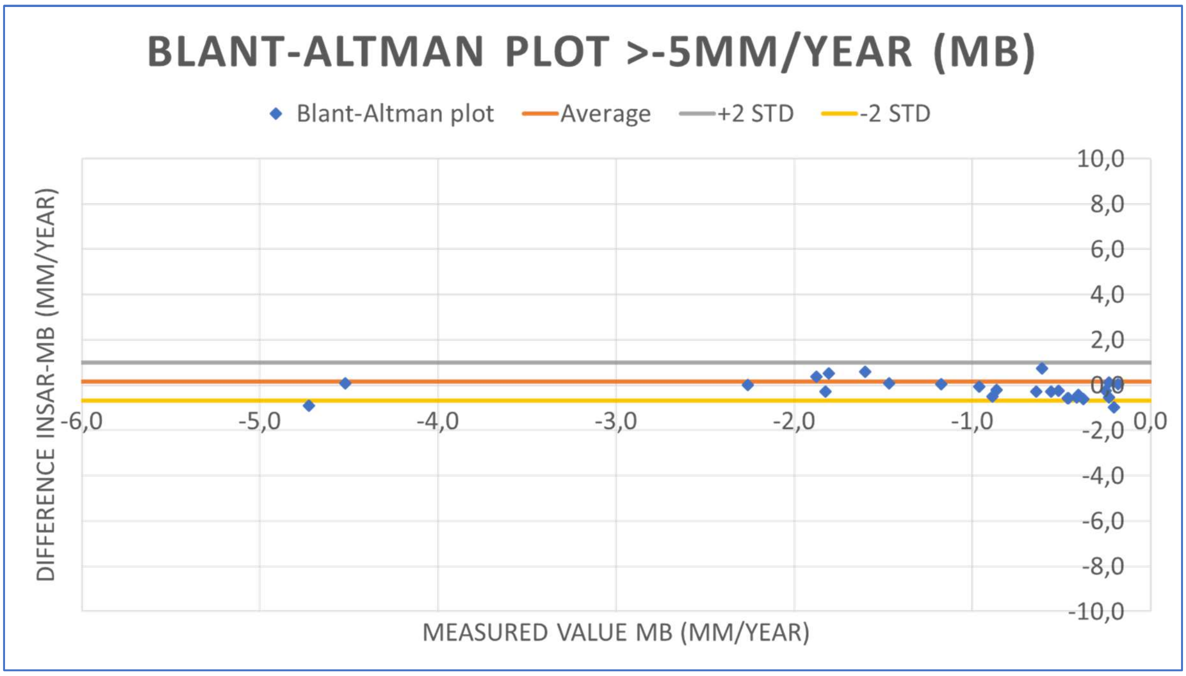
Blant-Altman plot

First, all measurement bolts are plotted in graphs to derive subsidence speeds see Appendix A.1. The Blant-Altman plot for all 32 comparisons is given in the following graph.



The x-axis is the value measured by measurement bolts in mm/year and the y-axis shows the value measured by InSAR minus the value measured by measurement bolts in mm/year. The orange line is the average of the difference in both methods and the yellow and grey line are showing the

95% - confidence interval. Also for the measured values below 5 mm/year a plot has been made (see graph below).



Interclass Correlation Coefficient

Secondly, the Interclass Correlation Coefficient has been calculated. Again for two situations: 1 - *All comparisons* and 2 - *Only measured values below 5 mm/year*. SPSS 24 has been used to calculate the ICC, input parameters are found in Appendix A.1. Results are given in the table below.

	Intraclass Correlation	95% Confidence Interval	
		Lower Bound	Upper Bound
Single Measures	**0,849**	0,714	0,923
Single Measures > -5mm/y	**0,926**	0,834	0,967

The ICC is classified in a similar way as the Cohen's Kappa. (Landis JR, 1977) Below a table is presented with the qualitative classification.

ICC = 0	'poor'
0 to 0,20	'slight'
0,21 to 0,40	'fair'
0,41 to 0,60	'moderate'
0,61 to 0,80	'substantial'
0,81 to 1,00	'almost perfect'
ICC = 1,00	'perfect'

Deviations in absolute terms only based on the researched project are calculated below.

The difference between InSAR and measurement bolts for measurements in a **95%** confidence interval is:

± 3,18 mm/year

The difference between InSAR and measurement bolts for measurements in a **99,7%** confidence interval is:

± 4,77 mm/year

The difference between InSAR and measurement bolts for measurements **under 5 mm/year** in a **95%** confidence interval is:

± 0,86 mm/year

The difference between InSAR and measurement bolts for measurements **under 5 mm/year** in a **99,7%** confidence interval is:

± 1,30 mm/year

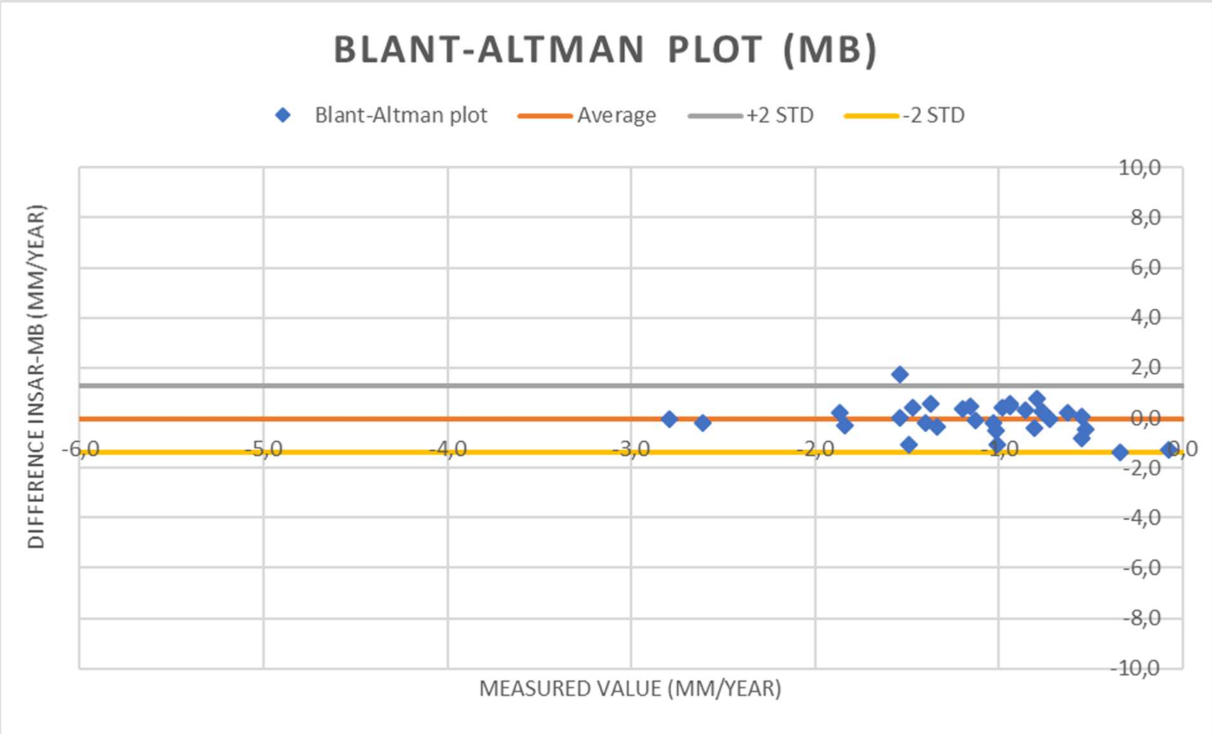
Case Study Block B, Amsterdam

Secondly, the results of the project on Case Study Block B will be discussed.

Both Blant-Altman and ICC has been performed. Results are given below.

Blant-Altman plot

First, all measurement bolts are plotted in graphs to derive subsidence speeds see Appendix A.1. The Blant-Altman plot for all 31 comparisons is given in the following graph.



The x-axis is the value measured by measurement bolts in mm/year and the y-axis shows the value measured by InSAR minus the value measured by measurement bolts in mm/year. The orange line is the average of the difference in both methods and the yellow and grey line are showing the 95% - confidence interval.

Interclass Correlation Coefficient

Secondly the Interclass Correlation Coefficient has been calculated only for one situation: *All comparisons*. SPSS 24 has been used to calculate the ICC, input parameters are found in Appendix A.1. Results are given in the table below.

	Intraclass Correlation	95% Confidence Interval	
		Lower Bound	Upper Bound
Single Measures	**0,553**	0,250	0,757

Deviations in absolute terms only based on the researched project are calculated below.

The difference between InSAR and measurement bolts for measurements in a **95%** confidence interval is:

± 1,31 mm/year

The difference between InSAR and measurement bolts for measurements in a **99,7%** confidence interval is:

± 1,96 mm/year

4.2 Results: Measurement bolts

A literature study has been done by the author to determine the accuracy itself and which factors influence the accuracy of the measurement bolts method. Below you find the results.

Accuracy	**0,3 to 0,5 mm between measurements**

Possible errors that can influence the accuracy of this method:

Personal errors determined by experience of the crew executing the measurement
Instrumental errors caused by imperfect construction and adjustment of the surveying instruments used
Natural errors caused by variation in or adverse weather conditions, refraction, unmodelled gravity effects, distance to NAP reference point etc.

4.3 Results: Subsidence sensor

The data of the subsidence sensor has been compared to a level measurement of the masonry. Backward extrapolation of the subsidence speed did not result in a shape similar to the level measurement for masonry.

It is unknown if the signal of the sensors is calibrated. Several intermediate factors can disrupt the signal of the sensor. The report of the installation of the sensors (Omnifor, 2016) states that the devices are consisting of a microcontroller, a communication module and the sensor itself. This device sends the measurement to a gateway which is connected to the internet to be able to send it to a database. In this last step the information is processed and extra information is added like origin, date/time and security information. Vibrations in the vicinity of the sensor can cause noise in the signal of the sensor. This can be caused by heavy traffic or other activities that create vibrations.

4.4 Results: Groundwater level sensor

A comparison of the groundwater sensors to the local monitoring wells has been performed. If the groundwater level sensors are compared to the level measured by the monitoring wells, it can be concluded that they all show a similar slightly raising trend. See the graph below.

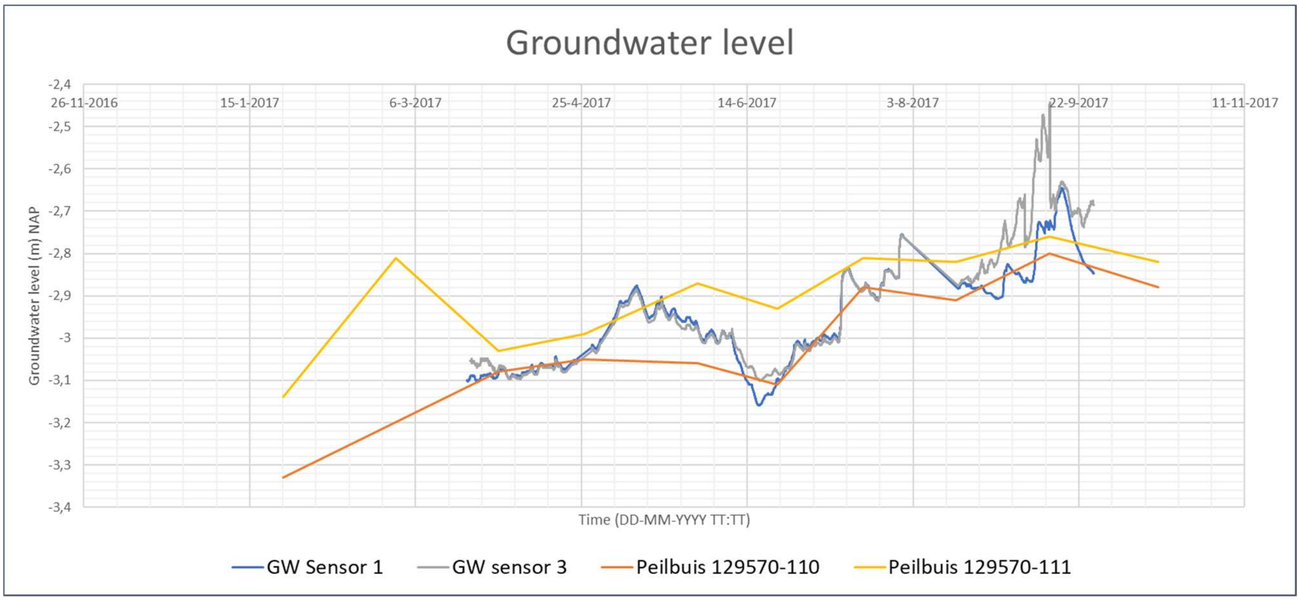


Figure 21 Groundwater level measurements

As well as the subsidence sensors, it is unknown if the signal of the groundwater level sensors is calibrated to measure millimetres.

Factors that can disrupt the signal of the sensor are: the devices consisting of a microcontroller, a communication module and the sensor itself, the gateway and vibrations in the vicinity of the sensor can cause noise to the signal of the sensor.

4.5 Results: Tilt sensor

In the current configuration of the tilt sensor in Case Study Block C, Rotterdam (placed 4 meter high on the façade), the sensor measures the rotation as well as the deformations of the masonry.

Factors that can disrupt the signal of the tilt sensor are: the devices, consisting of a microcontroller, a communication module and the sensor itself, the gateway and vibrations caused by heavy traffic or building activity in the vicinity of the sensor can cause noise to the signal of the sensor.

Based on experts views and literature study, factors that need to be considered before the installation of a tilt sensor are:

- The reference point of a tilt sensor is the initial measurement starting at 0°.
- The precision of the "Kelag KAS901-xxX inclination sensor" is ± 0,014°. The error can be almost 1 mm assuming the wall behaves like a rigid wall. If this error margin is not adequate, a sensor with higher precision should be used.

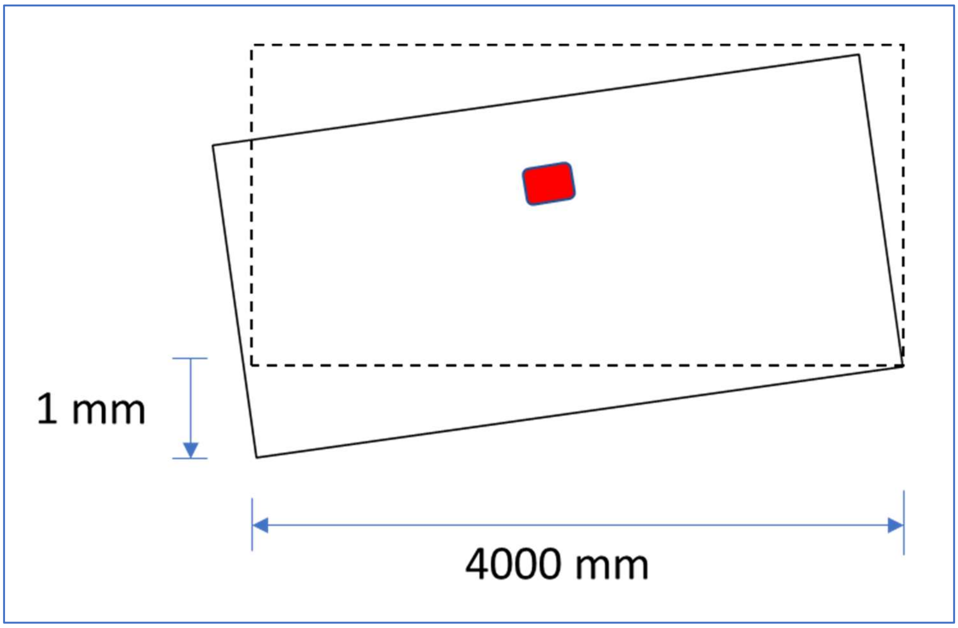


Figure 22 Error margin tilt sensor

- When a sensor is installed on a wall, the distance between the foundation and the sensor can reduce or increase the measured rotation due to curvature in the masonry.

- The tilt sensor should be installed on a load bearing wall in order to relate the deformations to the foundation because the loads are distributed to the foundation through the load bearing walls.
- The figure below shows a wall with a tilt sensor. The stiffness of a wall has consequences for the rotation measured by the tilt sensor. The wall on the left is sufficiently stiff to rotate as a result of sagging differences. The wall on the right behaves as a flexible wall and shows shear deformation. The sensor will not observe rotation.

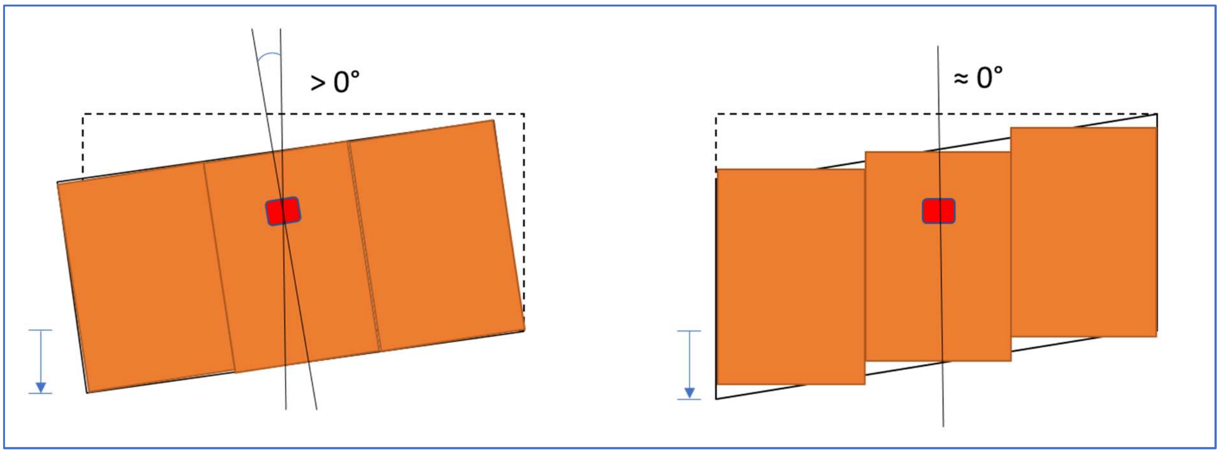


Figure 23 Observed rotation in relation to stiffness.

5. Analyses of results

5.1 Analyses of results: InSAR data

In order to validate results of the two cases where InSAR data is compared with measurement bolts, the methodology and the measuring instruments have to be discussed. For the methodology used in the two test cases it has to be noted that only points more than 2 meter above the Digital Terrain Model (DTM) are used. These points are considered to be located on the roof of a building. This means that the value of the DTM determines the high- and low points found in the InSAR data. If this value is incorrect, actual low points can be interpreted as high points which results in false information in regard to subsidence. According to SkyGeo technical report the precision of the Z-value of the location ranges for 1-1,5 meters.

The satellite used in the two cases is the Terrasar-X which has a resolution of 3,0 m x 2,4 m. Since this is considered as a high resolution satellite, it cannot be ensured to get similar results with low to normal resolution satellites. Moreover, the location of the measurement bolts and InSAR points can be almost on top of each other but can also be quite far away. For Case Study Block A, a comparison has not been made if no InSAR points are on the same building as the measurement bolt. But for Case Study Block B this has been ignored since almost no comparisons would be possible. This can result in bigger differences between InSAR and measurement bolts.

The time series used to compare measurement bolts (28-2-2014 to 2-8-2017) and InSAR (5-2-2009 to 31-10-2017) of Case Study Block A do overlap but are not the same. If a better fitting time series is used results may be different. SkyGeo's algorithm to find the best fitting trend (linear, quadratic or seasonal) can possibly find a different trend when other time series are considered. This is important because once a trend is found outliers are edited based on the trend.

The NAP reference points of the measurement bolts are different from the reference points used for InSAR data found by algorithms. That said, still the differences are small.

Unwrapping errors can cause a slightly different trend. These errors can be detected in the point scatter but require an experienced InSAR data-user. See Section 2.6 for an example of an unwrapping error.

In the foundation reports of Case Study Block A it is noted that the buildings tend to tilt forward since the street is subsiding faster than the garden side. Rotation towards the line of sight of the satellite can reduce the observed subsidence. The length of the signal will be shorter than a subsidence with only a vertical component. See the picture below.

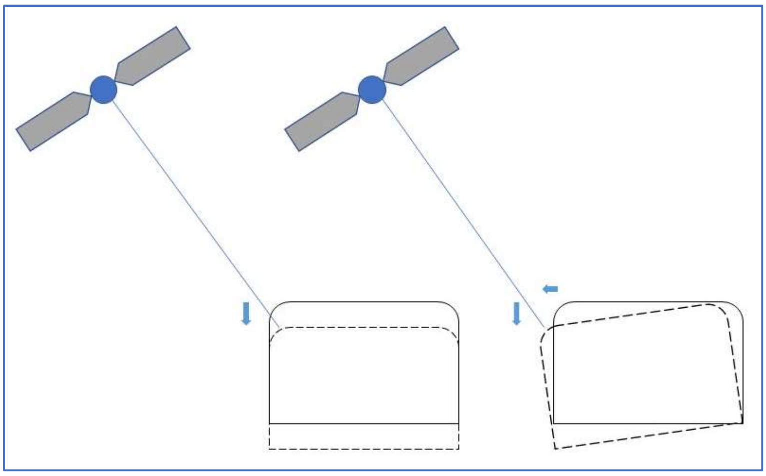
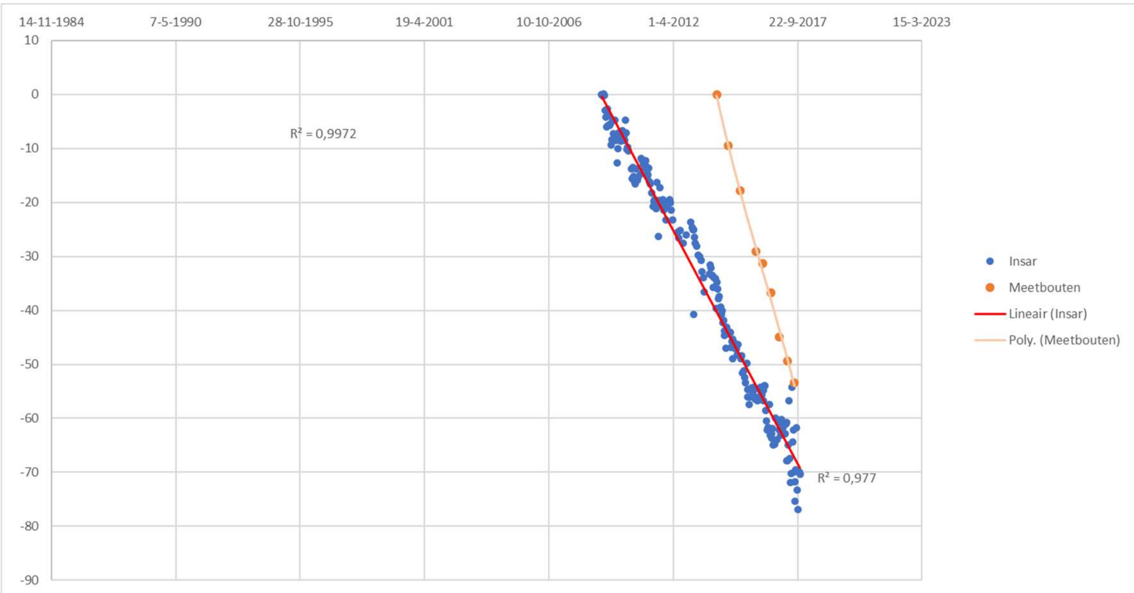


Figure 24 Horizontal movement of a building changes the length of a signal.

For the buildings in Case Study Block B with an average height of 16 meters, small rotations result in even larger horizontal displacements on roof level. To tackle this problem, a satellite with a different orbit can measure from the opposite direction. In this way the horizontal component can be eliminated.

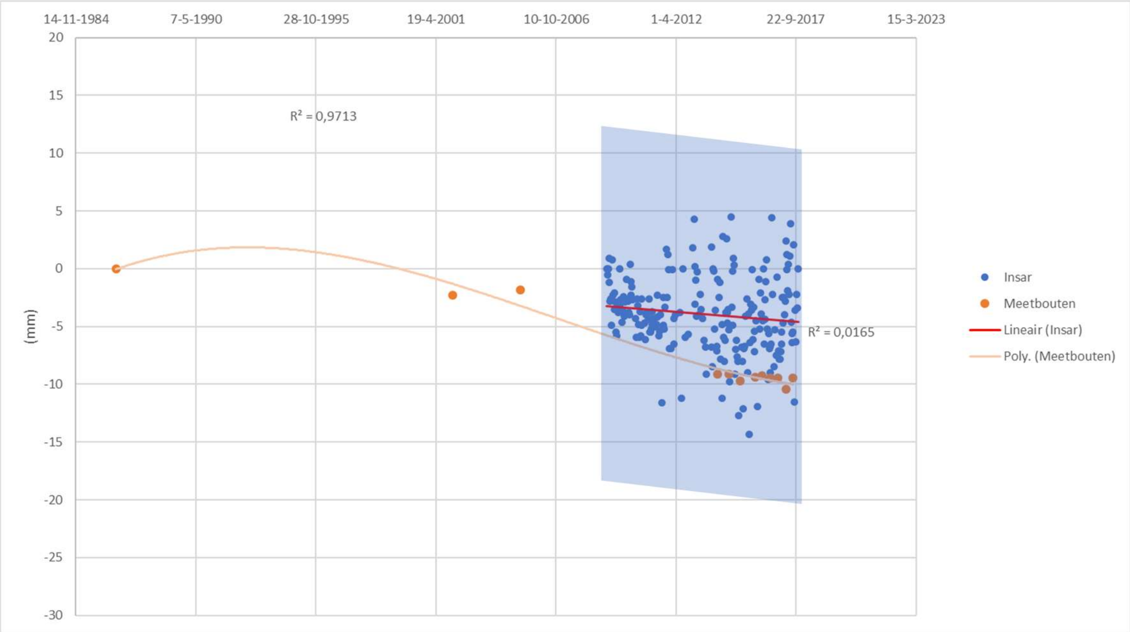
A few graphs from the comparison will be discussed and shown below. First the comparison of measurement bolt 120 in Case Study Block A test case.



InSAR	**-7,9**	mm/year
Measurement bolts	**-15,4**	mm/year

This comparison is one of the more interesting ones. The measurement values differ 7,5 mm/year. The measurement bolts (orange) show a straight line without too much deviation. The InSAR data points (blue) are almost in the shape of a saw tooth where better parallel lines can be seen. The reason why there are small jumps in this graph is unknown but possibly due to unwrapping errors. Further research can help to identify the cause of this deviating shape.

The next graph of measurement bolt 114 in Case Study Block A shows a perfect similarity. Still the InSAR data looks scattered. The points differ about ± 10 mm of the plotted trendline. This is well within the wavelength of one phase (30 mm) which comes down to a ± 15 mm bandwidth (marked in blue). Settlement changes bigger than 15 mm within 11 days (time of one full orbit) cannot be detected and will be “corrected” to a value within the bandwidth marked below.



InSAR	**-0,2**	mm/year
Measurement bolts	**-0,2**	mm/year

Foundation repairs can also influence the trend observed by the InSAR data. Usually after such a repair, stabilisation takes place and a certain equilibrium is found. The InSAR data can interpret this as an error in the measurement and thereafter discard the point or just use it as continuation in the trend. See the example below. Further research is needed to know to what extent this can lead to errors in relation to the measured subsidence speed.

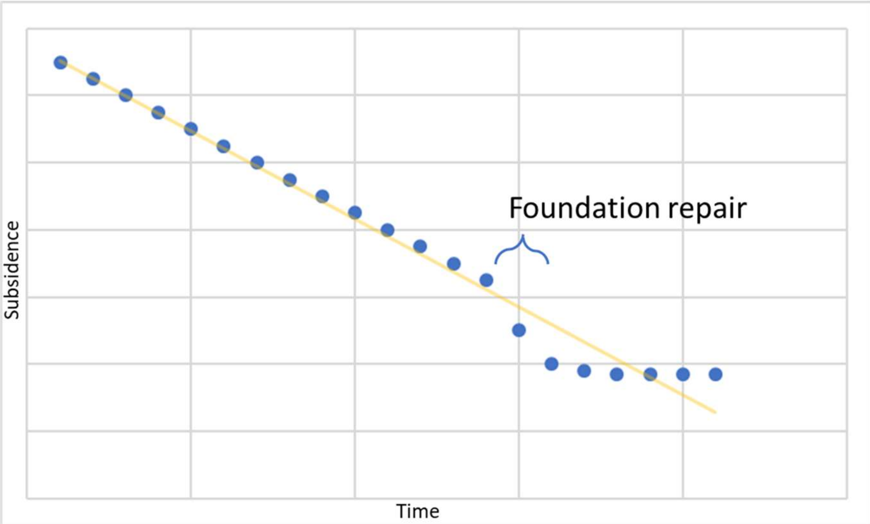


Figure 25 Foundation repairs can influence InSAR data trends

To calculate the ICC, “Single measures” is used even though more than one measurement is taken in the experiment, because reliability is applied to a context where a single measure of a single rater will be performed.

In Case Study Block A, the structure of every building basically the same. Almost every building block consists of semi-detached houses and typically two storey high. See picture below.

Figure 26 Structure of the buildings in Case Study Block A (source: maps.google.nl)

The buildings on Case Study Block B have relatively the same height. Building units which are structurally connected consist of maximum three houses. The picture below shows the front façade of the buildings on Case Study Block B. All the buildings have saddle roofs with four to five floors and an Amsterdam wooden pile foundation.

Figure 27 Front façade of Case Study Block B. (source: maps.google.nl)

Since the results for the error margin are better in Case Study Block A, possible explanations have to be discussed. Large differences between the measurement bolts and InSAR are marked in red on the map below.

Figure 28 Marked houses with large differences between measurement bolt and InSAR data on Case Study Block B.

The foundation reports available at Fugro show that location 1 is right on the connection of two building blocks. See figure below. Also during July 2013 foundation repair was requested for the houses Case Study Block B 75, 76 and 77 according to Stadsdeel West. These are most likely to be executed by now. If further research is done, potential causes can be found for the other locations or in general.

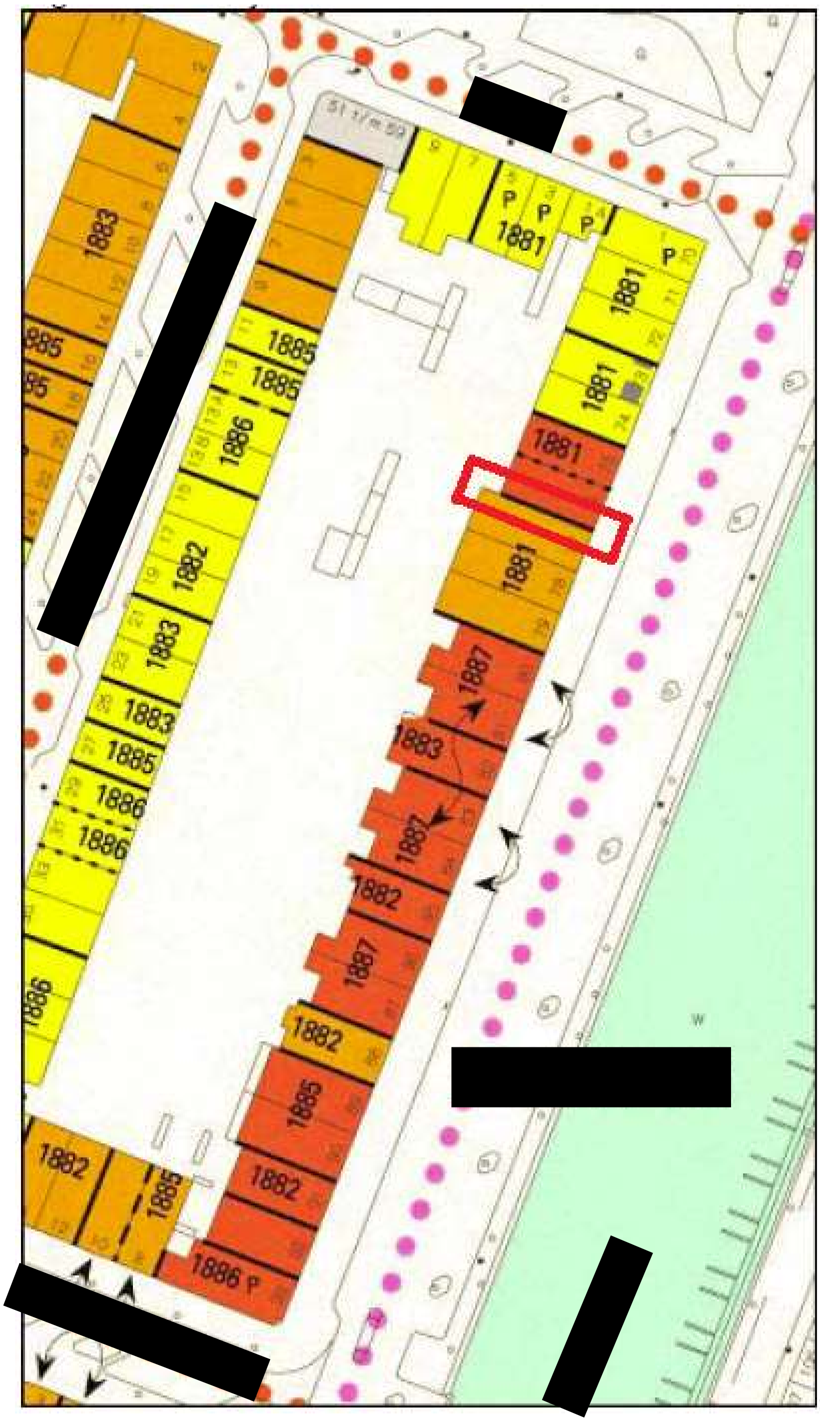


Figure 29 Location of boundaries between building blocks. Case Study Block B 76-77 (source: Fugro foundation reports)

One interesting finding in Case Study Block A is that the higher the subsidence speed, the greater the difference between measurement bolts and InSAR data. Expected was that InSAR would detect high subsidence speeds better than low subsidence speeds, this was based on common sense. But the results showed bigger differences in high subsidence speeds. A possible explanation is the difference in location of the measurement, the measurement bolts are measuring close to ground level and the InSAR points are measuring on the roof.

An application for the InSAR data is a pre-screening of urban area’s to detect possible foundation issues. Limitations have to be considered. In order to quantify foundation problems, more data is required. Low subsidence speeds do not necessarily mean that the foundation is in good shape, but also high subsidence speeds do not always indicate that there is a problem regarding the foundation.

To put the results in perspective, normal ground level settlements have to be considered. Below a map of the Netherlands is given where current settlement rates are shown. As the map shows, in Groningen a ground level settlement of 4-5 mm/year is normal, where in the peat areas (Zuid-Holland, Noord-Holland and Utrecht) a settlement of 0-3 mm/year is normal. To be able to use InSAR as a pre-screening tool, one has to consider the error margin and the expected settlement rate. Also the type of foundation is important to consider since shallow foundations usually settle at the same rate as the ground level. Pile foundations tend to subside slower than the ground level but the opposite case does not always indicate a problem. In some cases the error margin can overrule the observed measurement. If higher values than the expected rate are observed, it can be marked as a potential problem. A foundation research can give more certainty in these cases.

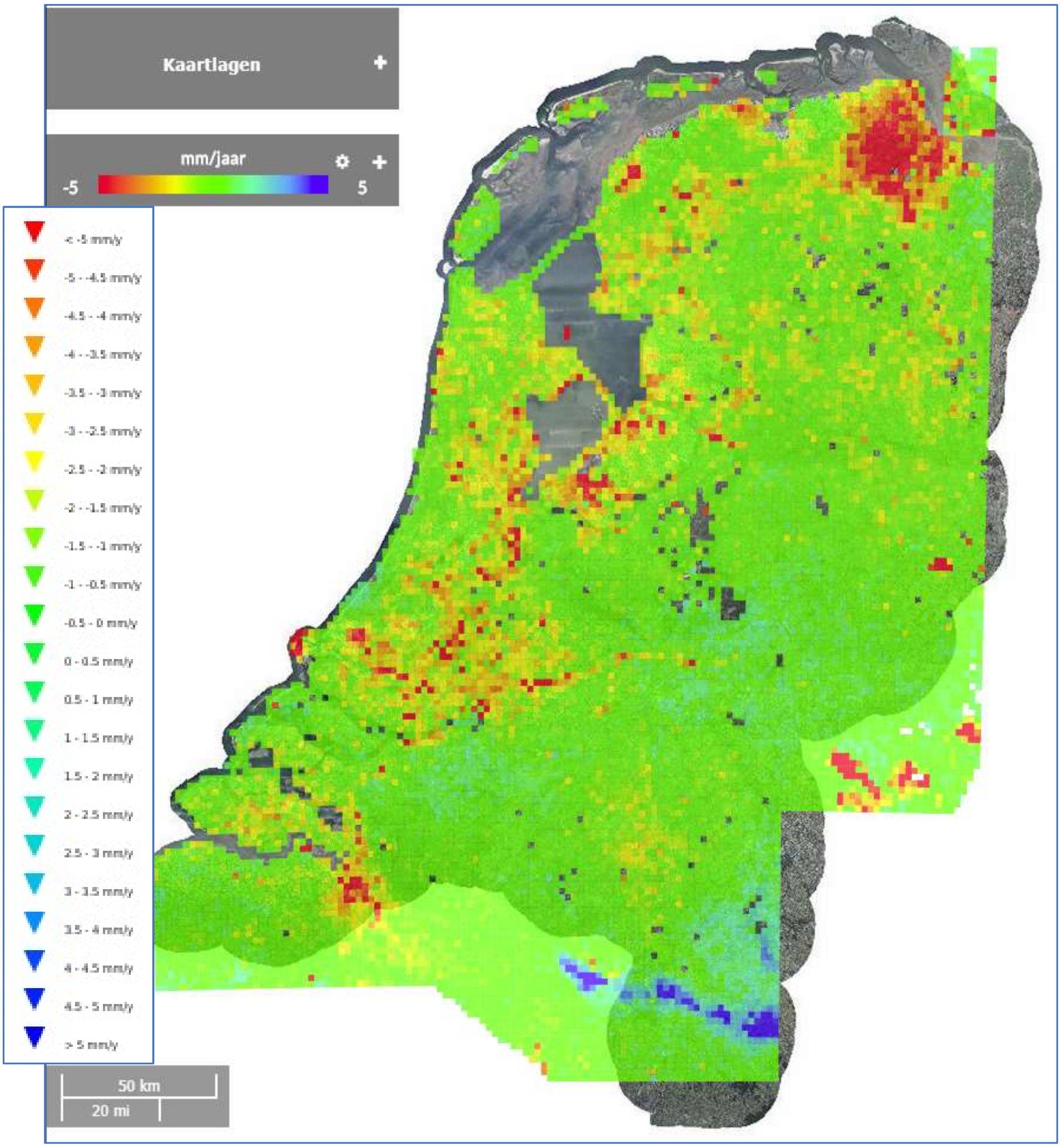


Figure 30 Ground level settlement in the Netherlands. source: (NCG)

Proven is that now, within the limitations, there exists a clear connection between InSAR data and measurement bolts. If further research is done, (e.g. with more changing parameters like a different location other than Krommenie and Amsterdam or houses with different shapes or houses with different height) a solid confidence interval can be established. Ultimately, this can be a powerful tool for KCAF to map large area's and detect potential foundation issues in the early stage.

5.2 Analyses of results: Measurement bolts

The measurement bolts data has a large portion in current assessment of foundations. Advantages are that it is very accurate and the location is exact but also time-consuming and labor-intensive (expensive). In the future, other methods such as InSAR might have similar accuracy, but currently it cannot match the accuracy (± 0,3 to 0,5 mm) of the measuring bolts. Determining the location of the measurement also plays a major role in being able to measure the foundation efficiently. InSAR measurement points are not always available on the points of interest.

5.3 Pros and cons analyses InSAR and measurement bolts

In order to compare the methods: InSAR and measurement bolts, pros and cons for each method are lister below. The following table shows the pros and cons of the InSAR method compared to the measurement bolts. This analysis is based on the literature study found in Appendix A.1 and A.2.

Pros	Cons
Not labour intensive	Moderately accurate subsidence measurements
Able to track back subsidence trends up until 2007 (high resolution)	Possible deviation of 1-1,5 m in X-Y plane (Source: SkyGeo technical report)
Lots of data points	Location of the data points is depending on reflecting objects
Developing technology	Accuracy for subsidence measurements on buildings is not yet determined

The next table shows the pros and cons of the measurement bolts method compared to the InSAR method.

Pros	Cons
Highly accurate subsidence measurements	Labour intensive
No deviation in X-Y plane	In most cases, only after the first repetition measurement, which is usually 1 year after installation, the subsidence speed can be calculated.
Location of the measurement bolts can be exactly determined	Accuracy can be influenced by personal errors

The most important difference has to be the accuracy. This characteristic mainly determines the application of the method. In some cases the error margin can overrule the observed measurement. A favourable characteristic of the InSAR method is the possibility to track back trends up until 2007, this can allow for a quick indication what the subsidence speed is in urban areas. The measurement bolts method requires more time to observe a subsidence trend. Another significant difference is the labour intensity. Every individual measurement bolt has to be measured one by one by an experienced crew, where the InSAR data points are being processed by a computer.

5.4 Analyses of results: Subsidence sensor

Considering the results of this research there is really too little information to apply decent analyses. Therefor no firm conclusions about this sensor will be drawn based on the given information.

5.5 Analyses of results: Groundwater level sensor

From the results, it can be concluded by the similar shape of both the sensor and the local monitoring wells that the sensors are working properly. As for any of the sensors a lot of factors are able to disrupt the signal of the sensor, so accuracy has to be determined. For this research more data is needed.

A possible use for the groundwater sensors is the following example. The graph (Figure 31) below shows fictive measurements of the groundwater level. The horizontal lines indicate the height of the foundation timber, the top of the pile and the groundwater level in NAP [m]. The marked areas (yellow) show the dry periods and the amount of timber or part of the pile exposed to air.

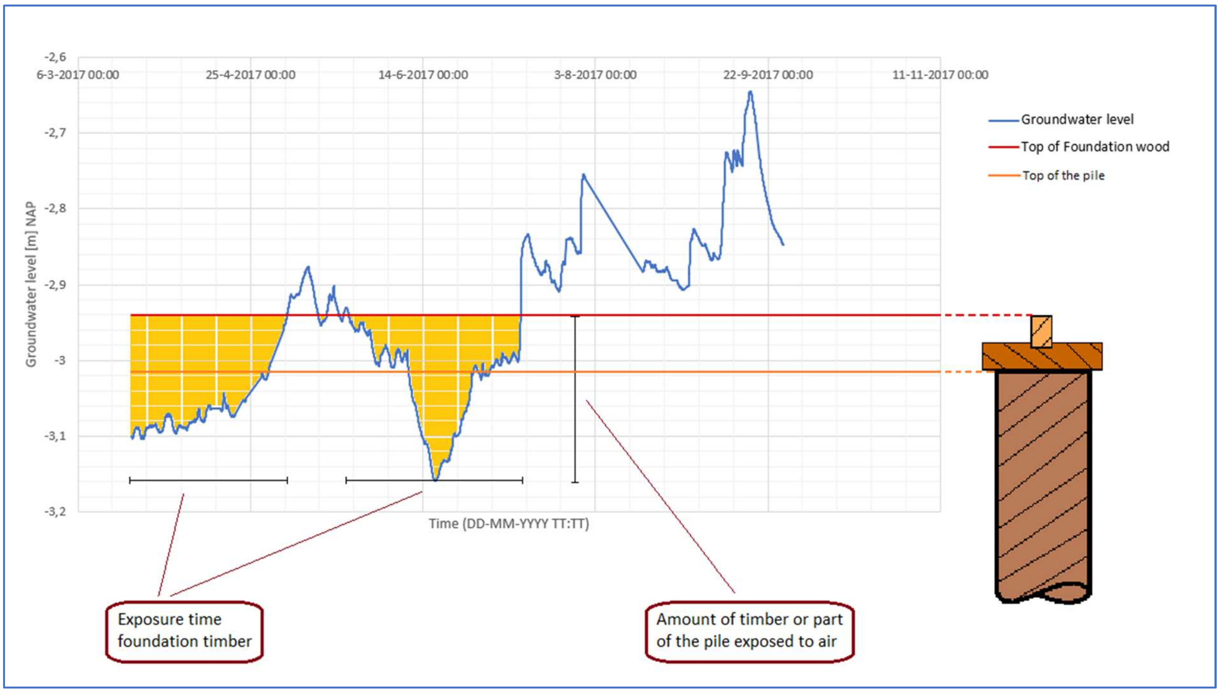


Figure 31 Relation groundwater - exposure to air

A CPT can give information about the water-holding capacity of the soil. Soils like clay, peat and loam have a high water-holding capacity in contrast to sand which has a low water holding capacity. In Amsterdam, the top layer usually consists of clay because during construction clay was excavated from the canals to raise the construction level. Top layers consisting of soils with a high water-holding capacity can have a positive effect on the resistance to fungus attacks due to foundation timber being less exposed to air compared with sandy top layers where water can easily flow through. Although, this should not be added to the model since cases are known where foundations in clay layers show activity of degrading fungi. That said, in general clay improves the service life of wooden piles but this should be considered as “hidden” safety.

5.6 Analyses of results: Tilt sensor

It is unknown how current configuration of the tilt sensor in Case Study Block C is determined and if the sensor is calibrated. The factors that can influence the data of a tilt sensor have to be considered carefully because they can be different for every case.

Level measurements for masonry or for floor can give a good indication on where to install the sensor in order to monitor a foundation because the reference point of a tilt sensor is the initial measurement starting at 0°. Therefore, this sensor cannot say anything about initial skewness of a building.

6. Conclusions and recommendations

The research question of this master thesis is:

Which possibilities can be used to monitor a foundation and to what extent are these useful and adequate?

There are 5 methods considered in this research: InSAR data, Measurement bolts, a subsidence sensor, a groundwater level sensor and a tilt sensor.

To what extent InSAR data is useful is mainly determined by its accuracy. InSAR data Case Study Block A has been compared to the present measurement bolts. The results show that those two methods have an ‘almost perfect’ relation according to the ICC value of 0,849. Although the confidence interval ranges from 0,714 to 0,923 (‘substantial’ to ‘almost perfect’). In absolute sense, the difference between InSAR and measurement bolts is ± 3,18 mm/year (with a confidence interval of 95%). InSAR measured values below 5 mm/year have a difference compared to measurement bolts of ± 0,86 mm/year (with a confidence interval of 95%). If the ICC value is calculated for measured values below 5 mm/year, 0,926 is found which is an ‘almost perfect’ relation.

InSAR data in Case Study Block B has been compared to the present measurement bolts. The results show that those two methods have an ‘moderate’ relation according to the ICC value of 0,553. Although the confidence interval ranges from 0,250 to 0,757 (‘fair’ to ‘substantial’). In absolute sense, the difference between InSAR and measurement bolts is ± 1,31 mm/year (with a confidence interval of 95%). It can be concluded that the outcome really depends on the location of the testcases. More research is needed to determine the actual accuracy when used for the application of monitoring foundations.

The measurement bolts are currently widely used to monitor a foundation. With an accuracy of ±0,3 to 0,5 mm, this method is highly accurate. Factors that influence the accuracy can be divided in three categories: personal factors, instrumental factors and natural factors.

InSAR and measurement bolts both have their strengths and weaknesses. Prescreening is an easier application for InSAR but highly accurate measurements in a specific location is more reliable if measurement bolts are used. In a way, these methods complement each other rather than measuring the same way.

Considering the results of this research there is really too little information to apply decent analyses on the subsidence sensors. Therefor no firm conclusions about this sensor will be drawn based on the given information. Machine learning can be another interesting way to approach data collected by subsidence sensors. Further research can investigate the value of machine learning for sensor data.

This research project has shown that the data showed a similar trend of the groundwater level as local monitoring wells. Therefore, it can be concluded that the sensors are adequate to measure the groundwater level if they are calibrated and referenced to NAP. Moreover, the groundwater level sensor can possibly be used to measure how long dry periods are and how much wood is exposed to air, in order apply measures well in time. Hidden safeties are often provided by the clay layer (if present) which causes the piles to remain in wet ground conditions. In combination with tilt sensors it can be really useful in areas where sewerage systems are leaking often.

Tilt sensors are currently not used for monitoring of foundations. Initial skew measurements can help to determine the optimal location for tilt sensors in order to gather useful information regarding the foundation. Depending on the age of a building a level measurement for floor or for masonry should give the most reliable indication. As the results show the measured rotation can be related to the stiffness of the wall where the sensor is mounted on. Quite some factors have to be considered when a tilt sensor is going to monitor rotation as a result of sagging differences caused by the foundation. Although these factors are not finite, there could be more factors that need to be considered before using tilt sensors to monitor a foundation. Further research with actual testing can possibly find more factors influencing the tilt sensor data. Also more data and information is needed to determine the accuracy of the sensor. Other further research can possibly investigate if using tilt sensors is a viable option for monitoring rotations caused by the foundation.

Recommendations

As for all sensors it needs to be sure if they are calibrated to actually measure what they observe. This can be done in the lab. Further research could usefully explore how viable a system of sensors is. Here, a trade-off can be made if the costs of a sensor system compared to the information gain is worth the investment. The sensors investigated in this research are high-end and quite expensive. Less precise sensors might help to reduce costs.

InSAR data can be sensitive for unwrapping errors. Further research might explore how measuring with different wavelengths can help to eliminate unwrapping errors.

In general, classification or a prediction of the remaining service life of a foundation can be challenging. There is a lot of information available and a good judgement is not only based on measurements but also local or historical events. This can be different per city. Further research might explore how useful it is when big dataset are combined to be able to give better judgement. Possible datasets and important factors are: Dinoloket, BAG register, Zaanatlas, Waternet, raisings, relevant historical events, local problems, environmental factors and so on.

Literature

AG, K. K. (2011, January 1). *Single Axis Inclination Sensor* . Retrieved September 26, 2018, from Distrelec: https://www.distrelec.de/Web/Downloads/_t/ds/KAS901-01-02_eng_TDS.pdf

Amsterdam, G. (2018, Januari 1). *City Data*. Retrieved November 2, 2018, from Gemeente Amsterdam: https://data.amsterdam.nl/#?mpb=topografie&mpz=11&mpfs=T&mpv=52.3731081:4.8932945&pgn=home&uvm=T

Bekken, L. (2018, July 18). Monitoring. (J. P. Verbeek, Interviewer)

Blass, H. (1995). *Timber Engineering Step 1.* Almere: Centrum Hout. Retrieved March 4, 2018

Brand, G. (2004). *Herberekening van het primaire net van het NAP.* Delft: Adviesdienst Geo-Informatie en ICT (AGI). Retrieved Januari 24, 2019

Bruine de Bruin, C. F. (1997). *Onderzoek kwaliteit fundering & casco.* Amsterdam: De Waal Ingenieursbureau bv. Retrieved November 15, 2018

Civil Engineer. (2016, Mei 28). *What is Negative Skin Friction, Calculation of Negative Skin Friction?* Retrieved April 5, 2018, from iamcivilengineer.com: https://www.iamcivilengineer.com/2016/05/what-is-negative-skin-friction.html

De Reister, J. (1971). Electric Penetrometer for Site Investigations. *Journal of SMFE Division, 2*(97), 457-472. Retrieved April 5, 2018

F3O. (2014). *Onderzoek en beoordeling van funderingen op staal (ondiepe funderingen).* Rotterdam: SBRCURnet. Retrieved November 15, 2018

F3O, & SBRCURnet. (2016). *Richtlijn Houten Paalfunderingen onder gebouwen.* KCAF. Delft: F3O. Retrieved April 12, 2018, from http://f3o.nl/F30__Richtlijn%20Houten%20paalfunderingen%20onder%20gebouwen.pdf

Fugro. (2016, Januari 1). Intern document. Amsterdam, Noord-Holland, Nederland. Retrieved Februari 7, 2019

Healy, R. &. (2002). *Hydrogeology Journal*, 10:91–109. doi:https://doi.org/10.1007/s10040-001-0178-0

Hebing, B. (2018, July 17). Funderingsonderzoek [redacted]. (J. P. Verbeek, Interviewer)

Hebing, D. B. (2016). *Funderingsonderzoek* [redacted]. MOS Grondmechanica, Geotechniek. Rotterdam: MOS Grondmechanica. Retrieved May 29, 2018

Heddes, A. (2014). [redacted]. Amsterdam: Fugro Geoservices. Retrieved Januari 28, 2019

Heddes, A. (2018, September 14). Lintvoegwaterpassing. (J. P. Verbeek, Interviewer) Amsterdam, Noord-Holland, Nederland.

Heddes, A. (2018). *Rapportage funderingsonderzoek* [redacted]. Fugro NL LAND B.V, Bestaande funderingen. Amsterdam: Fugro. Retrieved Augustus 6, 2018

Het Funderingshuis. (2017, Januari 1). *Funderingsonderzoek*. Retrieved November 25, 2017, from hetfunderingshuis.nl: https://www.hetfunderingshuis.nl/funderingsonderzoek-rotterdam/

Irvine, W., & Maclennan, F. (2006). *Engineering surveying.* New York: McGraw-Hill Education. Retrieved Februari 6, 2019

KCAF. (2016, januari 1). Presentatie code oranje 2016. Nieuwegein, Utrecht, Nederland. Retrieved november 25, 2017

KCAF. (2018, Januari 1). *Aantal woningen dat met funderingsproblemen te maken kan krijgen*. Retrieved November 15, 2018, from kcaf.nl: https://www.kcaf.nl/omvang-van-funderingsproblematiek-2/

Klaassen, R. K. (2012). Wooden foundation piles and its underestimated relevance for cultural heritage. *Journal of Cultural Heritage, 2012*(13), 123-128. doi:https://doi.org/10.1016/j.culher.2012.02.014

Klaassen, R. K. (2015). *Life Expectation of Wooden Foundations - a Non-Destructive Approach.* Timber Research. Wageningen: SHR Timber Research. Retrieved March 1, 2018, from http://www.shr.nl/uploads/pdf-files/2015-09-17-ndt-foundation.pdf

Klaassen, R., Nelemans, P., & den Nijs, P. (2013). Richtlijn voor onderzoek. *Land+Water*, 36-37.

Landis JR, K. G. (1977). The measurement of observer agreement for categorical data. *Biometrics*(33), 159–174. doi:10.2307/2529310

Lange, S. d. (2011). *Partieel funderingsherstel van woningblokken.* Delft: TU Delft. Retrieved Januari 28, 2019

MEDCALC. (2018, Januari 1). *Bland-Altman plot*. Retrieved September 12, 2018, from MEDCALC: https://www.medcalc.org/manual/blandaltman.php

Murphy, K. P. (2012). *Machine Learning : A Probabilistic Perspective.* London: The MIT Press. Retrieved Februari 6, 2019, from http://ebookcentral.proquest.com/lib/delft/detail.action?docID=3339490.

Omnifor. (2016). *Monitoring Code Oranje - Haalbaarheidsonderzoek digitale monitoringsoplossing.* Rotterdam: Omnifor. Retrieved July 16, 2018

Peduto, D., Nicodemo, G., Maccabiani, J., Ferlisi, S., D'Angelo, R., & Marchese, A. (2016, September 10). Investigating the Behaviour of Buildings with Different Foundation Types on Soft Soils: Two Case Studies in the Netherlands. *Procedia Engineering*(158), 529-534. doi:10.1016/j.proeng.2016.08.484

Ritzema, H. (n.d.). The Netherlands can be subdivided in three main HEZs based on soil type: (marine) clay areas, peat lands and sandy soil areas. . *Land drainage strategies to cope with climate change in the Netherlands.* Wageningen University & Research, Wageningen.

Sass-Klaassen, U., Vernimmen, T., & Baittinger, C. (2007, November 19). Dendrochronological dating and provenancing of timber used as foundation piles under historic buildings in The Netherlands. *Elsevier, 2008*(61), 96-105. doi:doi:10.1016/j.ibiod.2007.07.013

Schofield, W., & Breach, M. (2011). *Engineering Surveying* (6th ed.). New York: Spon Press. Retrieved Januari 21, 2019

SkyGeo. (2018, Januari 1). *InSAR TECHNICAL BACKGROUND*. (SkyGeo, Editor, SkyGeo, Producer, & SkyGeo) Retrieved September 19, 2018, from SkyGeo: https://skygeo.com/insar-technical-background/

Tol, A. v. (2006). *Funderingstechnieken.* (A. F. Tol, Ed.) Delft, Zuid-Holland, Nederland: Delft University of Technology. Retrieved March 8, 2018

Verruijt, A., & Broere, W. (2012). *Grondmechanica* (9e ed.). Delft: VSSD. Retrieved Januari 29, 2019

Vree, J. d. (2018, Januari 1). *fundering, stukje geschiedenis*. Retrieved from joostdevree: http://www.joostdevree.nl/bouwkunde2/fundering_een_stukje_geschiedenis.htm

Appendix A | Research

A1. InSAR

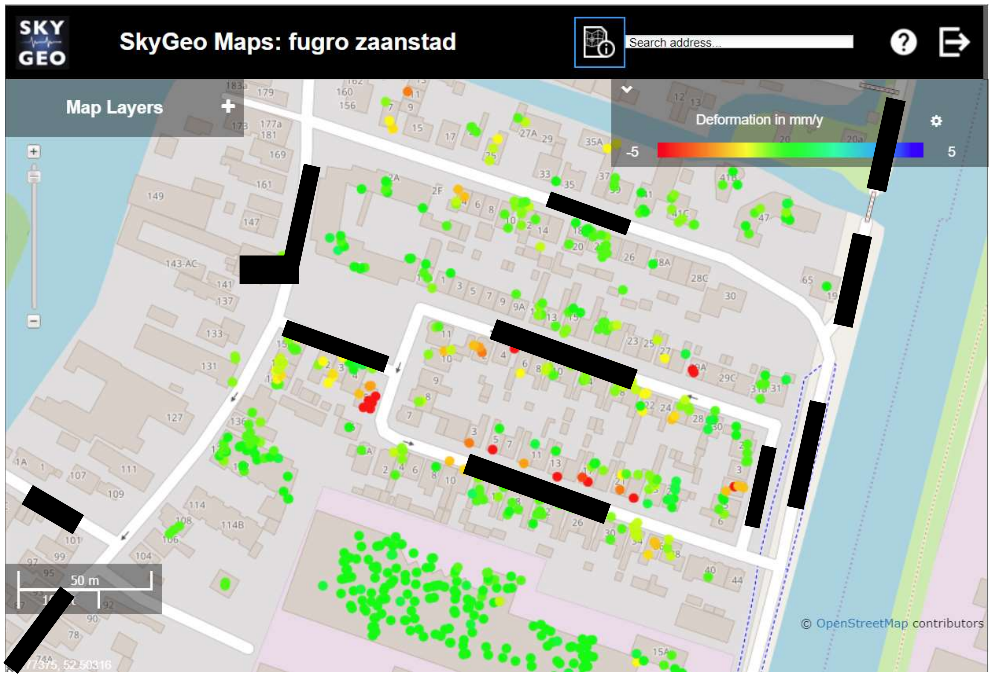
SkyGeo data

Case Study Block A InSAR data set information provided by © SkyGeo

Layer Properties: 2009-2017 Puntreflecties >2m (Kijkt uit ZW)

Property	Value
estimated models for time series	linear, quadratic, seasonal
number of observations in time	216
Antares version	Antares v2.2.0-83-g1fac345-dirty, 2017-09-18
satellite name	TerraSAR-X
description	
satellite incidence angle	31.1 [deg]
number of measurements in AoI	540
DEM	AHN
satellite pass direction	ascending (349 [deg])
acquisition period	2009-02-05 - 2017-10-31
reference point location	Virtual (0b8de581f72fad0c8ee0b6d96d5b9101)
resolution	3.0 x 2.4 m
processing id	d4d1822e123307b93e4f2856c9239455
deformation direction	vertical

Interface of © SkyGeo InSAR data Case Study Block A:

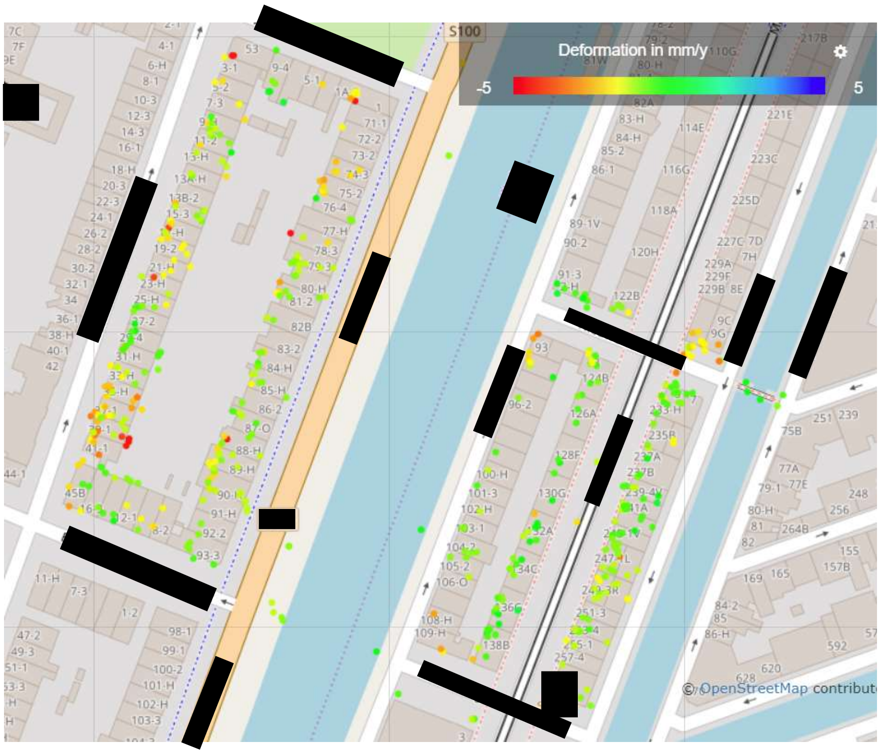


Case Study Block B InSAR data set information provided by © SkyGeo

Layer Properties: TSX asc PS Hoge Punten

Property	Value
estimated mode…	linear, quadratic, seasonal
number of obse…	219
Antares version	Antares v2.2.0-83-g1fac345-dirty, 2017-09-18
satellite name	TerraSAR-X
description	
satellite inciden…	31.1 [deg]
number of mea…	351
DEM	AHN
satellite pass dir…	ascending (349 [deg])
acquisition period	2009-02-05 - 2018-01-05
reference point l…	Virtual (98c710c74068f3ba55fa33c1e439336a)
resolution	3.0 x 2.4 m
processing id	381cdccae1e1ebd3799067b2cfcb2150
deformation dir…	vertical

Interface of © SkyGeo InSAR data Case Study Block B:



Comparison measurement bolts and InSAR data

This appendix shows 32 graphs of all measurement bolts plotted along the corresponding InSAR points for Case Study Block A and the 31 graphs of Case Study Block B.

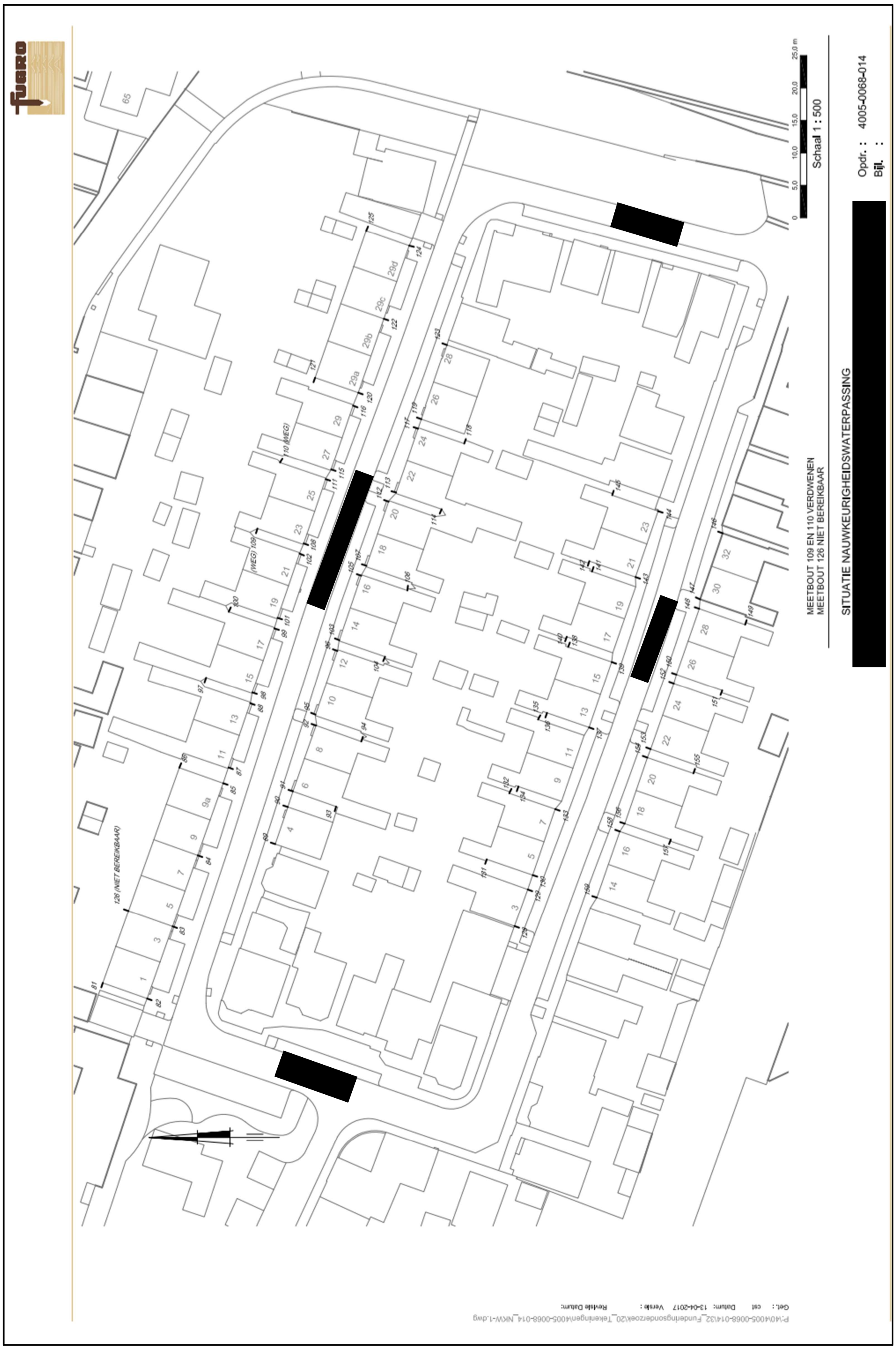
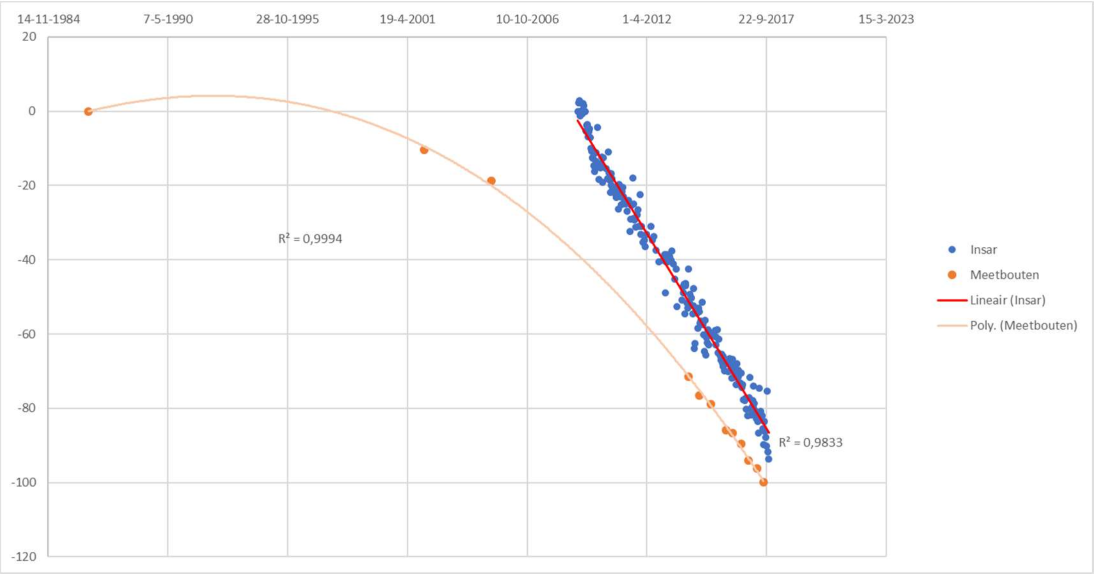


Figure 32 Map of Case Study Block A. The location of the measurement bolts are marked with a number.

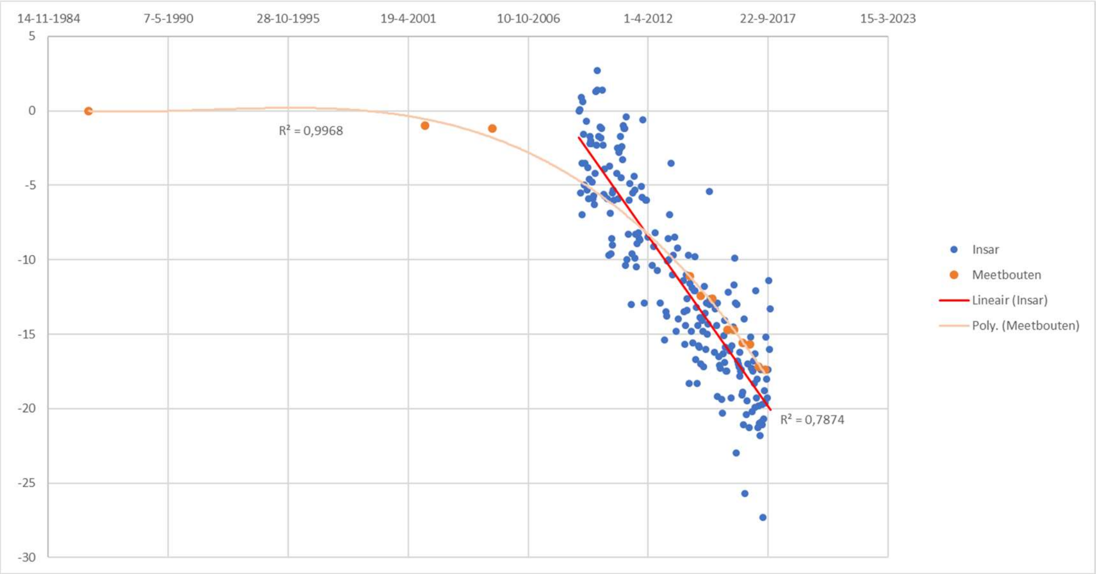
Case Study Block A measurement bolts:

MB 90



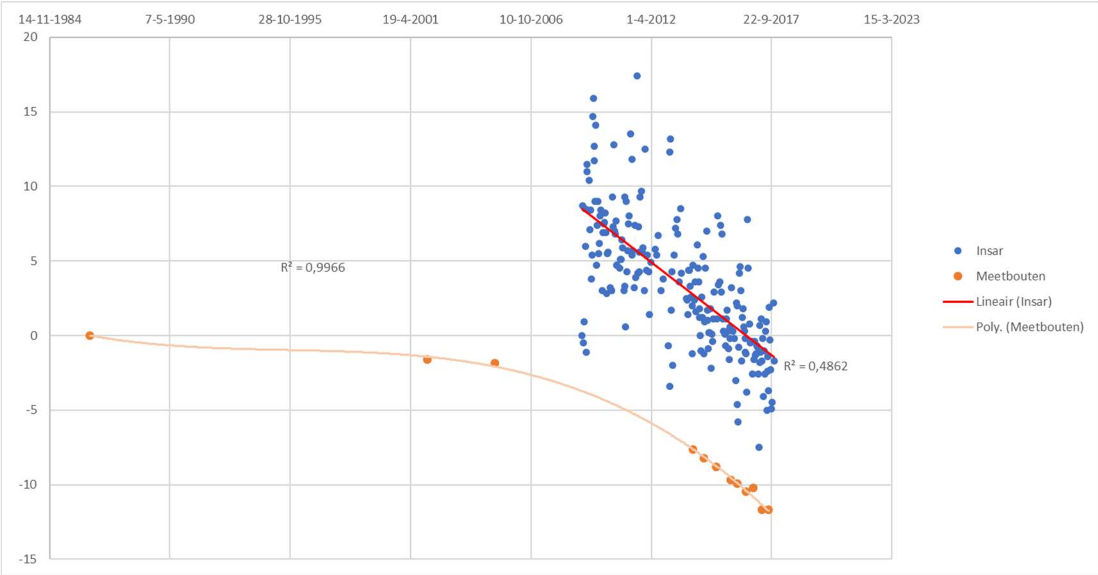
Zakking InSAR	**-9,6**	mm/year
Zakking mb	**-8,0**	mm/year

MB 93



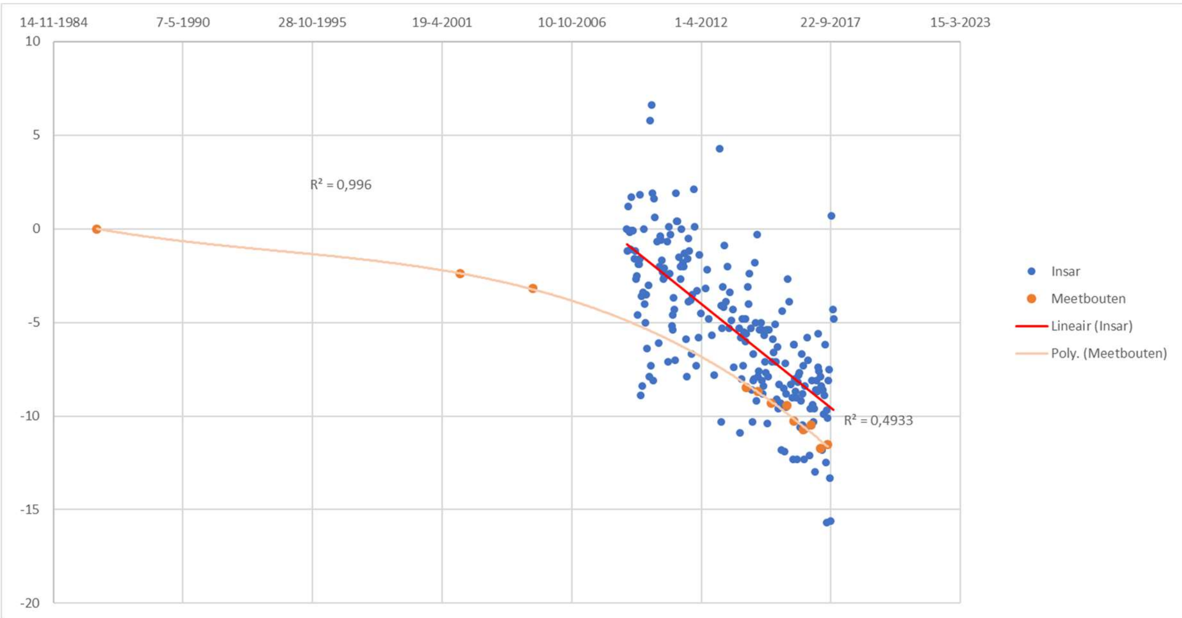
Zakking InSAR	**-2,1**	mm/year
Zakking mb	**-1,8**	mm/year

MB 95



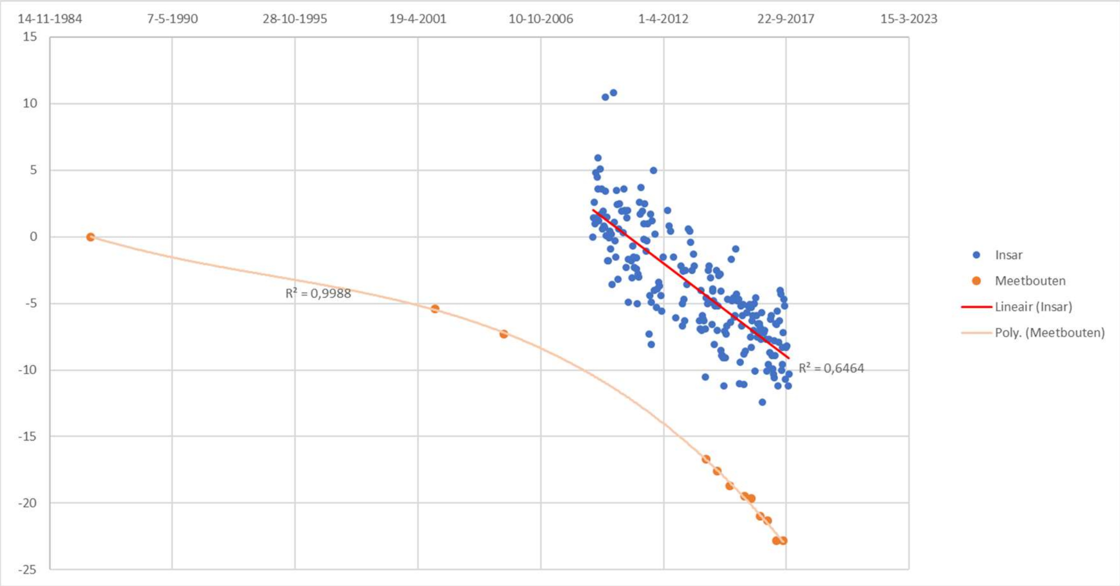
Zakking InSAR	**-1,1**	mm/year
Zakking mb	**-1,2**	mm/year

MB 96



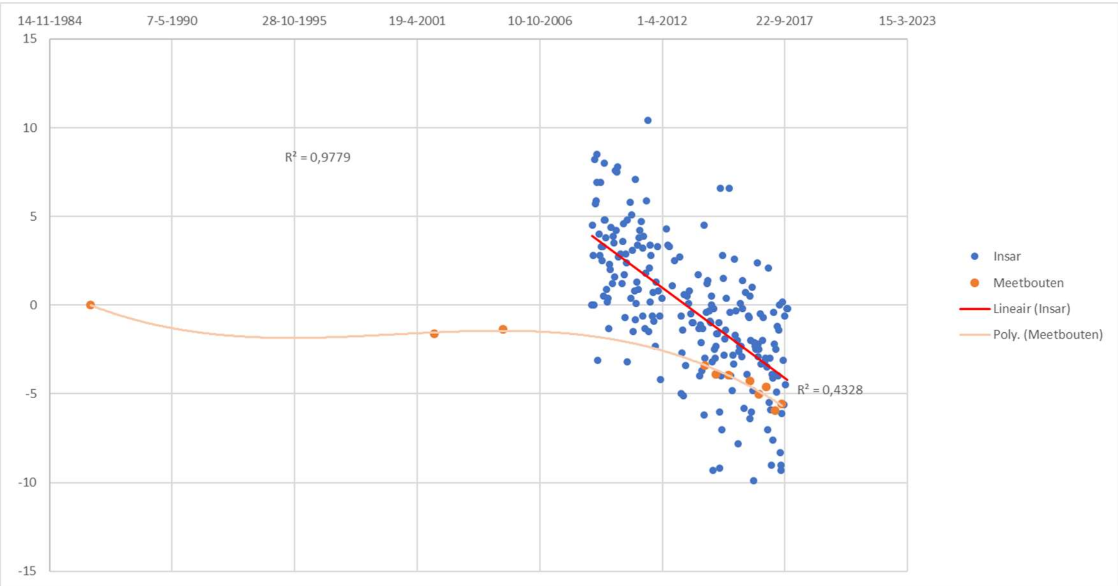
Zakking InSAR	**-1,0**	mm/year
Zakking mb	**-1,0**	mm/year

MB 103



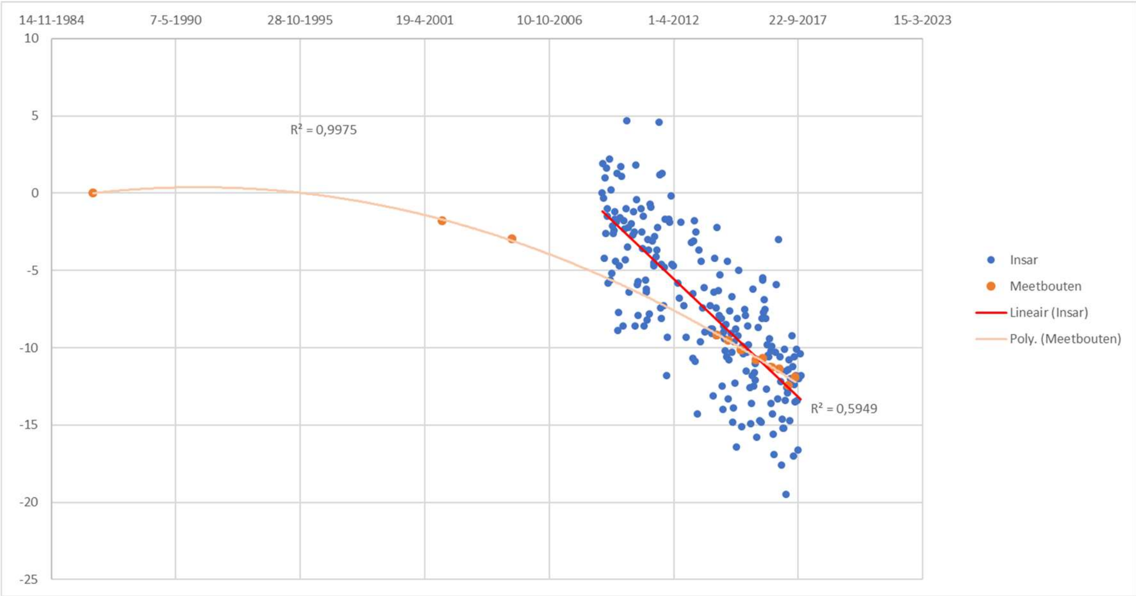
Zakking InSAR	**-1,3**	mm/year
Zakking mb	**-1,8**	mm/year

MB 104



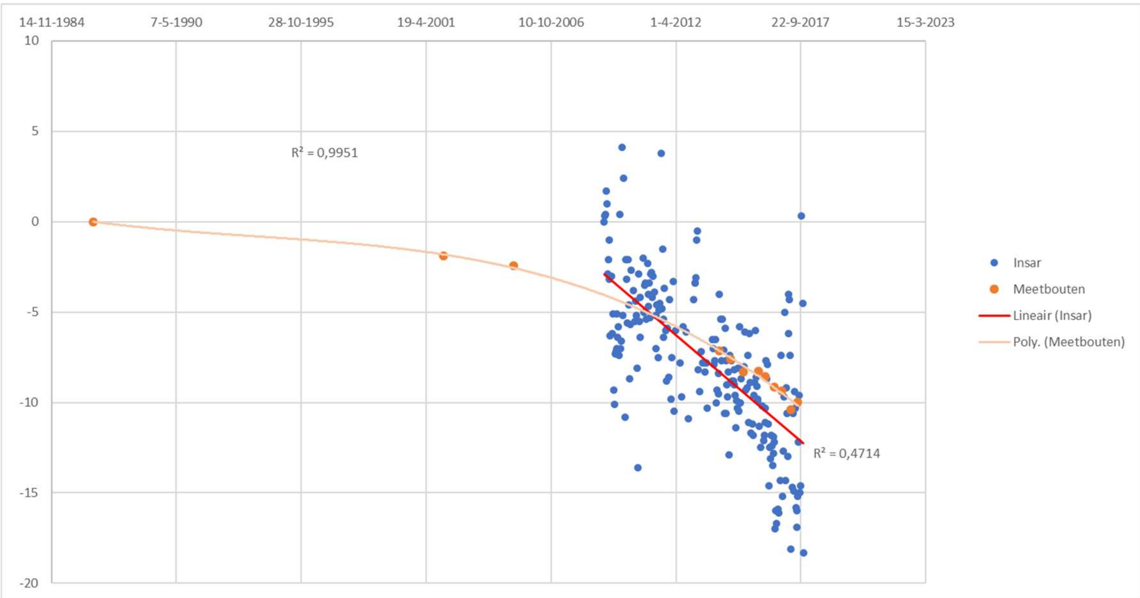
Zakking InSAR	**-0,9**	mm/year
Zakking mb	**-0,6**	mm/year

MB 105



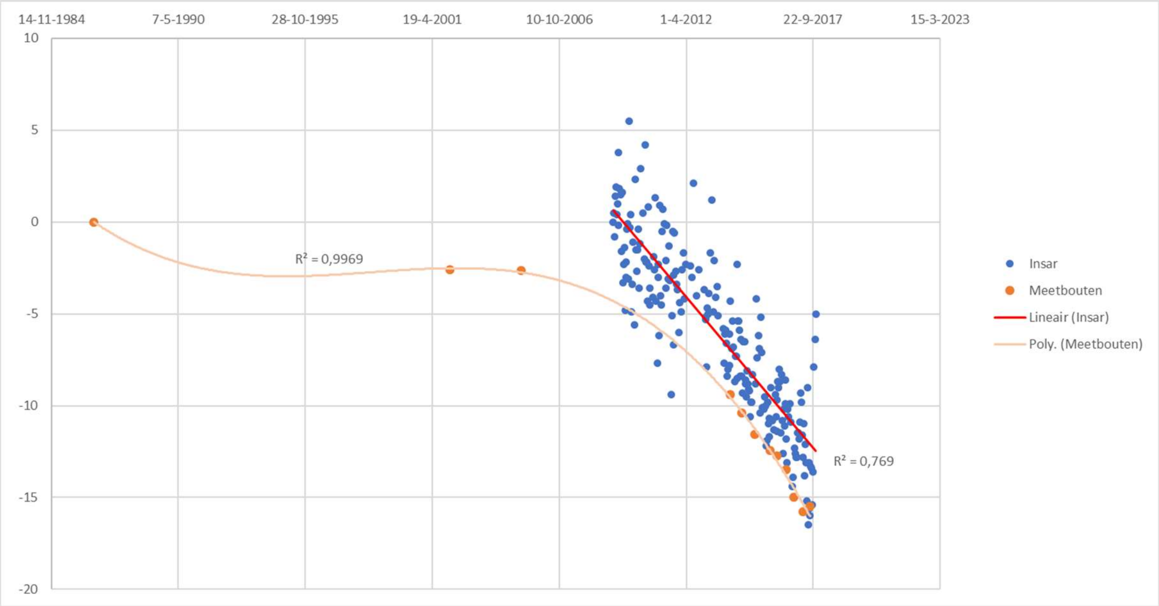
Zakking InSAR	**-1,4**	mm/year
Zakking mb	**-0,9**	mm/year

MB 107



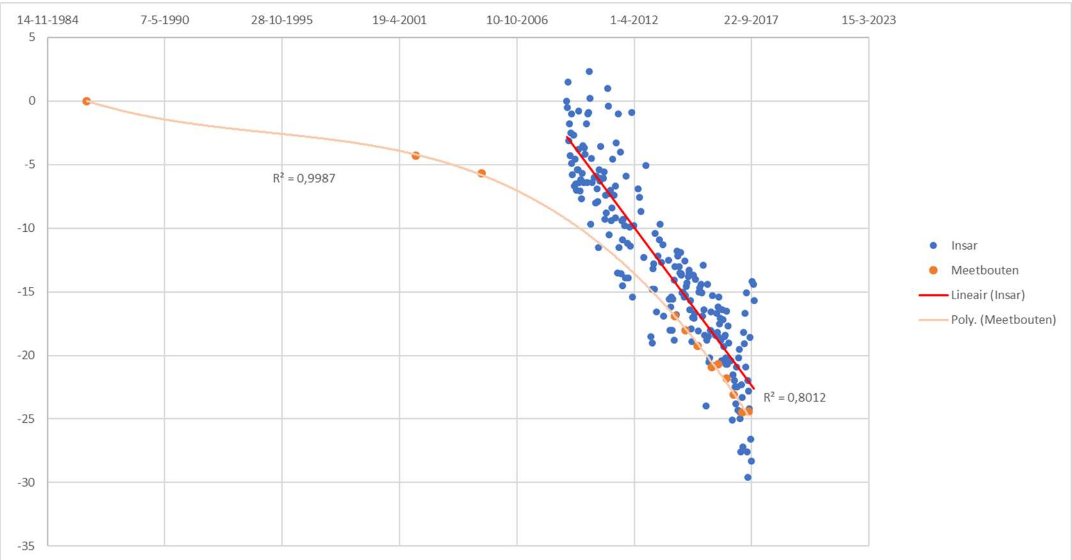
Zakking InSAR	**-1,1**	mm/year
Zakking mb	**-0,9**	mm/year

MB 112



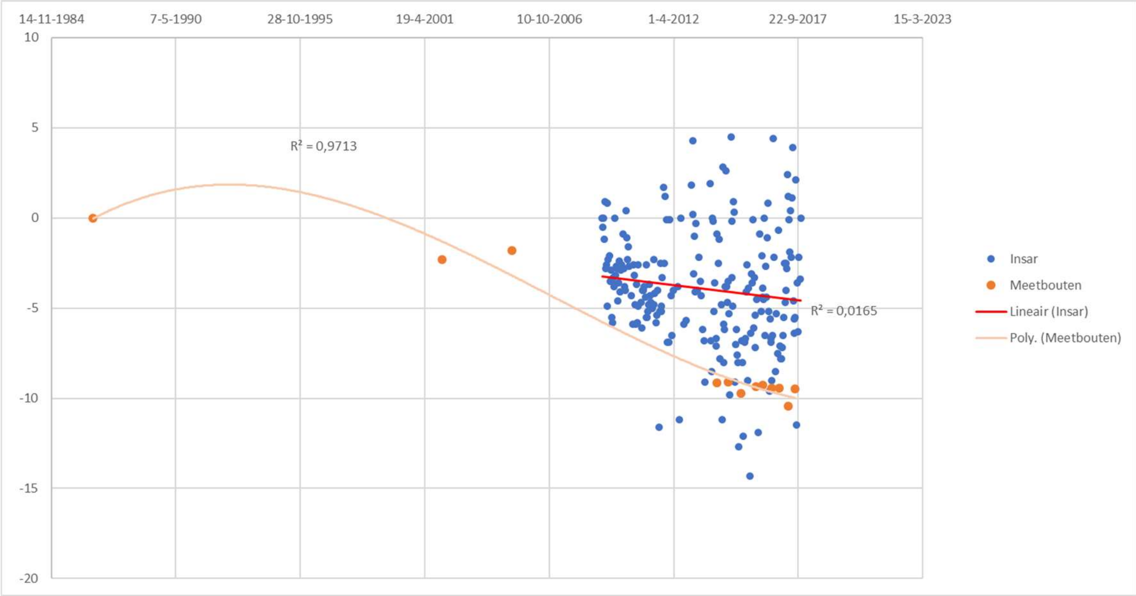
Zakking InSAR	**-1,5**	mm/year
Zakking mb	**-1,9**	mm/year

MB 113



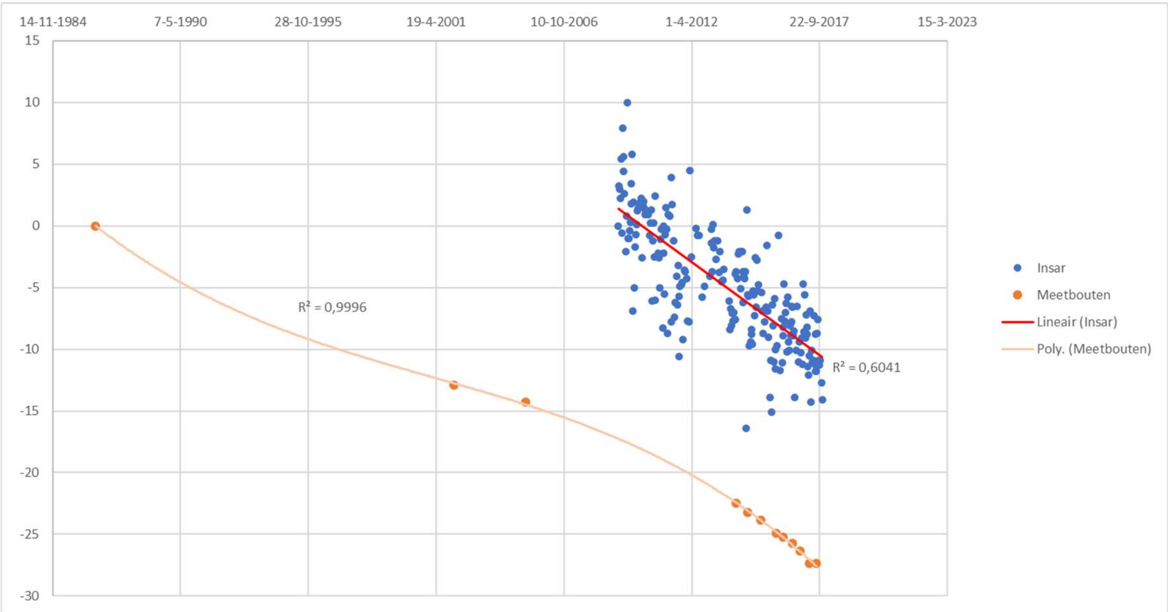
Zakking InSAR	**-2,3**	mm/year
Zakking mb	**-2,3**	mm/year

MB 114



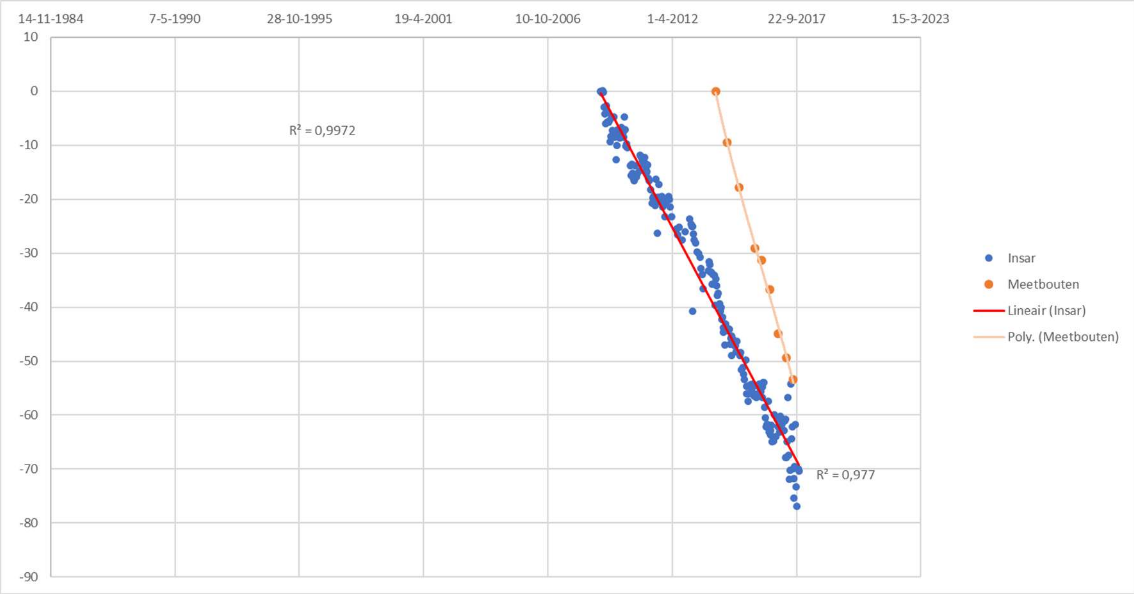
Zakking InSAR	**-0,2**	mm/year
Zakking mb	**-0,2**	mm/year

MB 119



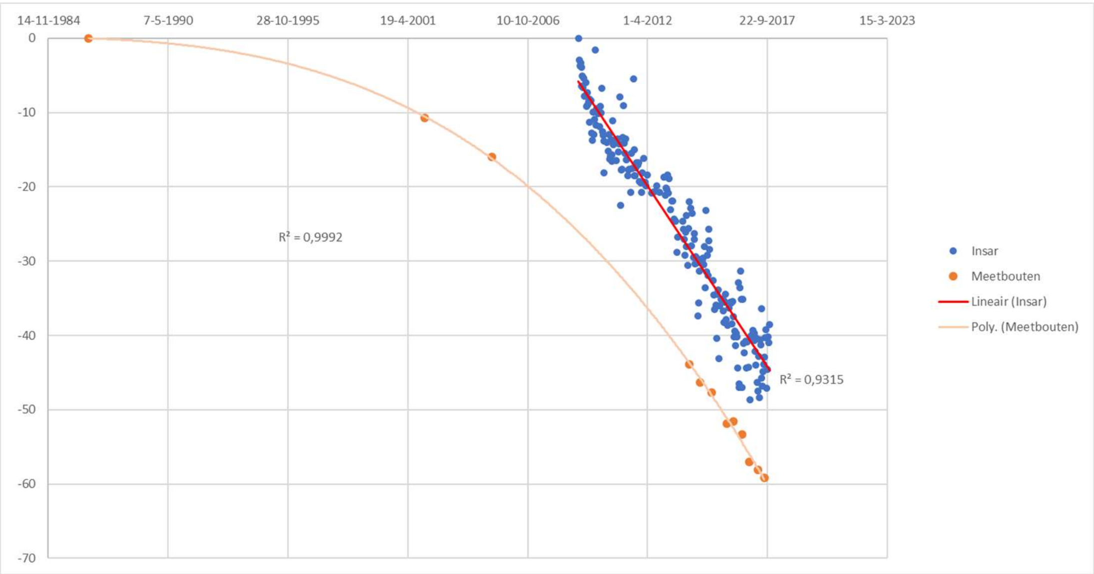
Zakking InSAR	**-1,4**	mm/year
Zakking mb	**-1,5**	mm/year

MB 120



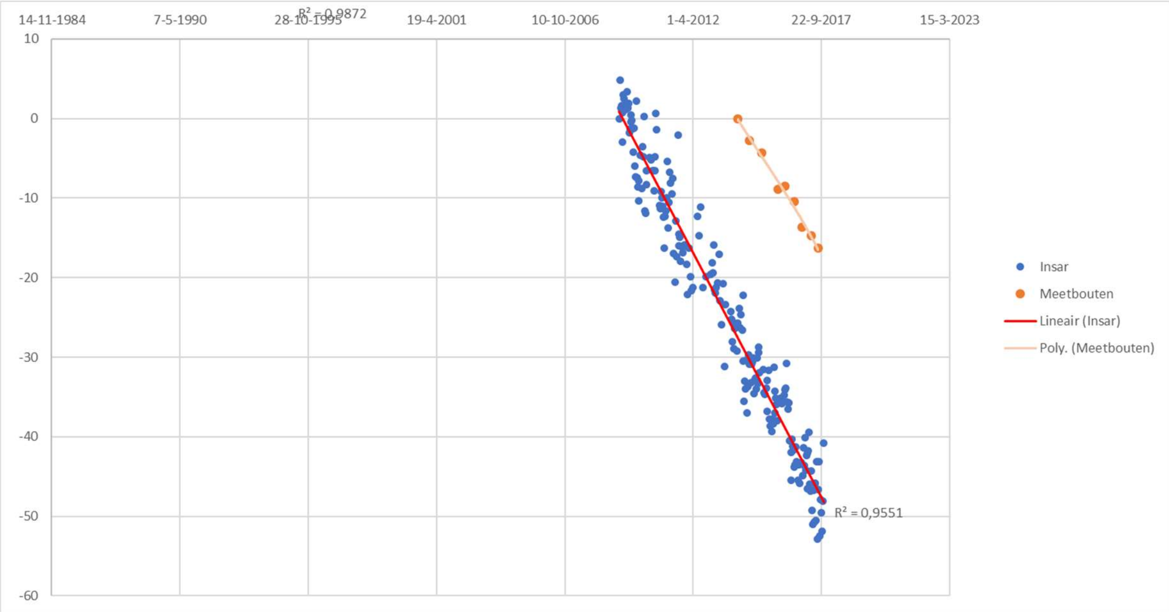
Zakking InSAR	**-7,9**	mm/year
Zakking mb	**-15,4**	mm/year

MB 128



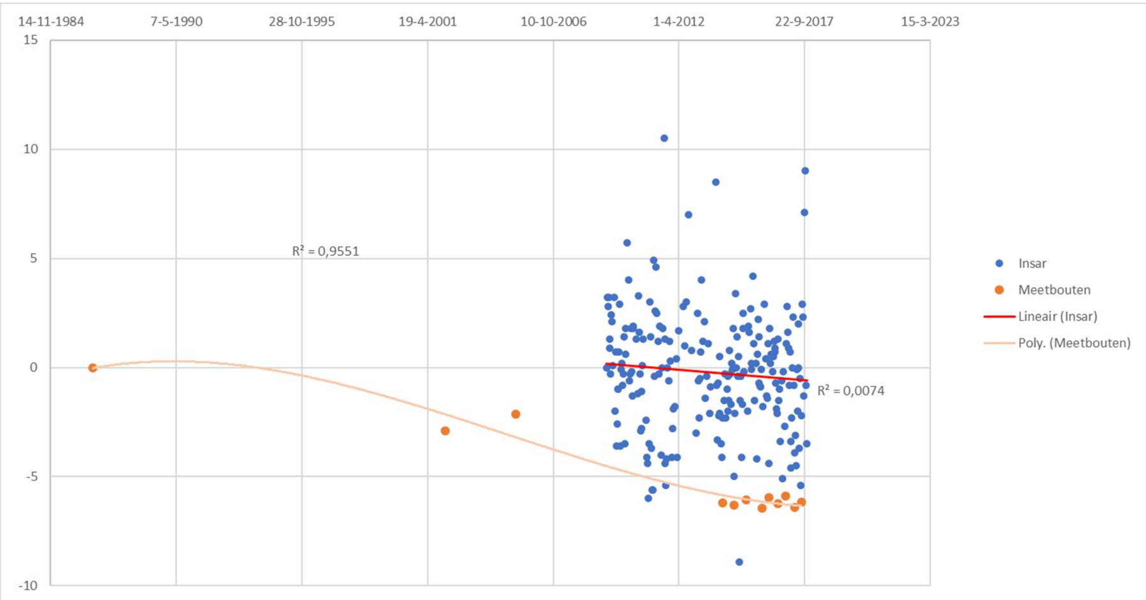
Zakking InSAR	**-4,4**	mm/year
Zakking mb	**-4,5**	mm/year

MB 130



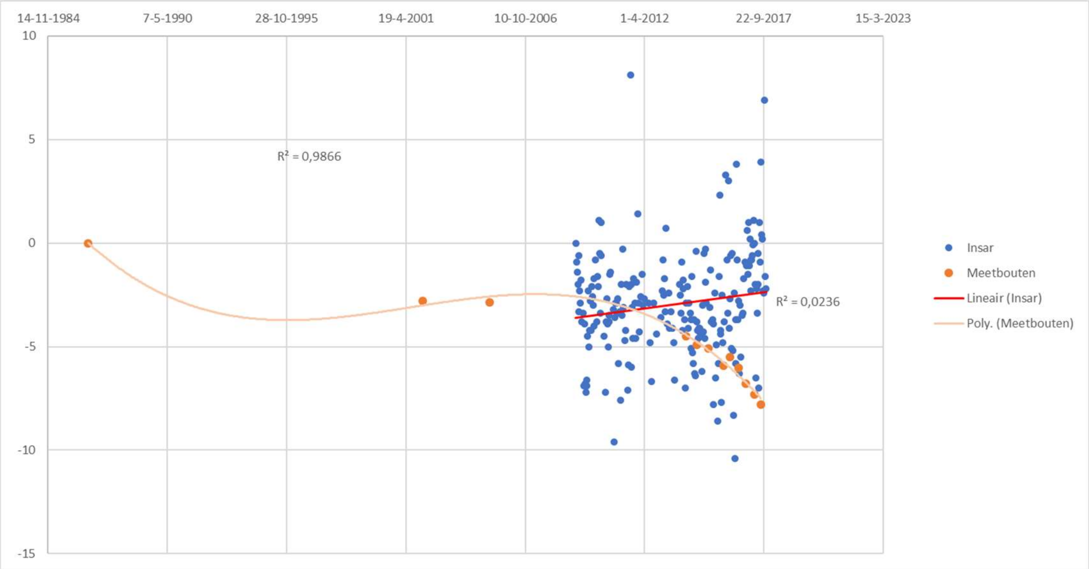
Zakking InSAR	**-5,6**	mm/year
Zakking mb	**-4,7**	mm/year

MB 131



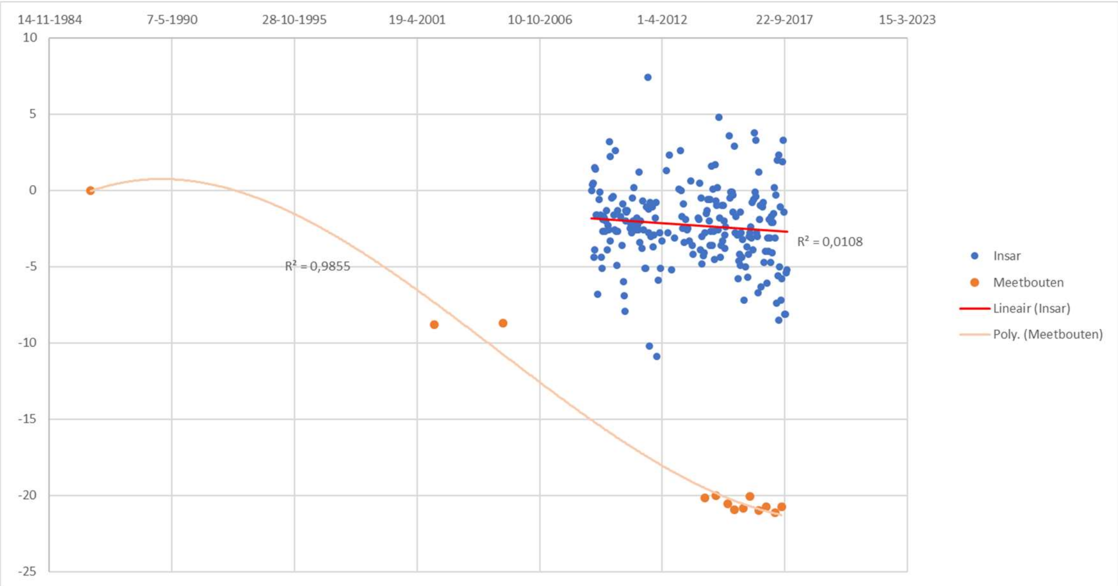
Zakking InSAR	**-0,1**	mm/year
Zakking mb	**0,0**	mm/year

MB 134 & 135



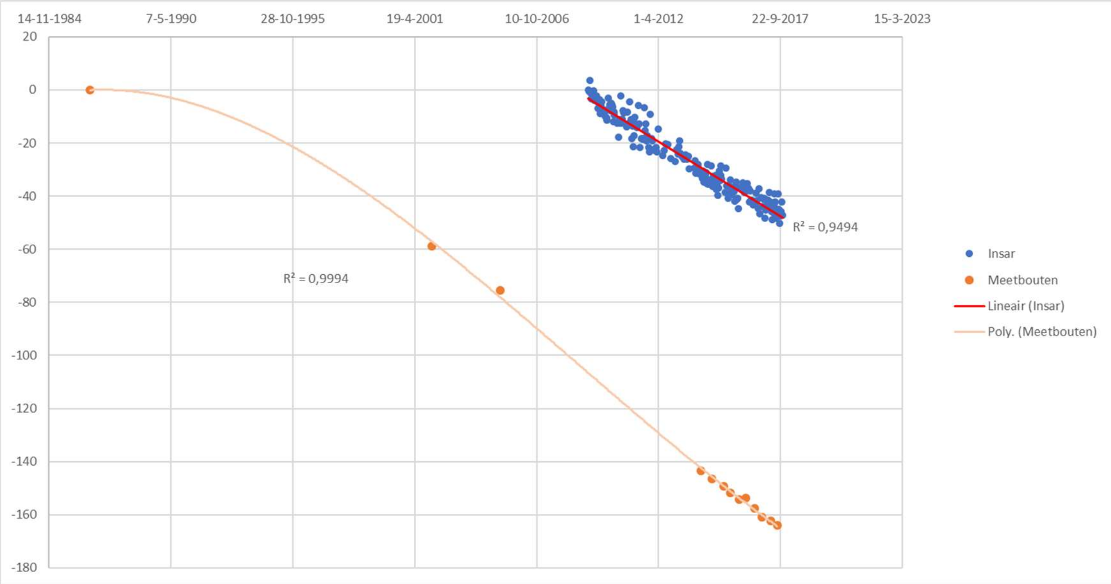
Zakking InSAR	**0,1**	mm/year
Zakking mb	**-0,6**	mm/year

MB 136



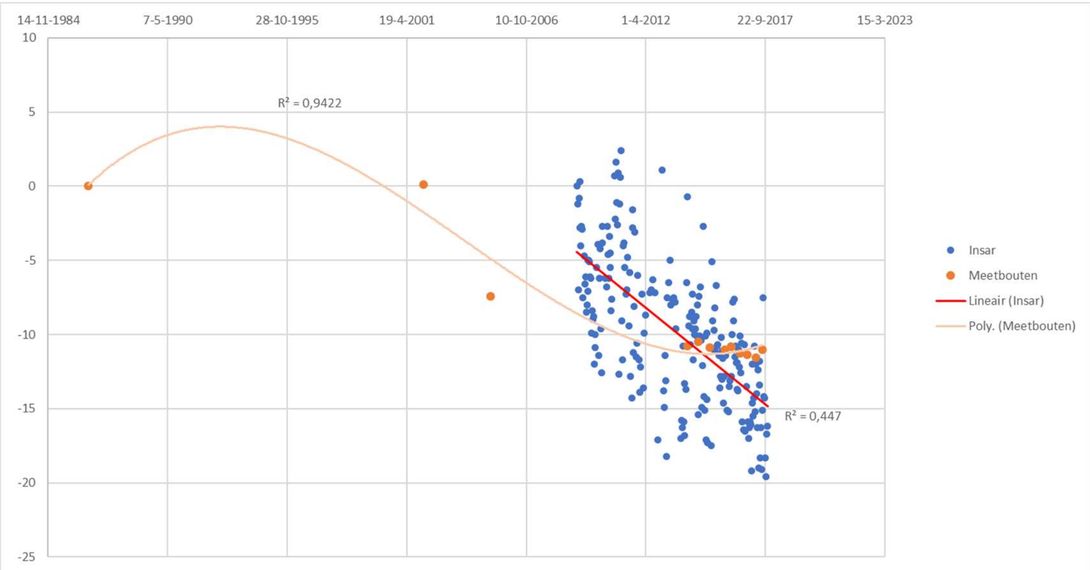
Zakking InSAR	**-0,1**	mm/year
Zakking mb	**-0,2**	mm/year

MB 137



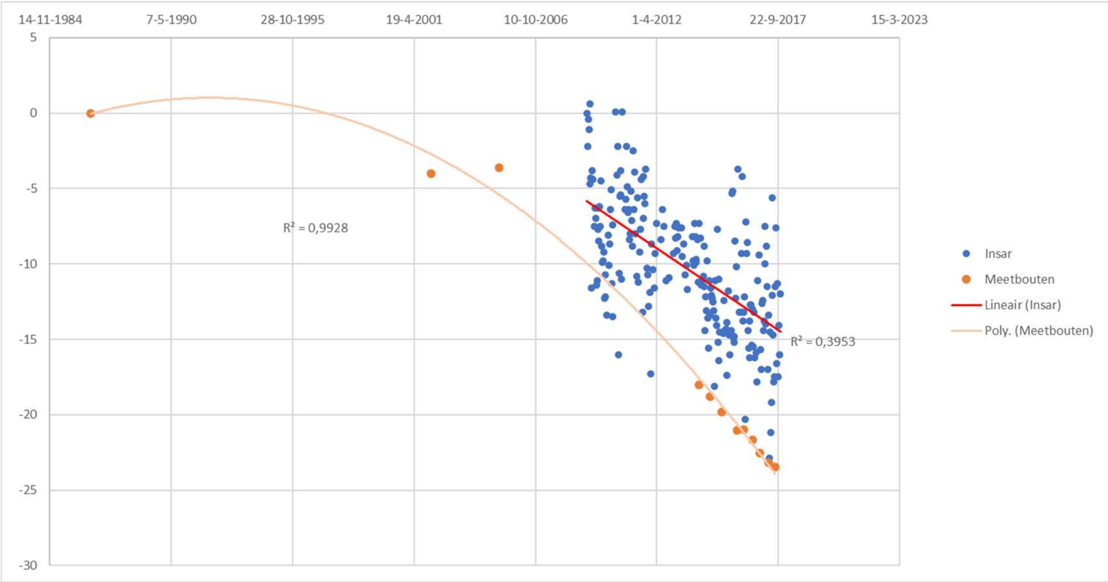
Zakking InSAR	**-5,1**	mm/year
Zakking mb	**-6,0**	mm/year

MB 140



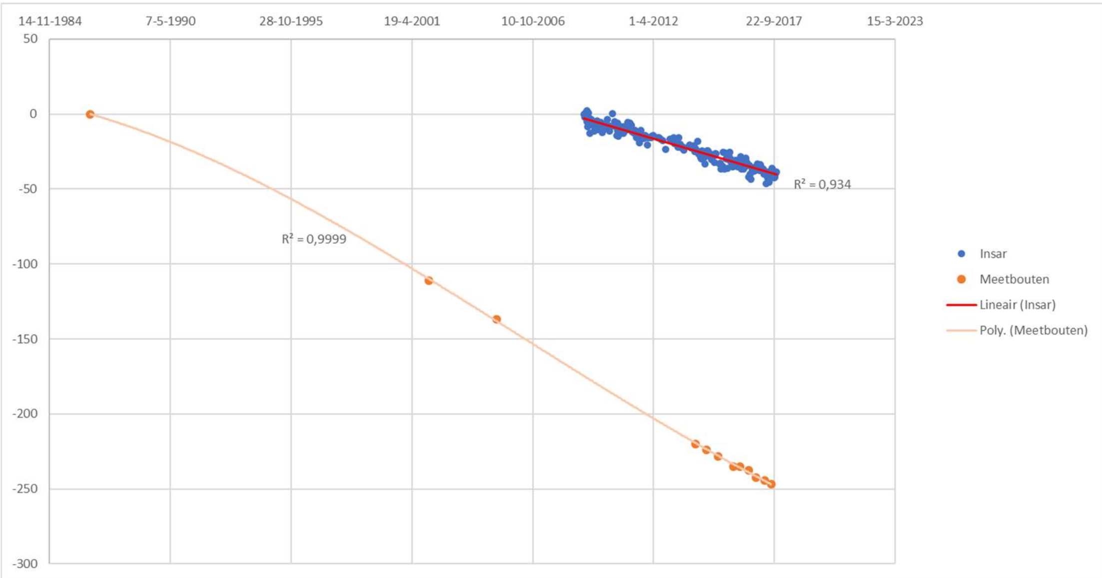
Zakking InSAR	**-1,2**	mm/year
Zakking mb	**-0,2**	mm/year

MB 141



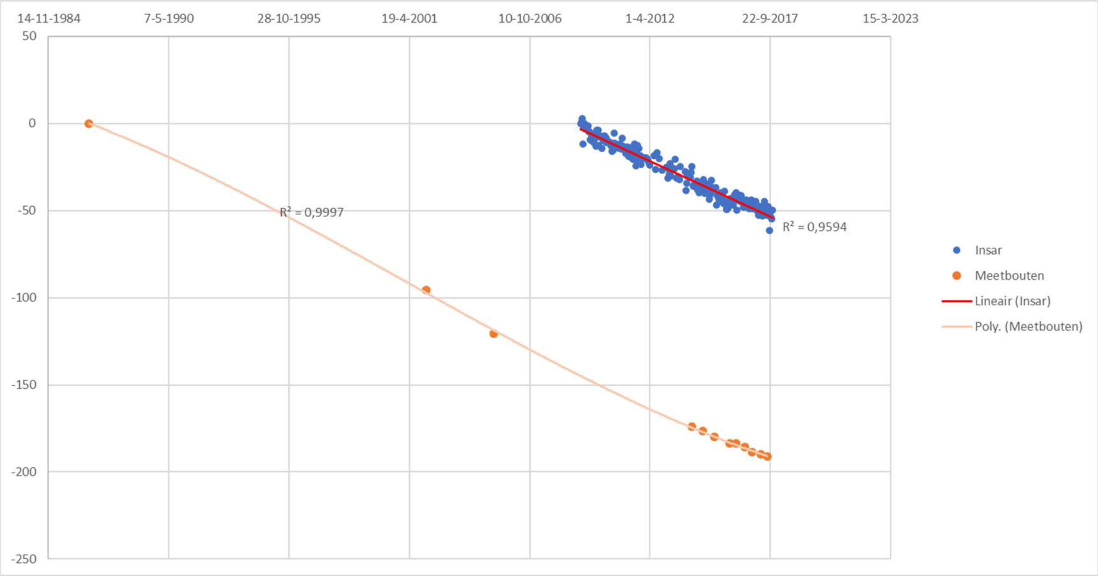
Zakking InSAR	**-1,0**	mm/year
Zakking mb	**-1,6**	mm/year

MB 143



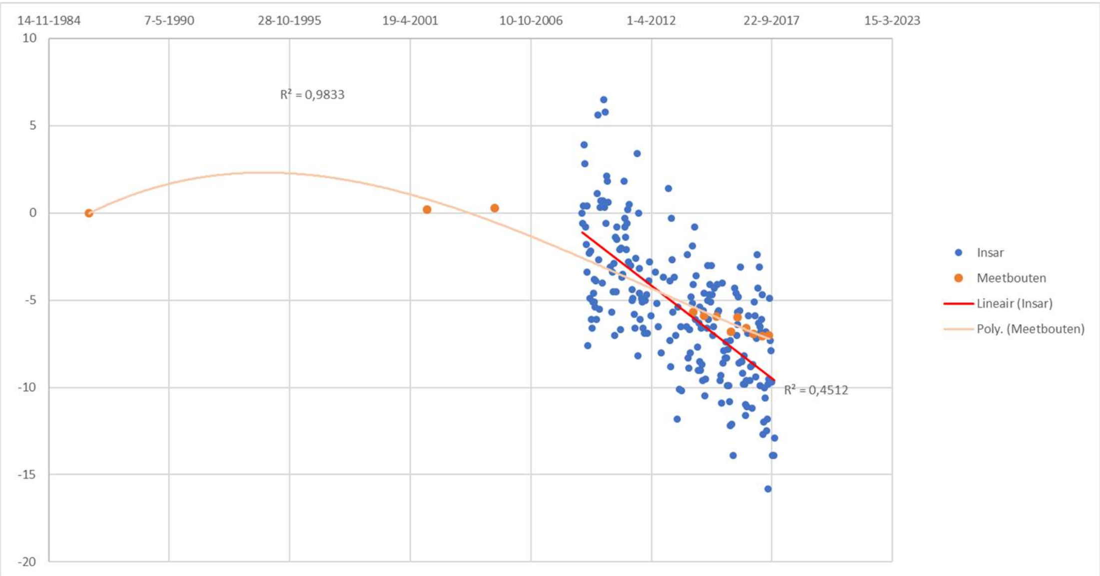
Zakking InSAR	**-4,3**	mm/year
Zakking mb	**-7,8**	mm/year

MB 144



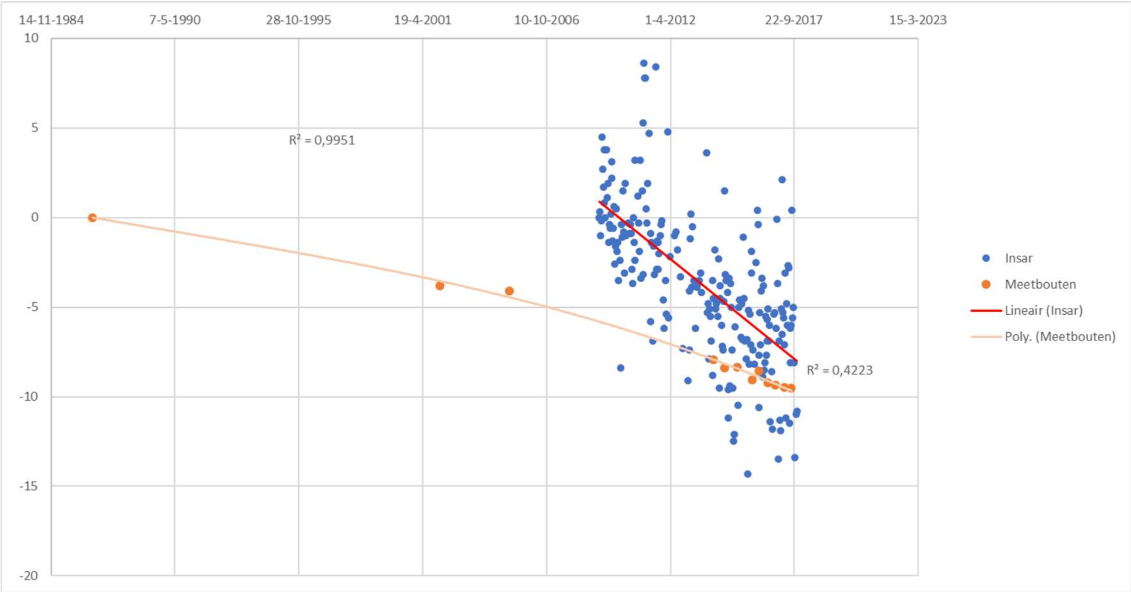
Zakking InSAR	**-5,8**	mm/year
Zakking mb	**-5,0**	mm/year

MB 146



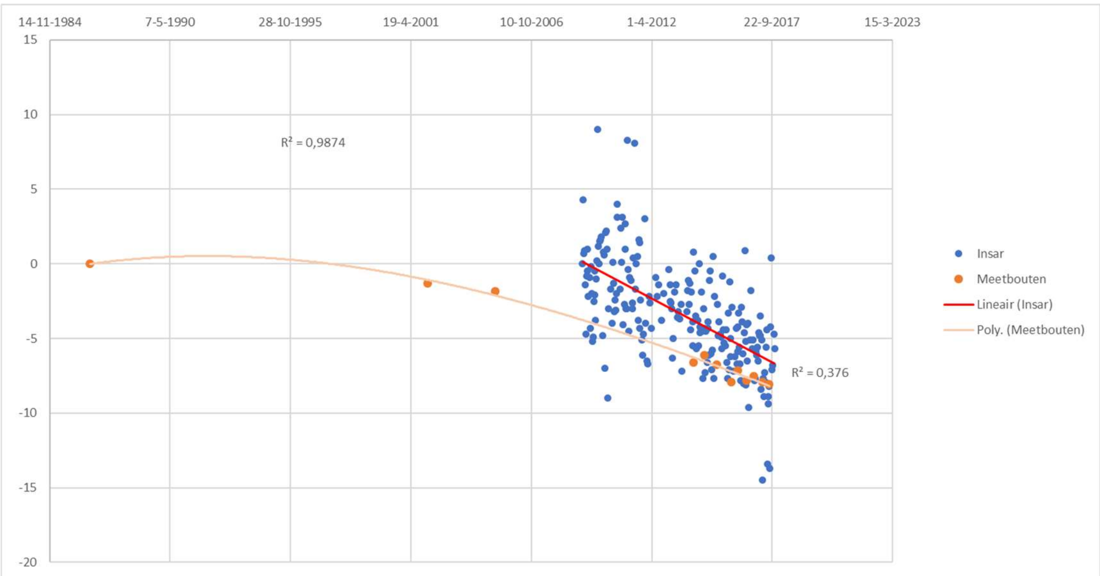
Zakking InSAR	**-1,0**	mm/year
Zakking mb	**-0,4**	mm/year

MB 147



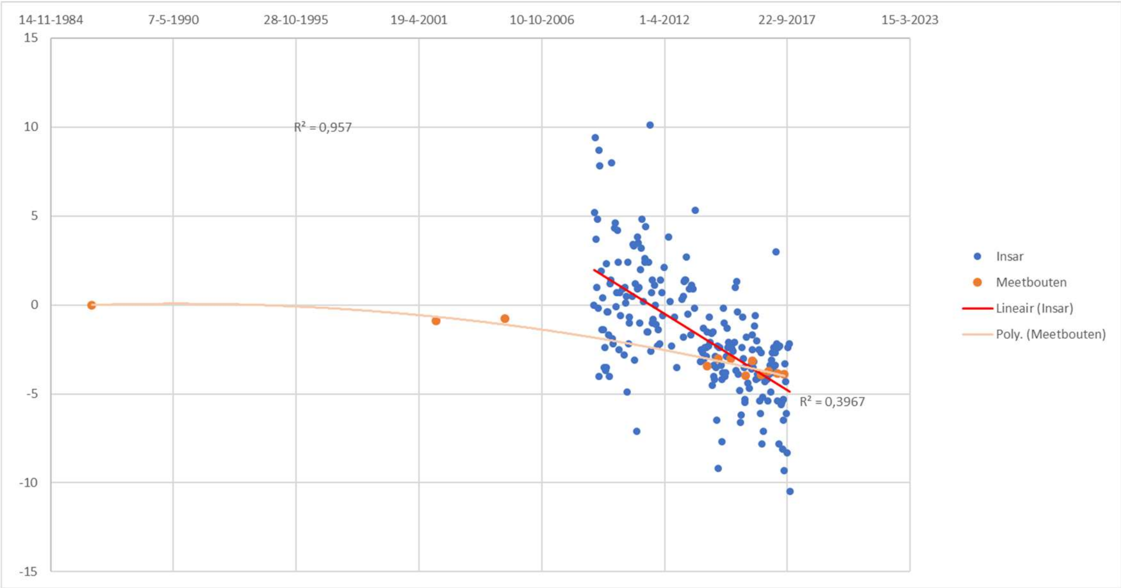
Zakking InSAR	**-1,0**	mm/year
Zakking mb	**-0,5**	mm/year

MB 150



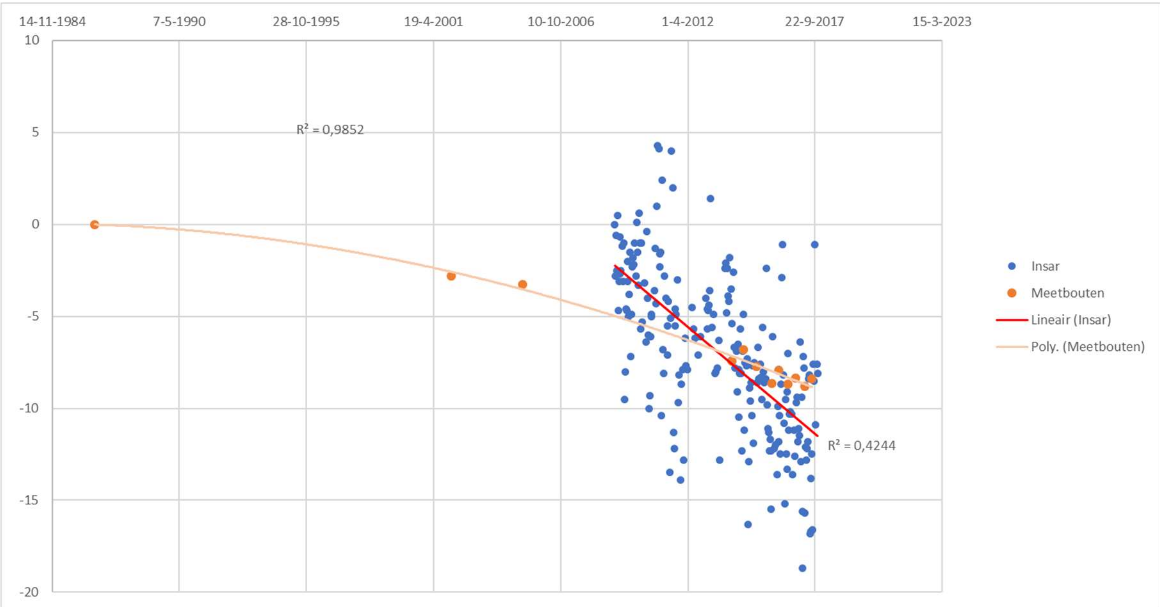
Zakking InSAR	**-0,8**	mm/year
Zakking mb	**-0,5**	mm/year

MB 152



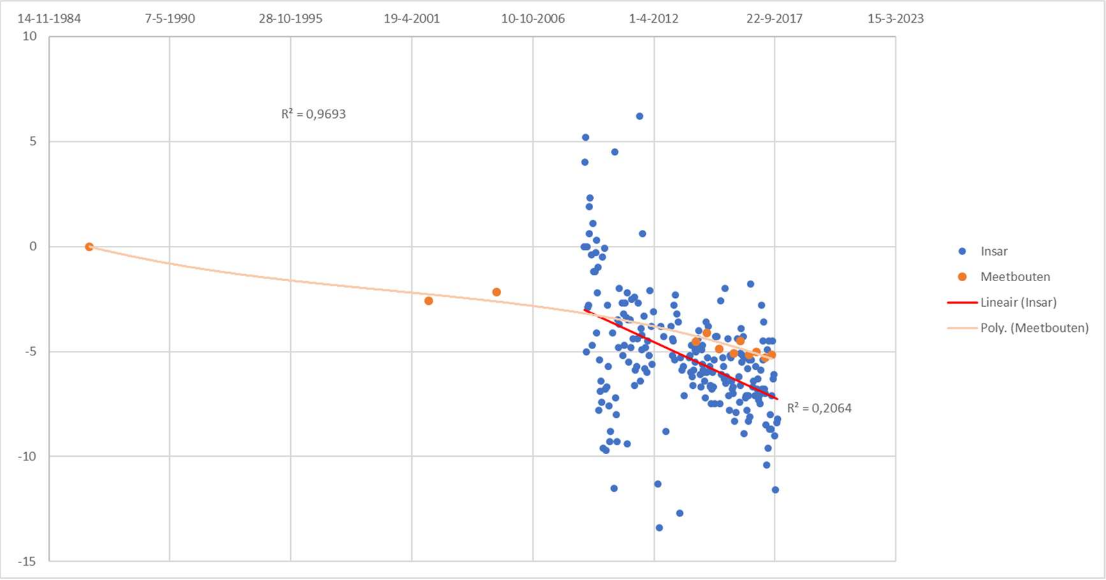
Zakking InSAR	**-0,8**	mm/year
Zakking mb	**-0,2**	mm/year

MB 153



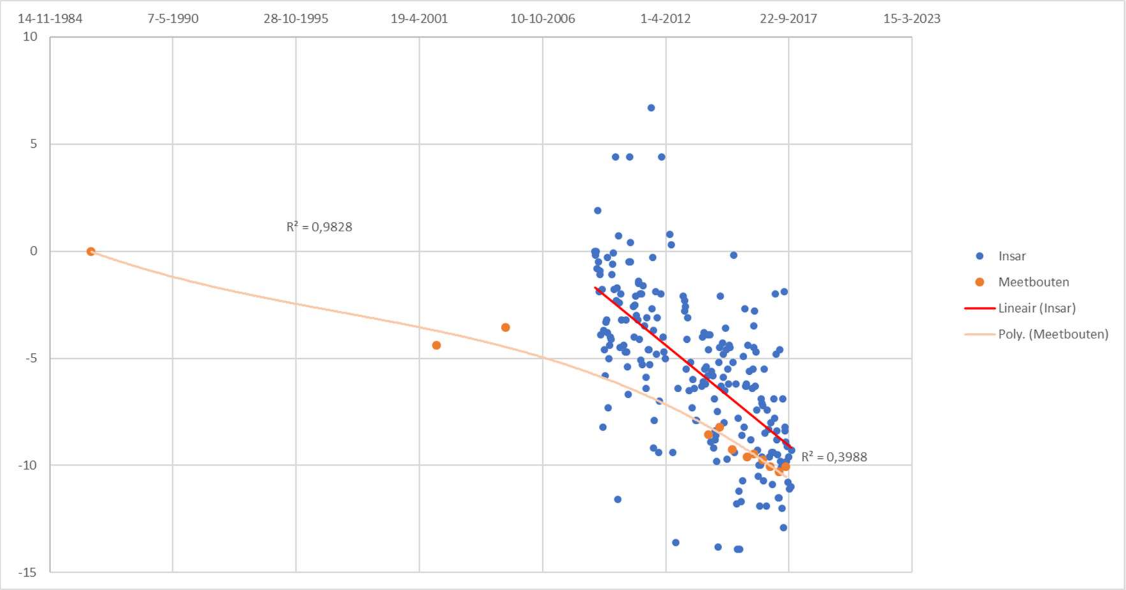
Zakking InSAR	**-1,1**	mm/year
Zakking mb	**-0,5**	mm/year

MB 155



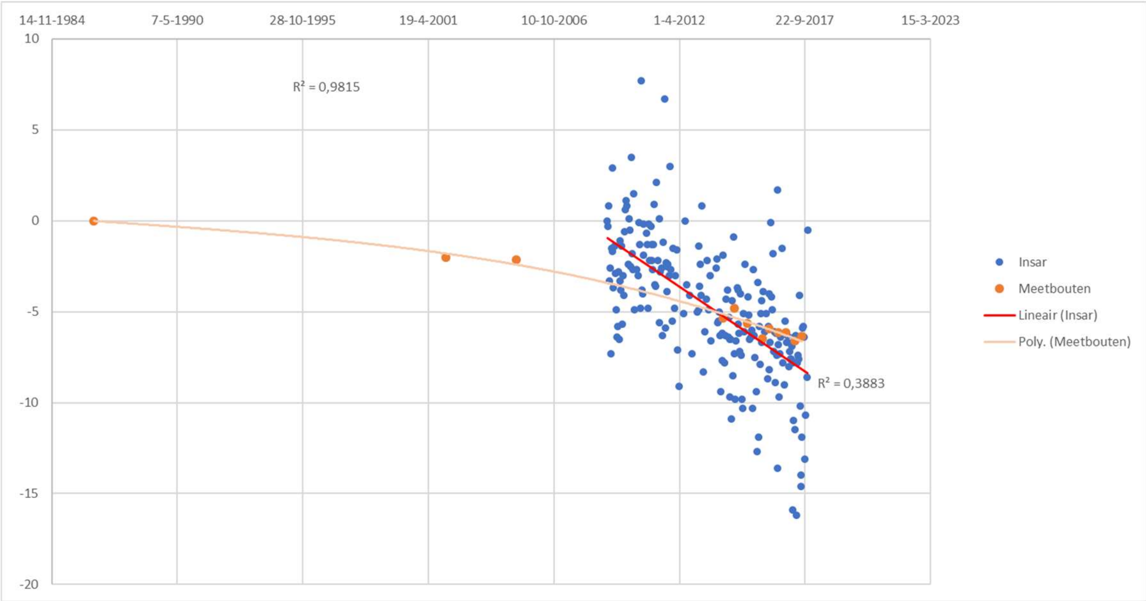
Zakking InSAR	**-0,5**	mm/year
Zakking mb	**-0,3**	mm/year

MB 156



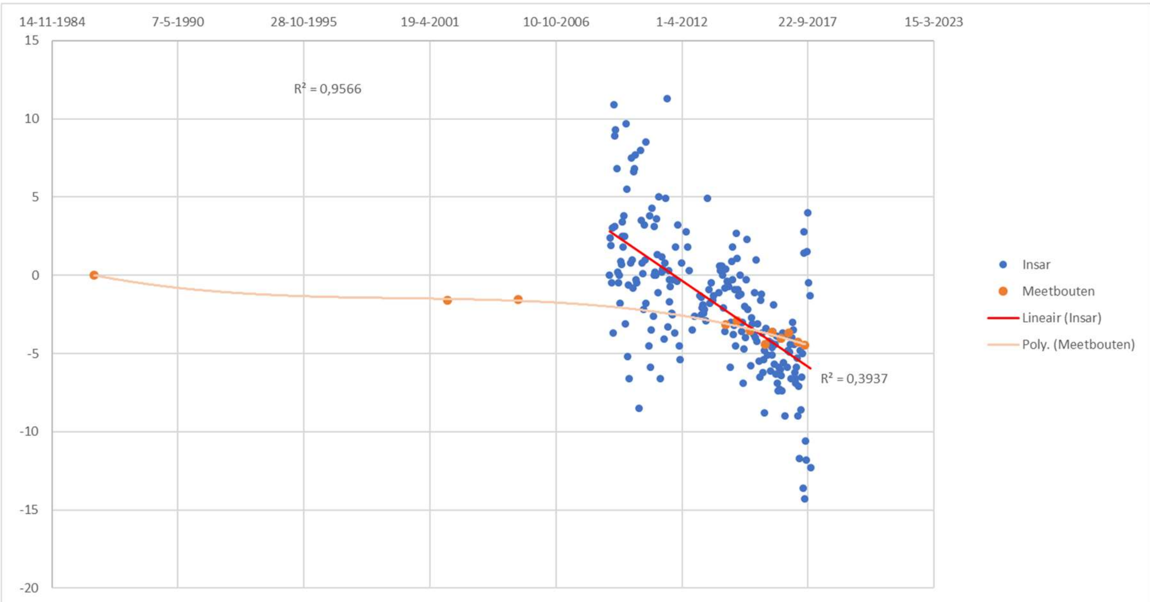
Zakking InSAR	**-0,9**	mm/year
Zakking mb	**-0,6**	mm/year

MB 158



Zakking InSAR	**-0,9**	mm/year
Zakking mb	**-0,4**	mm/year

MB 159



Zakking InSAR	**-1,0**	mm/year
Zakking mb	**-0,4**	mm/year

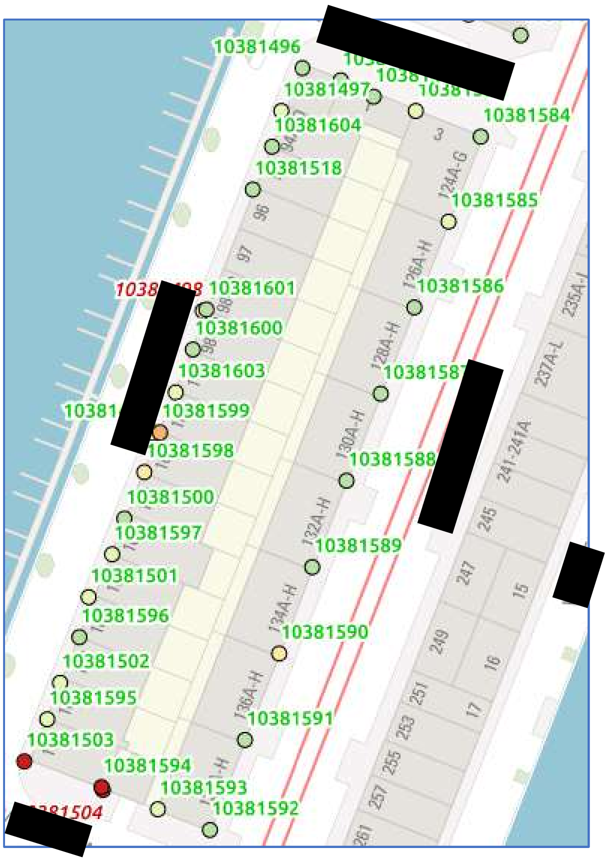
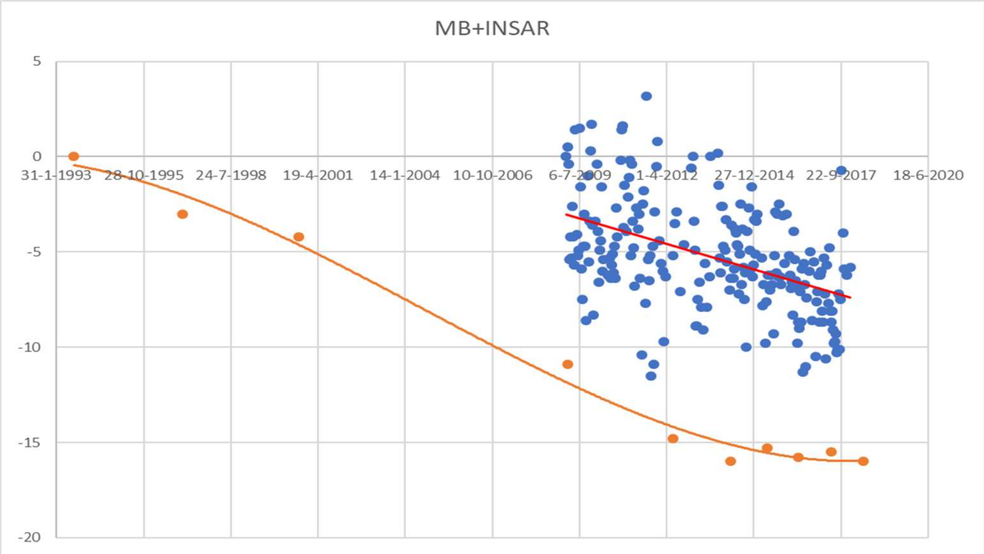


Figure 33 Map of Case Study Block B. The location of the measurement bolts are marked with a number. (source: City Data Amsterdam)

Figure 34 Map of Case Study Block B. The location of the measurement bolts are marked with a number. (source: City Data Amsterdam)

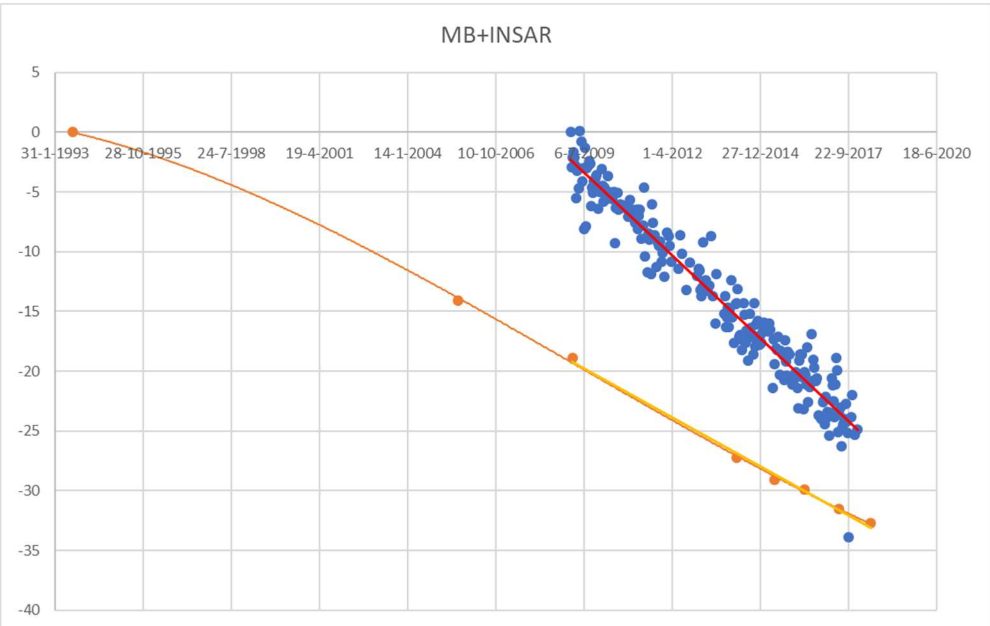
Case Study Block B measurement bolts:

MB 10381223



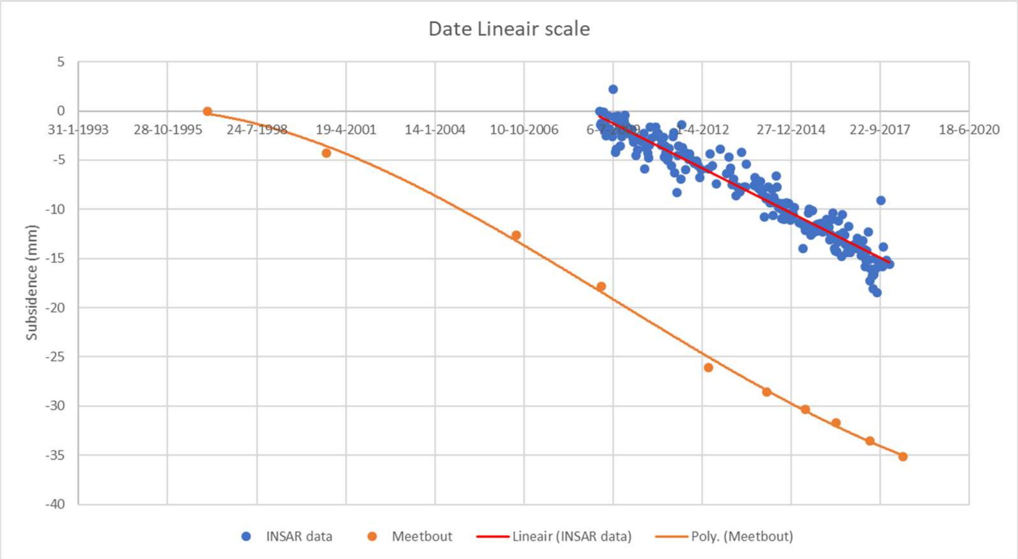
Zakking InSAR	**-0,491**	mm/year
Zakking mb	**-0,550**	mm/year

MB 10381225



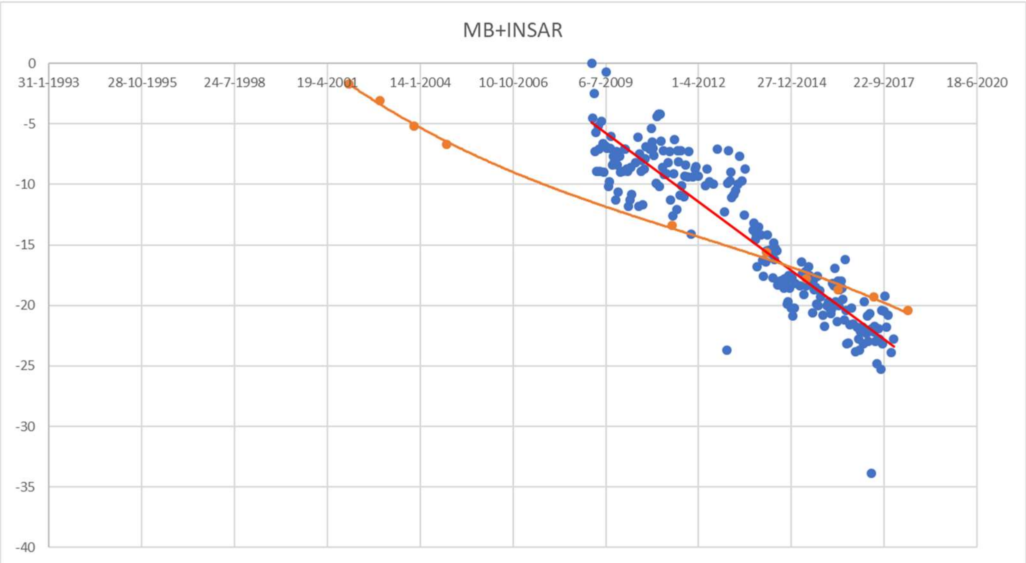
Zakking InSAR	**-2,538**	mm/year
Zakking mb	**-1,489**	mm/year

MB 10381285



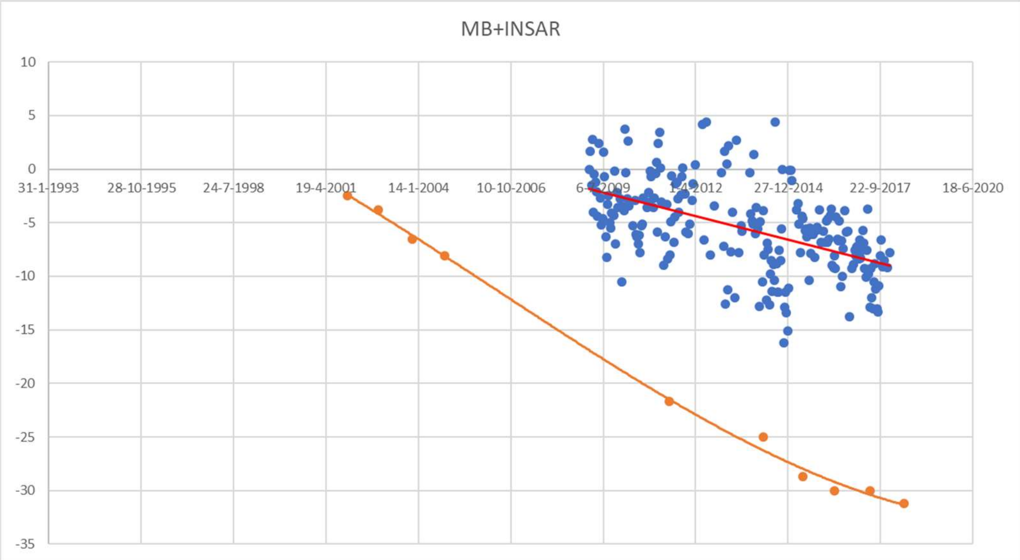
Zakking InSAR	**-1,666**	mm/year
Zakking mb	**-1,867**	mm/year

MB 10381604



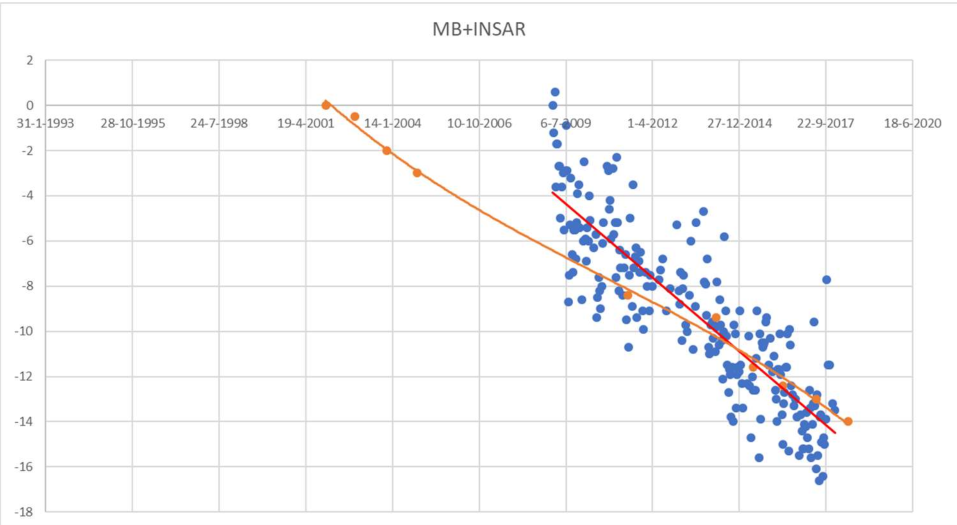
Zakking InSAR	**-2,075**	mm/year
Zakking mb	**-1,007**	mm/year

MB 10381499



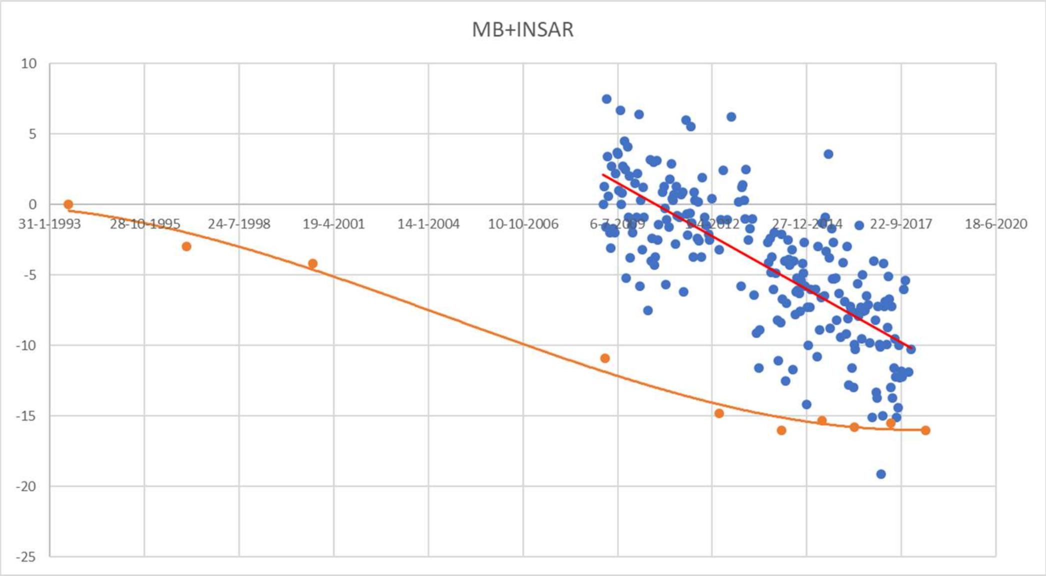
Zakking InSAR	**-0,802**	mm/year
Zakking mb	**-1,367**	mm/year

MB 10381500



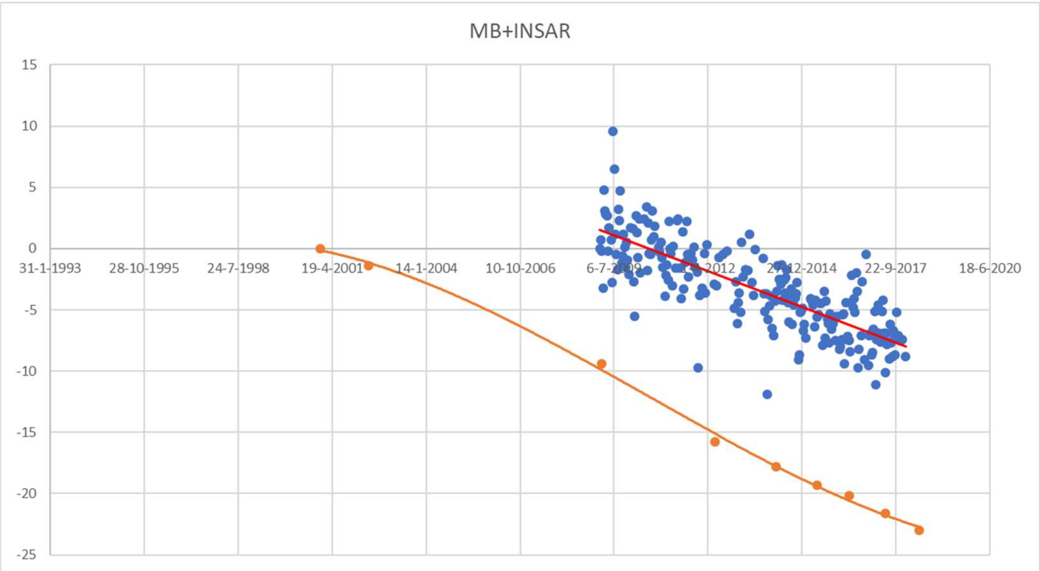
Zakking InSAR	**-1,192**	mm/year
Zakking mb	**-0,806**	mm/year

MB 10381518



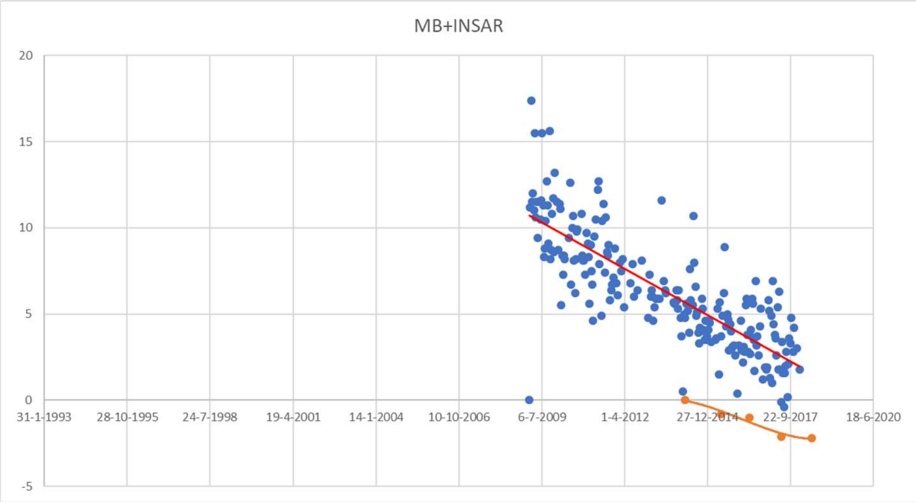
Zakking InSAR	**-1,377**	mm/year
Zakking mb	**-0,550**	mm/year

MB 10381523



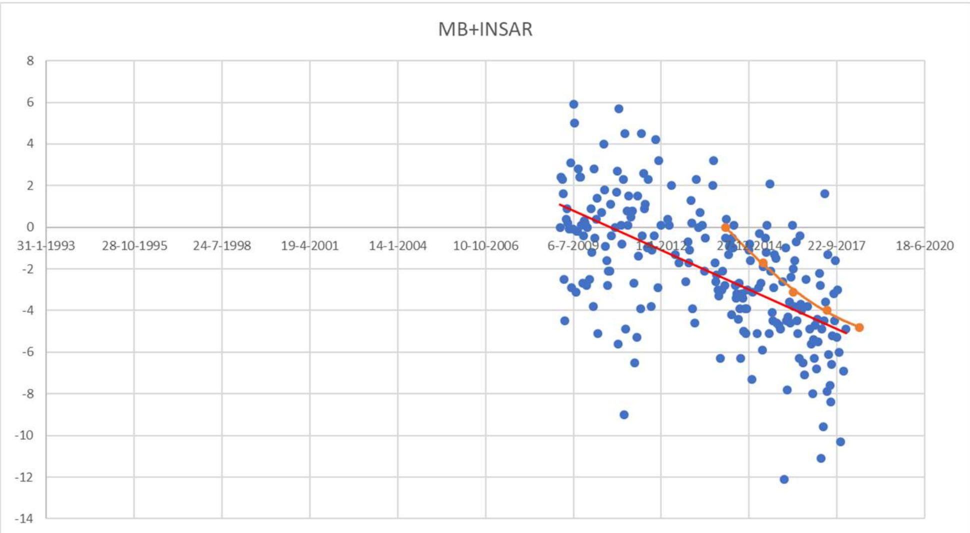
Zakking InSAR	**-1,069**	mm/year
Zakking mb	**-1,467**	mm/year

MB 10381576



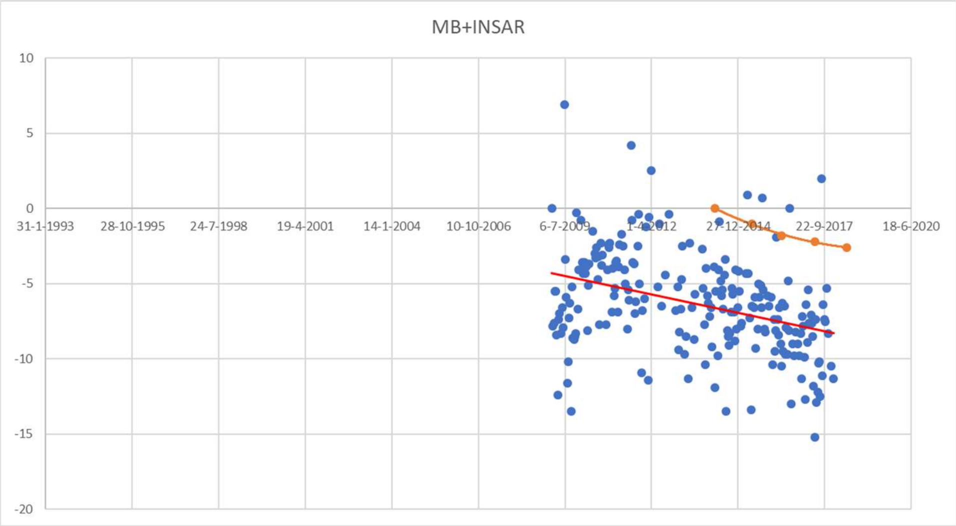
Zakking InSAR	**-0,980**	mm/year
Zakking mb	**-0,528**	mm/year

MB 10381583



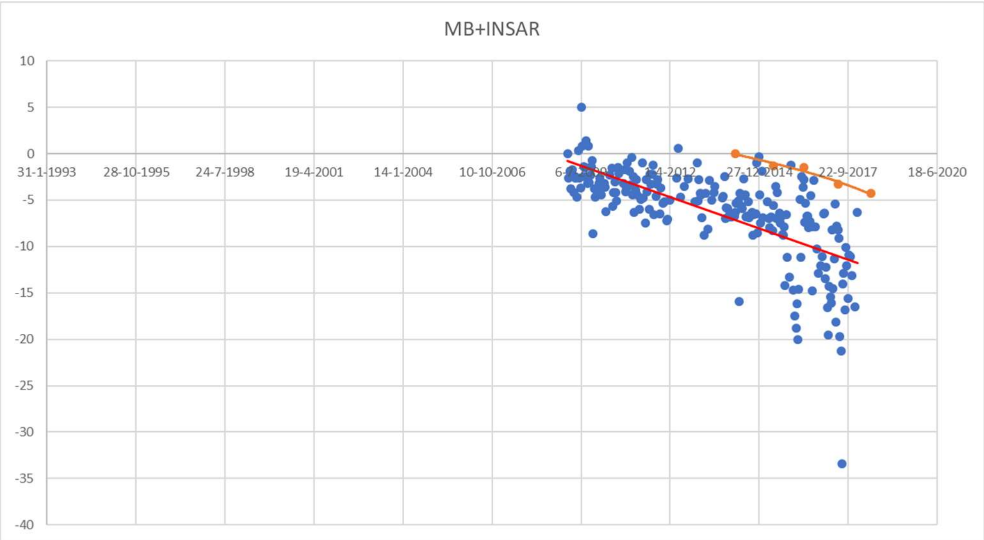
Zakking InSAR	**-0,690**	mm/year
Zakking mb	**-1,151**	mm/year

MB 10381584



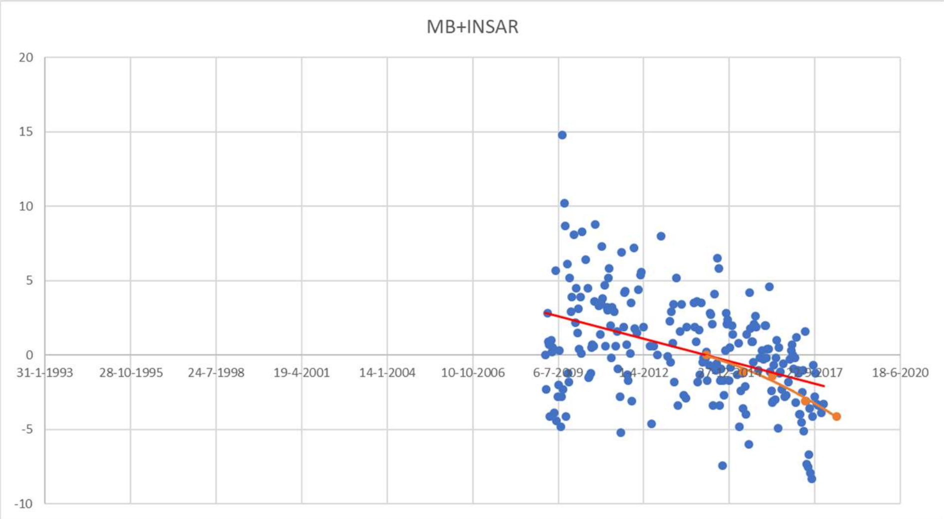
Zakking InSAR	**-0,442**	mm/year
Zakking mb	**-0,624**	mm/year

MB 10381585



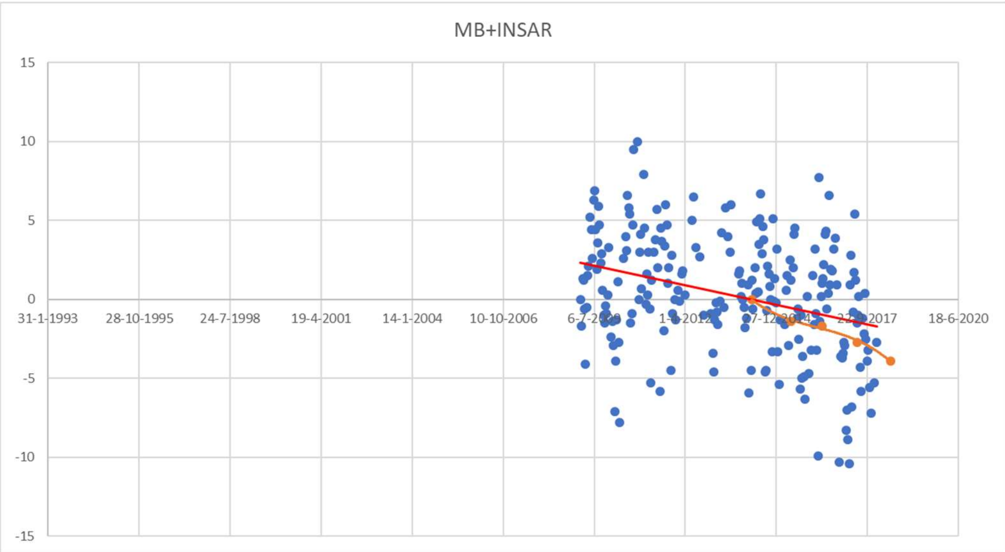
Zakking InSAR	**-1,228**	mm/year
Zakking mb	**-1,031**	mm/year

MB 10381586



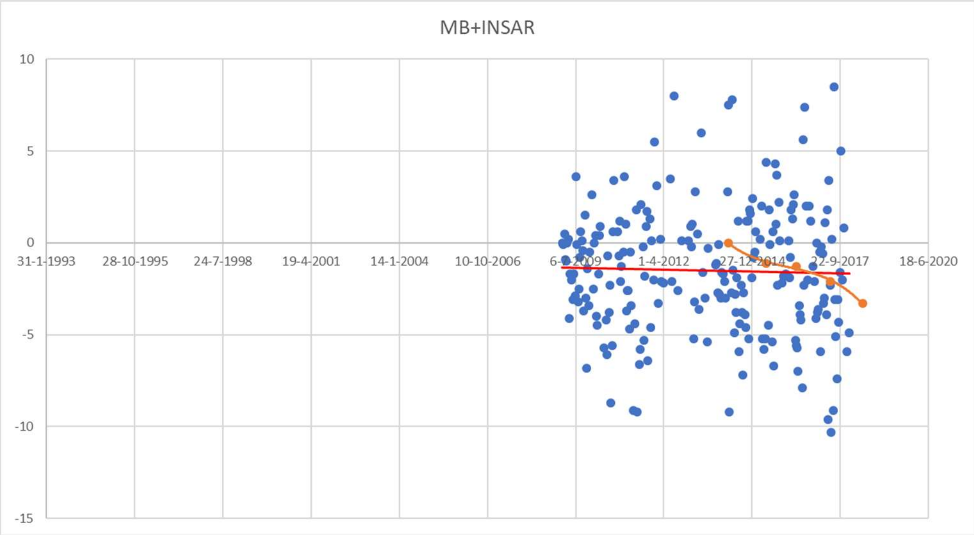
Zakking InSAR	**-0,552**	mm/year
Zakking mb	**-0,983**	mm/year

MB 10381587



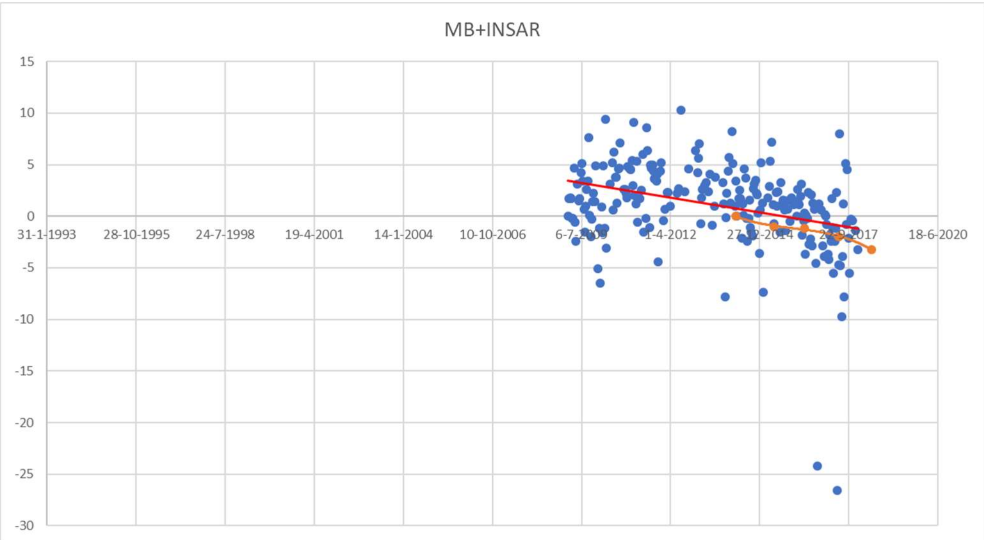
Zakking InSAR	**-0,454**	mm/year
Zakking mb	**-0,935**	mm/year

MB 10381588



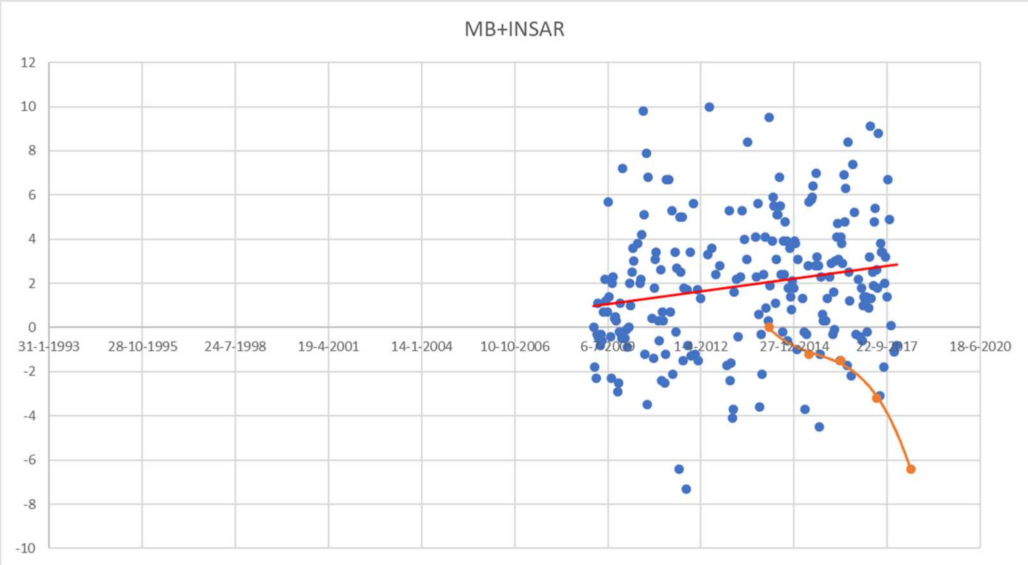
Zakking InSAR	**-0,035**	mm/year
Zakking mb	**-0,791**	mm/year

MB 10381589



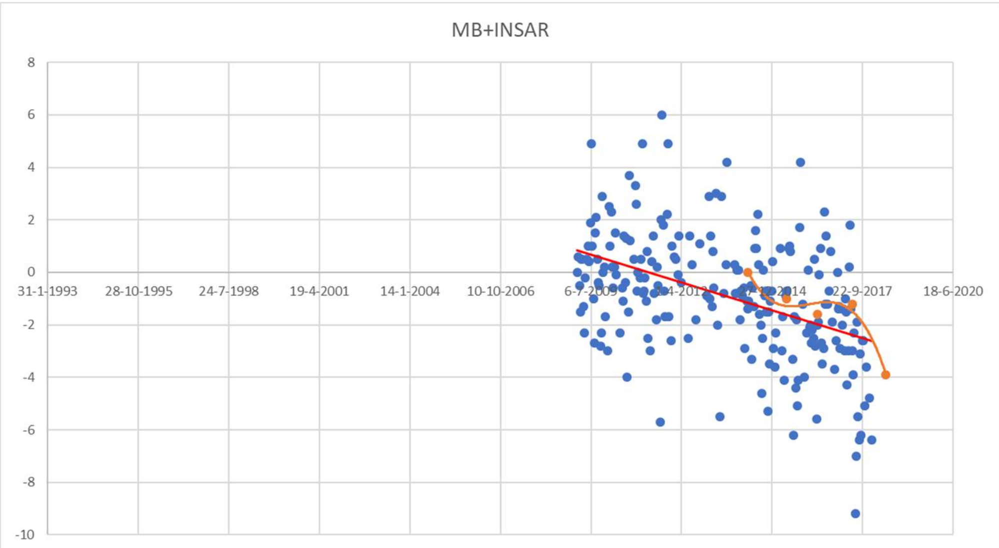
Zakking InSAR	**-0,529**	mm/year
Zakking mb	**-0,767**	mm/year

MB 10381590



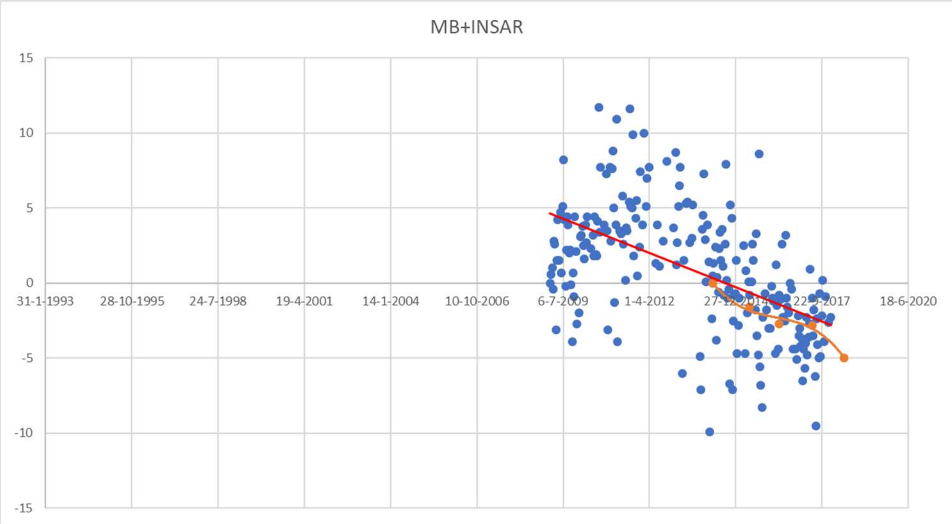
Zakking InSAR	**0,211**	mm/year
Zakking mb	**-1,535**	mm/year

MB 10381591



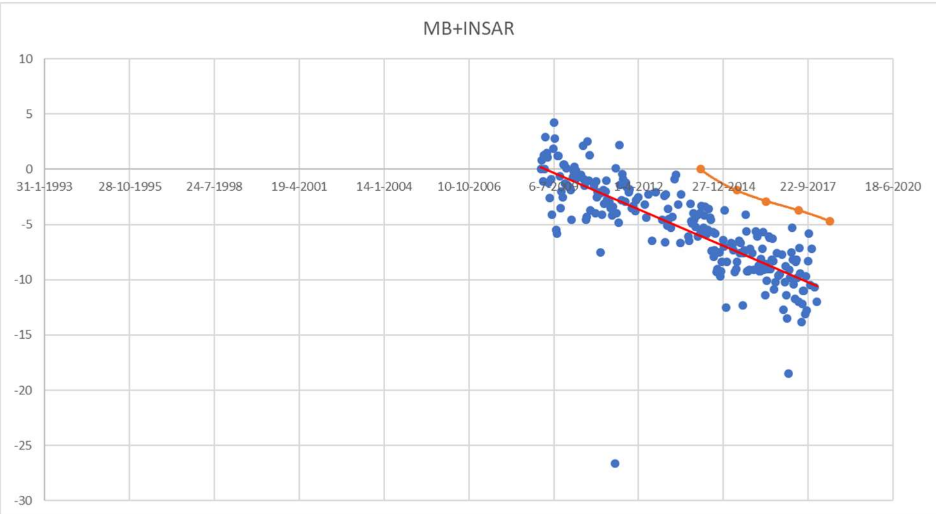
Zakking InSAR	**-0,390**	mm/year
Zakking mb	**-0,935**	mm/year

MB 10381593



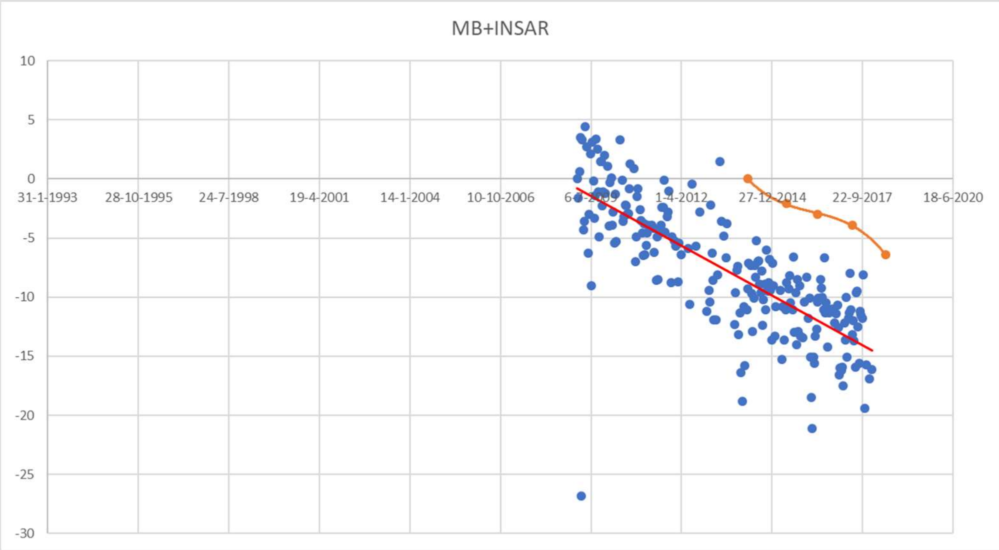
Zakking InSAR	**-0,832**	mm/year
Zakking mb	**-1,199**	mm/year

MB 10381597



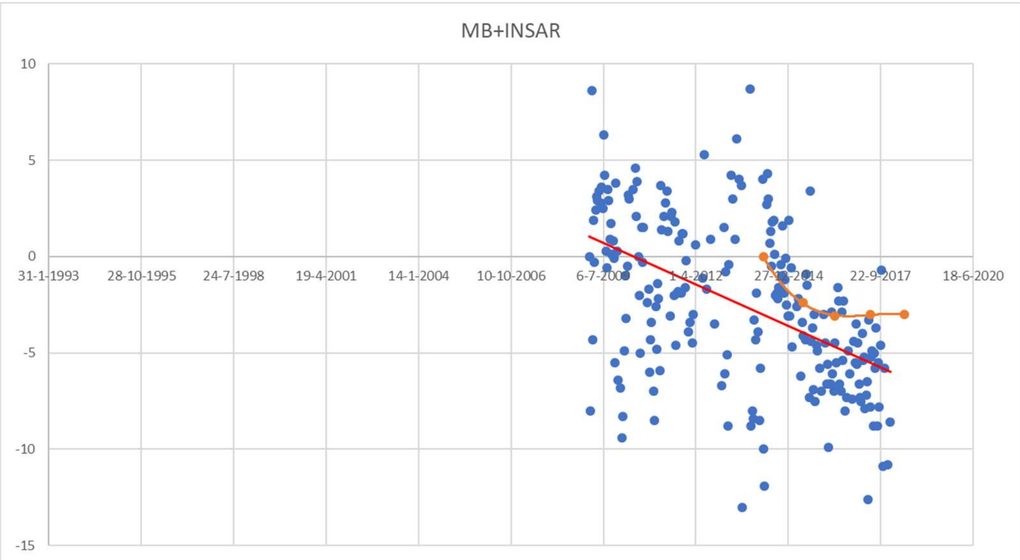
Zakking InSAR	**-1,207**	mm/year
Zakking mb	**-1,127**	mm/year

MB 10381598



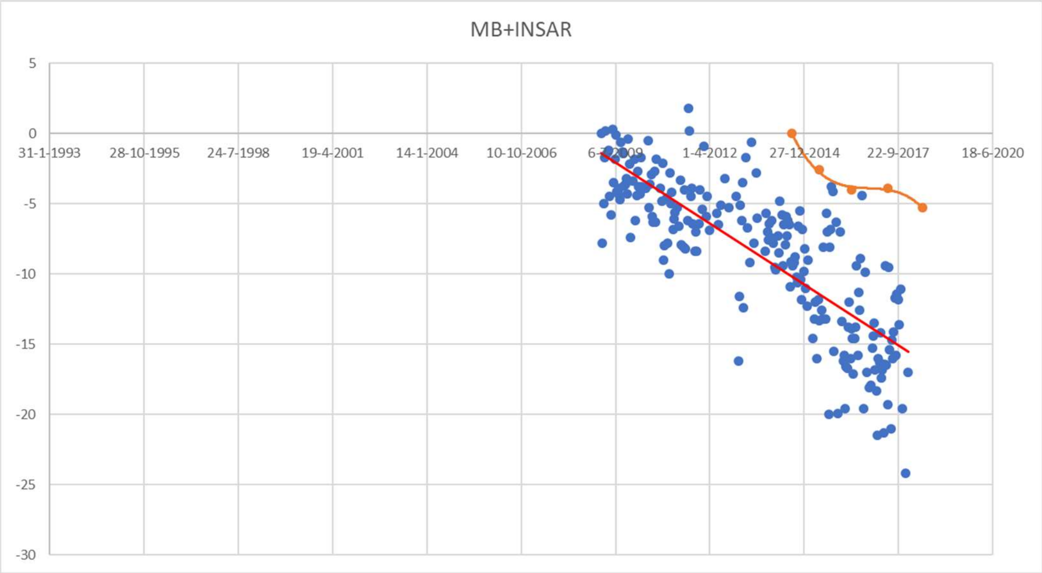
Zakking InSAR	**-1,539**	mm/year
Zakking mb	**-1,535**	mm/year

MB 10381601



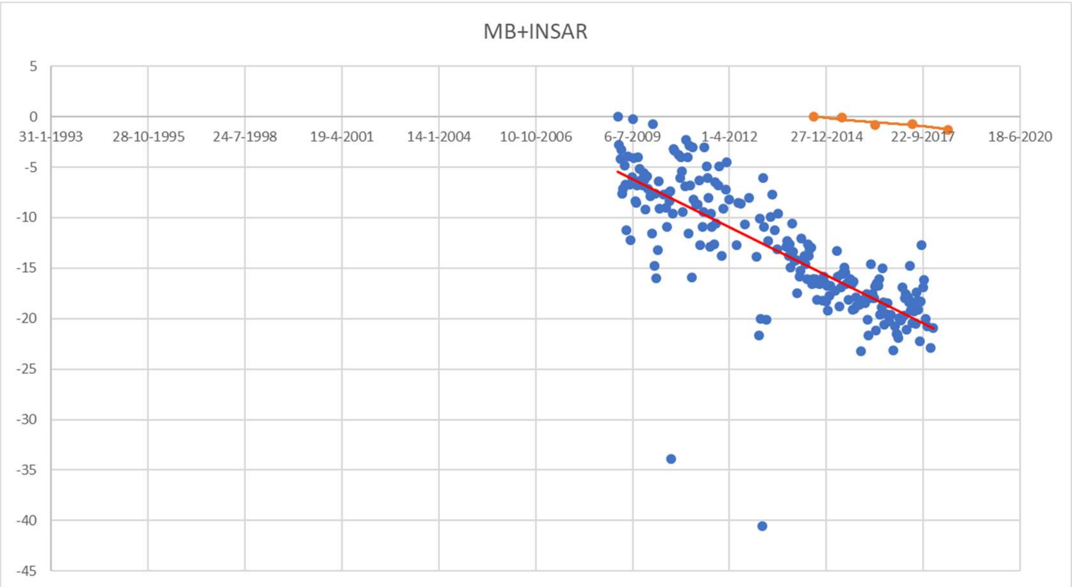
Zakking InSAR	**-0,788**	mm/year
Zakking mb	**-0,719**	mm/year

MB 10381603



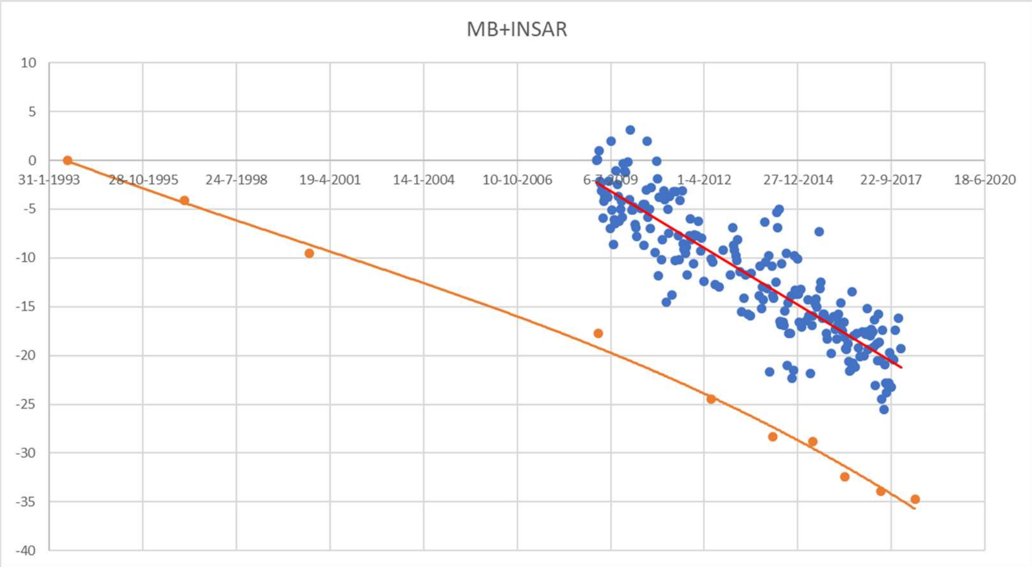
Zakking InSAR	**-1,586**	mm/year
Zakking mb	**-1,396**	mm/year

MB 10381604



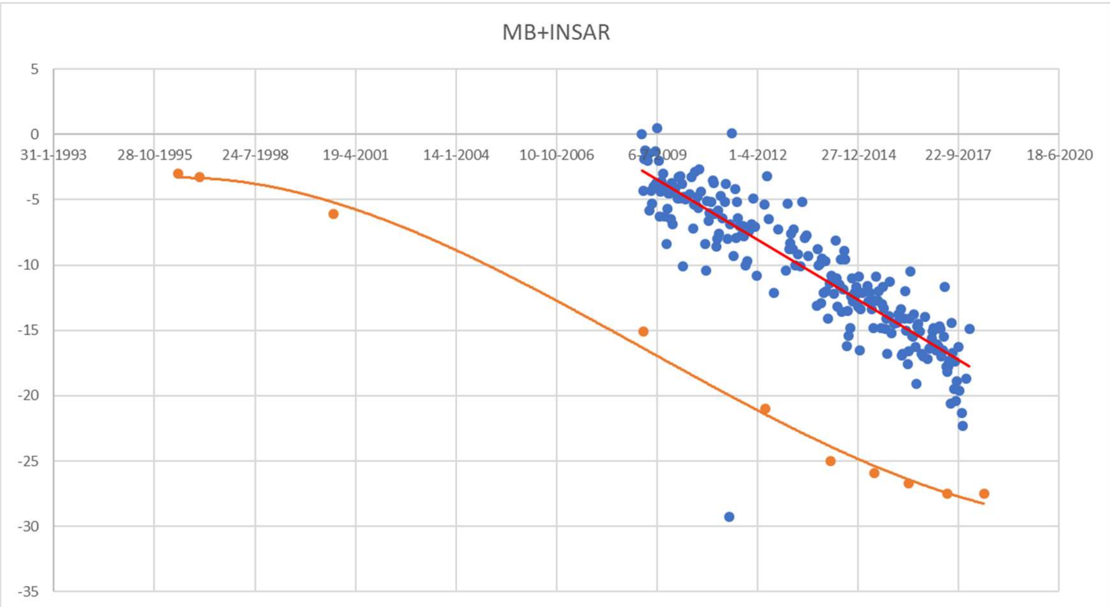
Zakking InSAR	**-1,742**	mm/year
Zakking mb	**-0,342**	mm/year

MB 25981490



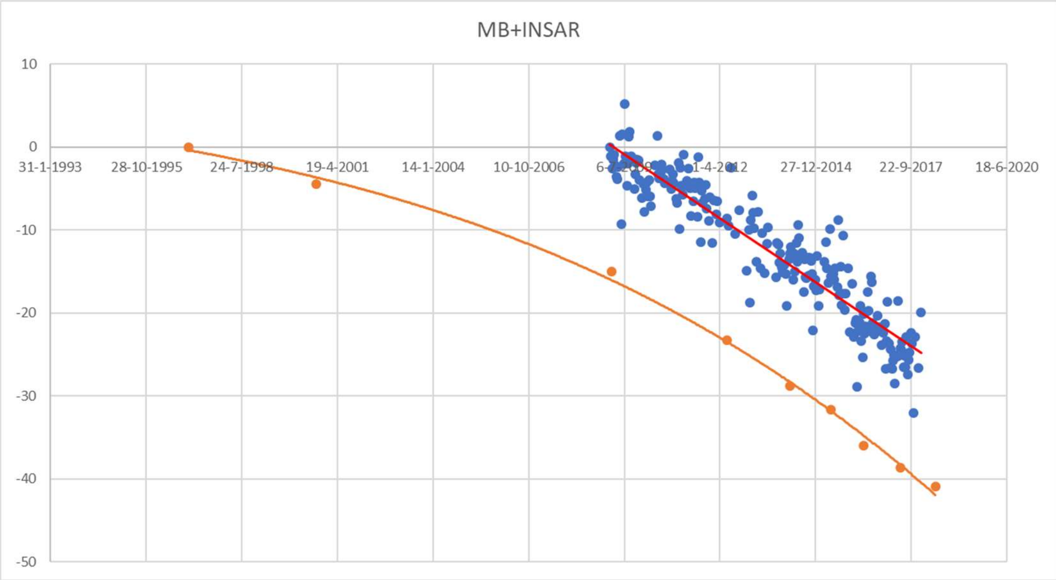
Zakking InSAR	**-2,133**	mm/year
Zakking mb	**-1,834**	mm/year

MB 25981494



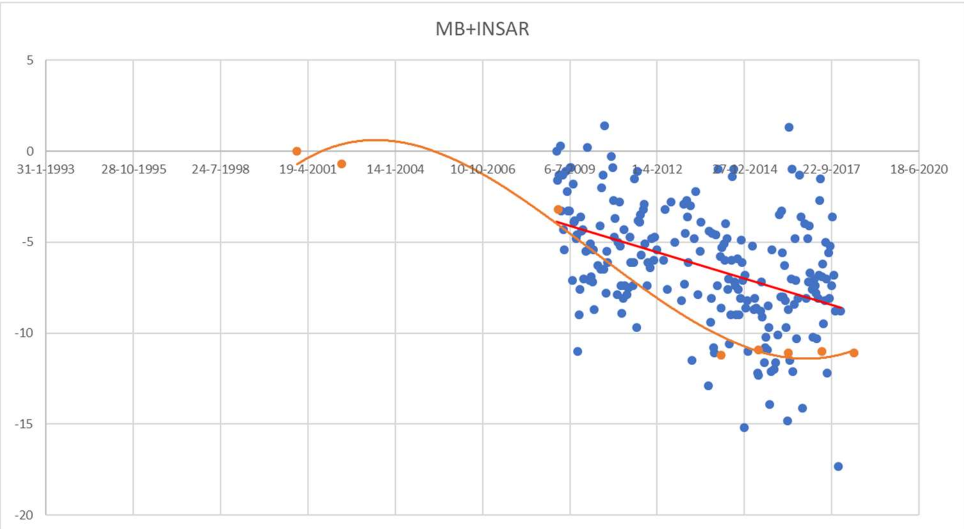
Zakking InSAR	**-1,676**	mm/year
Zakking mb	**-1,338**	mm/year

MB 25981714



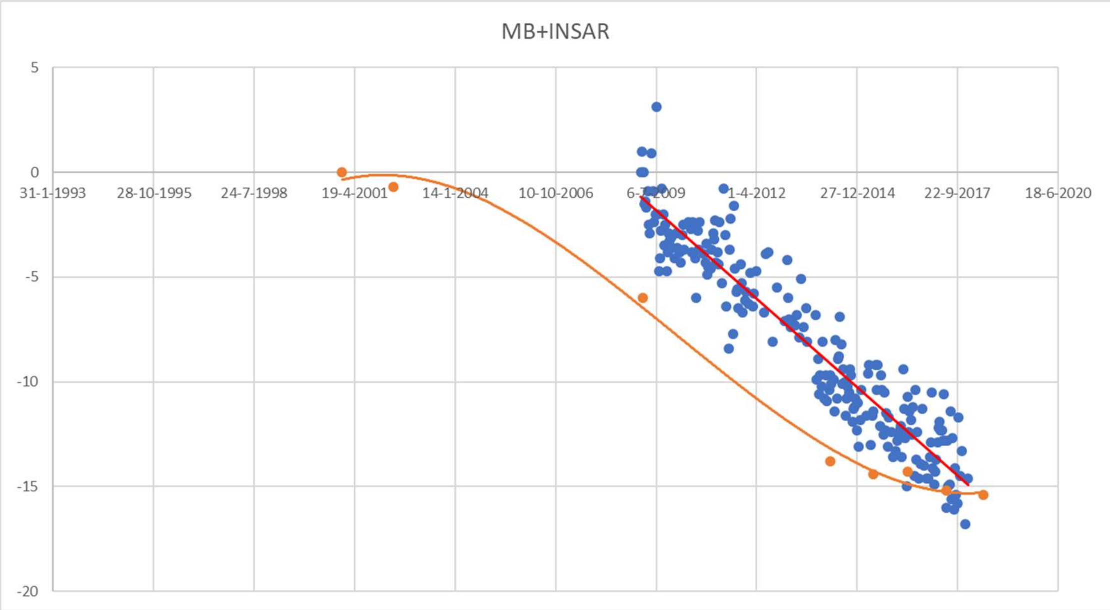
Zakking InSAR	**-2,824**	mm/year
Zakking mb	**-2,795**	mm/year

MB 25981776



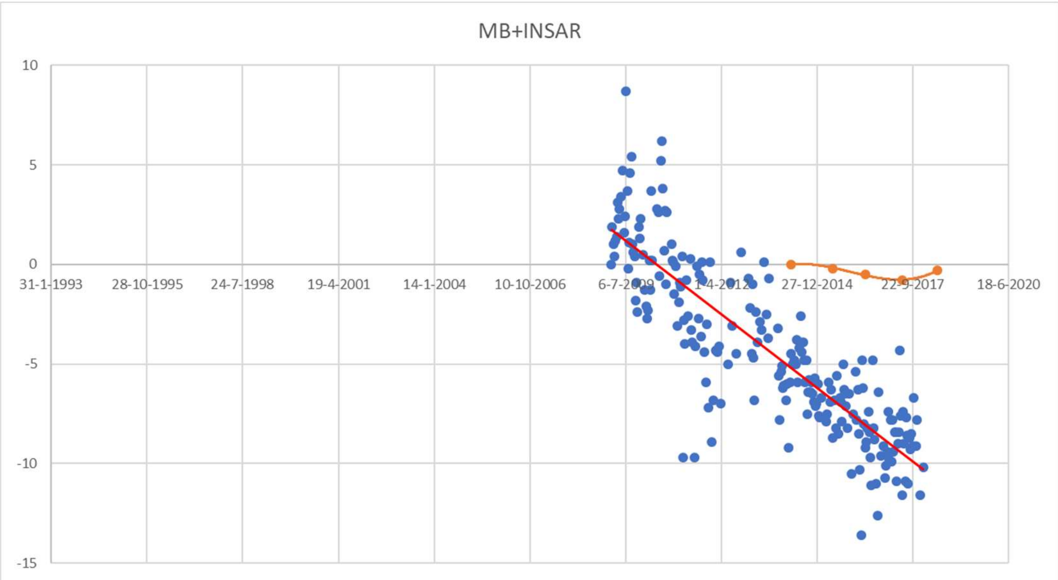
Zakking InSAR	**-0,528**	mm/year
Zakking mb	**-0,852**	mm/year

MB 25981781



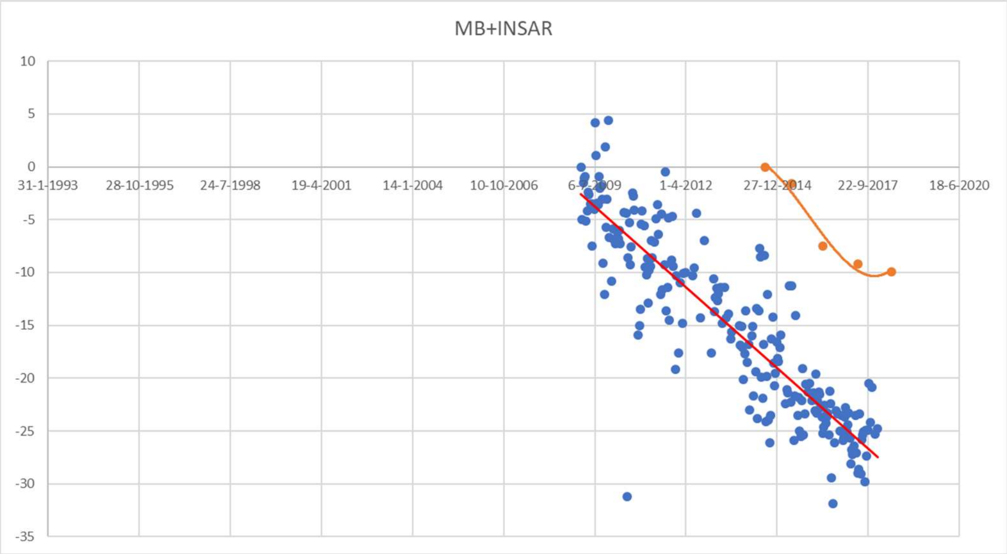
Zakking InSAR	**-1,539**	mm/year
Zakking mb	**-1,014**	mm/year

MB 25981873



Zakking InSAR	**-1,349**	mm/year
Zakking mb	**-0,072**	mm/year

MB 25981901



Zakking InSAR	**-2,787**	mm/year
Zakking mb	**-2,607**	mm/year

Intraclass Correlation Coefficient

Input + result SPSS 24

ICC for all data Case Study Block A

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	,849[a]	0,714	0,923	11,994	31	31	0,000
Average Measures	,918[c]	0,833	0,960	11,994	31	31	0,000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. The estimator is the same, whether the interaction effect is present or not.

b. Type A intraclass correlation coefficients using an absolute agreement definition.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

ICC for < -5 mm/y Case Study Block A

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	,926[a]	0,834	0,967	29,662	26	26	0,000
Average Measures	,962[c]	0,909	0,983	29,662	26	26	0,000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. The estimator is the same, whether the interaction effect is present or not.

b. Type A intraclass correlation coefficients using an absolute agreement definition.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

ICC for all data Case Study Block B

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	,553[a]	0,250	0,757	3,412	30	30	0,001
Average Measures	,713[c]	0,400	0,862	3,412	30	30	0,001

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. The estimator is the same, whether the interaction effect is present or not.

b. Type A intraclass correlation coefficients using an absolute agreement definition.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

A2. Measurement bolts

It should be apparent that position fixing simply involves the measurement of angles and distance. However, all measurements, no matter how carefully executed, will contain error, and so the true value of a measurement is never known. If the true value is never known, the true error can never be known either. As a result, the position of a point can only be known with a certain level of uncertainty. The error sources can be divided into three broad categories:

(1) Natural errors caused by variation in or adverse weather conditions, refraction, unmodelled gravity effects, etc.

(2) Instrumental errors caused by imperfect construction and adjustment of the surveying instruments used.

(3) Personal errors caused by the inability of the individual to make exact observations due to the limitations of human sight, touch and hearing (Schofield & Breach, 2011).

The measurement bolts method uses stainless steel pins in the façade to measure the vertical translation in time relative to local NAP-calibrated points see the Figure below. Although these points are considered as fixed, they are always subjected to (very small) subsidence.

Figure 35 Stainless steel pins

In addition to the fixed measurement bolts, one or more reference points are placed in the vicinity in constructions that are (almost) not subjected to subsidence. Otherwise, local NAP-calibrated points are used.

Immediately after application, the measurement bolts are measured relative to a fixed height, preferably the NAP. This baseline measurement serves as a starting point for the assessment of the results of repetitive measurements to be carried out later. When performing a repetition measurement, the heights of the measurement bolts are measured again. The height of the reference point is also tested if this was chosen correctly. This procedure is quite labour-intensive. The instrument used for this conventional method is the level (Figure 36), which is an optical instrument that measures the height of two different points. Thereafter, the height difference can be calculated. This device can be digital as well as analogue.

Figure 36 Level, an optical instrument to measure height differences (source:www.gereedschappelijk.nl)

For property management, the period between measurements is often chosen at 1 year. A shorter period is not recommended, as there is the risk of measuring values that are within the measuring accuracy. Accuracy and precision are not synonymous. In surveying, accuracy is defined by specifying the limits between which the error of a measured quantity may lie (Irvine & Maclennan, 2006). This means from the point measurement bolts are installed in order to monitor the subsidence of a foundation, only 1 year later you can have an indication of the subsidence speed (at low speeds).

If there is a well-founded suspicion that relatively large sagging speeds can occur, the period between the measurements can be limited to 3 to 6 months. This also applies if the influence of construction activities in the immediate vicinity has to be determined. Then measurements are carried out after the various construction phases.

The measurements are carried out with the help of a precision leveling instrument and a special temperature-insensitive beacon. Because several observations are made per measuring point, corrections can be made for the distance between the level gauge and the measuring point (adjustment error) and closing error. In this way, Fugro Geoservices, a company that carries out leveling measurements on a daily basis, is able to achieve a measurement accuracy of plus or minus 0,3 to 0,5 mm, depending on the experience of the crew, the distance between the NAP reference point and the measured point and the weather conditions (Fugro, 2016).

A3. Sensors

"Any 'product' is only as good as the most poorly executed part of it. It matters not whether that 'product' is a washing machine or open heart surgery, a weakness or inconsistency in the endeavour could cause a catastrophic failure. The same may apply in survey, especially with control. Modern methods of survey network adjustment allow for some flexibility in the application of the principle and it is not always necessary for all of a particular stage of a survey to be of the same quality. If error statistics for the computed control are not to be made available, then quality can only be assured by consistency in observational technique and method. Such a quality assurance is therefore only second hand. With positional error statistics the quality of the control may be assessed point by point. Only least squares adjustments can ensure consistency and then only if reliability is also assured. Consistency and economy of accuracy usually go hand in hand in the production of control." (Schofield & Breach, 2011)

A3.1 Subsidence sensor

The subsidence is the vertical downwards translation along the z-axis. The subsidence of the building has to be monitored because it can have negative structural consequences for a building (block) when large differences occur. Also the speed of the building subsidence can give important information about the condition of the pile foundation. Important to note is that a low subsidence speed does *not* always mean that the foundation is in a good condition. An example proving this phenomena is the [redacted], Zaandijk. In the foundation research report (21 June 2018) it is stated that subsidence in the building block in the period February 2017 until March 2018 are close to zero. Still the premises is classified as insufficient ("Onvoldoende"). Erosion bacteria have a detrimental effect on functional pile diameter. (Heddes A. , Rapportage funderingsonderzoek [redacted], 2018)

The sensors used for this project are the linear displacement sensor from the SLS190 series of Penny & Giles. These sensors are precise until ± 0,001 mm. The protocol "Richtlijn Houten Paalfunderingen onder gebouwen" describes the "Nauwkeurigheidswaterpassing" as a method with a required accuracy of 0,5 mm. With a precision of ± 0,001 mm this should be achievable. The sensor has to be attached as close as possible to the foundation on one end and the other end to a fixed point. A NAP reference point is considered as fixed point. For instance, this can be a building with a concrete foundation reaching into a dense sand layer. Usually this is not in range of the sensor.

Therefore, a sensor that measures the vertical translation should have its own foundation or another reference point. This can be very costly, especially when the dense sand layer is located more than 12 m (Amsterdam) or even 20 m (Rotterdam) below ground level. Also not every location is easy to reach so piling activities can be obstructed. Therefore, machine learning can possibly be a feasible option for data interpretation.

Case Study Block C

The building block number 3 up to and including 19 of Case Study Block C is currently monitored by the Code Oranje project of the KCAF. First some general information of this building block will be given. Furthermore the data gathered will be analysed and discussed alongside with factors that have an influence on the quality of the foundation. A foundation research of this block by MOS GRONDMECHANICA has been executed and reported (Hebing D. B., 2016). The date this report was released is 22th April 2016. The report contains a description of the former condition of foundation and was based on version 2 of the F3O protocol of September 2012. Version 3 of the F3O protocol for foundation research's is described in chapter 2.4.

The houses in this street were built in 1932 and have three storey's including the ground floor, see picture below.

Figure 37: Facade frontview of Case Study Block C. Source: Google Streetview

Earlier foundation reports date from 1989 for number 3 until 19 and from 2007 for number 7 where a maintenance interval were proposed of 40 years. These reports stated that the groundwater level was too low and did not cover every single pile (Hebing D. B., 2016).

Subsidence

On October 26th 2015 a level measurement for masonry has been executed. Important to note is that the only the front façade and the side wall of number 19 has been measured. The result is shown below. Measurements are given in millimetres.

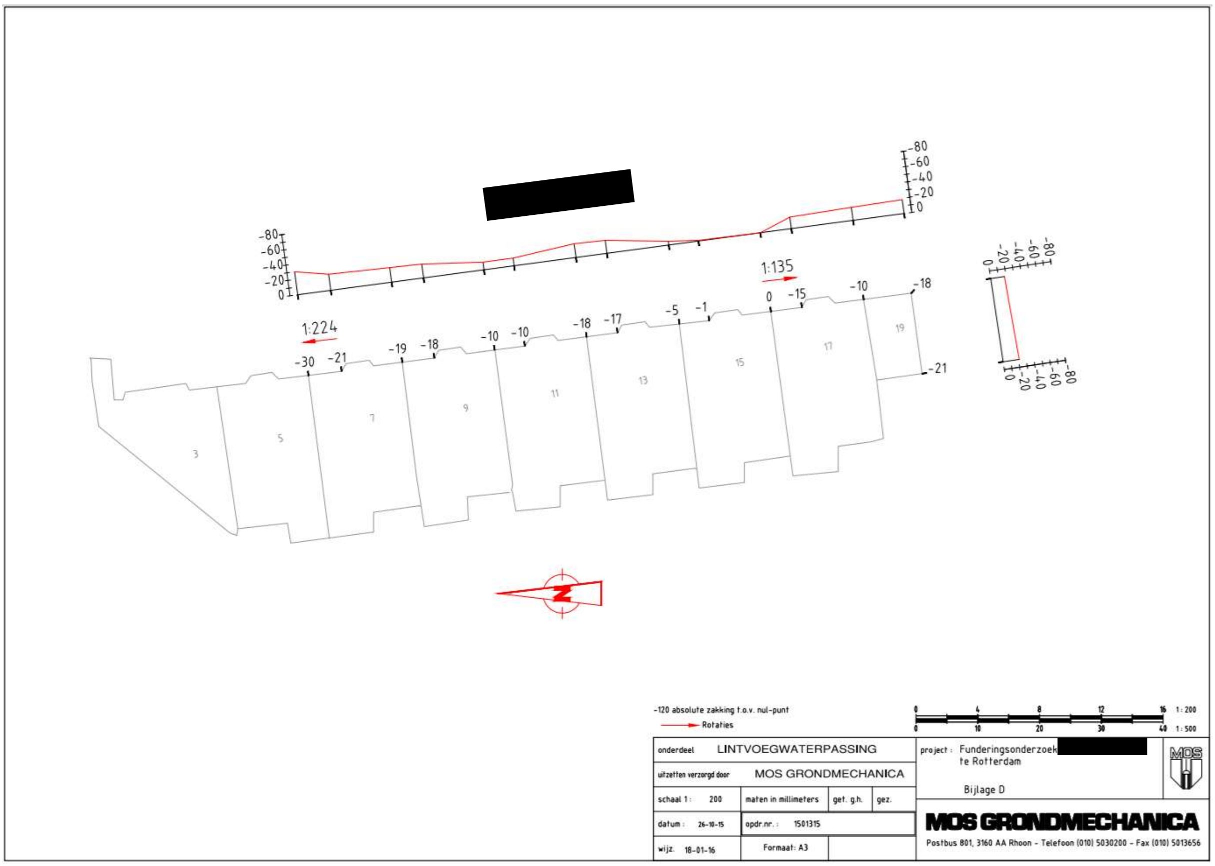


Figure 38 Level measurement for masonry Case Study Block C

Rotation is defined as the difference in subsidence between two points, divided by the distance of those points. The steepest rotation in the front façade is located is at nr. 17, namely 1:135. The rotation of 1:135 is classified as moderate according to the F3O protocol. Also the level measurement for floor (figure below) does not show severe rotations the exceed 1:210. Measurements are given in millimetres.

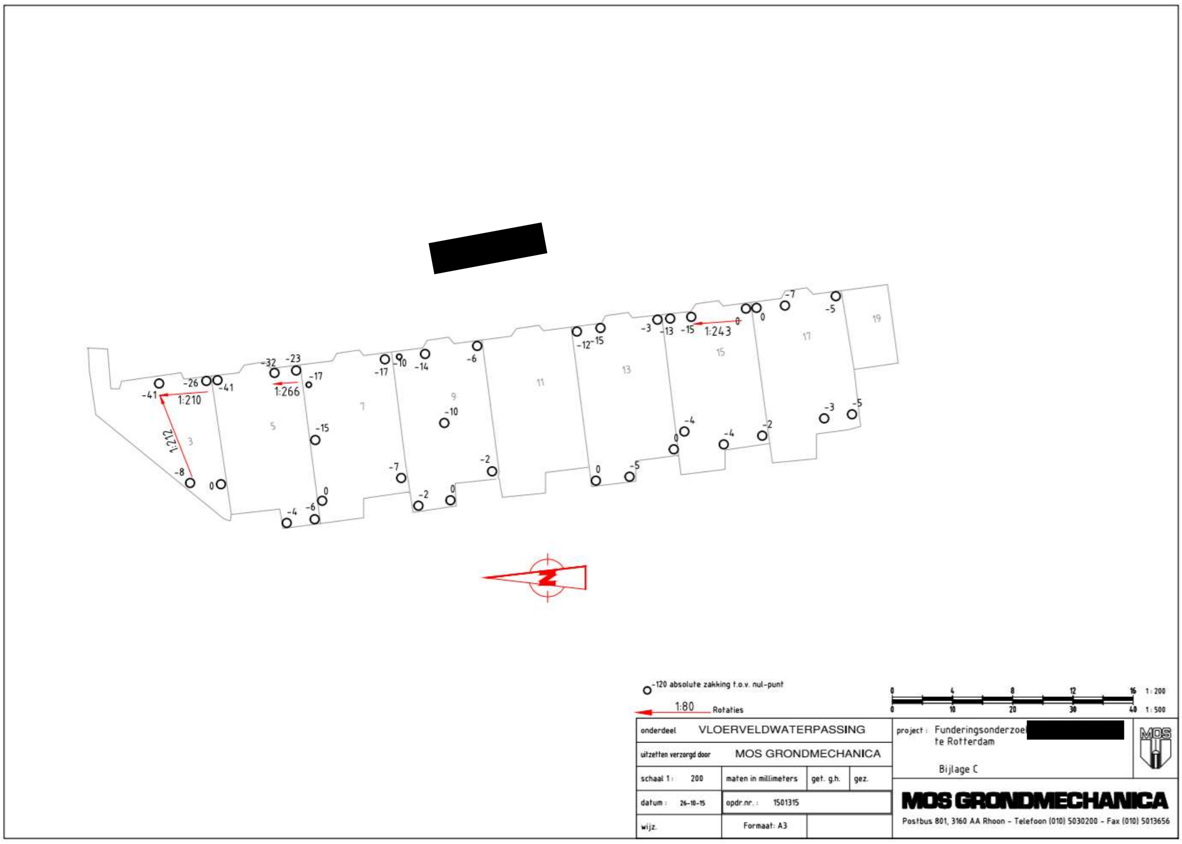


Figure 39 Level measurement for floor Case Study Block C

Considering these two measurements, it can be assumed that no large differences in subsidence – resulting in damage to the structure – have occurred. The observed damage is classified as architectural (see Table 1 Rotation classification). However, the front shows more subsidence than the backside of the building block. Reason for this could leakage in the sewer system. As also noted in the report, during that time (2015) the sewer was being renewed. Bas Hebing, project manager foundation research at Fugro and writer of the foundation report, confirms this (Hebing D. B., 2016).

The subsidence sensors of Code Oranje are analysed and subsidence speed for each individual sensor is calculated. See next subparagraph for details how this is calculated. Although roughly 6 months of data is available, the values are calculated to mm/year. Extrapolating of such a short period can be misleading, so that should be kept in mind. Nevertheless, sensors number 2, 5, 6, 7 and 8 are classified as very large subsidence (>2 mm/½year) according to foundation inspection protocol (see 2.4).

There is not a conformity in the results when the level measurement for masonry is compared to the subsidence sensors of Code Oranje, shown graphically in the figure below.

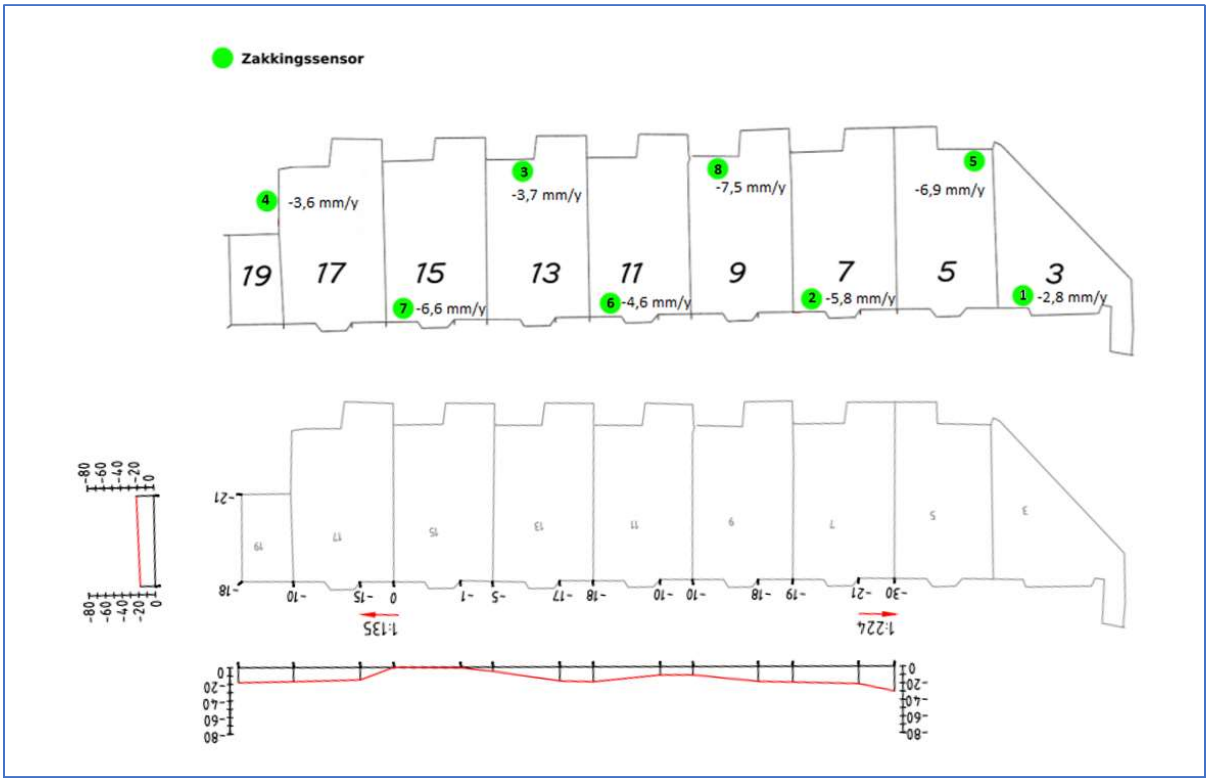


Figure 40 Comparison level measurement for masonry and sensors

With such low difference in subsidence, during the level measurement for masonry executed in 26-10-2015, is not likely to see such high differences in the subsidence speed measured by the sensors. Backward extrapolation of these subsidence speed do not result in a shape similar to the level measurement for masonry (Heddes A. , 2018). It is unknown if the signal of the sensors is calibrated to measure millimetres although the values say so. Several intermediate factors can disrupt the signal of the sensor. The report of the installation of the sensors states that the devices are consisting of a microcontroller, a communication module and the sensor itself. This device sends the measurement to a gateway which is connected to the internet to be able to send it to a database. In this last step the information is processed and extra information is added like origin, date/time and security information (Omnifor, 2016). Vibrations in the vicinity of the sensor can cause noise in the signal of the sensor. This can be caused by heavy traffic or other activities that create vibrations.

The absolute subsidence can be determined only where the historical construction level is known. During World War II, a lot of municipal archives were destroyed by bombings. Luckily, the residents of number 9 got their own blueprints with the construction level indicated in Rotte Peil (= +0,65 m relative to NAP). The table below shows the difference over 83 years.

Number	Year of Construction	Date measurement	Original level pile head	Current level pile head	Difference	mm/year	Classification
9	1932	11-11-2015	NAP -2,90	NAP -3,14	-0,24 m	2,8	Moderate

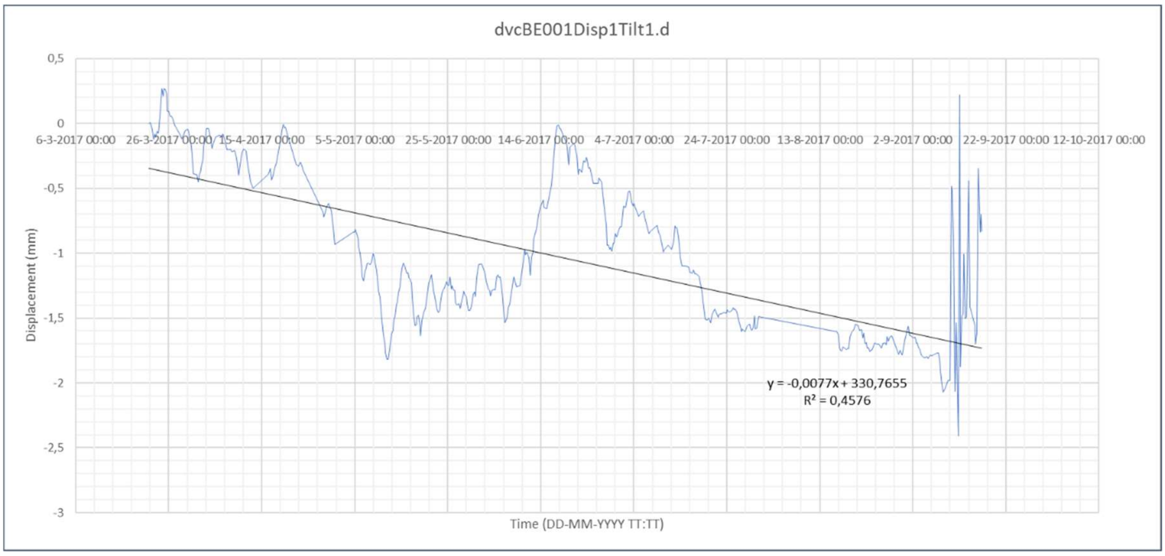
Table 4 Case Study Block C nr. 9 - Absolute subsidence

It can be questioned how reliable the original level is. Factors on the construction site could have influenced the actual level of the pile head.

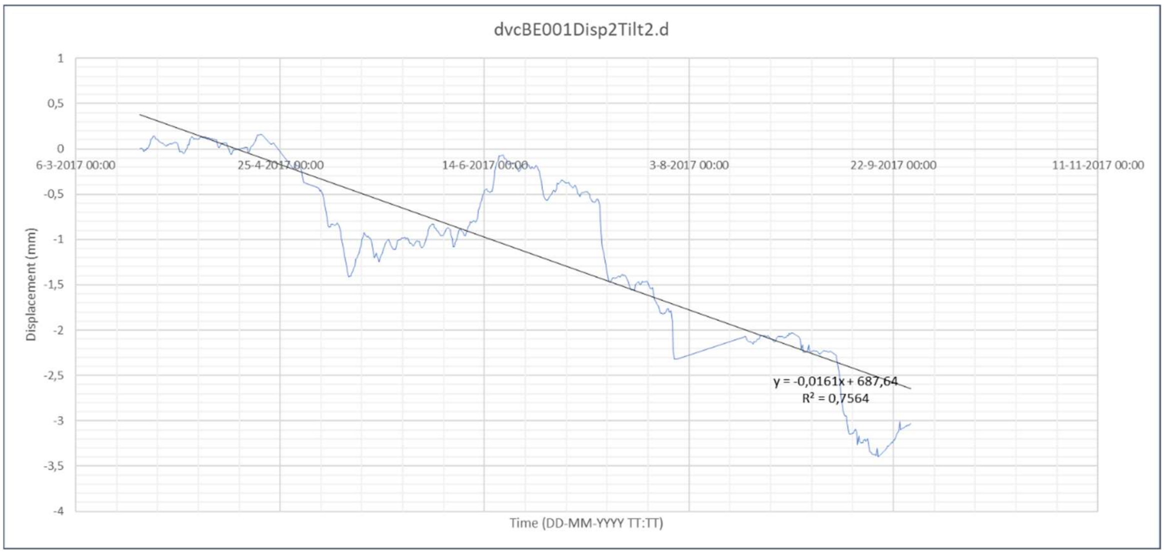
A3.2 Subsidence sensor data plots

In this subparagraph the data is put into graphs and linear trendlines are plotted. The sensor data is first filtered by removing outliers. The clean data of eight different sensors is given below alongside with the subsidence per half a year and per year.

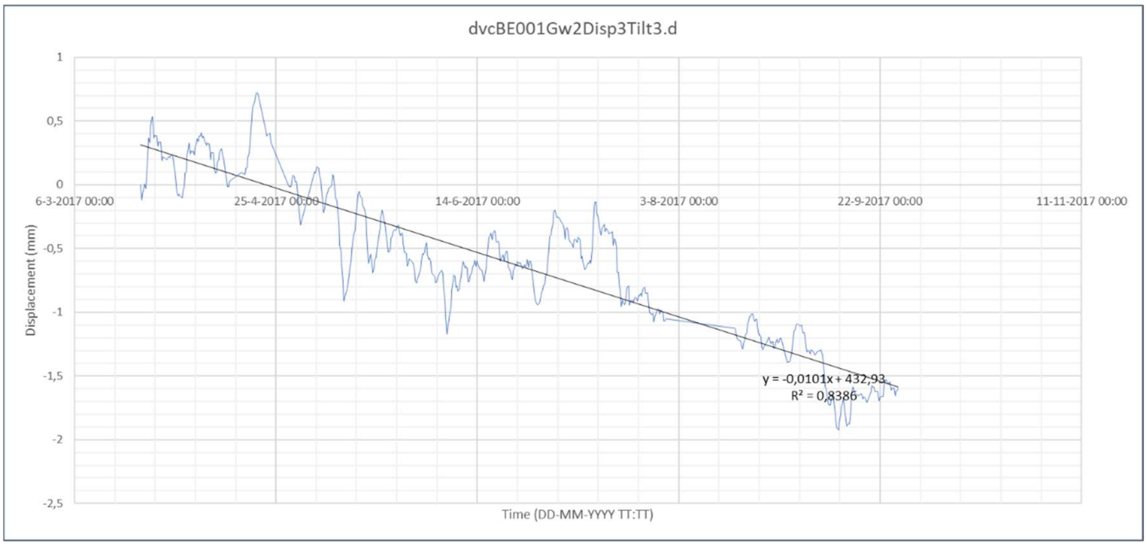
Sensor 1: -1,41 mm/½year ≈ -2,82 mm/year



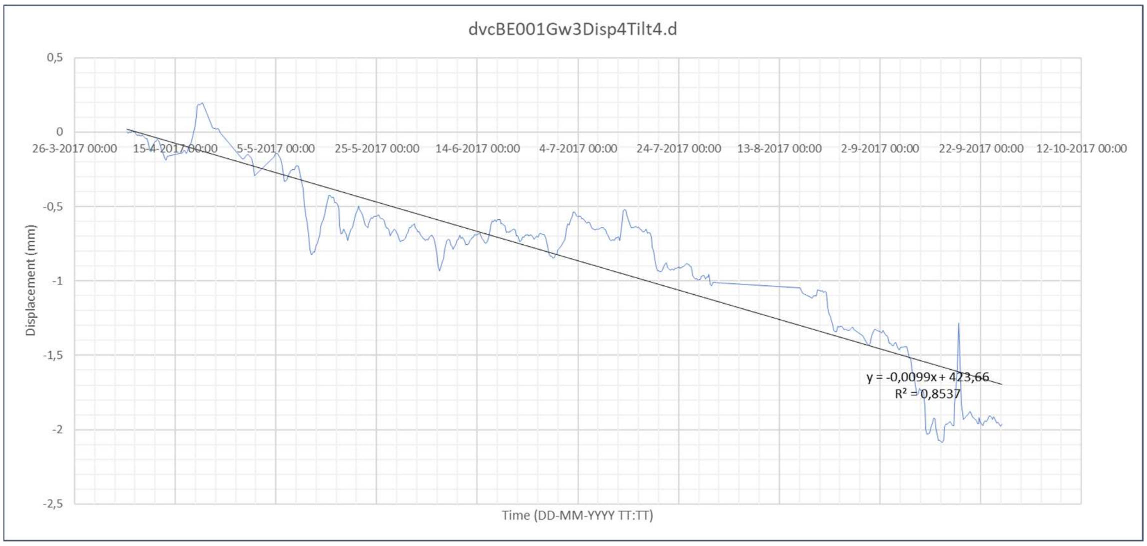
Sensor 2: -2,93 mm/½year ≈ -5,86 mm/year



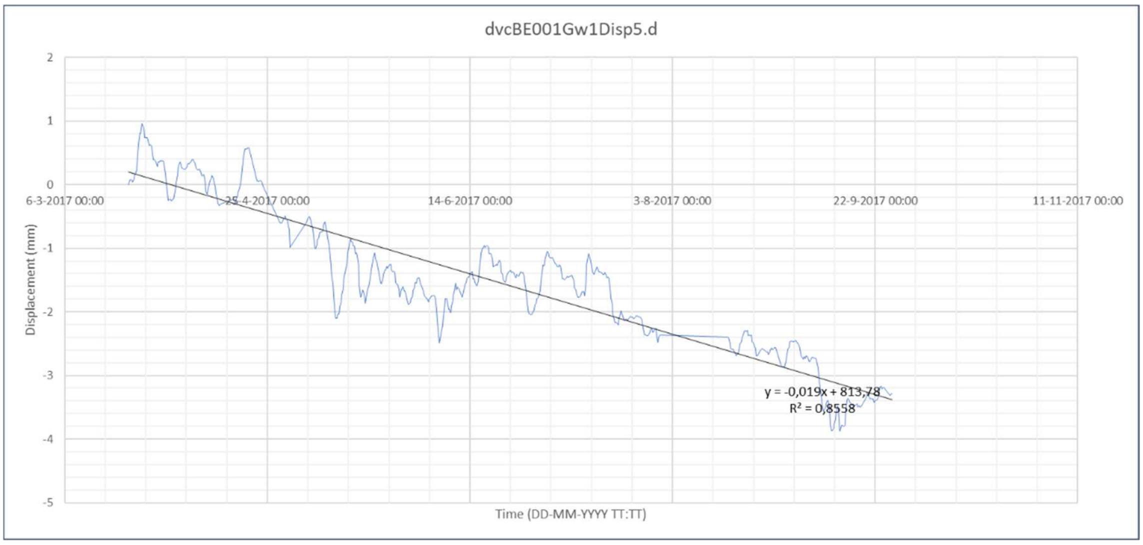
Sensor 3: -1,85 mm/½year ≈ -3,69 mm/year



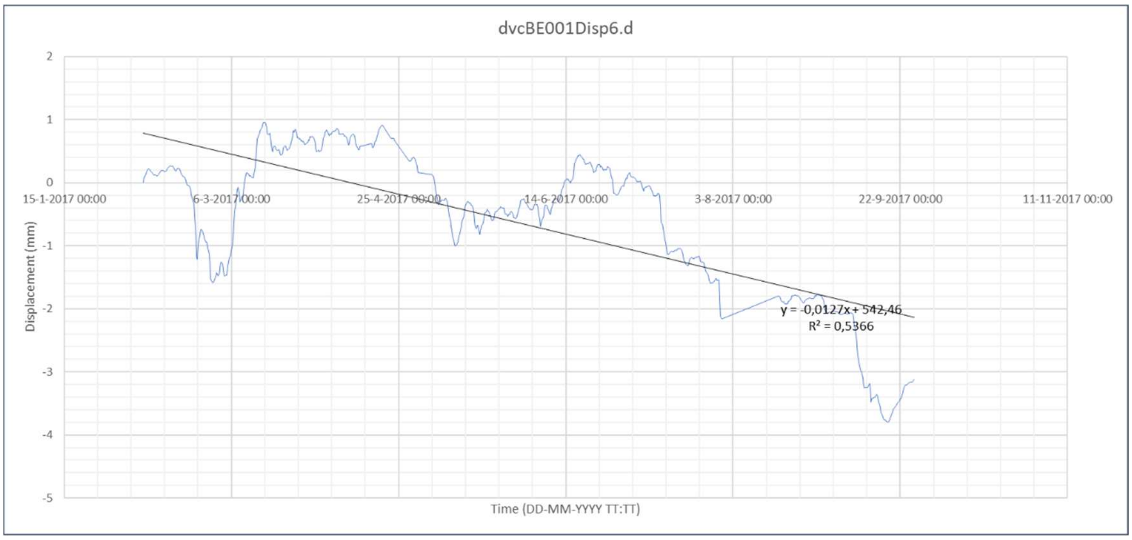
Sensor 4: -1,81 mm/½year ≈ -3,61 mm/year



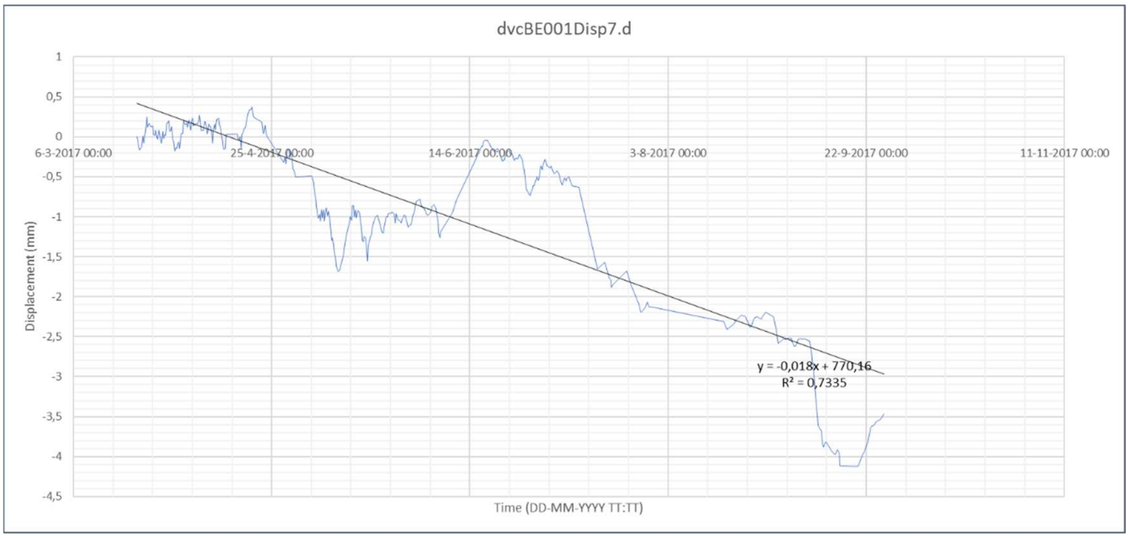
Sensor 5: -3,47 mm/½year ≈ -6,94 mm/year



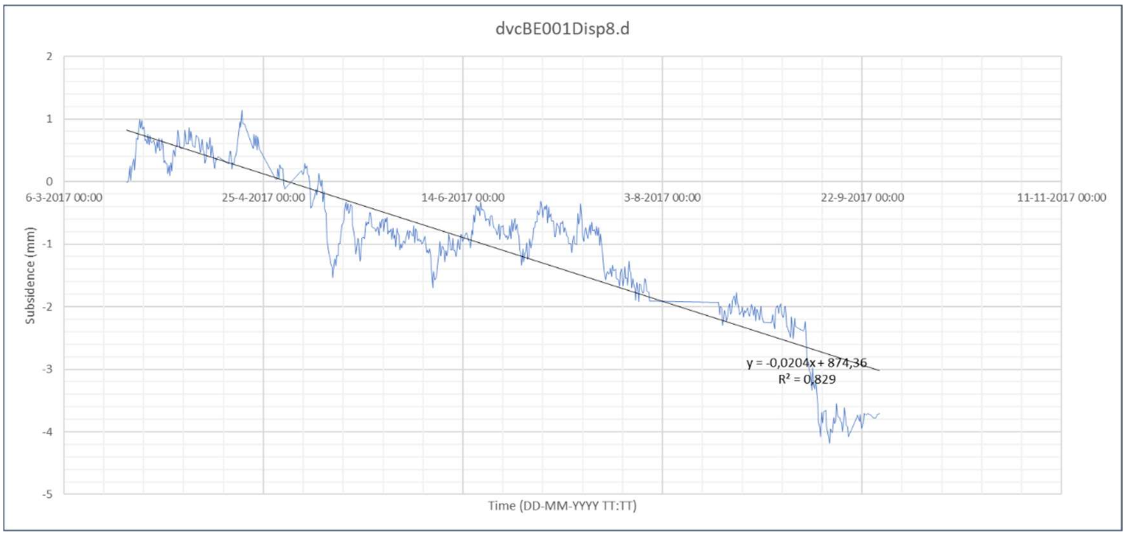
Sensor 6: -2,31 mm/½year ≈ -4,62 mm/year



Sensor 7: -3,28 mm/½year ≈ -6,56 mm/year



Sensor 8: -3,73 mm/½year ≈ -7,45 mm/year



A3.3 Groundwater level sensor

The groundwater table has to be monitored to be able to detect a period where the upper part of the wooden foundation (“langshout” see figure) is not below the groundwater table.

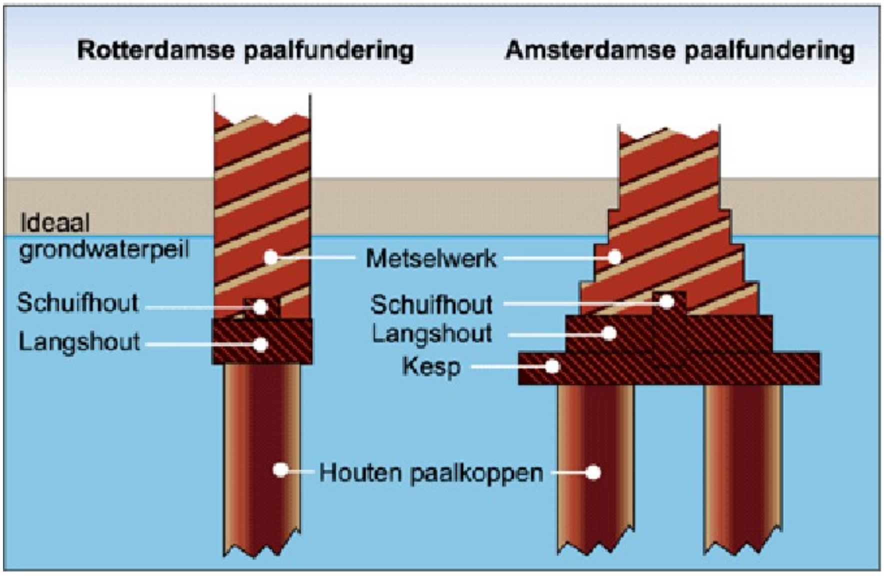


Figure 41 Schematic wooden pile foundation (Source: Platformfundering.nl)

Monitoring wells are used to monitor this parameter. To give a complete picture of the groundwater table, wells need to be located in front and in the back of a building block because the groundwater table can have a high fluctuation in a small area. This excludes the possibility to use the municipality groundwater data provided by monitoring wells in the surrounding area. Factors that can influence the groundwater table are precipitation, leaking sewers, evaporation by vegetation and water drainage. See picture below of an example where a leaking sewerage influences the groundwater table.

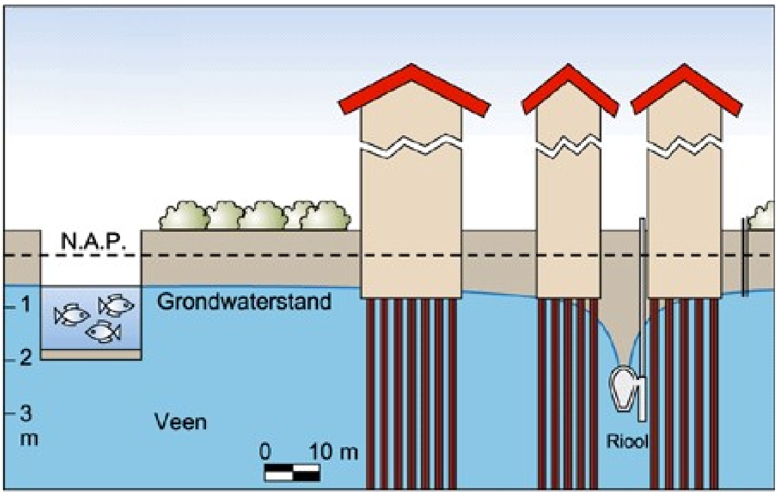


Figure 42 Leaking sewerage lowering groundwater table locally (Source: Platformfundering.nl)

The groundwater table can be measured electronically with two different methods. The first method measuring the distance between the sensor and the water level by ultrasonic sound waves. The second method uses a sensor that measures the hydrostatic pressure in the tube. This method requires water present in the tube at any point in time. In this pilot project the second method (hydrostatic pressure measurement) is chosen because of the ability to use smaller and already existing tubes. The figure below shows a schematic view of the sensor.

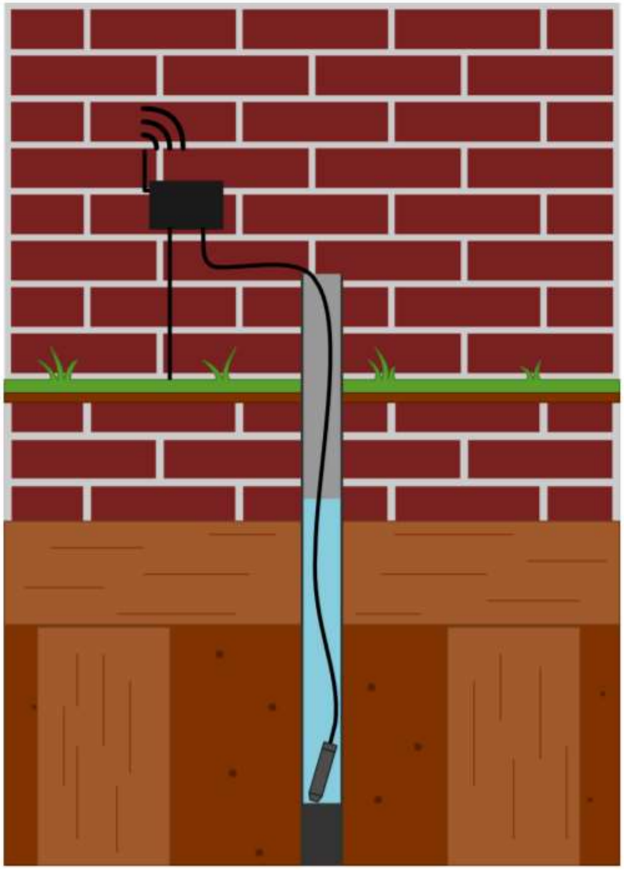


Figure 43 Schematic view of the hydrostatic pressure sensor (Source: Omnifor)

The sensor used in this project is the "UNIK 5000 piezo-resistive pressure sensor". This sensor has very low drifting so frequent recalibration is not needed. The measuring range between 0 and 5 meter also internal air pressure is compensated due to ventilated wiring. Pressure transducers are often used to monitor water levels; these devices can be affected by atmospheric pressure changes. Nonvented, or absolute, transducer readings may reflect atmospheric-pressure changes and could give the false impression that water-level fluctuations are much greater in magnitude than they are in reality (Healy, 2002). The precision of this sensor is ± 2 mm. According to the foundation protocol (sub paragraph 2.4.6) the groundwater coverage has to be measured with accuracy of ± 10 mm which is achievable with its precision. The actual accuracy of this sensor is unknown. The top of the tube is calibrated to NAP so the measurement can be converted to [m] NAP if the length of the tube is known. Drifting (deviating over the longer term) can only be prevented by periodic inspection (4 times a year) or if large differences compared to the other local monitoring wells occur (Omnifor, 2016).

The measurement interval in the data set is 1 hour. This makes it possible to take daily averages to reduce smooth out the error values. Conventional monitoring wells, for instance of the municipality in Rotterdam, have an interval of 1 month. The required information for the foundation is already covered when an interval of 1 month is met. In this way, seasonal fluctuations can be detected and long dry periods (> 1 year) are clearly detectable when shown in a graph. When the interval is short the costs increase - more data needs to be gathered and processed - but it also gives the possibility to monitor other factors, for instance the infiltration after precipitation.

Case Study Block C

Two monitoring wells are close to Case Study Block C owned by the municipality. If the groundwater level sensors are compared to the level measured by the monitoring wells, it can be concluded that they all show a slight raising trend. See the graph below.

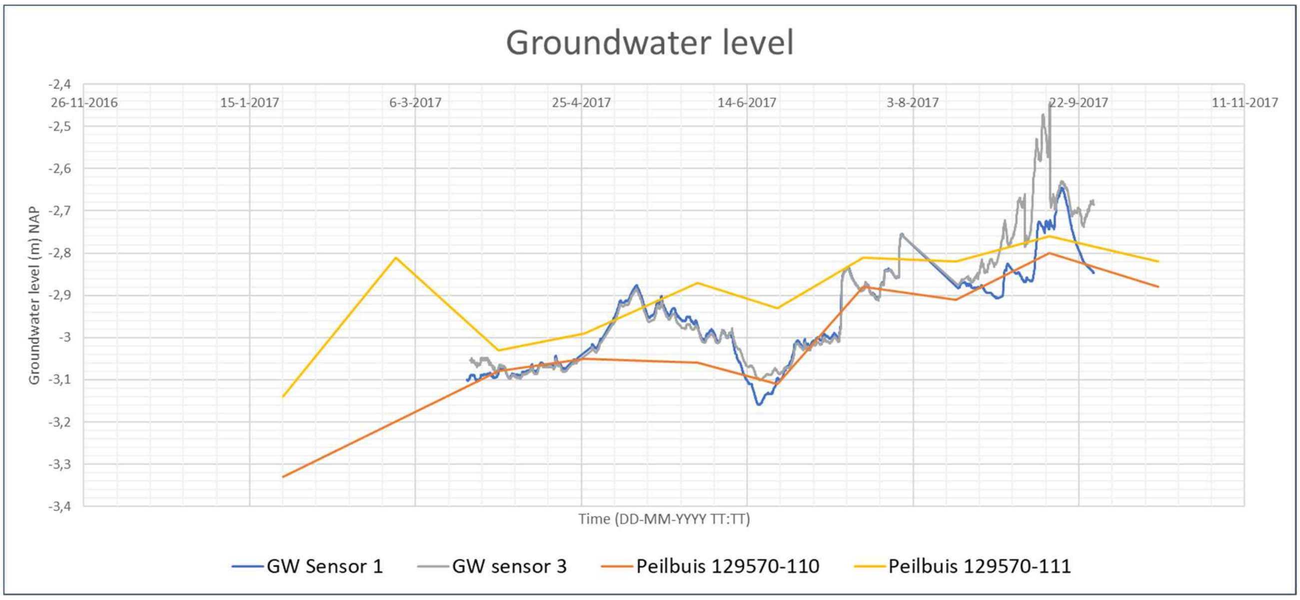


Figure 44 Groundwater level measurements

GW sensor 2 showed too many outliers and is therefore not considered. In order to measure reliable data, the sensor needs to be recalibrated once in a while. The location of the sensors in the building block is given below. Just like the subsidence sensors, several intermediate factors can disrupt the signal of the sensor. The report of the installation of the sensors states that the devices are consisting of a microcontroller, a communication module and the sensor itself. This device sends the measurement to a gateway which is connected to the internet to be able to send it to a database. In this last step the information is processed and extra information is added like origin, date/time and security information (Omnifor, 2016). Vibrations in the vicinity of the sensor can cause noise in the signal of the sensor. This can be caused by heavy traffic or other activities that create vibrations.

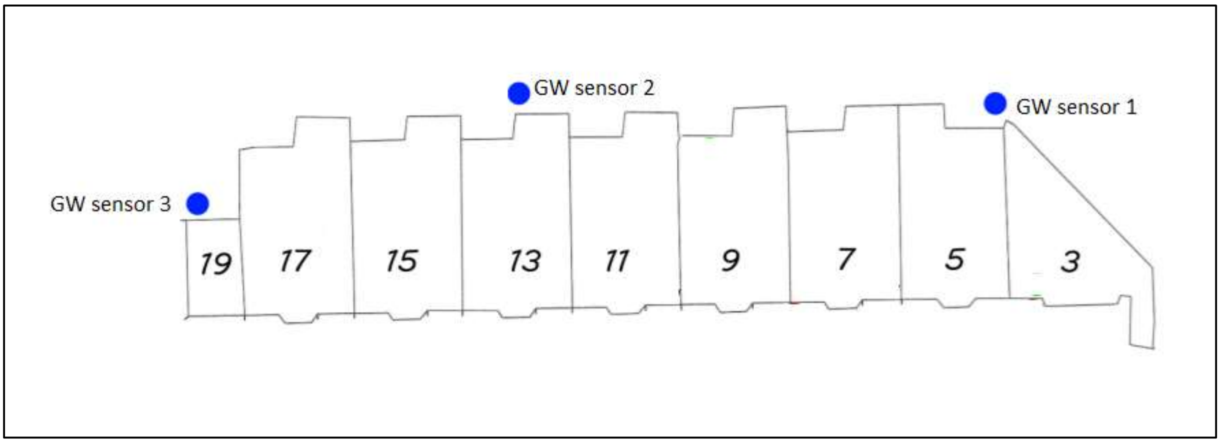


Figure 45 Location of the sensors on Case Study Block C

Important to note is the location of these sensors. In order to get a complete picture of the groundwater level around the building block, at least one sensor needs to be located in front of the block. Factors like raisings and sewerage systems can have great influence on the groundwater table. The location of the monitoring wells is given in the next map.

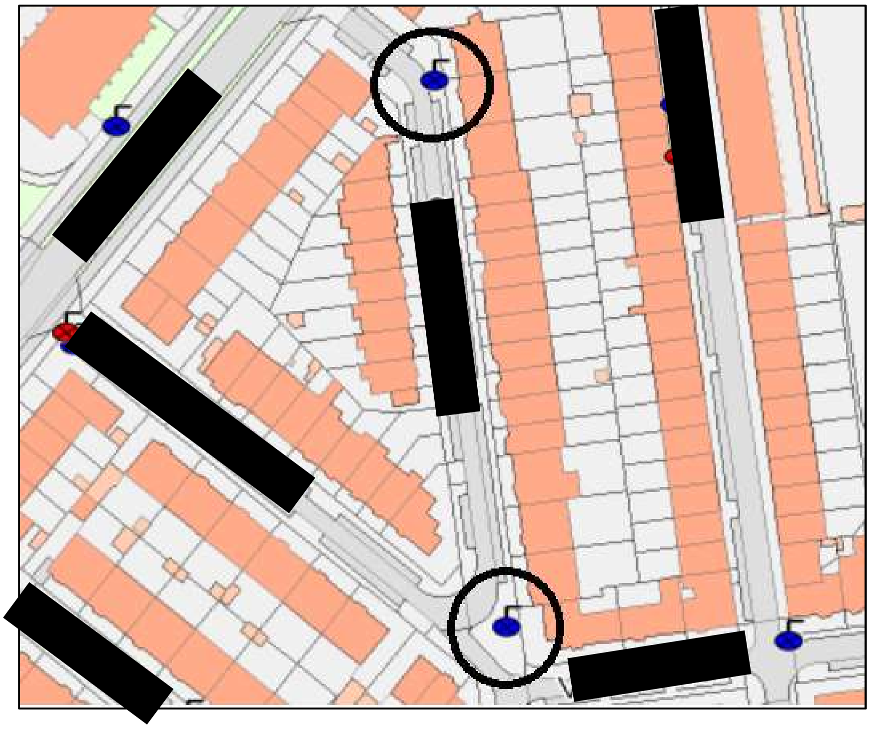


Figure 46 Location of the monitoring wells

There are a few things to consider when the groundwater level is measured. In Rotterdam, there can be a high fluctuation in groundwater level in very small areas, since clay prevents the flow of the groundwater (Hebing B. , 2018). Since the measuring period is not covering an entire year, seasonal influences cannot be derived. As noted earlier, the sewerage system has been renewed in 2015.

A3.4 Tilt sensor

A tilt sensor measures the rotation of a surface. The wall, where a tilt sensor is mounted on, will tilt inwards or outwards around the x-axis. Inwards movement generates negative values, outward movement positive values. The sensor used in the Code Oranje project is the Kelag KAS901-xxX inclination sensor (AG, 2011). This sensors comprise a pendulum made of mono crystalline silicon. Two silicon discs enclose the pendulum to form a shock resistant sensor. The resolution of the sensor is 0,001° and it ranges from ± 30°. A gas damping prevents overshooting and interfering resonance oscillation. An application-specific integrated circuit measures the change as a result of the movement of the pendulum. The reference point of a tilt sensor is the initial measurement starting at 0°. The precision of the sensor is ± 0,014°. Depending on the location of the sensor, this value can be converted to a vertical displacement in millimetres assuming the axis of rotation is at ground level. For instance, if the sensor is installed on a wall, 4 metres wide, the measurement of the rotation at the foundation can be off by:

$$tan(0{,}014) * 4000 \; = 0{,}974 \, mm$$

The following figure shows this schematically. The error can be almost 1 mm, assuming the wall behaves like a rigid wall. If this error margin is not adequate, a sensor with higher precision should be used.

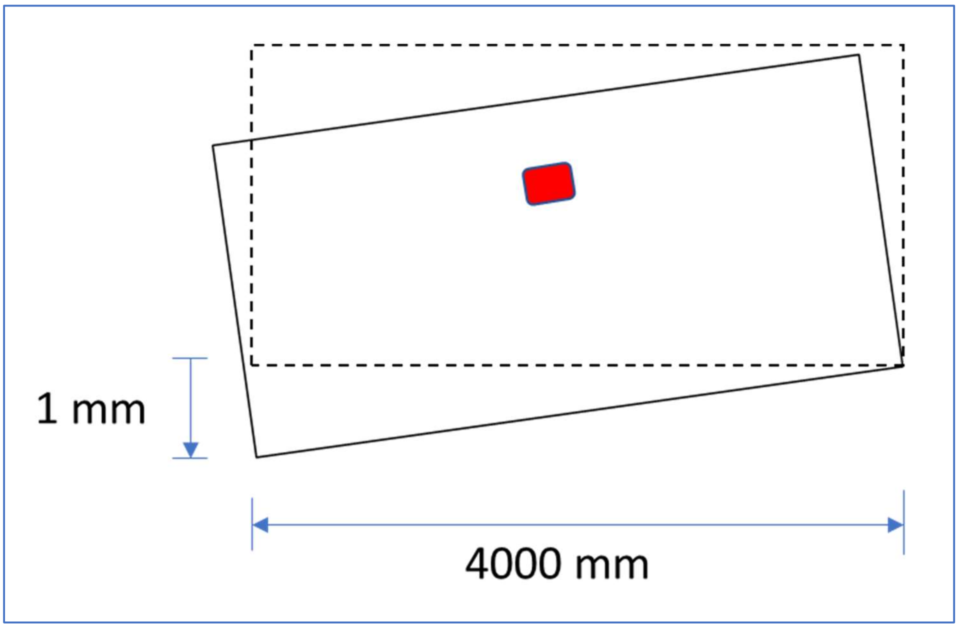


Figure 47 Error margin tilt sensor

Just like the subsidence sensors, several intermediate factors can disrupt the signal of the sensor. The report of the installation of the sensors states that the devices are consisting of a microcontroller, a communication module and the sensor itself. This device sends the measurement to a gateway which is connected to the internet to be able to send it to a database. In this last step the information is processed and extra information is added like origin, date/time and security information (Omnifor, 2016). Vibrations in the vicinity of the sensor can cause noise in the signal of the sensor. This can be caused by heavy traffic or other activities that create vibrations.

In Case Study Block C, the sensors are mounted on the façade about 4 meters above ground level. The picture below shows how the tilt sensor is installed.

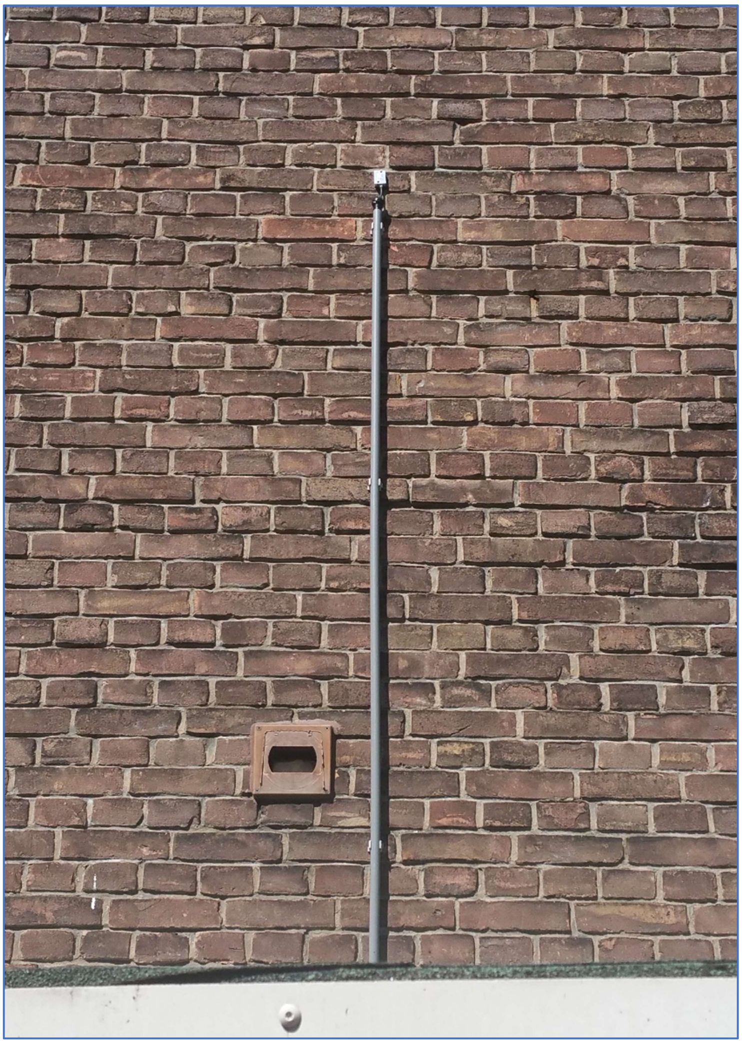


Figure 48 Placement of tilt sensor Case Study Block C, Rotterdam

In this configuration, the sensor measures not only rotation as a result of subsidence. The wall in between the foundation and the sensor can reduce or increase the measured rotation due to curvature in the masonry (Bekken, 2018). This makes it hard to determine whether the rotation is a result of the building's structure or the declining foundation. To depict this difference a sketch is draw where situation A represents rotation due to subsidence and situation B represents rotation due to movement of the masonry.

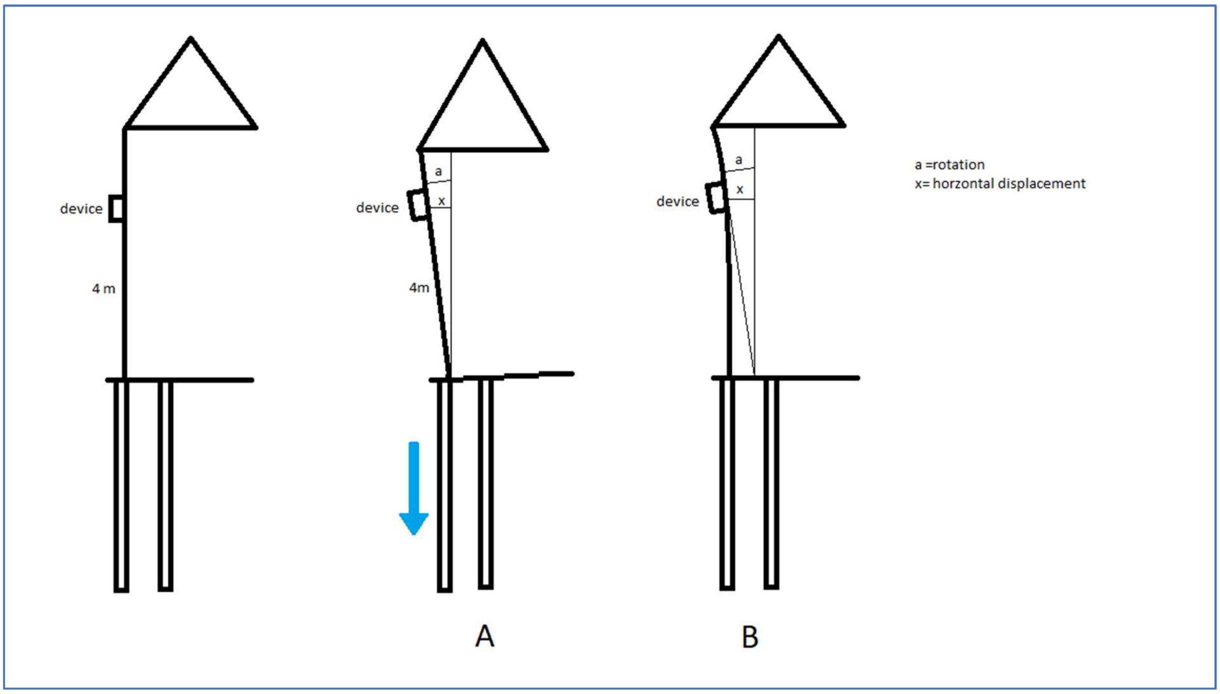


Figure 49 Sketch of possible rotation measurements

If factors like movement of the masonry need to be excluded, the location of the sensor needs to be closer to the foundation, preferably in the basement (if present). In this case the sensor will still be protected against vandalism.

In order to investigate data measured by tilt sensors, regional background information (raisings, local problems, groundwater level, etc.) and structural information (foundation type, blue prints, cracks and subsidence) about the building or building block is required. A level measurement for masonry or a level measurement for floors can help determine the optimal placement. It should be noted that a level measurement for floor can be quite misleading especially in old houses where floors are renewed several times. In these cases a level measurement for masonry is more reliable to determine optimal placement for a tilt sensor. As for all applications, the sensor should be calibrated and should be sufficiently precise.

Because the tilt sensors are currently not used for foundation monitoring, the measurements need to be validated first. In other words: what does the tilt sensor measure? For this the following theoretical model will be used.

A tilt sensor can be installed on a façade. This should be a load bearing wall in order to relate the deformations to the foundation because the loads are distributed to the foundation through the load bearing walls (Heddes A. , 2018). The behaviour of the load bearing wall depends on the stiffness. If the wall is modelled as a rigid diaphragm it will rotate if sagging differences occur. See figure 50.a.

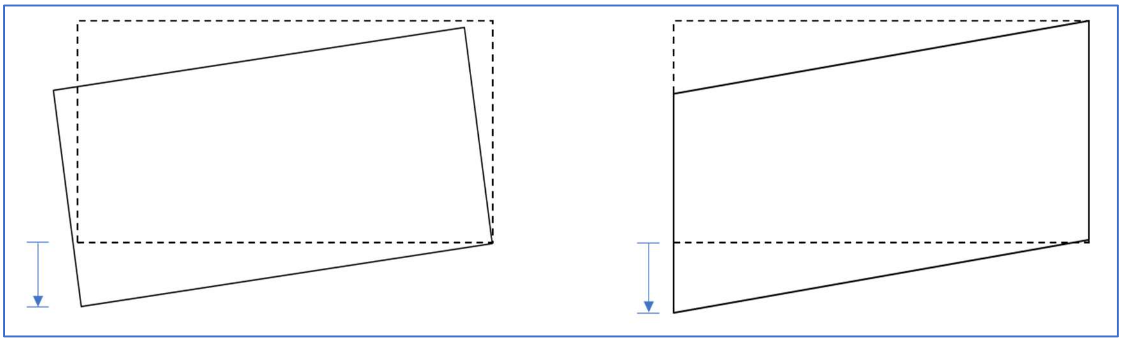


Figure 50.a modelled as rigid wall *Figure 50.b modelled as flexible wall*

A wall with openings in it like doors and windows will have less stiffness than a solid wall. This flexible wall (Figure 50.b) will not be able to withstand the shear force induced by the sagging differences and will therefore deform. This has consequences for the rotation measured by the tilt sensor. Figure 51 shows a wall with a tilt sensor. The wall on the left is sufficiently stiff to rotate as a result of sagging differences. The wall on the right behaves as a flexible wall and shows shear deformation. The sensor will not observe rotation.

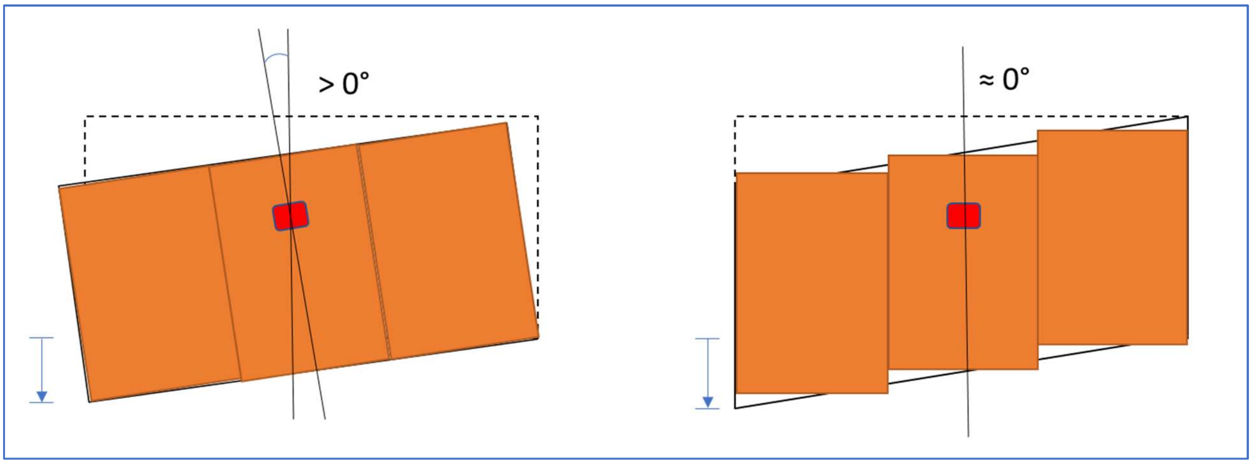


Figure 51 Observed rotation in relation to stiffness

The reality can be modelled as a combination of these absolute cases. It should be taken into account when tilt sensor data is analysed. To investigate if observed rotation is a result of the sagging differences, both subsidence and rotation should be measured.

A sensor that measures rotation around the X and Y axis can be more interesting than only around one axis. See figure below for the axial system.

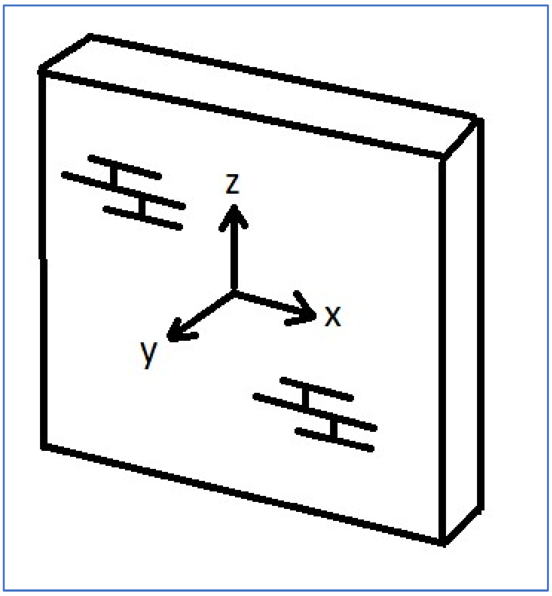


Figure 52 Axial system

Appendix B | Timber strength classes

Table 1 — Strength classes - Characteristic values

		Softwood species												Hardwood species							
		C14	C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50	D18	D24	D30	D35	D40	D50	D60	D70
Strength properties (in N/mm^2)																					
Bending	$f_{m,k}$	14	16	18	20	22	24	27	30	35	40	45	50	18	24	30	35	40	50	60	70
Tension parallel	$f_{t,0,k}$	8	10	11	12	13	14	16	18	21	24	27	30	11	14	18	21	24	30	36	42
Tension perpendicular	$f_{t,90,k}$	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6
Compression parallel	$f_{c,0,k}$	16	17	18	19	20	21	22	23	25	26	27	29	18	21	23	25	26	29	32	34
Compression perpendicular	$f_{c,90,k}$	2,0	2,2	2,2	2,3	2,4	2,5	2,6	2,7	2,8	2,9	3,1	3,2	7,5	7,8	8,0	8,1	8,3	9,3	10,5	13,5
Shear	$f_{v,k}$	3,0	3,2	3,4	3,6	3,8	4,0	4,0	4,0	4,0	4,0	4,0	4,0	3,4	4,0	4,0	4,0	4,0	4,0	4,5	5,0
Stiffness properties (in kN/mm^2)																					
Mean modulus of elasticity parallel	$E_{0,mean}$	7	8	9	9,5	10	11	11,5	12	13	14	15	16	9,5	10	11	12	13	14	17	20
5 % modulus of elasticity parallel	$E_{0,05}$	4,7	5,4	6,0	6,4	6,7	7,4	7,7	8,0	8,7	9,4	10,0	10,7	8	8,5	9,2	10,1	10,9	11,8	14,3	16,8
Mean modulus of elasticity perpendicular	$E_{90,mean}$	0,23	0,27	0,30	0,32	0,33	0,37	0,38	0,40	0,43	0,47	0,50	0,53	0,63	0,67	0,73	0,80	0,86	0,93	1,13	1,33
Mean shear modulus	G_{mean}	0,44	0,5	0,56	0,59	0,63	0,69	0,72	0,75	0,81	0,88	0,94	1,00	0,59	0,62	0,69	0,75	0,81	0,88	1,06	1,25
Density (in kg/m^3)																					
Density	ρ_k	290	310	320	330	340	350	370	380	400	420	440	460	475	485	530	540	550	620	700	900
Mean density	ρ_{mean}	350	370	380	390	410	420	450	460	480	500	520	550	570	580	640	650	660	750	840	1080

NOTE 1 Values given above for tension strength, compression strength, shear strength, 5 % modulus of elasticity, mean modulus of elasticity perpendicular to grain and mean shear modulus, have been calculated using the equations given in Annex A.

NOTE 2 The tabulated properties are compatible with timber at a moisture content consistent with a temperature of 20 °C and a relative humidity of 65 %.

NOTE 3 Timber conforming to classes C45 and C50 may not be readily available.

NOTE 4 Characteristic values for shear strength are given for timber without fissures, according to EN 408. The effect of fissures should be covered in design codes.

Appendix C | Graduation committee

GRADUATION COMMITTEE

The people who will provide aid and evaluation are:

Prof.dr.ir. J.W.G. van de Kuilen (chairman)
Organisation: *Delft University of Technology*
Faculty: *Civil Engineering*
Section: *Engineering Structures; Biobased Structures and Materials*

Dr.ir. H.R. Schipper (daily supervisor)
Organisation: *Delft University of Technology*
Faculty: *Civil Engineering*
Section: *Materials- Mechanics- Management & Design*

Drs. W.F. Gard
Organisation: *Delft University of Technology*
Faculty: *Civil Engineering*
Section: *Engineering Structures; Biobased Structures and Materials*

Ir. Dick A. de Jong
Organisation: KCAF

Dr. Ir. J. Coenders
Organisation: White Lioness technologies

A. Heddes
Organisation: Fugro NL Land B.V.

Appendix D | Contact information

Name: Joost Verbeek

Education program: Master Building Engineering, TU Delft University of Technology.

Contact information Fugro Amsterdam

Website: www.fugro.com

Contact information SkyGeo Delft

Website: www.skygeo.com