A feasibility study of building monitoring and forensic engineering with Interferometric Synthetic Aperture Radar

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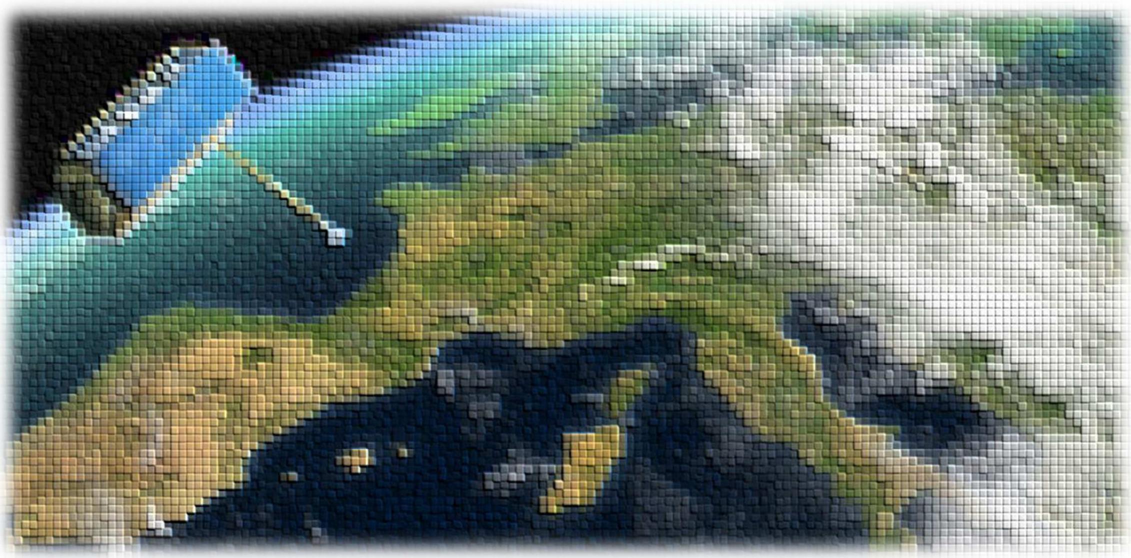

MSc. Building Engineering Thesis

A feasibility study of building monitoring and forensic engineering with Interferometric Synthetic Aperture Radar

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Foreword

This report presents the results of my graduation research as a student at the faculty of Civil Engineering and Geosciences, section Building Engineering Structural Design.

I was immediately excited about the thesis subject when I first read there was a satellite technique that recorded deformation data and could detect damages expressed in deformation. I wondered what the possibilities and opportunities could be for this technique. This excitement resulted in the selection of Interferometric Synthetic Aperture Radar (InSAR) as a building research tool as my thesis subject. This thesis aims at providing the reader with insight into the different aspects, and their impact, involving InSAR as a building research tool.

I would like to thank Ramon Hanssen for his contagious interest in InSAR. Furthermore, I would like to thank Karel Terwel for his thorough comments about my produced work throughout the graduation. Successively, I would like to thank Dick Hordijk for his opinion and his industry focused view about the subject. All in all I would like to thank the committee for their enthusiasm about my thesis subject.

Finally, I would like to thank my friends and family for their support and encouragement. Especially my mother, Laura, and my brother, Jaap, who always tried to motivate me and had to listen to thesis related subjects.

I hope you will read my graduation research with the same amount of curiosity as I enjoyed while conducting this research.

Henk van Waning,
Delft,
October 2014

ABSTRACT

Motivation

The last years have seen a few severe cases of structural damage to buildings in the Netherlands. A recent case was the shopping mall 't Loon in Heerlen. It would be beneficial if structural failures could be avoided, or at least be predicted. New satellite technology, Interferometric Synthetic Aperture Radar (InSAR), proves that it is possible to detect structural deformation in buildings at the level of millimeters and to receive weekly updates. TU Delft has shown that for the Heerlen case, the deformation could already be detected years before the collapse. The InSAR data was also used for forensic research at Heerlen.

Goal

The previously discussed developments resulted in the main research question of this thesis:

How can InSAR data contribute to forensic engineering and building monitoring in general?

The objective is to determine in which cases data provided by radar interferometry can be used, and how this data should be interpreted for building monitoring and forensic engineering.

Method

A literature review is conducted to identify the general properties and limitations of InSAR. To research the potential contribution to forensic engineering, an analysis of a damage database is made to determine InSAR's potential as a forensic engineering tool. The database is assessed according to the guiding principles of forensic engineering using InSAR as laid out by this thesis: opportunistic character, large deformations and no sudden deformations. A research methodology for forensic engineering with InSAR is proposed and tested with a couple of case studies. Building monitoring is subdivided into object-driven building monitoring and data-driven building monitoring. Conventional building monitoring techniques are analysed to research the potential of InSAR as a building monitoring tool. To research object-driven building monitoring, a literature study is conducted to examine the different variables that cause building movement that influence the InSAR data. One dominant variable is analysed to research the relation between a variable and the InSAR data. To research data-driven buildings monitoring, general building limits for deformations are discussed. InSAR data of Delft, provided by the TerraSAR-x satellite, is used to analyse the potential of InSAR as a data-driven building monitoring tool. Deformation areas with very high deformation rates are examined to find out how to work with InSAR as a data-driven building monitoring tool.

Results

The development of the movements caused by torsion, inelastic deformation, fracture, second order effects and buckling are hard to detect with InSAR. Deformation caused by failure needs to be visible on the outer shell of the structure. Damage on the outer shell is visible to InSAR, as are damages that influence the supporting structure of the building. Deformations of the supporting structure can be damped in the outer shell; this is caused by the structural integrity. One fifth of the damage cases of the damage database have potential to be researched with InSAR. Only failures caused by aging and structural errors were suitable for research.

Deformation measurements for buildings is one of the building monitoring fields in which InSAR can compete. Competitors in this field are Lidar, photogrammetry, levelling, and tachymetry. One of the main advantages of monitoring with InSAR is that large areas can be monitored with one measurement, and no one needs to be present at the site. Object-driven monitoring of buildings can be done by monitoring a building and identifying explanations for building movements. The movement of a Persistent Scatter point (PS-point) is caused by forces that work on a building and by the resistance of the building. Forces that do not change over time will not make the building move, unless there is degradation of the building elements. InSAR measurements are most suitable for vertical deflection monitoring because of the sensitivity of the satellite measurements. Factors that are suitable to monitor with InSAR are temperature, settlement and groundwater change.

Data-driven monitoring is most suitable for monitoring foundation problems. The movements are often gradual over time, and large deformations limits are allowed. Attention should be paid to the translation of the top structure of the movement. Movements of 3 mm/year of a PS-point in vertical direction, or 1.5 mm/year relative to another PS-point on a building, are alarming.

Conclusion

InSAR can become an addition to conventional monitoring techniques for building research. For forensic engineering InSAR can indicate which parts of building elements were influenced by the failure, and when deformation started to develop. InSAR can support evidence for the possible cause of the failure, when the failure is expressed in deformation. For building monitoring InSAR may support the indication of the development of deformation that may cause damage. The monitoring of vertical deformations is limited by the sensitivity and the phase ambiguity. These boundaries make InSAR most suitable for monitoring gradual deformations, often found in deformations of foundations.

Contents

1 Introduction

Imagine it is the year 2020. Interferometric Synthetic Aperture Radar (InSAR) is monitoring a building. InSAR can measure deformation. The system sends out a signal if it detects a change in deformation above a yet-to-be-defined threshold. If the cause of the anomaly cannot be determined, a manual inspection must be undertaken. If there is already enough evidence to alarm the building's owner that damage is possibly developing, then this will be done. If the anomaly is identified, then the building maps and recent elevation maps of the site will be required for further research into the cause of possible damage. A first step of this research will be to establish the location of the problem – in the foundation, the main structure, or in external components, like balconies. If damage is developing, then intervention can be considered and further damage avoided.

The previously described scenario could be a potential contribution of InSAR to the monitoring of buildings. This potential contribution would give building users an advantage, because it would lower the risk of failure. InSAR can also benefit building owners; damage could be halted at an early stage. Such monitoring could be useful in parts of the Netherlands where there is seismic activity, like Groningen, or in buildings with particular structures or dated structures.

Motivation for research

A local subsidence formed on December 3, 2011, under shopping mall 't Loon at Heerlen. This subsidence caused damage to the mall. After parts of the mall were demolished, 'Adviesbureau ir. J.G. Hageman B.V.' (Hordijk, 2012) began an investigation. The subsidence was an elastic deformation, with a slow build up over a range of about 2000 m^2 caused by a sinkhole.

The increasing speed at which this deformation formed could have been detected years earlier if satellites had been used (Chang and Hanssen, 2014). Satellites were used to determine the origins of the deformation and how it proceeded over time. The technology used, Radar Interferometry (InSAR), showed that the ground under the mall subsided 4 cm over the past eight years. Satellites could collect data on the deformation of a building, increasing structural safety, identifying structural failures, and preventing costs incurred by damage to buildings. This thesis will study how In SAR data should be interpreted for monitoring buildings.

First, an introduction to InSAR will be given in this section. This will be followed by the research objective and an introduction to other definitions relevant to this study.

Figure 1.1, Partial demolition of shopping mall 't Loon after the accident.
Source: http://www.deondernemer.nl

InSAR
Radar interferometry makes it possible to observe the surface night and day, even in cloudy conditions (Hanssen, 2002). The radar transmits thousands of pulses per second, reflected by the surface. Advanced techniques process the received reflections to a pixelated radar image that can be matched to a specific, satellite-dependent area. Within a pixel there are certain objects – for instance, the roofs of houses – that make up the dominant share of the observed reflection. Using the dominant and stable reflection, deformations of these objects can be identified before it is too late. This highlights an important characteristic of this method: InSAR is an opportunistic technique. This means that the location is not determined by the data user but by the reflection of the pulses from the satellite to Earth and back to the satellite. This characteristic of InSAR means that data is not available for all buildings. However, point densities in urban areas between 1.500 to 2.000 PS/km^2 are not uncommon (Luo et al. 2014). The precision of deformation measurements is in the millimetre range and for linear deformations even better than 1 mm/year (Hanssen, 2003).

Currently, several satellites are in orbit to perform these measurements (see Table 1.1) The acquired images of the TerraSAR-x satellite have a resolution of 2x11m. Large areas can be rapidly and frequently monitored for an arbitrary point in the Netherlands. Every 11 days a measurement can be taken. The archive created from these measurements can be retrieved, and a deformation analysis can be performed. This makes InSAR, with its repeated measurements, a potential technique for building monitoring and forensic engineering.

Satellite	Cycle repeat	Range resolution	Wave-length	Launch year of satellite	End of mission
ERS-1	35 days	20x4 m	5.6 cm	1991	2000
JERS-1	44 days	24x18 m	23.6 cm	1992	1998
ERS-2	35 days	20x4 m	5.6 cm	1995	2001
ERS-1/ERS-2	1 day	20x4 m	5.6 cm	1995	1996
Radarsat-1	24 days	8x8 m	5.6 cm	1995	2013
Envisat	35 days	20x4 m	5.6 cm	2002	2010
ALOS	46 days	10x10 m	23.6 cm	2006	2011
Cosmo-SkyMed	16 days	30x30 m	3.1 cm	2007	Still active
TerraSAR-x	11 days	2x11 m	3.1 cm	2007	Still active
Radarsat-2	24 days	10x3 m	5.6 cm	2011	Still active
Sentinal-1A	12 days	4x20 m	5.6 cm	2014	Still active

Table 1.1, Satellites that provide InSAR data.

The objective of this thesis is to create guidelines for conducting building research using InSAR. In this thesis, building research is divided into forensic engineering, object-driven building monitoring and data-driven building monitoring (Figure 1.5). Forensic engineering is a posteriori research, while building monitoring is near-real time research.

Forensic engineering
In the case of ‘t Loon, InSAR acted as a forensic tool. InSAR supported the theory that the cause of failure was a sinkhole. The use of InSAR as a forensic engineering tool will be explored in chapter 3. The investigation and determination of the causes of structural failures of buildings, bridges, and other constructed facilities is called forensic engineering (Ratay, 2000). InSAR data can give insight into the development of a structural failure.

Building monitoring
The behavior of a structure is observed with building monitoring. The monitoring system can signal changes that may lead to damage in an earlier stage. The owner may then take action to prevent further damages in order to reduce repair costs. The use of InSAR for building monitoring could contribute to the application domain of InSAR by giving this technology the function to monitor buildings in near-real time. The possibilities for building monitoring will be explored in this thesis. Building monitoring can be subdivided into object-driven building monitoring and data-driven building monitoring.

Object- and data-driven building monitoring
These two types of monitoring are different approaches to building monitoring. With object-driven building monitoring, the object – the building – is known. This provides knowledge about the location of the satellite measurements and which parts of the structure can be monitored. This results in clear deformation limits

and the possible understanding of changes in satellite data. With data-driven monitoring, data is evaluated with predefined general deformation limits for buildings. When limits are exceeded and the data actually represents a building, then further research on the building may be required.

Both building monitoring and forensic engineering research the events leading up to building failure. The definition of structural failure generally implies damage, the total collapse of a structure, or the partial collapse of a structure. According to Ratay (2010), structural failure may be characterized as an unacceptable difference between the intended and the actual structural performance. This thesis will focus on the visible aspect of structural failure. Only failures with deformations can be researched by InSAR.

The main goals of this thesis are to determine what can be monitored and what the process of conducting research with InSAR is. The research objective, with its accompanying research questions, will be described in the next section. This will be followed by the methodology and the structure of the thesis.

1.1 Definition of the research project

In this section, the research objectives are formulated (1.1.1). The research questions are also stated (1.1.2).

1.1.1 Objective

This is a feasibility study for the use of InSAR as a building monitoring and forensic engineering tool. Radar interferometry was chosen, as this technique has not been fully explored. Every couple of days, the satellite performs a measurement of the deformation of the landscape within its range (the interval depends on the satellite). This data might be used to monitor buildings, identify building deformations at an early stage, and prevent further damage to buildings.

A basic principle behind this research is that a building is often a stable reflector for InSAR. Radar interferometry was used to investigate structural damage in Heerlen and also to investigate monumental buildings in Italy (Giannico et al. 2013). These examples indicate that deformation research with InSAR is possible. This resulted in the following objective for this research:

- *The research objective is to determine in which cases data provided by radar interferometry can be utilized, and how this data should be interpreted for building monitoring and forensic engineering. These outcomes may lead to guidelines on how InSAR can contribute to building monitoring and forensic engineering in the Netherlands.*

The distinction between building monitoring and forensic engineering has been made, due to the different stages of research on which each field focuses. These different stages call for individual research approaches with InSAR. This will be described in the research methodology.

1.1.2 RESEARCH QUESTIONS

The research objective leads to the following general research question:

- *Main research question: How can InSAR data contribute to forensic engineering and building monitoring?*

The research question tries to determine InSAR's potential as a building monitoring technique and as a forensic tool. To answer the main research question, various sub-questions must be answered. These sub-questions can be divided into two categories: forensic engineering and building monitoring. The first sub-question is the same for both categories:

- *Sub-question 1: How should deformations measured by InSAR be interpreted?*

The introduction stated that radar can take measurements every 11 days with millimetre accuracy. However, there are limitations to the InSAR technique. These limitations should be mapped before significant conclusions can be drawn regarding this data. This sub-question will be treated in chapter 2.

The sub-questions for forensic engineering are the following:

- *Sub-question 2: What kind of damage can the satellite recognize, and how do these failure mechanisms express themselves in deformation?*

How can damage expressed in movement be recognized by InSAR? The location, magnitude, and development of the damage play an important role in answering this question. This sub-question will be answered in chapter 3, section 5.3 and appendix 5.

- *Sub-question 3: Is InSAR's potential contribution to damage research of significance?*

The cause of a building's collapse is often researched. This sub-question tries to determine whether deformation research with InSAR can be used in practice. This sub-question will be treated in section 3.3.

The category building monitoring will be subdivided into object- and data-driven building monitoring. Sub-question 4 is about building in monitoring in general. Sub-questions 5 and 6 are about object-driven building monitoring.

- *Sub-question 4: What are the potential advantages and disadvantages of InSAR as compared to conventional monitoring techniques?*

Building monitoring is a field of study that monitors the health of a structure with different monitoring tools. These monitoring tools all have different properties. What are the possible advantages and disadvantages of InSAR as compared to these conventional techniques? This sub-question will be answered in section 4.1.

- *Sub-question 5: How can InSAR data be interpreted for use in object-driven building monitoring?*

In this monitoring scenario, information on the building and its surroundings are known. This means that an extensive analysis of the deformation can potentially be conducted. How should this analysis be made, and what can be analysed? This sub-question will be treated in sections 4.2 and 4.3.

- *Sub-question 6: What is the procedure for object-driven building monitoring with InSAR?*

The number and location of satellite reflections on a building play an important role for data interpretation. How do different basic principles influence object-driven building monitoring? This sub-question will be treated in sections 4.3 and 5.2.

The sub-questions for data-driven building monitoring are the following:

- *Sub-question 7: Is there a potential general threshold to indicate building damage?*

Can general assumptions be made about the magnitude or rate of deformation so as to identify possible building damage? Timely identification of damage might prevent a total collapse of a building. If damage can be repaired at an early stage, money and lives could be saved. This sub-question will be treated in section 4.4.

- *Sub-question 8: What is the procedure for data-driven building monitoring with InSAR?*

The number and location of satellite reflections on a building play an important role for data interpretation. How do different basic principles influence data-driven building monitoring? This sub-question will be treated in sections 5.1.

After answering the eight sub-questions, the main research question can be answered (Chapter 6). The methodology for obtaining the research’s objective and answering the research questions is discussed in the next section.

1.2 Methodology

This research can be subdivided into the following research fields: structural safety and radar interferometry. Where these subjects overlap is the research focus of this thesis. By monitoring buildings with InSAR, structural failure, with deformation, could be prevented and the structural safety of a building could increase.

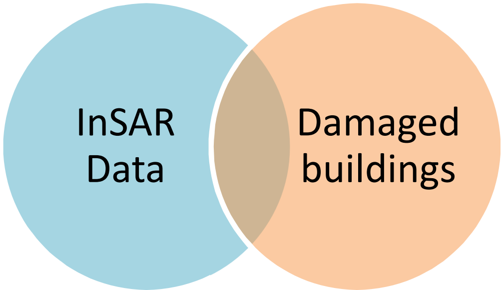


Figure 1.2, Available data for research.

The research is divided into two building research fields: forensic engineering and building monitoring. This is in order to study the full potential of InSAR as a building research tool. To answer the main research question and satisfy the research objective, the sub-questions must be answered.

A literature review is conducted so as to identify the general properties and limitations of InSAR. This answers sub-question 1. The difference between the research methodologies of forensic engineering and building monitoring can be explained by the process of failure, this is explained in chapter 4.

An analysis is made of the damage database provided by Terwel to determine InSAR's potential as a forensic engineering tool. The database is assessed according to the guiding principles of forensic engineering using InSAR, as laid out by this thesis. The relationship between the data and the expected deformation is put into practice using 't Loon as a case study. This case study assesses whether the InSAR data matches the expected deformation of the failure. The case study focusing on Kerkrade demonstrates the proposed research methodology for forensic engineering. After these steps, sub-questions 2 and 3 can be answered.

Conventional building monitoring techniques are analysed to highlight the potential of InSAR as a building monitoring tool. This answers sub-question 4.

An object-driven building monitoring research method is arrived at through the formulation of a building movement equation to answer sub-questions 5 and 6. The different variables of the equation are discussed so as to identify InSAR's potential as an object-driven building monitoring tool. One dominant variable is analysed in the case study of the Erasmus MC to emphasize the possibilities of InSAR as an object-driven building monitoring tool. A process for analysing

InSAR's possibilities with different numbers of InSAR reflections is proposed at the end of the case study.

In a literature review, general building limits for deformations are discussed. InSAR data on Delft, provided by the TerraSAR-x satellite, is used to analyse the potential of InSAR as a data-driven building monitoring tool. Deformation areas with very high deformation rates are examined to find out how to work with InSAR as a data-driven building monitoring tool.

This research methodology gives sufficient insight to answer all the sub-questions. By answering the sub-questions, general conclusions can be drawn, and the main research question can be answered.

1.2.1 RESEARCH LIMITATIONS

The main research limitations can be found in the different research methodologies for the different building research fields:

The ideal approach to test the feasibility of InSAR as a forensic tool would be to examine Terwel's database along with InSAR data and to analyse whether the InSAR data could detect deformation caused by damage. To process all this data would be very time-consuming. Therefore, the theoretical approach that has been chosen is database research of building damage in the Netherlands and a limited number of case studies to demonstrate InSAR as a forensic tool.

The ideal approach to research InSAR as an object-driven building monitoring tool is to find a building where all the influences of deformation are completely known. Each factor that causes deformation could be calculated and interpreted in terms of the total deformation found in the InSAR data. The difference could be analysed and conclusions could be drawn about InSAR's potential as a building monitoring tool. Unfortunately, this approach is not possible. The assumption that all of the influencing factors could be known can hardly be validated and would also be very time-consuming. Therefore, the potential influence of one of the factors of building movement will instead be analysed, so as to demonstrate the impact of a known influence, such as temperature, on a building.

Finally, data-driven research should be analysed by reviewing the ideal proposed research for forensic engineering feasibility. Can common signs of change in deformation be found in the data? This is very unlikely, because damage never occurs in completely the same manner. Cases with a high degree of comparability are limited. This makes this research approach unfeasible. This study instead chooses to gain a first impression of data-driven research by reviewing the most notable indications of possible damage.

The research is limited by the database detailed building damage information, InSAR data, and time. An indication of the feasibility of InSAR as a building research tool can still be gained despite these limitations. While the number of case studies may be limited, they still give insight into how to work with InSAR data for building research.

1.3 Structure of the thesis

The research can be separated into the previously described topics: forensic engineering with InSAR and building monitoring with InSAR. The structure utilized to introduce and study these two topics is described in the following figures:

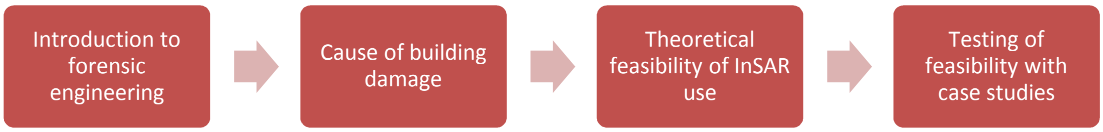


Figure 1.3, The research process for the use of InSAR as a forensic tool.

Figure 1.4, The research process for the use of InSAR as a monitoring tool.

Because both topics make use of InSAR and are about buildings, there is more overlap then these figures may suggest. For both topics, it is InSAR's goal to detect damage in buildings. The research can be divided into four parts: an introduction to the technique utilized, fields of building research, theoretical feasibility, and case studies, as can be seen in Figure 1.5.

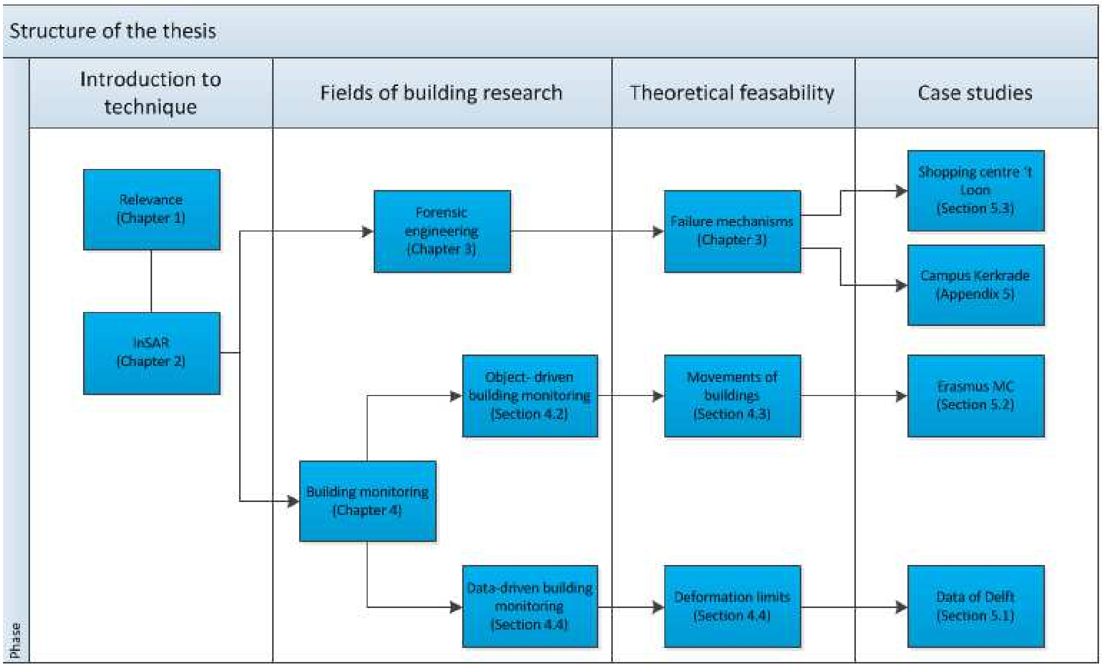


Figure 1.5, Structure of the thesis.

Introduction
The introduction briefly describes why the research is relevant. It follows with a general description of InSAR. A general description how the technique works, how the technique can produce valuable data, and how the data should be interpreted can be found in this section.

Fields of building research
This part of the thesis is divided into two chapters: InSAR as a forensic tool and InSAR as a monitoring tool. These chapters start with an introduction to the different subjects. The theoretical feasibility of InSAR as a useful tool is researched for both subjects. For forensic engineering, this is done by comparing past failures with InSAR-data basic principles. For building monitoring, this is done by comparing InSAR with conventional monitoring techniques.

Theoretical feasibility
The building monitoring chapter continues with a theoretical description of how building movement can change InSAR data. The chapter ends with a suggestion for alarming values derived from InSAR data.

Case studies
In the research's final phase, the different case studies are assessed to review the usability of the previously defined research fields. These studies clarify whether InSAR can be a useful tool for building monitoring and forensic engineering.

1.3.1 Reading guide

The thesis contains six chapters. The content of each chapter can be described as follows:

Chapter 1:
The motivation for this research is stated. This is followed by a description of the research objective and the research questions. The methodology and the structure of the thesis are also described in this chapter.

Chapter 2:
An introduction is given to the basic features of InSAR. Research limitations and how the data should be interpreted are discussed.

Chapter 3:
This chapter starts with a short introduction to forensic engineering. A database of damage cases is reviewed along with basic principles for InSAR research to study the usability of InSAR as a forensic tool.

Chapter 4:
A general description of structural health monitoring (SHM) is given. The field of interest and a couple of conventional tools are discussed. The types of displacements that InSAR can monitor and what causes these movements are the topic this chapter addresses. At the end of this chapter, potential alarming values are discussed.

Chapter 5:
In this chapter, the different fields of research are put into practice with different case studies. The chapter begins with a data-driven building monitoring case focusing on Delft. This case study is followed by a case study examining Erasmus MC and the visibility of the influence of temperature differences. The final section is comprised of case studies about forensic engineering. The potential feasibility of the data is tested in a case study focusing on the 't Loon shopping mall. The final case study is about the campus in Kerkrade and the proposed research methodology for forensic research with InSAR. This final section is moved to appendix 5.

Chapter 6:
The conclusion and recommendations of the thesis can be found in this chapter.

2 RADAR INTERFEROMETRY

The first part of this chapter describes what InSAR is, how it works, and the advantages its use. How InSAR data should be interpreted is described in the final part of this chapter.

2.1 AN INTRODUCTION TO RADAR INTERFEROMETRY

The measurement technique that will be used for this research is the radar technology, radar interferometry, also often referred to as InSAR. InSAR stands for Radar Interferometric Synthetic Aperture. In brief, this technique can measure deformation of the Earth by using the phase difference of electromagnetic waves transmitted by satellites. This technique allows the measurement of ground displacement to millimetre accuracy (Ferretti et al. 2010).

Since 1978, the first radar images of the Earth's surface, obtained from Synthetic Aperture Radar (SAR), have stimulated interest in the sector of Earth Observation, creating new monitoring opportunities for surface deformation analysis, such as groundwater extraction, earthquakes, volcano dynamics, slope instability, mining, and coastland reclamation. There are also examples where InSAR has already been used to monitor structural damage. This has been accomplished, for example, in Italy on historic buildings (Giannico et al. 2013).

2.1.1 HOW INSAR WORKS

The following paragraph will explain the basics of how InSAR works. This explanation is primarily drawn from the book Data Interpretation and Error Analysis (Hanssen, 2001) and from the articles Synthetic aperture radar interferometry to measure Earth's surface topography and its deformation (Burgmann et al. 2000) and Deformation Monitoring by Satellite Interferometry Design Parameters and Environmental Factors Affecting Feasibility (Hanssen and Ferretti, 2002).

SAR is an active sensor; this means that it does not make use of the Sun's radiation reflection on the Earth. SAR transmits electromagnetic waves that are backscattered from the Earth to the satellite. The radar satellites record the phase and the amplitude of the backscattered waves. These microwaves can pass through clouds and are not affected by night or day; this gives these satellites an advantage with respect to remote sensing sensors. SAR collects the amplitude and the wrapped phase from the backscattered waves. The wrapped phase is one complete cycle between −π and + π. For SAR images, the amplitude of a pixel is used, and the phase remains unused.

For InSAR, the wrapped phase of each pixel is used. This wrapped phase is a part of the distance from the satellite to the surface in the line of sight. The signal needs a large number of complete phases, and maybe an uncompleted phase, to travel from the satellite to the ground and then back to the satellite. The wrapped phase shows this uncompleted phase.

If this acquisition is done another time for the same place on Earth, and a new SAR image is created, then the same phase may be expected. A shift in phase may show the difference in the sensor-Earth distance. This distance is, in an ideal situation, the displacement of an object (see Figure 2.1). This is the basic principle of InSAR – measuring deformation by comparing phase differences of two or more SAR images.

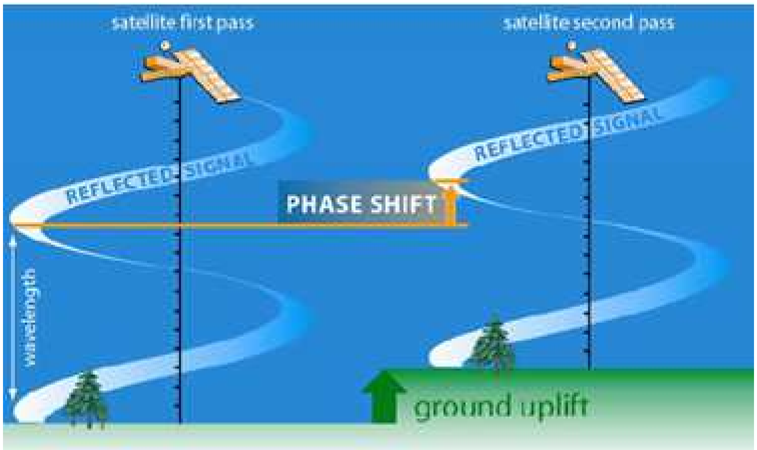


Figure 2.1, An example of the phase difference caused by a displacement on Earth. Source: www.halliburton.com

A minimum of 25 to 30 images is needed to determine deformation with millimetre accuracy (GMES, 2008). This number of images is needed to ensure millimetre accuracy. The shift in phase measured not only depends on an object's deformation but can also be influenced by other factors. The different design parameters, according to Hanssen (et al. 2002), can be seen in Figure 2.2.

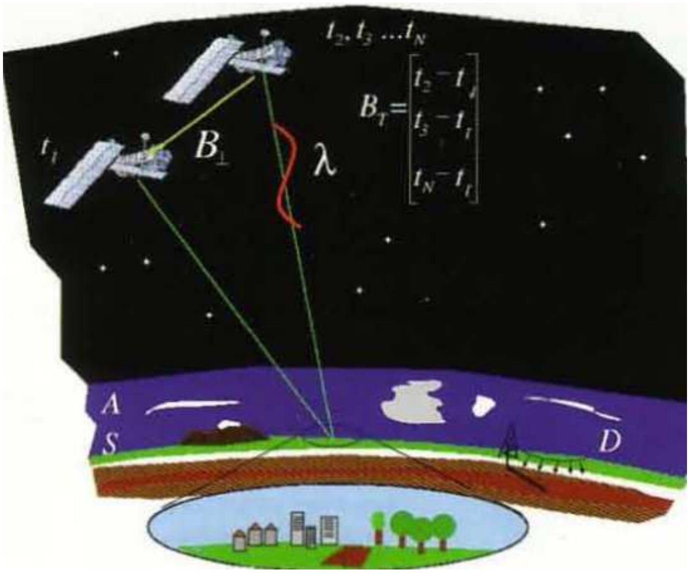


Figure 2.2, Design parameters of InSAR. Source: (Hanssen et al. 2002) Design Parameters and Environmental Factors Affecting Feasibility Deformation Monitoring by Satellite Interferometry

Parameters can be divided into design parameters and environmental factors. Design parameters consist of several factors: the radar wavelength (λ), the effective distance ($B_\perp$) between the satellites that took an image of the same place on Earth, and the temporal baseline (B_T). This final parameter is the time interval between the image acquisitions and the total number of images. The environmental factors are the Earth's atmosphere (A), the characteristics of the deformation (D), and the surface (S). These factors will be discussed briefly for a better understanding of the parameters and of InSAR.

Radar wavelength (λ)
The satellites use a long radar wavelength. This is because this wavelength can penetrate clouds while maintaining a coherent signal. Large objects are used for coherent reflections, because, contrary to smaller objects, these do not move frequently. This limits the disturbance in the phase signal analysis and results in a smaller signal-to-noise ratio (SNR).

Effective distance ($B_\perp$)
This parameter is the distance between the locations of the satellites when they measure a particular object. The smaller the effective distance, the less influence is played by topographic height. A large effective distance between satellites locations provides a more accurate estimation of the height. This is because the phase has a larger bandwidth and is less sensitive to phase ambiguity. However, it then delivers less accurate deformation measurements. Using a Digital Elevation Model (DEM) from another source makes it possible to verify if values are correct.

Temporal baseline (B_T)
The temporal baseline is a multiple of the orbit revisit interval. The orbit revisit interval is a term that describes how many times a satellite can measure a particular point in a particular time interval.

Earth's atmosphere (A)
This factor depends on weather conditions. The weather influences radio waves non-homogenously. Water evaporation, for example, can cause a signal error up to several centimetres.

The characteristics of the deformation (D)
This term describes the deformation of an object. This can be, for example, movement of the Earth caused by an earthquake. A measurement with a lot of noise may also look like a deformation; this is an error that may occur with this parameter.

The surface (S)
Not all kind of surfaces can produce valuable information for InSAR. If the reflection characteristics of a landscape change over time, as is the case for water, then no valuable information can be retrieved from the set of images. Construction work may also lack the coherence to produce valuable data. This is because a building under construction is continuously changing. Buildings, rocks, or infrastructural works maintain their scattering characteristics over long time periods and under varying viewing geometries. The coherence needs to be estimated per pixel. For this, repeated measurements under identical conditions are needed. Many images should be produced with a high coherence to gain valuable information. The coherence is the degree of interferometer correlation between images.

These different parameters contribute to the total phase shift per pixel. The total phase shift can be expressed with the following formula (Hanssen 2001):

$$\Delta\varphi_t = \Delta\varphi_{topo} + \Delta\varphi_{def} + \Delta\varphi_{atm} + \Delta\varphi_{geom} + \Delta\varphi_{noise} \tag{2.1}$$

With:

$\Delta\varphi_t$	Total phase shift
$\Delta\varphi_{topo}$	Phase shift due to shift in topographic phase
$\Delta\varphi_{def}$	Phase shift due to deformation
$\Delta\varphi_{atm}$	Phase shift due to the atmospheric delay
$\Delta\varphi_{geom}$	Phase shift due to a change in the scatter characteristics of the Earth's surface
$\Delta\varphi_{noise}$	Phase shift due to noise (e.g. thermal noise, co-registration errors, and interpolation errors)

The phase shift due to deformation is the parameter of interest. The other phase shifts need to be dissolved and can be seen as error, if the phase shift is linked to deformation. To find this error, a large number of SAR images are needed. Most errors can be filtered by using single-difference and double-difference observations. Single-difference observations compare two different points measured by one satellite. Double-difference observations compare two different points, both measured by two satellite recordings, compared with a reference point. With double-difference observations, the error produced by the reflection (the surface error) is filtered (Garcia 2005). To convert the phase shift to displacement, the following equation is used:

$$\Delta\varphi_{def} = \frac{4\pi}{\lambda} * \Delta R \tag{2.2}$$

With:

λ	Wavelength
ΔR	Displacement

The wavelength is the frequency of the pulses transmitted by the satellite. Short wavelengths allow higher resolutions but are more sensitive to noise. X-band (3 cm), C-band (6 cm), and L-band (24 cm) are examples of wavelengths that are used for InSAR. Building displacement as monitored by InSAR is relative to the reference point. According to the data, a building may move, although this may not be the case in reality if the reference point utilized is unstable.

2.1.2 PS-InSAR

Conventional InSAR makes use of only two images to measure deformations in a region. To create a coherent dataset, a large number of images is needed. An important factor is the amount of coherent scatter points, also known as persistent scatter points (PS-points). These are large objects, like rocks and buildings, as described under the above heading 'The surface (S).' These buildings have a high SNR. The phase of the point does not change much between SAR images. The large number of images and the PS-points are the fundaments of the Persistent Scatter technique. Persistent scatter points are pixels that are little affected by temporal changes. With these points, errors such as atmospheric delay, topography, and deformation can be filtered. The accuracy of the persistent scatter deformation measurements is in some cases better than 0.1 mm/year. The high rate of new satellite images leads to the timely identification of changing deformation patterns. This is important, for example, in the monitoring of the stability of individual buildings (Hanssen, 2002).

A disadvantage of this method is that the PS-points are found by chance and cannot be optimized, although the point density is far greater than a typical global positioning system (GPS) survey. According to Hanssen (2002), other limitations are:

- The uncertainty of the satellites series continuation in the future, in connection with the lifespan of the satellite.
- There is less valuable information in non-urban areas. The number of PS-points is lower in these areas.
- The method is dependent on a minimum number of images to acquire valuable information.
- Phase ambiguities, which will be discussed in the next section.

- Temporal and geometric decorrelation, resulting in a loss of coherence. Temporal decorrelation is caused by physical terrain changes. Geometric decorrelation is caused by the effective distance between sensors.
- Various computational aspects, which will not be further discussed in this paper.

Hanssen (2002) also describes the advantages of using this technique:

- The high PS-point density in urban areas.
- The high accuracy of deformation measurements.
- The wide spatial coverage of SAR images.
- The large archive of data (dating back to 1991) and the high repetition rate of particular measurements.
- No survey equipment is required on the ground. SAR observations can be developed in places that cannot be accessed due to disaster or rugged topography.
- Observations are possible in all weather conditions.
- The relatively low cost per radar image.

InSAR technology is still evolving. One of the newest patented techniques of processing SAR information is SqueeSAR (Giannico et al. 2013). This technique not only makes use of PS-points, but also DS-points. Distributed Scatterers (DS-points) collect signals received from several homogeneous, weaker reflectors over an area covering a number of pixels. These signals correspond to rocky outcrops, debris, non-urban areas, and non-vegetated areas. The same analogy holds for SqueeSAR, as for PS-InSAR; the higher the number of images, the better the result.

2.2 Interpretation of InSAR results

There are still some interpretation errors in the data produced after estimation using the iterative least-square method. According to Sithole (et al. 2004), two types of errors can be found: type 1 and type 2. Type 1 errors are points that have been neglected as PS-points, when they should have been detected. This can be caused by nonlinearity in the deformation or by a high deformation rate. Type 2 errors are PS-points that should not have been detected as PS-points. By chance, there was a large coherence in these points caused by undetected errors. Possible errors are, for example, caused by a reference point that moves over time or by side lobes. The reference point is the point within the study area to which all deformation measurements are relative. It is assumed that the reference point is steady; otherwise the data is incorrect. Side lobes are pixels near a PS-point that reflect near this point without actually being the PS-point.

Data on a building is location-dependent. Signals on a roof often reflect as stable points. On the side of a building, double bounce points can be formed (Ketelaar, 2004). These signals bounce from the curb to the side of the building and back to the satellite. These points reflect incorrect values in reference to other nearby points (see Figure 2.3). The shadow area of a building is the area that the satellite may reflect as the same height of the building that created the shadow;

this is because of the angle of the satellite. The actual values of this data cannot be measured. The points in the shadow area and the double bounce points can often be recognized by lower amplitude.

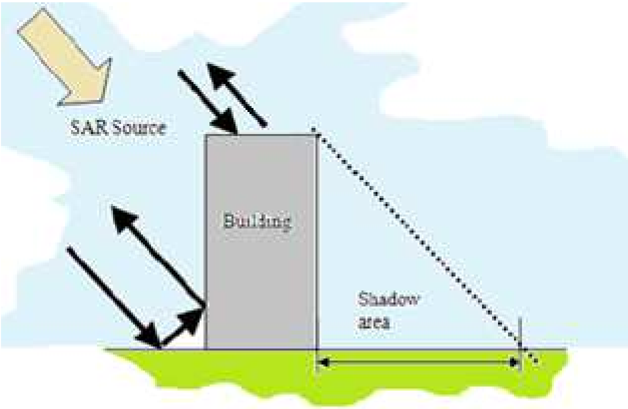


Figure 2.3, Interpretation of a building with a satellite. To the left, arrows reflect double bounce points; in the middle, arrows reflect the building correctly; and to the right, the shadow area caused by the satellite's viewing area can be seen.

Foreshortening and layover can occur when a slope is measured. When a slope is facing the radar, the top of the slope is closer to the radar then if it were lying flat. This reduces the signal's two-way travel time. Therefore, the slope is artificially compressed in the ground-range direction. This is called foreshortening. Layover occurs if the slope angle is so steep that the top of the slope arrives before the bottom signal (see Figure 2.4) (Olmsted, 1993).

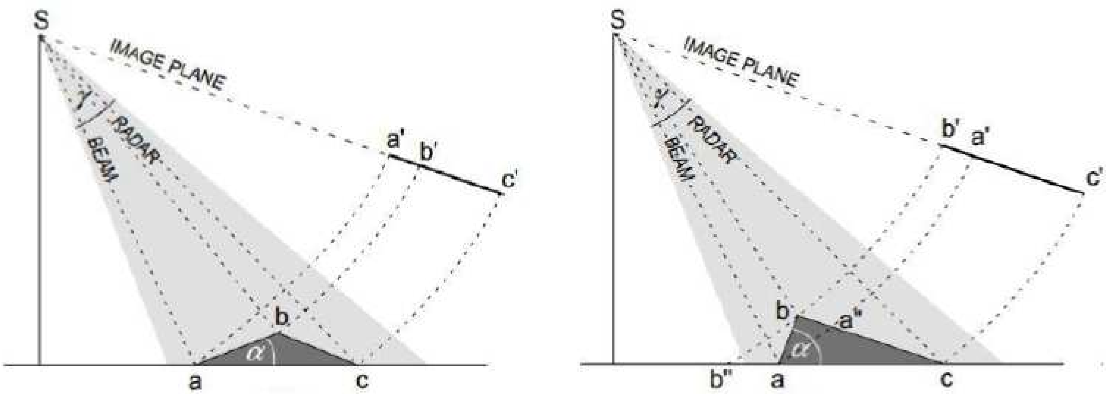


Figure 2.4, Foreshortening can be seen in the left figure. The slope of hill a-b is represented as shorter than it is in reality. Layover can be seen in the right figure. Due to the steep slope and the height of hill a-b, the hill is presented incorrectly in the data. (Olmsted, 1993)

Phase ambiguity causes difficulty when large displacements are viewed. The phase of the satellite is wrapped. If the satellite is x-band, then a phase (2п) is 15 mm wide (λ/2): this means +7,5 mm and –7,5 mm. If a displacement is larger than 7,5 mm in the line-of-sight (LOS) direction with respect to the reference point, then a phase should be added to the measured phase difference. This ambiguity is solved using phase unwrapping methods that calculate the correct number of phase cycles. These cycles need to be added to each wrapped phase measurement. However, the phase unwrapping may fail in areas with a deformation rate where more than one phase cycle of displacement has occurred between two acquisitions. In such an area, the estimated deformation rate is less accurate. With phase unwrapping, the distance from the satellite to the Earth can be estimated. To accomplish this, there are many different algorithms and methods, since this is not a straightforward procedure. This will not be discussed further, as it is outside the scope of this thesis.

In addition to all these interpretation errors, the coherence of the InSAR data must also be considered. The coherence can be divided into two elements: geometric distribution and temporal distribution.

Geometric distribution refers to the certainty of the location of the PS-point on the ground. According to Colesanti (et al. 2003), most radar satellites have an uncertainty for target positioning of around one metre. The accuracy both depends on factors applying to all PS-points and effects that influence PS-points individually, according to Van Leijen (2014). Geolocation errors for all points are caused by errors that affect the whole dataset. These are caused by errors of the reference PS-point in height and sub-pixel position and other errors that influence the whole dataset like timing errors, uncompensated atmospheric signal delay and orbit errors. InSAR data is often aided by DEM information to increase the accuracy of PS-InSAR and to minimize the error in the geometric distribution. The geolocation error for all PS-points can be corrected for the most part while individual inaccuracies per PS-point remain. These inaccuracies are caused by uncertainty in a PS-point sub-pixel position and the error in the estimated topographic height of a PS-point. The height accuracy influences the geolocation with a factor dependent on the local incidence angle, as can be seen in figure 2.5.

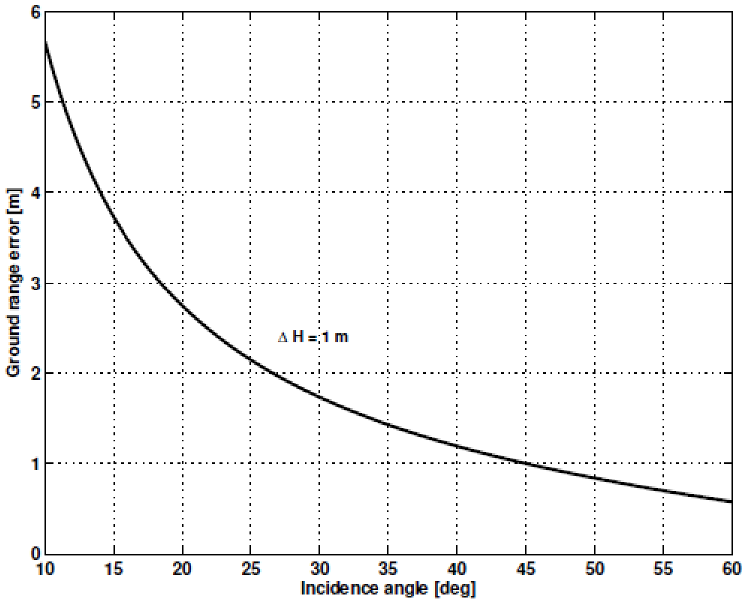


Figure 2.5, Geolocation error in ground range (m) due to height error of one metre. The error is dependent on the incidence angle. Source: Van Leijen (2014).

The temporal distribution is determined in time. The coherence of the temporal distribution depends on how much the phase of a PS-point change over time with respect to the real deformation of a measured object. The coherence of this parameter is often calculated with respect to a presumed model. According to Ferretti (et al. 2001), sub-millimetre coherence is possible. The precision is dataset-specific and depends on the number of acquisitions, the PSs' density, and the temporal baseline's dispersion. Hanssen (2003) found a standard deviation better than 0.4 mm/year for the velocity of the ERS-1/2 satellite. See Figure 2.6.

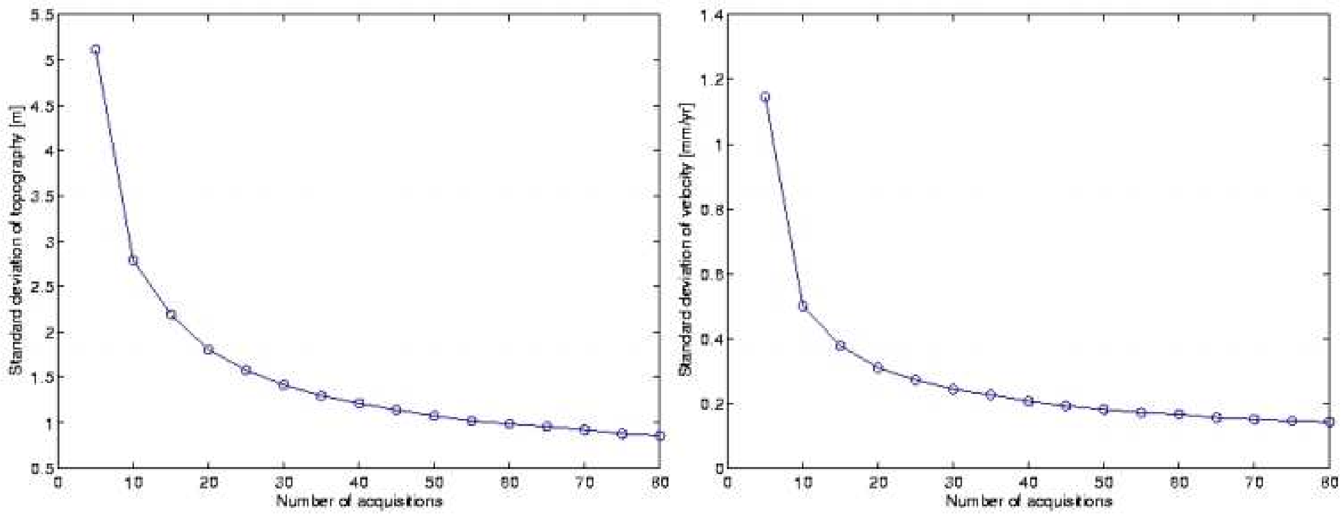


Figure 2.6, Standard deviation of estimated deformation and topography as a function of the available images for ERS-1/. Source: Hanssen (2003)

2.2.1 VIEW DIRECTION OF THE SATELLITE

The viewing direction of the satellite plays an important role in the interpretation of the data. The view direction of the satellite is in the LOS direction. This results in a deformation in the LOS direction. The direction can be Up, East, or North. To derive these directions, the heading of the satellite and the incidence angle must be known.

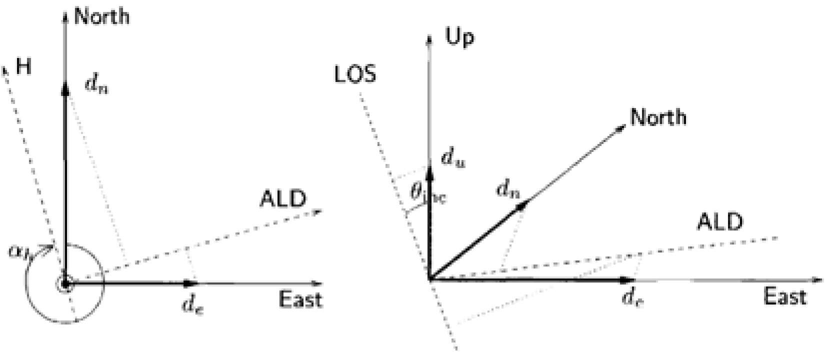


Figure 2.7, Projection of the three components of the deformation vector (Up, East, and North) onto the satellite line-of-sight (LOS). The left figure shows the top view, showing the North and East components on the azimuth look direction (ALD), which is perpendicular to the satellite's heading (H). The heading angle is indicated by α_h. The right figure includes the projection of the Up component to the LOS via incidence angle θ_{inc}. Source: Hanssen (2001)

The observed deformation in the LOS direction can be derived with the following formula (Hanssen, 2001):

$$\Delta R = \Delta R_U * \cos(\theta_{inc}) - \sin(\theta_{inc}) * \left[\Delta R_N * \cos\left(\alpha_h - \frac{3\pi}{2}\right) + \Delta R_E * \sin(\alpha_h - \frac{3\pi}{2})\right] \qquad (2.3)$$

With:

ΔR_U	Deformation in Up direction
ΔR_N	Deformation in North direction
ΔR_E	Deformation in East direction
α_h	Heading of the satellite

In this formula, there are three unknown directions. All of the directions can be derived theoretically, if there is data from three different satellite tracks (with another heading or inclination angle) for the same PS-point. In general, this is not the case. Often there is only data from one satellite direction. For an incidence angle of 23° and a heading of 190°, a sensitivity in the LOS direction of 0,92 in the Up direction, -0,07 in the North direction, and 0,38 in the East direction is found. This is illustrated in Figure 2.8. For the Up and East direction, the standard deviation is assumed to be 3 mm (Van Leijen, 2014).

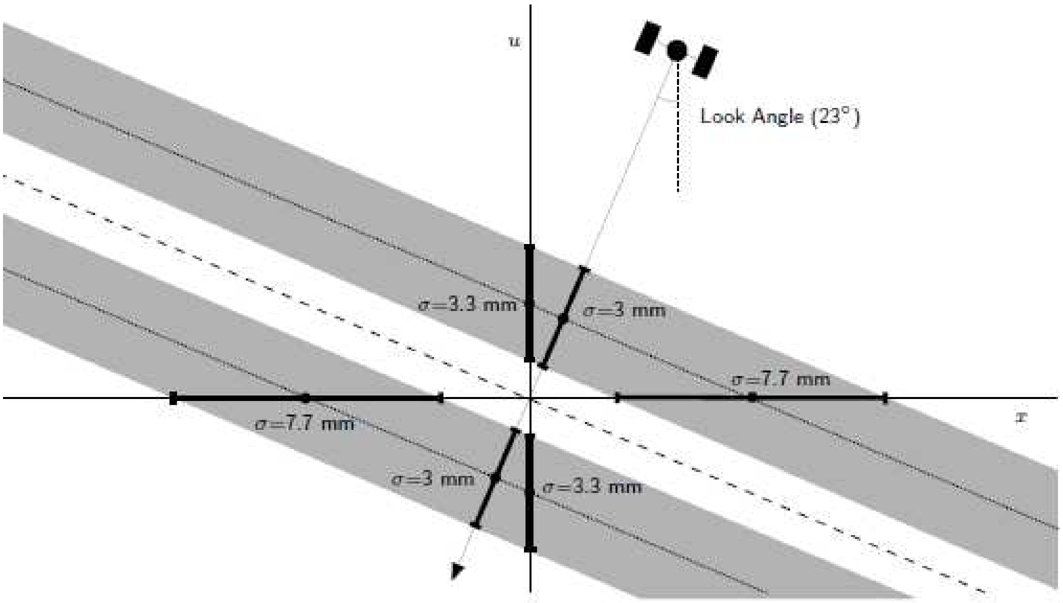


Figure 2.8, Sensitivity of a satellite (Envisat) in the Up and East direction. (Van Leijen, 2014)

Therefore, displacement in the Up direction can be assumed to equal:

$$\Delta R = \Delta R_U * \cos(\theta_{inc}) \quad (2.4)$$

If there are two satellite directions that measure the same PS-point, often the ascending and descending track of a satellite, and it is assumed that one direction remains constant over time, then the displacement of the other two directions can be derived. The two directions of the displacement often do not correspond to the global axis, and that is why the directions need to be transformed to a local coordinate system. This can be done by measuring the angle (γ) of an object in reference to the global coordinate system. See Figure 2.9. The Up direction is the same as the z-direction of the local coordinate system.

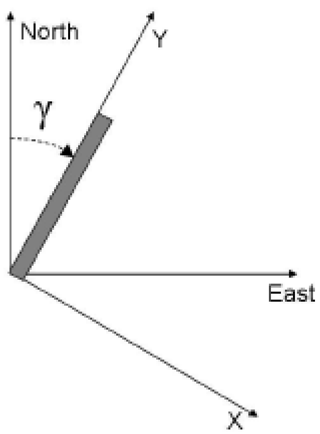


Figure 2.9, Transformation of the coordinate system from global to local.

If it is assumed that the deformation of a building in the y-direction is zero, due to for example rotation of the foundation, then the deformation in a local coordinate system becomes:

$$\Delta R = \Delta R_z * \cos(\theta_{inc}) - \Delta R_x * \sin(\theta_{inc}) * \cos(\alpha_h - \gamma) \qquad (2.5)$$

As previously mentioned, different viewing directions produce different deformations in their LOS directions. One direction can often not be assumed to be zero, only for some foundation problems.

Current satellites operate in a nearly polar orbit. The rotation of the Earth allows satellites to image the planet without wasting additional resources on steering. A satellite travels in two directions: From the South Pole to the North Pole (ascending orbit), and from the North Pole to the South Pole (descending orbit). In both cases, the heading is primarily in the north or south, with the LOS oriented in a plane perpendicular to the along-track direction. Since the projection of the north dimension onto the LOS is very small (close to zero) (Figure 2.10b), the primary components of the ascending and descending vectors are east and up. As a result, polar orbit geometry is not sensitive to deformation in the North direction, which defines a missing component that cannot be observed with traditional InSAR (Figure 2.11) (Wortham, 2014). This is a large disadvantage for monitoring buildings with InSAR, because an element of a building can be moving to the east or the west, as well as to the north or the south.

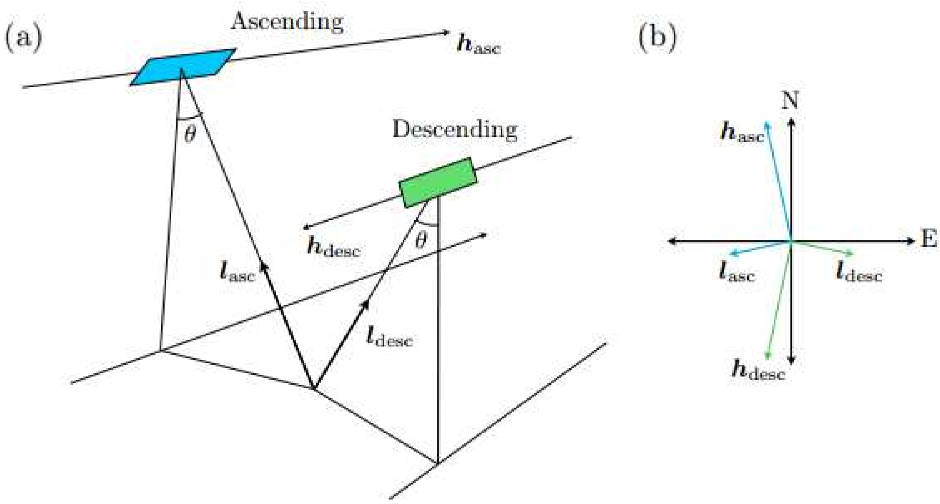


Figure 2.10, (a) Geometry for ascending and descending satellite directions. (b) Projection of heading and LOS vectors onto the ground, with "l" as LOS and "h" as heading. (Wortham, 2014)

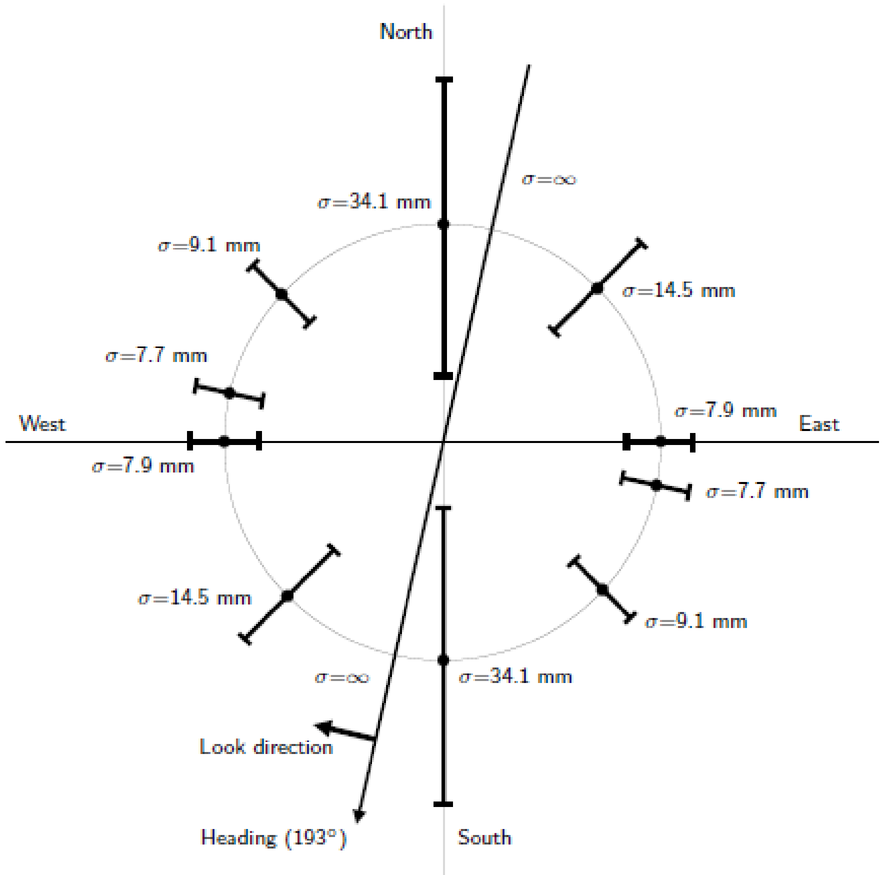


Figure 2.11, Insensitivity for displacement in the North direction. A standard deviation of 34.1 mm can be expected, when a standard deviation of 3 mm in the LOS direction is assumed for the Envisat satellite. (Leijen, 2014)

The satellite directions of the TerraSAR-x can be seen in Figure 2.12. In this figure, it can be noted that the ascending direction is primarily toward the north(west), and the descending track is primarily toward the south(west).

Figure 2.12, Heading directions of the satellite. The blue arrow represents the ascending satellite track, and the red arrow represents the descending satellite track.

A PS-point that moves further from the satellite can mean that the point moves in a different direction in its ascending or descending track. A point moves up or down if the distance from Earth to the satellite is decreasing or increasing, respectively. The difference is in the horizontal motions. In figure 2.13, the thick dark blue line is the displacement, and the light blue lines illustrate how this is interpreted for different satellite tracks. With horizontal movement, the LOS increases for one satellite track but decreases for the other satellite. It can quickly be seen if an object undergoes horizontal motion (in cases of east-west direction). This is when the data of the satellite tracks is in opposite direction.

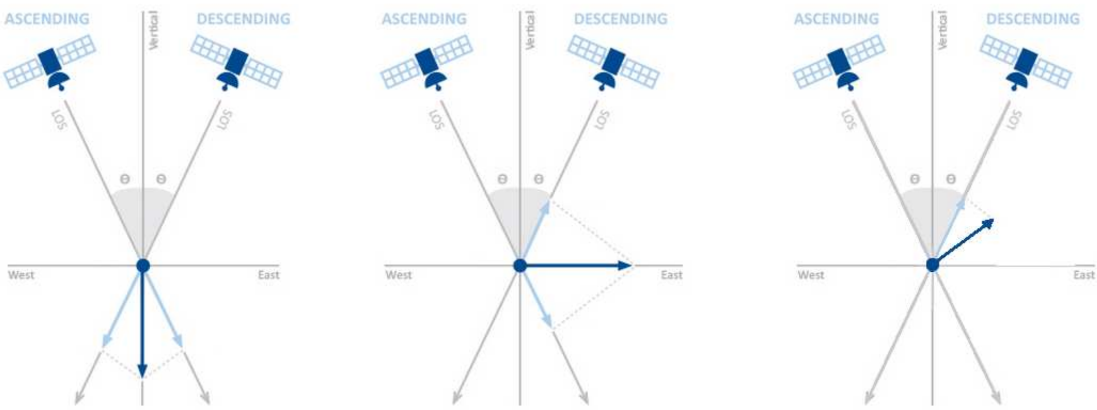


Figure 2.13, The difference between ascending and descending data for the Up and East direction. The dark blue arrows are the direction of movement of a PS-point, while the light blue lines are the information recorded by the satellite for different tracks. (TRE website)

2.3 Data used for this research

The satellite data available for this research was provided by Hansje Brinker. Hansje Brinker is a company that provides a continuous and global view on deformation processes, based on radar images taken by satellite. The data is derived from different satellites. One of the current, active satellites retrieving data is the TerraSAR-x. It collects data every 11 days. An overview of different satellites used for InSAR throughout the years is listed in Table 1.1 in the introduction. The table shows that, of the still-active satellites, the TerraSAR-x collects more data per time period than the other satellites. Its range is also smaller. Furthermore, the satellite uses X-Band (31 mm) and orbits 514 km around planet Earth. The heading direction is 347° in its ascending track and 193° in its descending track (North as zero degrees, clockwise). The incidence angle is about 24° for ascending data and 39° for descending data.

The data is divided into PS-points. Each point has its own longitude and latitude. The points can be found on a map with these coordinates. These points are persistent scatter points. The first measurement of the height difference in time is zero; this is the reference distance between a point and the reference point in time. Hansje Brinker placed all of a point's deformation in reference to the first measurement and to another point in a graph (double-difference). Point quality is measured by the deviation of the point cloud as compared to a linear plotted line or another predefined model. The point quality is better the closer it is to the number one. This regression is an ambiguous parameter. A regression close to one means a steady point, but if the point moves (caused by damage) the regression will decrease. These points may be marked as not valuable information, although these points may describe the damage. The point linear deformation is an estimated total deformation over the time. With this data, the following variables can be assessed: displacement, velocity of the displacement, and acceleration. These variables will be briefly discussed.

Displacement
Displacement is the deformation of a point in time in reference to the first measurement of this point with reference to another point. If there are two or more PS-points on a building, then these points can be compared to each other, and one of these points can be chosen as a reference point. When the difference in displacement is large while the distance between the points is small, then it might indicate that there is something wrong with the structure. The data is not dissolved in different directions. This means that the direction of displacement is unknown, without further dissolving different datasets recorded by different viewing angles of the same point.

Velocity of the displacement
Velocity can be derived if the deformation and the time between the deformations are known. An increase in the velocity of the deformation of a building could be an indication that the construction of a building might be failing. The velocity of the displacement is a quantity that can be used to indicate the state of the foundation.

2.4 Conclusion

The Earth's surface can be monitored with satellites' phase differences. The phase difference can be the result of deformation and is recorded periodically over time. Large objects, such as buildings, often have a stable reflection, and are therefore often persistent scatterers. This makes buildings potential objects for deformation monitoring with InSAR.

InSAR can monitor with millimetre accuracy and is most accurate in a vertical direction. This makes it primarily a useful tool for researching vertical deformations. A clear indication of horizontal deformation can be found if, for one satellite track the data is positive and for the other negative, when different tracks of a satellite are compared with one PS-point. Deformations larger than a phase within consecutive measurement are more difficult to interpret with satellite data.

3 FORENSIC ENGINEERING WITH INSAR

"Engineering investigation and determination of the causes of structural failures of buildings, bridges and other constructed facilities, as well as rendering opinions and giving testimony in judicial proceedings, has become a field of professional practice of its own, often referred to as forensic structural engineering." (Ratay, 2000)

Forensic engineers investigate collapsed or partly collapsed buildings. A common purpose of investigations is to determine who was at fault for the collapse by researching how the structure failed. The research conducted by forensic engineers can be a resource for learning more about how structures fail. Research findings can also improve the future performance of structures. The main goal of forensic engineering is to find the cause of failure. InSAR data's ability to look back in time after an unforeseen failure has occurred is a unique tool that might be a very useful resource for forensic engineers. With this feature, the development of a failure can be seen, in cases when the failure resulted in displacement in the outer shell. A forensic engineer develops different propositions concerning the possible cause of failure. To prove such hypotheses, evidence is needed, and this evidence can be provided with InSAR.

The following basic principles should be used as guidelines when conducting research with InSAR:

- Opportunistic character: The location and the number of PS-points on a building are predetermined.
- Large deformations: Large deformations can be researched with InSAR, but because of phase ambiguity, the data's reliability decreases. This may result in a unstable point.
- Sudden deformations: The damage's development cannot be researched if the damage develops within a measurement cycle.

Section 3.1 provides a short introduction about structural failure. Failure mechanisms involving deformation – and therefore potentially detectable with InSAR – will be discussed in Section 3.1.2. Section 3.1 and 3.2 provide information for answering sub-question 2. Finally, this chapter concludes with a short study investigating InSAR's potential for forensic engineering. This study utilizes a database of building failures in the Netherlands. Could InSAR have provided insight in these cases, either by identifying the cause of the failure or by proving the occurrence of the failure? This answers sub-question 3.

3.1 Failure

This section first provides a description of the cause of a failure, so as to help indicate how InSAR can potentially contribute to failure analysis. Failure analysis is the process of collecting and analysing data to determine the cause of a failure. Failure depends on the amount of load on a structure versus the structure's ability to resist this load without losing structural integrity. An increase in load or a loss in resistance can have different causes. According to Eurocode 0 (2011), there are three different types of loads: dead, live, and accidental loads. Dead loads do not vary much during the reference period. The weight of the elements, groundwater pressure, the pretension of the elements, and imposed deformations are examples of dead loads. Live loads differ in size during the reference period. People, furniture, machines, vehicles, wind, rainwater, snow, and temperature differences are examples of live loads. Accidental loads are characterized by their large magnitudes and catastrophic consequences, but have only a small chance of occurring. Examples of these loads are fires, explosions, collisions, and earthquakes.

Classifications of why buildings fail can be found in the literature. In this research, the cause of failure is classified in the following schema:

- Failure cause
- Failure mechanism
- Failure

The failure cause is the event that leads to a loss in stability, stiffness, or strength (failure mechanism) that eventually causes the building to fail (Figure 3.1). While studying a failure, forensic engineers try to determine the responsible failure mechanism and the cause of the failure. It might be said, in fact, that forensic engineers study the schema in presented in Figure 3.1 backwards. First, forensic engineers study the failure, then they try to determine how it occurred, and finally, they research its cause.

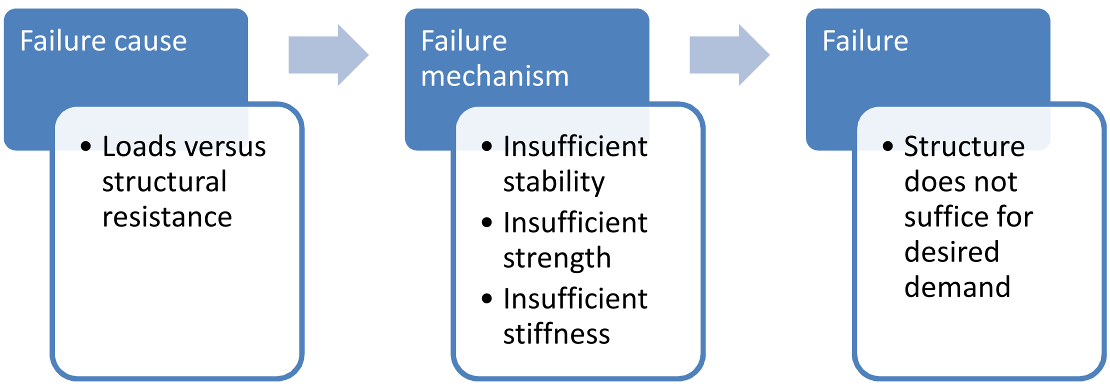


Figure 3.1, The cause of failure.

3.1.1 THE CAUSE OF FAILURE

A failure is caused by the loads that work on a structure and the ability of that structure to resist those loads. In the building decree, this is expressed as follows:

$$S_d \leq R_d \tag{3.1}$$

S_d is the load, force, or stress acting on the structure (S stands for sollicitance: dead, live and accidental load). R_d is the resistance (R stands for resistance: strength, stiffness, and stability) of the structure. In other words, R_d is the limit load (the d stands for design). Remaining within this limit is the objective of structural safety. The influence of structural safety is discussed in Appendix 1 and stands at the basis of the capacity of a structure before failure mechanism occurs.

The cause of failure always originates in a structure being overloaded or lacking the required resistance for the load. The causes of failure, as described by Van Herwijnen (2009), are in line with this statement. According to Van Herwijnen, there are four main causes of failure:

1. *Aging:*
   With aging, biological and chemical processes degrade the structure's materials. This can include, for example, the corrosion of steel. Structural elements can also fail over time due to impact loads or fatigue loads. Maintenance of structural elements can prevent these types of failure.
2. *Nature:*
   Earthquakes, floods, hurricanes, and other types of extreme weather that can influence the integrity of a building are natural causes of structural failure.
3. *Human intervention:*
   Human interventions can be either intended or unintended causes of failure. Intended causes can include terrorist attacks, such as collisions of airplanes or explosives. Unintended causes of failure can include fires caused by short circuits or vehicle collisions due to drivers losing control of the wheel. Fires and car collisions can, of course, also be intentional.
4. *Structural errors:*
   Structural errors can be divided in the following subcategories:
   a. Design errors:
      This encompasses a wide spectrum of causes, from choosing the wrong material to calculation errors. Using new materials can also lead to design errors. Mistakes in the detailing can also lead to poor design.
   b. Construction errors:
      Many human errors can occur during construction, such as improperly installed rebars or connections that are flawed.
   c. Unforeseen loads:
      Unforeseen loads can include extreme snowfall and rainfall. Changing the function of a building can also introduce design errors, in cases in which the structure is loaded with forces for which it was not designed.
   d. Unexpected failure modes:

These include buckling and torsional buckling. (Unexpected failure modes can also be seen as errors in design, because the designer should have taken these failure modes into account.)

According to Platform Constructieve Veiligheid (2010), the causes of collapse can be:

- Design errors
- Production errors
- The improper use of a building
- The usage of new materials
- Force majeure

The causes of failure as identified by Van Herwijnen cover most of Platform Constructieve Veiligheid's causes of failure. Force majeure can be seen as human intervention (as defined by Van Herwijnen) and failure caused by nature. The improper use of buildings is covered by unforeseen loads. Production errors are partly covered by Van Herwijnen, as production errors during construction are taken into account. However, supplier-caused production errors of the elements are not taken into account. Terwel (2012) researched the causes of structural errors in the Netherlands. Terwel identified 401 cases, which comprise the database for this research. According to Terwel's findings, 30% of structural errors are caused by construction errors. These result in the collapse of the (main) supporting structure in 48% of cases. Most of the errors are discovered during the use period of the building lifecycle (66%). See Figure 3.2.

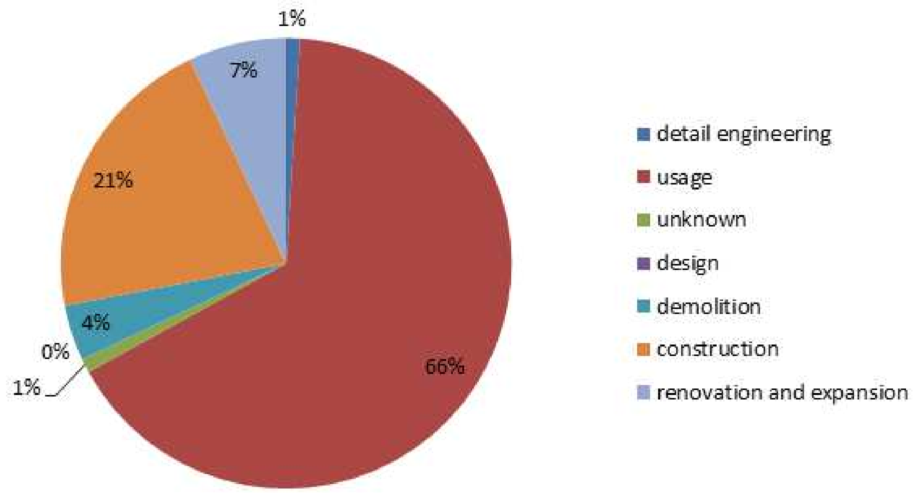


Figure 3.2, Phase in which failure is discovered. Source: Terwel (2012), Constructieve incidenten in Cobouw 1993-2009

3.1.2 FAILURE MECHANISMS

A failure mechanism is how a material, a part of a structure, or an entire structure fails. The emergence of a failure mechanism is always due to a lack of strength, stiffness or stability in relation to the loads working on the structure. In this thesis, only failure mechanisms that cause movement are explored. This is because InSAR measures deformation. A search of the literature related to failure mechanisms led to further investigation of the basic design principles for structures regarding strength, stiffness, and stability. However, this search did not provide insight into how structures move during failure. The basic principles of failure mechanisms can be found in Appendix 2. Table 3.1 gives an overview of failure mechanisms that cause movements.

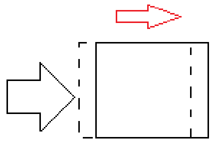
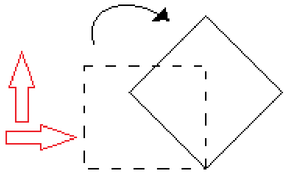
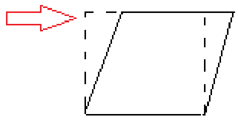
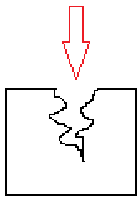
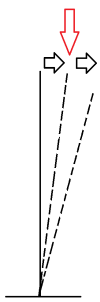
Movement of an element:		Caused by a lack of:	Resulting in a lack of:
Translation (in all directions)		Connection strength of the element, Stability of the element	Stability of the element
Rotation and torsion		Connection strength or stability of the element	Stability of the element
Deformation		Stiffness or strength	Stability
Fracture		Strength	Strength, stability, and stiffness
Forms of buckling		Stiffness	Stability and strength
Second order effect		Stiffness	Stability and strength

Table 3.1, Examples of failure mechanisms that cause movements. The red arrow represents force, and the dotted objects represent the structure before movement occurred. Combinations of these movements can also occur.

Translation

Translation is the movement of an element caused by a force. This movement is caused by a lack of strength or a lack of stability and can result in a lack of stability by the movement of the element. The connections to other elements provide insufficient resistance, causing the element to move in the direction in which the force is working and in which the resistance is too low. Loss in stability can also result in translation. Sinkholes or settlements are also examples of translation. In cases of sinkholes, the foundation’s connection to the soil is lost, and this causes the translation of the unsupported element. The magnitude and direction of this movement is very case dependent.

Rotation and torsion

The rotation of an element can be external or internal. If the rotation is external, than the element rotates along a rotation point and can be seen as a form of translation with the difference being that the element moves in two directions. External rotation can also be caused by instability; this may be the case if boundary conditions of the element change or the place of loading changes. Rotation of an element can only be seen if the rotation results in the movement of the element. When the element rotates around its central axis, hardly any displacement can be noticed. If rotation causes instability or the collapse of the element, then it results in larger displacements.

Internal rotation of an element can be seen as torsion. Torsion is the twisting of an element over the longitudinal axis. Torsion is caused by instability of the element. Internal rotation causes small movements and cannot be noticed with satellite data.

Deformation

Deformation means the transmutation of an object. Deformation is caused by a force and the lack of resistance against that force. Deformation can be divided into elastic and inelastic deformation. Elastic deformation is caused by an external load or temperature change, and inelastic deformation is caused by creep and shrinkage. Elastic deformation can be in either a horizontal or vertical direction. Deformation in a horizontal direction is caused by horizontal forces, such as wind. Vertical deformation is caused by vertical loads. The weight of an object on a floor is an example of a vertical load. These forces cause a stress in the element, and these stresses then cause a strain in an element. Strain is related to deformation. The length, cross-section, material, stiffness, and extent of the force determine the magnitude of the deformation. Movement caused by deformation is the only movement that is described in building codes. It is the only movement where clear limits have been formulated.

Fracture
Fracture is a first signal of deformation of brittle materials. It occurs when the tensile stress in the material is too high compared to the strength of the material. Fractures occur in brittle materials, such as concrete. Reasons why cracks may occur include corrosion of the reinforcement, which then expands, or small, imposed displacements. For reinforced concrete, the maximum crack width is 0.4 mm, according to the design rules of NEN-EN 1992-1-1 table 7.1N (2011). This width is very small and cannot be detected by satellite.

Buckling
Buckling is caused by an unstable equilibrium of a centric pressure-loaded bar. The vertically loaded element deforms the horizontal element due to buckling. Buckling can occur in the two main directions of a slender bar or beam. The load at which buckling occurs is called the buckling load. The buckling load is an upper limit for the capacity of a centric pressure-loaded bar and is derived from Euler's formula for buckling. Different buckling shapes are possible. The shapes depend on the boundary conditions of the element. Some buckling forms will be hard to detect with InSAR. This is because the top of some buckling forms barely move (see the related figure in Table 3.1). The magnitude of movements also grows quickly – from almost no movement to large movements – when buckling occurs. This makes InSAR unsuitable for detecting forms of failure related to buckling.

Second order effects.
The vertical loads on a column can become more eccentric, causing extra deflection, if a building deflects because of horizontal loading. Second order effects only play a role in tall buildings, because usually the effect is small, and therefore can be ignored. Second order effects are also an amplification of a movement caused by another force. This is why these movements cannot be researched independently.

Conclusion
Movements caused by torsion (internal rotation), inelastic deformation, fracture, and second order effects are too small to be recognized by satellite. The sudden character of deformation caused by buckling also makes it impossible to research. Movement due to translation and external rotation got the potential to be detected by satellite, if the movement is large enough.

InSAR's ability to visualize a failure mechanism not only depends on the development of the failure but also on the location of the failure. This is because the satellite monitors from the sky. The visibility of the failure location will be discussed next.

3.2 THE VISIBILITY OF MOVEMENTS AND THE POSSIBLE MOVEMENTS OF BUILDING ELEMENTS

The structure of a building can be divided into different parts. Each part has its own function. The main supporting structure can be divided into columns, beams, and the foundation. The outer shell of the building is comprised of the façade and the roof. Not all parts of a building can be researched with InSAR. The different parts of a building will be described next, as well as how they affect satellite measurements. See Figure 3.3 for an overview. The possible movements that elements may undergo have also been added to the different elements of a building.

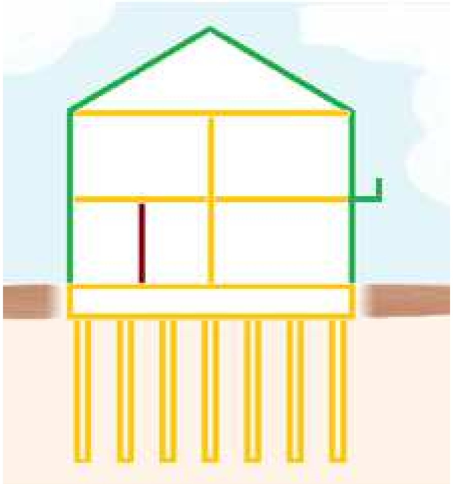


Figure 3.3, Schematization of a building. Green represents the outer shell, yellow the inner supporting structure, and red the non-load-bearing part of the building.

1. *Outer shell of the building (green in Figure 3.3)*

Deformation of the outer shell of a building (as marked in green in Figure 3.3) should be visible with the satellite. The green parts represent the roof and the façade. The façade may also contain balconies. The displacement of the green parts can be caused by displacement of the outer shell itself or can be influenced by the displacement of the yellow parts that can also be seen in Figure 3.3. Displacement can have different causes. The outer shell is often part of the main supporting structure, and it forms a barrier against exterior loads. These exterior loads are, for example, wind, temperature, rain, snow, and impact loads. The outer shell is also important in ensuring a hospitable indoor climate, as it provides a temperature, water, and light barrier.

1.1 Roof

A building's roof can be sloped or flat. In the Netherlands, sloped roofs are often made of roof tiles. This kind of roof system plays an important role in building integrity. A type of failure that often occurs and that can be translated in movement is the detachment of roof tiles during heavy wind loads. If the roof tiles cause a PS-point, and these roof tiles detach, then there is no constant measurement. This may result in a loss of PS-point.

Failure that express in displacement for flat roofs is often caused by sag, snow load, or water accumulation. Precipitation changes a roof's reflection (Gazkohani, 2008). This makes it harder to extract the deformation from the roof. Sloped roofs can also bend too much because of the above-mentioned loads. If a flat roof is part of a parking lot, it can displace too much through extra loads and changing loads. A roof can also bulge if wind loads get under the roof structure. This is caused by overpressure. The visibility of sloped roofs for InSAR depends on the viewing direction. The visibility is further explained under section 1.2 Façade.

1.2 Façade

A façade can be load-bearing or non-load-bearing. Brick and prefab concrete wall elements are often load-bearing, and this is often the case in housing. Other buildings, such as offices, often work with columns made of steel or concrete attached to façade elements. For load-bearing façades, impact, wind, and temperature loads can deform the façade. Much of the failure that occurs to non-load-bearing façade types is due to cladding that detaches from the façade. This can be caused by wind loads and/or by mounting errors. This type of failure is notable the same reason as failure that occurs with roof tiles. Small movements caused by temperature loads can also detach a building's glass; this will be hard to see with a satellite, because of the small displacement. The load-bearing parts of the façade also must be strong and stiff to withstand vertical loads. The load-bearing capacity can be compromised if the material is affected by, for example, corrosion. The steel will turn brittle and will expand; this can cause internal tension in armed concrete and can make the concrete crumble. This will initially lead to small displacements, probably not noticeable by satellite.

The viewing direction and the location of a building are important. This can be seen in the following figure (Figure 3.4). The satellite looks toward Earth in a specific direction, as mentioned in Section 2.4. The viewing direction is influenced by the direction of the satellite as can be seen in the figure. Not all façades can be monitored if the façades match the wind directions, as can be seen in Figure 3.4. This is often not the case.

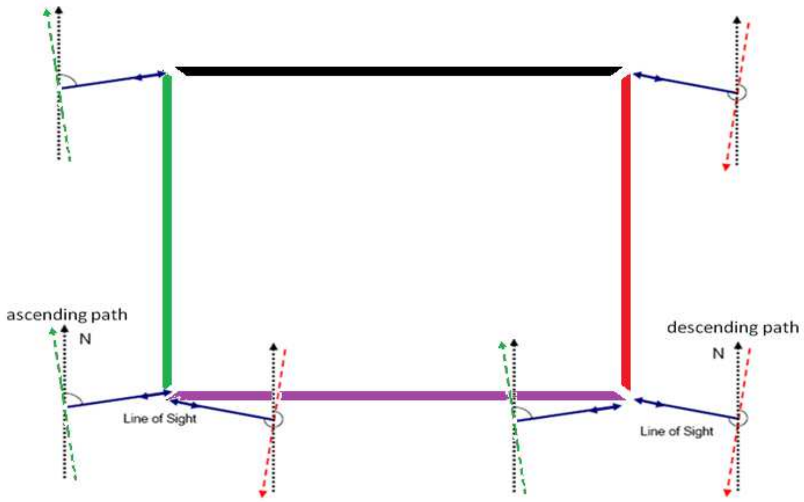


Figure 3.4, A building with façades that match the wind directions. In this case, both the ascending and descending orbit cannot monitor the north façade if the TerraSAR-x satellite is utilized. Green represents the façade that is monitored by the ascending track, red represents the section that is monitored by the descending track, and purple represents the façade that is monitored in both directions.

1.3 Balconies

Balconies are also part of the outer shell of a building. Balconies are susceptible to unforeseen loading, because of their often-cantilevered character. A vertical load or a temperature load often causes movement in balconies. The visibility of balconies for InSAR depends on the viewing direction.

2. *Main supporting structure, excluding the outer shell (yellow in Figure 3.3)*

The displacement of the yellow parts can only provide data for the satellite if it affects the shell of the building. A sagging first floor, for example, may lead to displacement of the middle of the floor but does not necessarily effects the main supporting structure of the building and therefore its outer shell. For the yellow parts, deformation measurements depend on the type of structural system. The connections of the elements play a lead role. Whether the inner building connections are hinged or fixed will result in different movements on top of the building. Hinged connections will lead to equal movements, while fixed connections redistribute the forces over the structure. This can result in damped movements on the roof. Displacements of the main supporting structure can occur due to impact loads or heavy objects in the building. Also, if a column or beam is removed, a new force distribution can cause displacements. Many failures caused by the supporting structure involve changes in the foundation of a building. Changes in the foundation can lead to the subsidence of the entire building. The main supporting structure can be divided into three parts: columns, beams, and the foundation.

2.1 Columns

Columns are vertical elements of the main supporting structure. Columns transfer the loads acting on a building to its foundation. Columns can be deformed vertical by axial loads and temperature loads. Temperature, buckling, and second order effects cause horizontal deflection in columns. Whether these movements can be seen by satellite depends on the location and the structural system of which the column is part. The connections between the column and the rest of the structural system can be hinged or fixed. If the system is hinged, then the same movement can be seen on the roof. If the system is fixed, then the movement on the roof, where the satellite can measure displacement, will be damped.

2.2 Beams

Beams carry the floor and the floor load. Examples of steel beams are hollow sections, IPE, INP, H, I, and U profiles. For concrete, rectangle, I, and T beams are examples. These beams carry the floor system. To decrease the floor height, THQ-girders can be used. Typical floor systems include hollow core slabs, rib, combination, concrete slab, and composite floors. Beams and floor systems may sag due to the loads they carry. Sag can be caused by temperature differences and dead weight on the beams. Beams or floors that sag between columns inside the building at the floor level cannot be seen with InSAR. Only beams that cause the sagging of elements connected to the outer shell can be seen in satellite data as movement.

Thin-walled beams are also susceptible to torsion, rotation, or buckling around the vertical axis of the element. These displacements will be too small to detect in satellite data.

2.3 Foundation

The foundation of the building is the element that connects a building to the ground. The foundation leads the forces into the ground. It ensures that a building does not subside or tilt because of unequal subsidence. In this part of the building, the largest deformations are allowed, and this makes foundation problems that express themselves in movement suitable for satellite research. Two kinds of foundations can be distinguished: raft and pile foundations. Raft foundations adopt carrying capacity by spreading the load over a wide surface area. The settlement of the soil must not be too large or too unequal, in order to prevent tilting. Changes in the soil's water level can also cause building movement. Water levels can change due to seasonal effects or changes in the building's surroundings, for example, by a new building next to an already-existing structure.

If the soil on the surface does not have enough strength to carry the weight of the building, than the building should be founded on a soil layer with more carrying capacity deeper in the ground. To reach these soil layers, piles are needed. A pile foundation can also tilt or subside. The main reasons this can occur are: (1) reductions in the carrying capacity of the pile or the soil, or (2) an increase in weight of the structure. A loss in strength can occur, for example, when wooden foundations have rotten or suffered bacterial degradation.

Local foundation problems only affect part of a building. The visibility of this movement depends of the structure on top of the foundation. Also, it is applicable here that fixed connections can make the floor function like a bridge, so that hardly any displacement caused by the foundation can be noticed on the roof.

3. *Non-load-bearing parts of the building, excluding the outer shell (red in Figure 3.3)*

The red column in Figure 3.3 illustrates a non-load-bearing wall. Displacement of such elements will not lead to valuable satellite information. These parts do not affect the shell of the building and cannot be seen by the satellite. Also, failures in other parts of a building, like ventilation shafts that collapse, are not relevant to this research.

Expansion joints also influence the behavior of a building's movement. If an element sags and there is an expansion joint between it and the element next to it, than the element next to the moving element will not move. This is because the expansion joint separates the elements from each other. In conclusion, when movement is found or failure occurs, the structural system and location of the movement are important for determining whether or not the movement can be found with InSAR.

3.3 STRUCTURAL FAILURES THAT INFLUENCE THIS RESEARCH

In this section, the feasibility of InSAR as a forensic engineering tool is examined. Cobouw's database, which Terwel (2012) used for damage research in the Netherlands, is utilized. Using this database, Terwel conducted a case study investigating the origins of structural damage in 401 cases from 1993 to 2009.

The building cases from 1997 to 2009 are used for this feasibility study. This study examines whether InSAR could have contributed to damage research by identifying damages with deformation. Terwel (2012) provided information in his database about these cases. The following information is useful for this research:

General information about the building

The following general information is provided for each case: location, number of storeys, building type, and project name. The location includes the town where each building was located. Exact coordinates must be found using Google Earth. The function of the building is described under building type.

Information about the damage

Information about the damage is provided in the following categories: failure year, damage, description of the damage, phase of discovery, involved materials, involved structural parts, load case, and technical cause. These categories explain how the damage occurred and what was damaged.

Terwel's (2012) research also described if the damage could be expected because of physical warning signs. Warning signs of damage include cracks, displacement, corrosions, and other indications of physical damage arise. For this research, this category is very important, because a search for indications of damage is part of the investigation of each structure.

Potential cases can be selected to investigate damage with InSAR without finding out if there were PS-points on the structure when the damage occurred. The principles mentioned at the beginning of this chapter for conducting research with InSAR are used as guidelines. These are large deformations, visibility, and no deformations with a development period shorter than 11 days (the cycle time of the TerraSAR-x satellite). Cases that do not meet these requirements were left out. The following case selection steps were taken:

- First, building type was examined. Only buildings are researched in this thesis. This requirement left 239 cases to investigate.

- The satellite cannot make valuable observations in all stages of a building's lifecycle. During design and detailing, there is no information to gather, and during construction, renovation, and demolition the height of the building changes too quickly for the satellite to determine values. This only leaves only the use phase for the satellite to examine. According to Terwel (2012), 66% of total structural errors can be detected in the use phase. These damages could have originated in earlier phases. This leaves damage that occurred during the construction phase and during renovations out of the scope of this research. (190 cases left)

- Temporary structures cannot be researched because of the short period of time during which InSAR can research these structures. This results in a lack of data. Scaffolding, tents, and other temporary structures cannot be researched with InSAR. (182 cases left)

- Damage caused by accidental loads was also excluded. This is because of the short development time of this type of damage. Accidental loads make up only 5% of the cases' origin of error. Data can be sorted on load cases, and accidental load cases were not included. (170 cases left)

- The damage should be visible in the outer shell. Damage visibility is divided into two groups: directly visible and indirectly visible damage. Directly visible damage means damage to the outer shell. Indirectly visible damage can arise if parts of the main supporting structure are damaged and therefore also influence the outer shell. Sixty-one percent of failures are on the main loadbearing system, including the foundation (Figure 3.5). The visibility of the damage is a less straightforward criterion to find in the data compared to the previously mentioned criteria. The cases were selected by reading the main description of the damage. Direct visibility was selected by looking for outer shell elements of a building in the description – namely, roof, façade, and balconies. Indirectly visible damage was selected by looking at damage to the main loadbearing structure and foundation. (143 cases left)

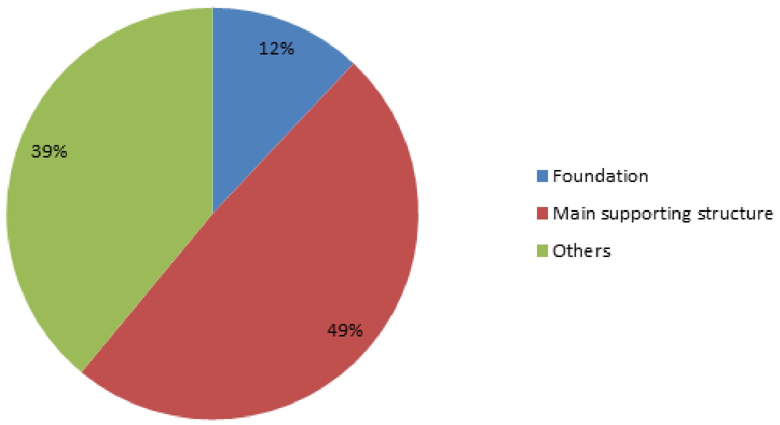


Figure 3.5, Main classification of failed elements. Source: Terwel (2012), Constructieve incidenten in Cobouw 1993-2009

- Next, it was verified whether it was plausible that the damage caused deformation in the outer shell. Identifying whether the damage resulted in (partial) collapse or structural damage was key in making this determination. (Partial) collapses occurred in 51% of cases. These types of damage often resulted in deformation in the outer shell. The description was also examined to determine whether displacement was defined or could be inferred. This condition is therefore more subjective than the previously described boundary conditions for InSAR. Because of this, the residual cases were divided into two groups: certain deformation in the outer shell and probable deformation in the outer shell. Cases were placed into the group "certain deformation" if deformation of the outer shell was described. In this phase, no distinction was made between horizontal and vertical deformation. Probable deformations are the cases where struts and cracks are described. (88 cases left)

- For the cases with probable deformation more background information is needed. Background information was searched for on the Cobouw website and in the database Terwel created for his study. Cobouw is a website with an extensive news archive about buildings and everything that has to do with buildings and the building environment. Cases that described the placement of struts because of precaution were left out. Cases with only hair cracks were also left out, deformation in these cases is too small to notice with a satellite. (72 cases left)

Deformation may be detected with InSAR data after applying the previously described criteria. The application of these criteria left 72 cases where in theory the detection of deformation is possible out of the total 239 building cases. Satellite data may verify that damage occurred between cycles (11 days for the TerraSAR-x satellite). To research the development of the damage by studying deformation in the outer shell, more InSAR data is needed. This means that deformation must take more than 11 days to develop in order for it to be suitable for study with InSAR. This gives the final criterion for damage research with InSAR:

- A gradual development of the deformation is needed to do damage research with InSAR. Besides damage caused by accidental loads, there also other reasons for sudden deformations:
  - Damage that occurs under the influence of extreme weather, like heavy rain showers, high-speed wind gusts, or heavy snow loads lead to the quick development of deformations and are not suitable for research with InSAR.
  - Façade elements that fall off the structure because of mounting errors often have only a short development time where deformation can be seen because of brittle fracture. These failures are also not suitable for research with InSAR.
  - Failure caused by construction near the buildings can also cause prompt deformations that cannot be foreseen. This is situation-depended.

Forensic research with InSAR for the development of the deformation is certainly possible for 33 cases of the 239 total examined cases, and it might be possible for an additional 18 cases. The 51 residual cases can be divided into deformation of the three outer shell elements that the satellite might detect: 36 roof cases, 7 façade cases, and 8 balcony cases. Deformation of the roof and indirect deformation caused by the foundation or the rest of the main supporting structure can be researched with InSAR. This is the largest group, partly because indirect deformation is also visible via the roof. Flat roofs are not view-direction-dependent, whereas sloped roofs are. Façade cases are less likely to be detectable, because the visibility of the facade is view-direction-dependent. Secondly, often deformation of the façade is in the horizontal direction. Balconies are a part of the façade but are a relatively large group and are therefore taken separately. Balconies are very susceptible to deformation, because of their often-cantilevered structure. The visibility of balconies by InSAR is view-direction-dependent.

Almost all cases are the cause of structural errors. Only 2 cases can be assigned to aging. Failures due to nature and human intervention cannot be researched with InSAR, because of the sudden character of these failures. In appendix 6, the 51 useable cases can be found. The presence of actual InSAR data on these cases is not researched. InSAR can also be used to verify if parts of the structure did not move, and this is not taken into account. The process used to find suitable cases for study with InSAR can be found in Figure 3.6. The possible detection of indications of horizontal movement is added as well as proposing a hypothesis. Damage research is not possible with InSAR without a hypothesis for the outer shell movement.

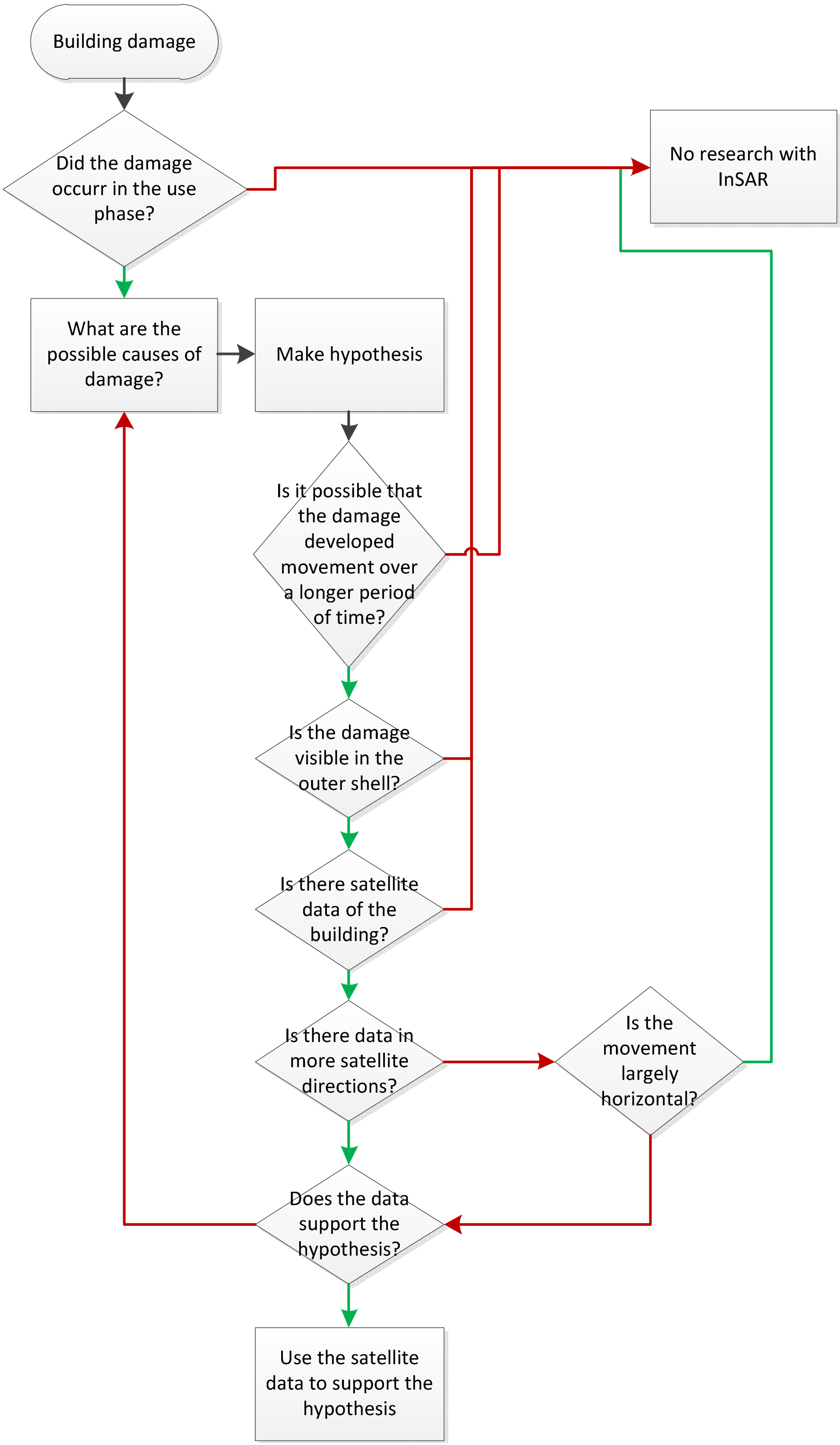


Figure 3.6, The decision tree for using InSAR in forensic engineering to support a hypothesis about a failure mechanism. Diamond shapes are decisions, rectangles are processes, red arrows are negative, and green arrows are positive.

3.4 Conclusion

In forensic engineering the cause of building failure is examined. A failure cause initiates a failure mechanism, and this leads to failure. The development of the movements caused by torsion, inelastic deformation, fracture, second order effects and buckling are hard to see with InSAR. Deformation caused by failure needs to be visible on the outer shell of the structure. Damage on the outer shell is visible to InSAR, as are damages that influence the supporting structure of the building. Deformations of the supporting structure can be damped in the outer shell; this is caused by the structural integrity.

One fifth of the damage cases found by Terwel (2012) have potential to be researched with InSAR. Only failures caused by aging and structural errors were suitable for research. Failures of balconies, facades and foundations have most potential to be researched with InSAR. One of the reasons is the vertical character of most of the deformations on these elements. However, research on balconies and facades depends on whether damage is visible from the viewing direction of the satellite. This is not taken into account. It should be kept in mind that even if no deformations are found on a structure, InSAR still has the potential to be a successful forensic engineering tool, due to its ability to also identify undamaged parts of buildings. The fact that InSAR can research a structure without setting it as a target makes InSAR unique. InSAR can be a useful tool to support a hypothesis in forensic engineering.

4 BUILDING MONITORING WITH INSAR

Building monitoring seeks to detect indications of damage or indications that damage may occur in the future. The objective of this chapter is to determine how InSAR can be used as building monitoring tool.

The difference between forensic engineering and building monitoring
Forensic engineering researches the failure mechanism and its cause after the occurrence of a failure. Building monitoring, on the other hand, tries to detect the beginning of failure in order to prevent failure. In Figure 4.1 these different approaches can be seen. The small arrows indicate the workflows of each discipline. Chapter 3 focused on the movements caused by failure from the standpoint of forensic engineering. This chapter focuses on movement that may indicate future failure. As starting point, it is assumed that variances from expected behaviour may indicate future failure. In this chapter, the causes of failure that introduce structural movement are central. Deformation of a structure is caused by the forces working on the structure and the resistance of the structure. A change in the forces or the resistance of the structure may result in a change in the deformation of the structure.

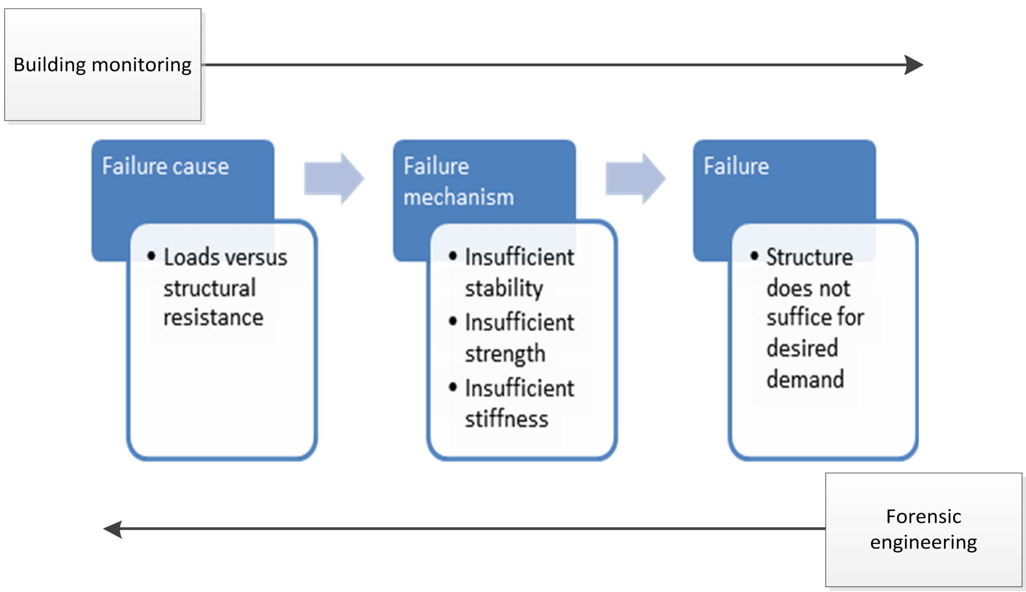


Figure 4.1, Workflows of the different disciplines. With building monitoring, changes in the behaviour of a structure are monitored. Forensic engineering researches the cause of failure.

To show the relevance of the field of research, an introduction will be given on the subject of building monitoring in the next section (section 4.1). This introduction outlines why building monitoring is used, and conventional monitoring techniques are discussed. The rest of the chapter can be divided into two parts: object-driven building monitoring and data-driven building monitoring. Object-driven monitoring looks at how a specific building can be monitored with the data. Data-driven monitoring focuses on how InSAR data can be interpreted without looking at a specific building.

With object-driven monitoring of movements, a specific building is monitored. The properties of the building are known. The movement of a structure can be derived from the forces that work on the structure and the resistance of the structure. Assuming the building is healthy at the start of deformation monitoring, a change in deformation may indicate the formation of a failure. In section 4.2, general basic principles are described for object-driven building monitoring. In section 4.3, the causes of structural deformation are discussed in terms of how object-driven building monitoring can be used to detect anomalies.

In the case of data-driven monitoring, a specific structure is not pre-identified, but an area of data is instead examined. An anomaly in the data could also indicate building damage, if the data point represents a building. That is why this chapter also looks at general limit values for buildings. This is discussed in section 4.4. The chapter ends with a conclusion detailing how InSAR could be used as an object- and data-driven building monitoring tool.

4.1 INTRODUCTION TO BUILDING MONITORING

According to Liu and Tomizuka (2003), the engineering community is pursuing new sensing technologies and analytical methods that can be used to identify the beginning of structural damage in an instrumented structural system, in order to design safer and more durable structures. This system is called structural health monitoring (SHM). According to Farrar (et al. 2001), this process involves the observation of a structure over a period of time using periodically spaced measurements. By analysing these measurements, the current state of a system's health can be determined. The output of this process is periodically updated information regarding the ability of the structure to continue to perform its desired function, taking into account the inevitable aging and degradation resulting from the operational environment. Basic principles for building monitoring can be found in Appendix 3.

According to Lynch and Loh (2006), structural monitoring systems have been widely adopted to monitor the behaviour of structures during earthquakes, winds, and live loading. Structural monitoring systems can be found in a number of common structures, including aircrafts, ships, and civil structures. For example, some building design codes mandate that structures located in regions of high seismic activity have structural monitoring systems installed (International Conference of Building Officials, 2002). Regulatory requirements in eastern Asian countries, which mandate that companies that construct bridges periodically certify their bridges' structural health, are driving current research and development of vibration-based bridge monitoring systems and SHM. (Doebling et al. 1998) In the Netherlands, NEN 2767 (2008) provides guidelines for domestic building monitoring. The content of this code is described in Appendix 4. Next to infrastructural monitoring, hydrological monitoring, and other monitoring fields, InSAR has the potential to contribute to the development of SHM as a building monitoring system.

Why building monitoring is used is described in 4.1.1. In section 4.1.2 relevant conventional monitoring techniques in the field of deformation monitoring are described.

4.1.1 REASONS FOR BUILDING MONITORING

There are several reasons to monitor a structure, according to companies, such as Sensr and Inventec, which monitored the Burj Khalifa and the HSL-line. These reasons can be divided into four subjects, introduced by Inaudi (2008). See Figure 4.2 for details. The confirmation of the design of a structure is the biggest part of structural monitoring. A more detailed description of the different reasons to monitor a structure and if InSAR can potentially contribute are described below.

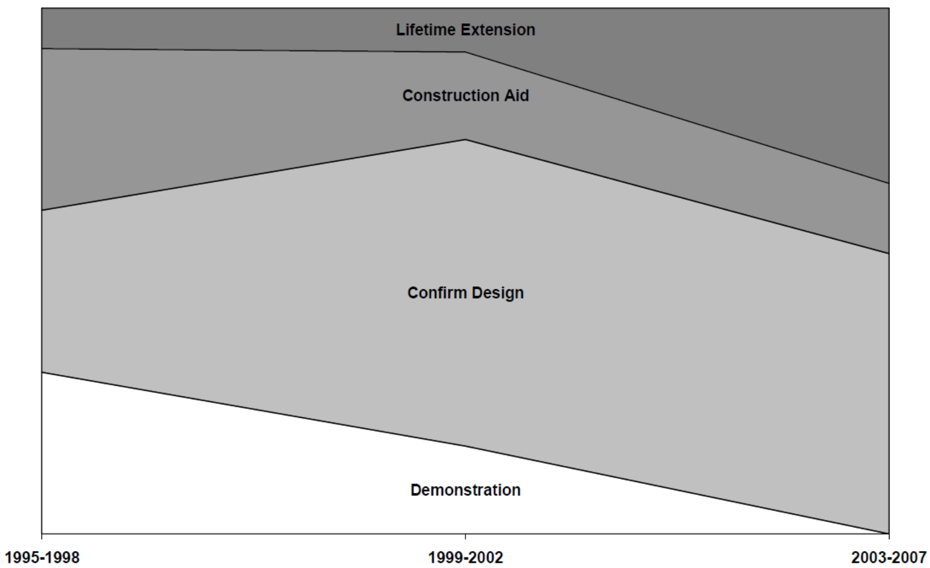


Figure 4.2, Reasons for monitoring bridges. Source: Inaudi (2008), Overview of 40 Bridge Structural Health Monitoring Projects.

- *Construction aid*

Structures are constantly changing during construction. Loads are increasing, and different load paths are introduced. It can be helpful to monitor structures to ensure no dangerous situations temporarily arise. During construction, no stable PS-points can be found in the data, and this makes this phase impossible to monitor with InSAR.

- *Confirm design*

Monitoring can be used to validate or improve the calculations and design rules applied to structures. This is already often done to validate that seismic design codes have been met and to monitor structural responses during earthquakes. Monitoring systems can also audit how structures respond to new circumstances, such as a building pit next to a building. Construction work can cause ground movements, resulting in changes to the structural integrity of nearby buildings. Monitoring building movements caused by changes in the surroundings can be researched with InSAR data.

- *Lifetime extension*

Damage can be detected at an early stage if structures are monitored. This is an advantage, because damage can be more easily prevented at an early stage, and the consequences can be decreased. If the owner's intended purpose for a structure changes, it is also useful to validate the current state of the structure. InSAR may locate structural movements at an early stage.

- *Demonstration*

To test monitoring systems, convincing parties and other demonstrations was in the past decades a decreasing reason for monitoring. This is because structural monitoring is a relatively new technology. In this thesis, InSAR as monitoring technique is demonstrated.

A fifth reason to monitor structures, which is not mentioned by Inaudi, is to solve legal issues. The cause of damage can be found more easily, or it can be proven that damage could not have been predicted. In these cases, InSAR can also be used as forensic tool, by going back in time to find out when and where damage that expressed in displacement could be found.

InSAR can be used for four of the five purposes of building monitoring. A general disadvantage for monitoring via InSAR is the related costs. Another disadvantage is that not all damage can be found by monitoring with InSAR. Only damage that is expressed as deformation can be found.

4.1.2 Conventional building monitoring techniques

InSAR monitors deformation. With deformation measurements, a structure is monitored over time and the movement of the building is observed. The movement of a point in the building is measured with respect to other points in or near the structure. Deformation measurement supports the visual inspection of civil structures, according to Rijkswaterstaat's website. Rijkswaterstaat must judge whether a civil structure is behaving as predicted in its design. Rijkswaterstaat can interfere to prevent hazardous situations.

Other techniques that monitor the deformation of buildings and are comparable to InSAR are tachymetry, levelling, GPS, Lidar, and photogrammetry. This section will give brief insight into these different techniques and their limitations. Finally, these techniques will be compared to InSAR.

Tachymetry

This technique usually makes use of a total station and reflectors (prisms). The total station can measure the angle and the distance of a reflector. With a known angle and distance, the distances in the x, y, and z directions can be calculated with trigonometry. After the first measurement (the reference measurement), deformation can be derived by comparing data of new measurements with the first measurement. The sight of the total station is limited by its surroundings in the field. It is not possible to measure the target if an element obstructs the line of sight to the target area. The accuracy of a total station with prism is 0.6 mm. According to Leica-Geosystems, accuracy is 2 mm without prism. An advantage of a modern total station is that no post-processing is needed. The results are directly available.

Levelling

With a dumpy level difference, height can be measured in relation to a horizontal plane. Height can be read using a levelling rod in the field. By doing this multiple times, differences in height can be found if an object subsides. This technique only measures height differences (it is not able to measure horizontal displacements), but it is very accurate. According to a producer of dumpy levels, the Leica DNA 0.3 is accurate to 0.3 mm/km. Sight is also limited to objects in the field of the levelling instrument. Mounting bolts are made use of to ensure the same objects are measured during repeat measurements. This technique is one of the techniques used for monitoring the buildings surrounding the train tunnel in Delft.

GPS

With a GPS receiver, heights can be measured in the field. The receiver is connected to a minimum of 24 satellites that measure its location. The accuracy of GPS in the x and y directions is 20 to 30 mm and 50 mm in the z direction, according to PelserHartman, a company that supplies deformation measurements with GPS. Objects that are between the GPS and the receiver (such as clouds) can influence the accuracy and/or accessibility of the GPS.

Lidar

Lidar stands for Light Detection and Ranging. This 3D laser scan technique uses a laser to obtain data. The distance to an object is derived by the traveling time of a laser pulse to an object and back. The distance is expressed in the x, y, and z directions. Lidar can be measured from a satellite, plane, or in the field. Measurements with a satellite are not accurate enough for building monitoring. The footprint is 70 metres in diameter and spaced every 175 metres (Duong et al. 2007). For Lidar measurements by plane, the flight track and what the location of the plane was during the laser measurement needs to be known. The deformation can be found to centimetre-level accuracy, according to Fugro (FLImap). This is also not accurate enough to measure building deformation. A stationary 3D laser scanner in the field has a high level of accuracy. FARO Focus 3D X 130 has an accuracy of 2 mm per 100 metres, according to FARO. It can only measure points that are in the line of sight of the laser scanner. It scans the whole environment around the scanner (horizontally 360° and vertically 270°) and collects millions of location points with a spot size of 4.5 mm, spaced 1 mm apart.

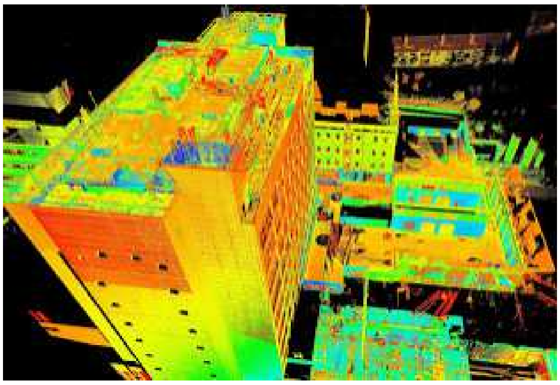


Figure 4.3, Lidar data in a Revit BIM model. Source: http://severnpartnership.blogspot.nl/2011/09/laser-scan-to-3d-revit-bim-model.html

Photogrammetry

With this technique, objects can be measured by using multiple photos with different lines of sight. Triangulation is used to measure the objects. The size of the object can be calculated if the scale of the photo is known. When multiple pictures are used, the distance can be calculated between objects. Aerial photogrammetry can be obtained by satellites and airplanes but is very weather-dependent. Clouds can block the view of the object. The accuracy is not very high, according to Honkavaara (2006). Photogrammetry's accuracy at measuring height is clear at 3 cm. Satellites are even less accurate. Close range photogrammetry (at a distance of less than 300 metres) can be very accurate (1.5 mm) and can be suitable for building monitoring (Jianga, 2007).

Building monitoring with sensors inside a building

Another deformation monitoring technique that can be found in the literature is monitoring with sensors inside a building. Sensors are installed at parts of the structure where monitoring is required. Examples of such sensors are inclinometers, tiltmeters, electrolevel beams, and tape extensometers (see Figure 4.4). A data logger is installed along with the sensors. A data logger is another name for a data recorder; it records data measured by a sensor. With this technique, the movement of a building in all directions is measured, including the angle and acceleration of the movement (Lynch and Loh, 2006).

According to the company Strainstall, data collection systems can be divided into two categories: dynamic and static. Dynamic systems are designed to capture data resulting from, for example, traffic loads (as well as trends due to diurnal and seasonal effects). Static systems are designed to collect data that ignores the effect of temporary loads. These systems have relatively slow scanning rates. Static monitoring is comparable to monitoring with INSAR. Static monitoring differs in that the measurements are inside a building and therefore have features other than those of the previously mentioned techniques. This makes monitoring inside a building not comparable to InSAR.

Figure 4.4, Examples of, from left to right: inclinometer, tiltmeter, electrolevel beam, and a tape extensometer. Source: http://www.wikipedia.org.

Table 4.1 shows different monitoring tools. If only accuracy, and not cost, is of importance for choosing a deformation monitoring technique, then the on-sight techniques of Lidar, tachymetry, and levelling are preferable to InSAR. The disadvantages of these techniques are the relatively small data coverage areas and the fact that objects can block the view. This is not the case with InSAR. A disadvantage of levelling is that it can only measure in a vertical direction. An advantage of these techniques is that they measure continuously over time, have high levels of accuracy, and can determine the direction of displacement very accurately. InSAR's ability to monitor large areas and to go back in time make it a potentially attractive building monitoring tool, as does the fact that no field work is required.

Monitoring instrument	Accuracy	Point spacing	Covered area per measurement	Measurement interval	Limitations
Tachymetry	0.6 mm	decimetres	small	continuous	obstruction of elements in line of sight
Levelling	0.3 mm	manual	small	manual	obstruction of elements in line of sight
GPS	50 mm	metres	medium	continuous	accuracy and availability is weather-dependent
Stationary Lidar	2 mm	millimetres	medium	continuous	obstruction of elements in line of sight
Stationary photogram-metry	15 mm	millimetres	small	continuous	obstruction of elements in line of sight
InSAR	2 mm, 0.4 mm for time series	metre	large	different per satellite (For TerraSAR-x, 11 days)	lower density of accurate data in vegetated areas, measurement in the LOS direction

Table 4.1, Different monitoring techniques and their properties.

4.2 Object-driven building monitoring

In this section, object-driven building monitoring is discussed. In this scenario, the structure of the building is known, and therefore specific boundaries can be formulated. The properties of a building that are of interest for object-driven deformation monitoring will be discussed first, followed by different properties of a number of PS-points on a building. This section will conclude with an introduction on how object-driven building monitoring should take place.

Properties of a building

The number of PS-points on a building is known. Boundary conditions can be made object-specific. To formulate the boundary conditions for InSAR data, different pieces of information about the structure are of importance. Following is a list of different elements of a building and why they are of importance for deformation monitoring:

➢ Span of beams:	Limit values of vertical deformation can be derived.
➢ Height of structure:	Limit values of horizontal deformation can be derived.
➢ Structural system:	Deformation of the outer shell caused by inner building deformation cannot be derived without knowledge of the structural system. Whether the structure is monolithic or hinged, whether there are expansion joints, and how the structure is connected to the outer shell are important parameters.
➢ Differences in surroundings:	Activities near the building and extreme weather conditions can lead to deformation.
➢ Forces working on the building:	The forces that work on the building will primarily cause the deformation of the building over time.

Properties of PS-points on a building

In object-driven building monitoring, the number and location of PS-points on a building are known. Different locations of the PS-points, the number of PS-points, and the number of satellites providing data on a building provide different information. The more PS-points and satellites on a building, the more information is available. Mounting corner reflectors on a building can increase the chance of a PS-point being on a building. In Figure 4.5 an example of a corner reflector can be seen.

Figure 4.5, Example of a corner reflector. Source: Central Federal Lands Highway Division (2008)

Only vertical deformation can be monitored with one PS-point. The relationship between satellite data and horizontal movement is not clear enough from which to draw conclusions if the movement is unknown. This can be seen in Figure 4.6. What can also be seen is that the deformation in the horizontal, east direction is more or less opposite when ascending data is compared to descending data. This was also mentioned in Chapter 2.

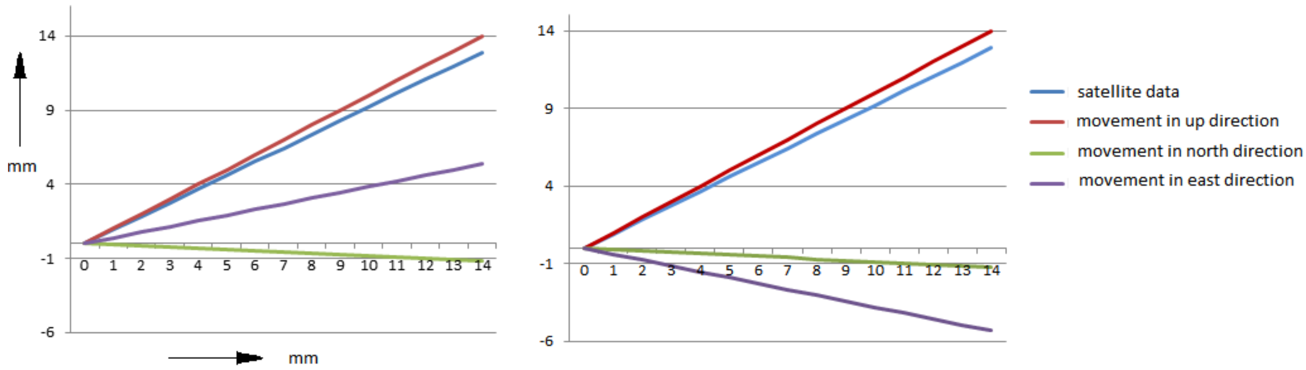


Figure 4.6, Red indicates the measured satellite data, and blue, green, and purple indicate movement, if it is assumed that the point does not move in any other direction. The right figure shows ascending data, and the left figure shows descending data.

When there are more PS-points on a building, then two scenarios may occur regarding the location of the PS-points. The points may measure different parts of the structure or the same parts of the structure. Different parts are formed by expansion joints, balconies, or parts that do not have any structural properties. Two points on different parts of the structure can be seen as one satellite with one PS-point on the building. The only advantage is that the deformation can be compared to the other point on the building. When two points are on the same part of a structure, then relative displacement can be calculated. Relative displacement can be linked to the structure, and a more detailed analysis of potential damage can be undertaken. The more points on the structure, the more related parts can be analysed. If on one part of the building, all points move in one direction and are equal in magnitude, then it might indicate foundation problems. If at one place on the structure, the deformation is the highest and it decreases gradually over the structure, then it might indicate structural problems caused by a deficiency of a column. The neighbouring points may give a more exact location, where the cause of the damage can be found. Movement of the soil can be identified as well, if many points near the building move in the same direction.

When the location of PS-points for the ascending track and descending track are more or less equal and the deformation is also equal, then it can be assumed that there is a vertical movement. When the data is in the opposite direction, then it can be assumed that movement is horizontal. In the case that three satellites can provide data and monitor more or less the same location, then the direction of the displacement or rotation can be derived. The number of satellites and PS-points on the building clearly influences the monitoring possibilities. In figure 4.7 a workflow scheme can be found of the relation between the availability of data and the monitoring process.

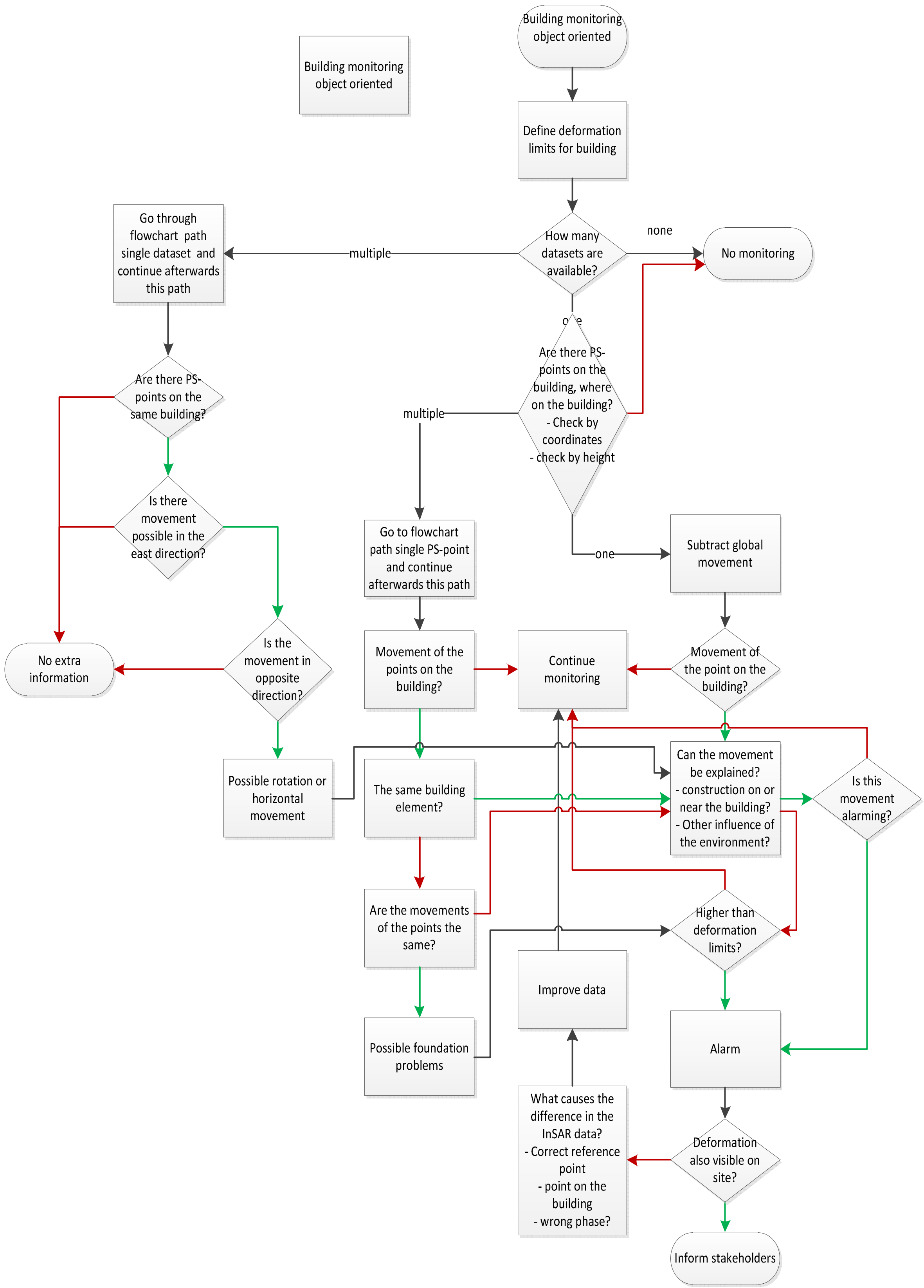


Figure 4.7, the decision tree for the monitoring process and its possibilities by using InSAR in object oriented building monitoring. Diamond shapes are decisions, rectangle a process, red arrows are negative and green arrows are positive.

Monitoring process

To understand changes in InSAR data and when alarming situations arise, the expected movement of the structure needs to be analysed. A structure deforms continuously over time under the influence of the forces working on the building and the resistance of the building. These movements can be predicted if the structure and its surroundings are known. When the movement of the building is inexplicable, then a failure mechanism may be forming. By InSAR monitoring the cause of failure may be identified at an early stage, before the failure mechanism fully develops. This is why building monitoring focuses on failure causes instead of on failures and their mechanisms. This introduces another approach than that of forensic engineering, where different failure hypotheses are tested to find the failure and its cause. In section 4.3, an analysis is made of what causes building movements over time for a better understanding of how to interpret InSAR data and how to find anomalies with object-driven building monitoring.

4.3 THEORETICAL MOVEMENTS OF A BUILDING

Buildings deform continually. These deformations are caused by changing forces that work on structures over time or by the reduction of structural resistance over time. In this section, the cause, direction, and magnitude of building movement will be researched.

According to elasticity theory, an element can undergo rigid body displacement, rotation, and deformation. These are the three movements that an element can make (see Figures 4.8 and 4.9). According to elasticity theory, if the change of a specific load is known and the structure is also known, then the movement can be calculated. This can be compared to satellite data. In reality, this is not completely true, because the design equations used to calculate movements are models with different assumptions that only approximate reality.

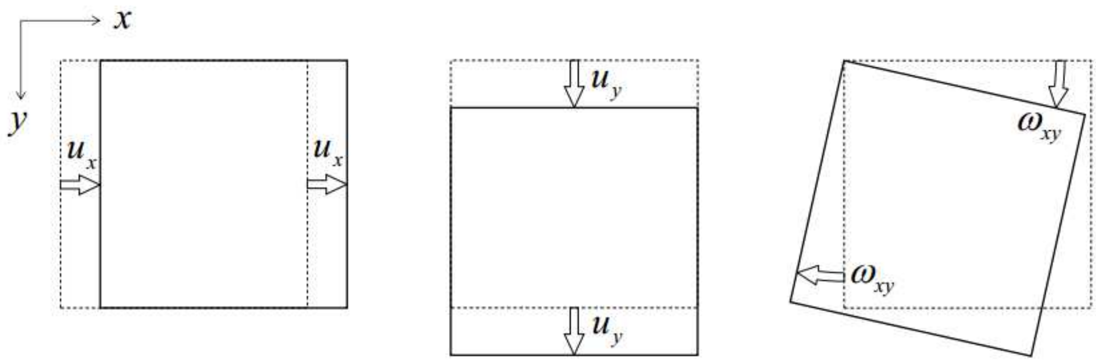


Figure 4.8, Horizontal translation, vertical translation, and rotation, according to elasticity theory. Source: Lecture notes plates and slabs (2011)

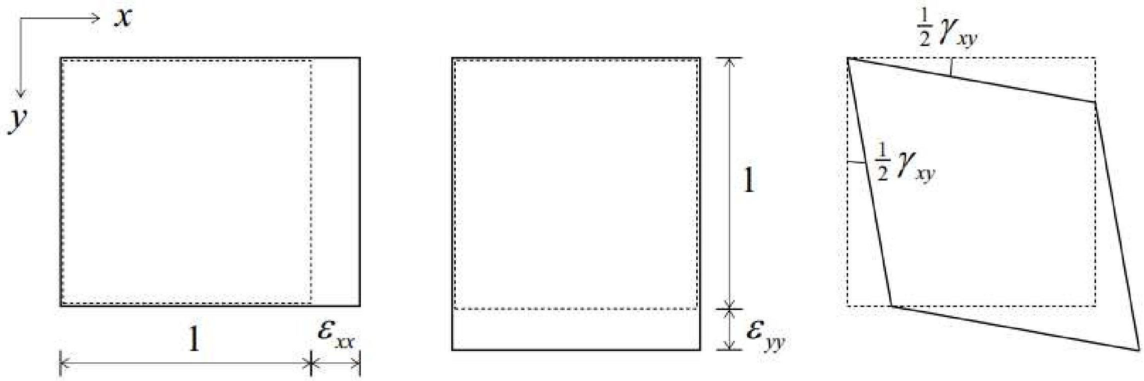


Figure 4.9, Different deformations of an element. Source: Lecture notes plates and slabs (2011)

The deformation detected by a satellite can be expressed by the previously described equation:

$$\Delta\varphi_{def} = \frac{4\pi}{\lambda} * \Delta R \qquad (2.2)$$

The ΔR is the movement of a PS-point. In this thesis, only the movement of buildings is researched, and an attempt is made to find an explanation for the change in movement recorded by the data. The total movement of a building is called ΔR_{bt} in this thesis. The movement of a building is caused by different partial movements, caused by different forces that work on a building and the resistance of the building. The forces are not constant over time and therefore cause structural movement. The impact of a force on a building is location-dependent. For example, a gust of wind may deform the façade that is hit by the gust but not move the other side of the building.

The cause of failure is influenced by the loads that work on a building and the resistance of the building. Loads can be described by the categorization method described in Chapter 3, as stated by the Eurocodes (2012):

- Variable loads
  - Wind load
  - Snow load
  - Rain load
  - Temperature load
  - Total weight of people
  - Total weight of furniture
- Dead load
  - Total weight of the structure, inclusive of installations and building services
- Accidental load
  - Explosion loading
  - Impact loading (car crash)
  - Fire load
  - Earthquake load

The resistance of the structure is influenced by the change of materials and/or the connections due to devaluation. Mold, rot, corrosion, creep, shrinkage, and relaxation are examples of devaluation of materials. With the change of loads working on the building above ground, not all movements are taken into account. Movements that affect the foundation of a building should also be included in the total movement equation. These movements are caused by the connection of the building to the soil:

- Settlement
- Change in groundwater pressure

Some loads will directly influence PS-points, others will have an indirect influence. Loads that directly influence PS-points are loads that cause movement directly on a building's outer shell. Loads that indirectly influence the movement of a PS-point are movements of the main supporting structure. This is explained in section 3.2.

The difference in total movement of a building (ΔR_{bt}), caused by all of the potential loads working on a building over time in the LOS direction, is known:

$$\Delta R_{bt}(t) = \Delta R_w(t) + \Delta R_p(t) + \Delta R_T(t) + \Delta R_{ds}(t) + \Delta R_{df}(t) + \Delta R_v(t) + \Delta R_a(t) + \Delta R_m(t) + \Delta R_s(t) + \Delta R_{gw}(t) \quad (4.1)$$

Change in movement of a PS-point on a structure ($\Delta R_{bt}(t)$), with respect to the previous InSAR measurement, caused by a change in:

ΔR_w Movement caused by a change in wind load
ΔR_p Movement caused by a change in precipitation (snow and rain load)
ΔR_T Movement caused by a change in temperature load
ΔR_{ds} Movement caused by a change in total weight of the structure (dead load)
ΔR_{df} Movement caused by a change in interior load
ΔR_v Movement caused by a change in total weight of people in the building
ΔR_a Movement caused by a change in accidental loads (explosion, impact, fire, and earthquake load)
ΔR_m Movement caused by devaluation of a material or connection
ΔR_s Movement caused by a change in settlement
ΔR_{gw} Movement caused by a change in groundwater pressure

The specific parameter is zero when a specific load does not occur or remain constant in reference to the previous measurement. Movement over time can be derived by the changes in forces that influence the movement of a PS-point. If in theory these movements exceed design limits or have larger movements than expected, then there might be building damage.

In sections 4.3.1 to 4.3.9, the variables of the equation will be described. The objective of the next sections is to understand how specific variables can influence the movement of a building and therefore, InSAR data. Most of the loads are described on the basis of the design equations suggested in the Eurocodes, so as to identify which factors are important for certain variables.

4.3.1 DEAD LOAD

Dead load is the load caused by the structure itself. This vertical force is the total weight of a not-in-use building. It can be assumed that this load does not change over time after the construction of the building, and therefore the change in load will be zero. The structure itself will not deform much after construction due to its own weight, although settlement can make the building sag. Sag by settlement will be discussed in section 4.3.9.

If the structure deforms under dead load, then the movement will be for the most part vertical, and therefore only one satellite is theoretically necessary to measure this load. If renovations occur, the dead load of the building may change. This change has an incidental nature but can take time to form equilibrium within the structure. This can cause movements.

4.3.2 DEVALUATION OF THE MATERIAL OR CONNECTIONS

The devaluation of the material can also cause movements or can weaken the structure, making it susceptible to other loads. Changes in material can lower the strength, stability, and stiffness. Examples are mold, rot, and corrosion.

Creep and shrinkage only occur in concrete and cause a volume change. 40% of the inelastic deformation (creep and shrinkage) occurs in the first 28 days. In the next 3 to 6 months 60 to 70%, and after two years there is still 10% left. (Lecture notes Concrete structures 2, 2011) Shrinkage is a volume change due to a loss of moisture, and it is primarily affected by the humidity of the surrounding air, member size, and the strength class of the concrete. Most shrinkage occurs during the construction phase, right after casting. It can be expected that no more shrinkage will occur after two years under continous drying conditions, although this is concrete-quality-dependent. Shrinkage causes small deformations. According to Parmentier (et al. 2009), shrinkage results in an estimated shortening of 0.1 to 0.8 mm/m. This means that a concrete beam of 10 metres shrinks 1 to 8 mm. The deviation is caused by differences in relative humidity, the strength class of the concrete, the dimensions of the cross-section, and the age of the concrete. The short period of two years and the small deformation make it difficult to detect this phenomenom with InSAR.

Creep depends mainly on time and load. Humidity, the age of the concrete, the strength of the concrete, and the dimensions of the cross-section influence the magnitude of creep as well. Creep can be defined as the increase of the deformation over time under a sustained load. It is a slow, time-dependent change in dimensions, mainly in the load direction. Creep takes approximately 25 years to stablize. Creep can be calculated by multiplying the elastic deformation by a creep coefficient. The magnitude of the creep coefficient can vary from 0.8 to approxomatly 4.2 (lecture notes concrete structures 2, 2011). This factor increases the deformation caused by a force, making this phenomenon difficult to study with InSAR as well.

When it is assumed that ΔR_m only consists of the discussed devoluation processes, then ΔR_m can be written as:

$$\Delta R_m(t) = \Delta R_{mold}(t) + \Delta R_{rot}(t) + \Delta R_{corr}(t) + \Delta R_{creep}(t) + \Delta R_{shrink}(t) \quad (4.2)$$

The equation is material-dependent. For armed concrete, the equation consists of corrosion, creep, and shrinkage. For steel structures it consists of corrosion, and for wooden structures, mold and rot. All of these parameters change the structure's properties and therefore indirectly contribute to possible movements.

4.3.3 WIND LOAD

A structure moves in the direction of the wind load. This is in a horizontal direction. The constant difference of the wind load in time makes it impossible to monitor the movement caused by wind with InSAR. The movement caused by the wind is described, because it still influences the movement of the building and thereby the total movement equation.

The wind load on a building depends on the wind speed, wind direction, the surrounding terrain, and the shape of the building. A higher wind speed means a higher wind load. The wind speed and the wind direction can be found in the KNMI's database, located on their website (see Figure 4.10). In this database, wind speed and wind direction at a 10-metre height can be found from 1951 until a day in the past. Measurements are recorded every 12 hours for various cities in the Netherlands.

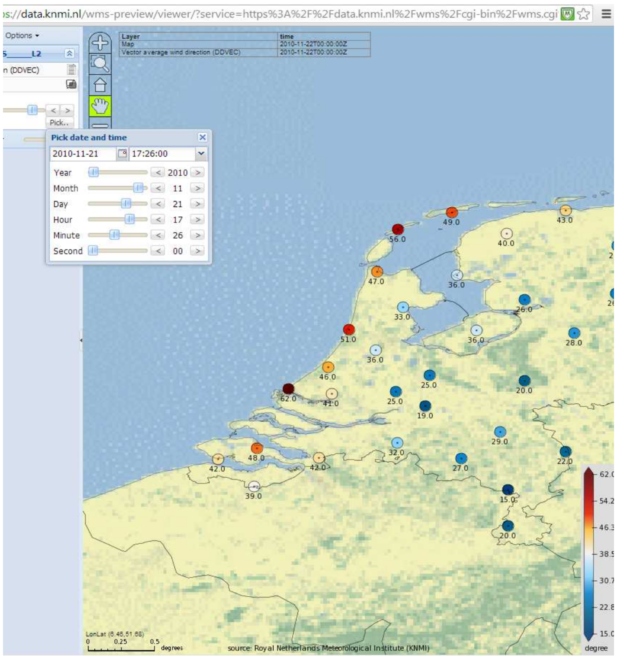


Figure 4.10, The KNMI database. From the website http://www.knmi.nl

Wind speed is just one of the factors for calculating the wind load for the design equations formulated in NEN-EN 1991-1-4 (2005). In this equation, many other factors are described that influence wind load. Important factors are the orientation of the building, the surroundings, and the height of the building.

The orientation of the building, in reference to the wind direction, influences the magnitude of the movement, because the movement depends on the stiffness in a particular direction. Changes in wind speed change the wind load parabolic, according to the equation in NEN-EN 1991-1-4 (2005).

The height of the building also influences the wind load's magnitude. Wind speeds are higher if there no objects are present that influence the wind – this is how the surrounding terrain influences wind load. This causes an uneven distribution of the wind load, as can be seen in Figure 4.11. The façade's area and shape also influence the building's total wind load. A large area of façade that meets the wind results in a higher wind load. Convexly curved shapes are less influenced by wind.

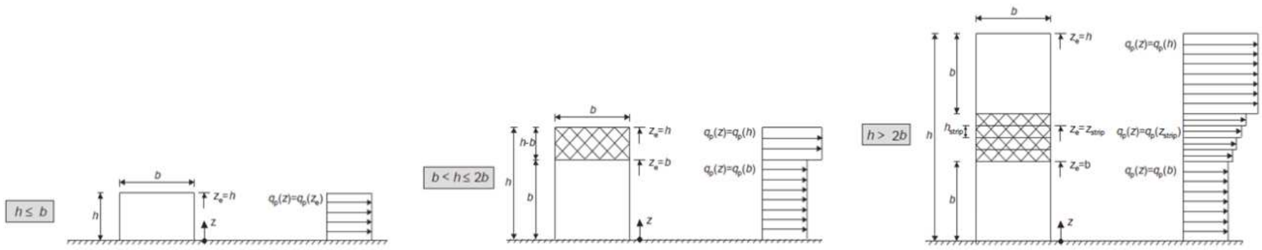


Figure 4.11, Distribution of the wind load to calculate the design wind speed, according to NEN-EN 1991-1-4. (2005)

To calculate the movement caused by wind load, the building's stiffness must be identified. An approximation of the stiffness can be calculated with a computer, if the building's structure is known. Movement depends on the structure and cannot be calculated by a general equation.

It is assumed that horizontal movement is of equal magnitude over the whole façade that faces the wind load, proportional to its height. To examine movement caused by wind load, multiple datasets are needed to derive horizontal movement, as captured by satellite data. Tall buildings are the most compelling targets for testing whether InSAR can see horizontal movements caused by wind, because the magnitude of the movement will be the largest. Changing the surroundings of lower buildings in ways that influence the wind could also be interesting cases to study.

The constant variation of the wind load on a building makes it impossible to monitor with InSAR and its repeat cycle (11 days for TerraSAR-x). Besides this at least two datasets are needed, to derive horizontal movement from InSAR data, both monitoring the same part of a building. It must be assumed that the building only moves in the direction of the wind, keeping in mind that InSAR is not equally accurate in all wind directions. This makes it almost impossible to derive movement caused by wind.

4.3.4 SNOW LOAD

Snow loads can cause sag on flat and sloped roofs. The load can be calculated with the following equation, according to NEN-EN 1991-1-3 (2011):

$$s = \mu_i * C_e * C_t * s_k \quad (4.3)$$

s	Representative snow load
μ_i	Snow load shape coefficient
C_e	Exposure coefficient
C_t	Thermal coefficient
s_k	Characteristic value of the snow load

The snow load shape coefficient depends on the shape of the roof. The influence of the angle of the roof can be seen in Figure 4.12. In this figure, μ_1 is the coefficient for roofs that are detached; μ_2 is the coefficient for enclosed roof surfaces.

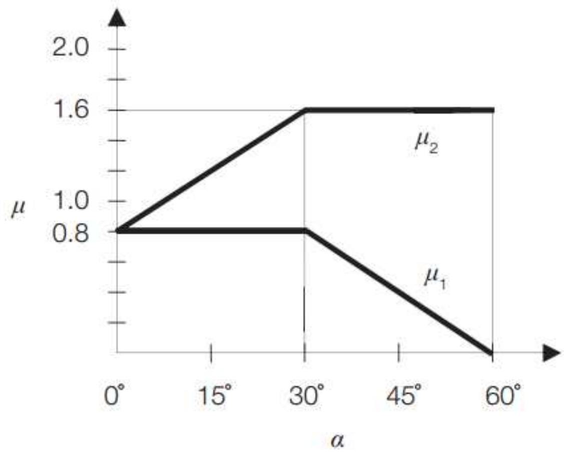


Figure 4.12, Snow load shape coefficient. Source: NEN-EN 1991-1-3 (2011)

The exposure coefficient is a coefficient that takes the exposure for wind and shelter into account. The thermal coefficient reduces the snow load of the roof caused by the thermal transmittance; this causes the snow to melt. In the Netherlands, C_e and C_t are always assumed to be 1.0.

The movement of a roof caused by snow load can be noticed by satellite if there is a point in time when the roof has a large amount of snow on it. The KNMI's data can be utilized to find days when snow accumulated on roofs. If it is known that there was no snow load, then this parameter is zero.

The snow package can influence satellite data: "As at radar wavelengths dry snow is transparent, the main reflection is at the snow/ground interface. The high refractive index of ice creates a phase delay which is linearly related to the water equivalent of the snow pack" (Gazkohani, 2008). The phase delay should be filtered out to reflect the correct deformation caused by snow. This makes it difficult for InSAR to correctly identify incidental snow loads. This movement rarely influences the total movement equation because of the lack of snowfall throughout the year.

4.3.5 RAIN LOAD

Rain load on a building is caused by water accumulation on flat roofs. Puddles can arise on a roof, if its drainage is not working properly or if its slope does not lead water to a drainage. These puddles cause a rain load on the structure. According to NEN-EN 1991-1-3 (2011), the load caused by water accumulation can be calculated with the following equation:

$$p_w(x) = \left(d_{hw}(x) + d_n(x)\right) * \gamma_w \tag{4.4}$$

$p_w(x)$	Characteristic value of the present rain load on position x on the roof
$d_{hw}(x)$	Water level on the non-deformed roof
$d_n(x)$	Water level caused by the deflection of the roof, as caused by water accumulation
γ_w	Volumetric weight of water (10 kN/m^3)

The water level on a non-deformed roof is limited by water drainage caused by the roof edge or by an emergency drain. The water level caused by deflection can be iteratively computed by calculating only the water load on the roof. Water accumulation causes roofs to sag. If it is assumed that the roof is a continuous beam, then the roof may lift in some places. See Figure 4.13.

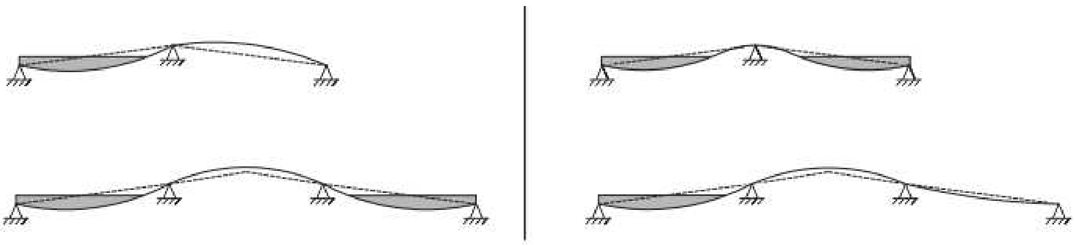


Figure 4.13, Upward and downward movements caused by rain load. Source: NEN-EN 1991-1-3 (2011)

To research this load with the satellite, a flat roof is needed with a known and improperly working drainage. To find out when the roof could have been subjected to water accumulation, data is needed from the KNMI. If there was a period of high rain intensity and it was likely that a satellite measurement took place on a day when there was a good deal of water accumulated on the roof, then the satellite should be able to detect roof movements. The rain load movement is zero, if it can be assumed that the drainage functions properly.

Rain loads can cause upward movements or downward movements, as already described. The rain flows to the lowest point and will accumulate at that point, if there is no drainage. To measure rain load with InSAR, a building with a flat roof and an inoperative drainage is needed. A large amount of rainwater is also needed to cause large displacements. This makes movement caused by rain load rare. Just as with snow, puddles may also change the reflection to the satellite.

4.3.6 TEMPERATURE LOAD

Deformation caused by temperature is a seasonal movement that requires knowledge about the lowest and highest temperatures to which an object is exposed. The perimeter columns change in length relative to the interior columns, due to changes in the exterior temperature, solar radiation, and condensation. The inner columns are mostly subjected to a temperature of approximately 20° during the day. This may result in stresses in horizontal elements that connect the internal and external columns with each other. The displacement caused by temperatures can be calculated with the following equation:

$$\Delta l = \alpha * \Delta T * l \qquad (4.5)$$

In this equation, (α) is thermal expansion coefficient, (ΔT) is the difference in temperature, and (l) is the length of the element. The thermal expansion coefficient of steel is $12*10^{-6}/^{\circ}C$, and for concrete this is $10*10^{-6}/^{\circ}C$, according to NEN-EN 1991-1-5 (2003). This equation shows that the deformation depends on the material, the temperature differences, and the length of the element. If it is assumed that the expansion coefficient and the length of an element do not change over time, then only the difference in temperature affects the element's length over time. The magnitude of the temperature difference is seasonal and can be seen as a periodical function with maximum expansion in summer and minimum expansion in winter. The equation can be used for elements that are entirely inside or outside of the building. This equation is more difficult to use if columns are partly outside and partly inside of a building, because the entire element is not exposed to the same temperature. It has already been confirmed that InSAR can note seasonal effects.

Sunlight also influences a building's temperature. In the following table from NEN-EN 1991-1-5 (2003), it can be seen that different solar radiation effect coefficients are found. The temperature of the northeast side of a building should increase between 0 and 4 degrees in summer, and the temperature of the southwest side should increase between 18 and 42 degrees. The temperature increase in the southwest direction is very significant and should be taken into account.

Season	Significant factor		Temperature T_{out} in ^{0}C
Summer	Relative absorptivity depending on surface colour	0,5 bright light surface	$T_{max} + T_3$
		0,7 light coloured surface	$T_{max} + T_4$
		0,9 dark surface	$T_{max} + T_5$
Winter			T_{min}
NOTE: Values of the maximum shade air temperature T_{max}, minimum shade air shade temperature T_{min}, and solar radiation effects T_3, T_4, and T_5 may be specified in the National Annex. If no data are available for regions between latitudes 45°N and 55°N the values T_3 = 0°C, T_4 = 2°C, and T_5 = 4°C are recommended, , for North-East facing elements and T_3 = 18°C, T_4 = 30°C, and T_5 = 42°C for South-West or horizontal facing elements.			

Figure 4.14, Temperature increase caused by solar radiation. Source: NEN-EN 1991-1-5 (2003)

Movement caused by temperature differences can be split into horizontal and vertical movements. A few cases were chosen to test if InSAR data is capable of distinguishing this movement. Deformation caused by temperature will be most visible for tall buildings. Looking at Rotterdam, various cases could be chosen. The Erasmus MC, Delftse Poort, the Millenniumtower, and the World Port Centre are all useable cases. A brief look at displacement over the years reveals that the periodic function can directly be detected on some points on the building for all of these cases (Figure 4.15). Temperature loads may have caused these periodic movements.

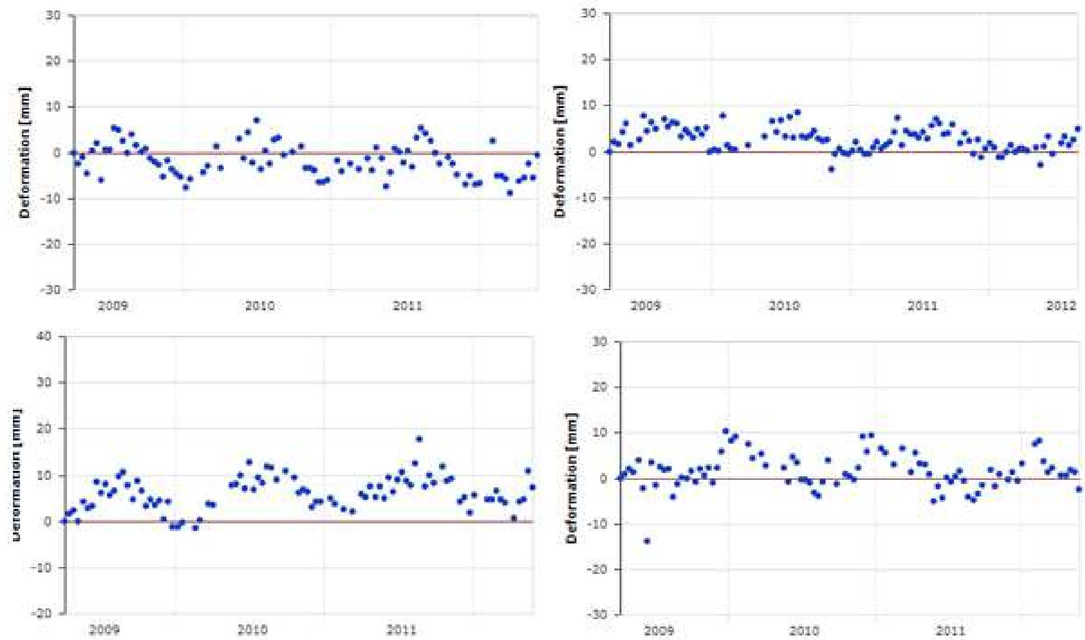


Figure 4.15, Deformation data for Erasmus MC, Delftse Poort, the Millenniumtower, and the World Port Centre from the TerraSAR-x, April 2009 to May 2012.

4.3.7 WEIGHT OF THE INTERIOR

Vertical loads cause a significant part of the loads working on a structure. A part of the vertical load is the building's interior. This can include chairs, tables, closets, beds, and etc. This load can cause a displacement of the floors where furniture is located and can cause the shortening of columns. Satellites cannot see the sagging of floors between columns, although the extra weight on the floors introduces extra weight on the columns. This extra weight can cause column shortening. Column shortening may be noticed by satellite on the outer shell.

Column shortening

Columns are subjected to high vertical loads. The more storeys the building has, the more weight the floor columns must carry to the foundation. The elastic vertical shortening of a column (u) caused by an axial load (F) can be calculated with the following equation:

$$u = \frac{F*L}{E*A} \tag{4.6}$$

This shortening will not be very large for a one-storey building, but it can be large for tall buildings, because the load on the ground floor columns accumulates. The magnitude of the shortening is influenced by the number of storeys, column span, and the building's function and structure. The column shortening of an entire building (Δ_n), with (n) number of storeys can be calculated with the following equation, according to lecture notes from Structural Design of Tall buildings (2011):

$$\Delta_n = \frac{1}{E}\sum_{i=1}^{n}\frac{h_i}{A_i}\sum_{j=1}^{s}F_j \tag{4.7}$$

Here, (h_i) is storey height. The taller the building, the more significant (Δ_n) becomes. Columns at the ground floor will shorten the most, because these columns have to carry the most weight. The elastic shortening of an entire building can be measured by satellite, because the deflection can be measured on top of the building. If it is assumed that the vertical load on the building remains equal over time, then there will be no movements.

A case where there might be measured movement is if a building becomes vacant. In such a case, all the previous owner's furniture is removed. The vertical loading on the building becomes less and may cause less column shortening; this can result in an uplift of the building if the furniture load was significant enough in relationship to the total weight of the building.

The effect of the load can be researched by satellite if the date of vacancy of a tall building is known. If the function and owner of the building remain the same for a long time period, then it can be assumed that the furniture load also does not change much over time. It can be assumed to be zero. The former Fortis building in Rotterdam, ‘de Generale Bank,’ has been empty, for the most part, since 2011, when the Fortis Bank moved out of the building. This could be an interesting case. After viewing satellite data from the TerraSAR-x satellite, no indication could be found of building uplift. The uplift may still be too small. This gives an indication that this variable is negligible.

4.3.7 WEIGHT OF PEOPLE

The weight of people in and on a building can cause a movement. This weight in a building can be estimated over time. For office buildings or housing, this load, and therefore the movement, will not be very significant. This movement can become significant in event buildings, where many people are in a building at the same time. This is the case, for example, in stadiums and theatres. The load can cause column shortening or the sagging of floor beams. The sagging of floor beams cannot be noted directly by satellite. Column shortening caused by the changing weight of people over time will, in most cases, not be very significant. This load is vertical and the duration is mostly short. The visibility of the influence of this load is time-dependent.

4.3.8 ACCIDENTAL LOAD

Accidental loads – such as fires, earthquakes, and explosions – damage the structure persistently (the building’s lower strength, stability, and stiffness) and are therefore not included in this report. Another reason not to include these loads is because of the abrupt manner in which they occur. These loads cannot be predicted and have no development over time.

4.3.9 THE FOUNDATION

If a house is built and a new foundation is constructed, then there can be settlement of the soil layers under the foundation. Settlement is the compression of soil layers by the weight of the structure. If the soil conditions, groundwater level, condition of the foundation or the distribution of the building’s loads do not change over time, then there will be no further movements caused by the foundation. All of these factors can change over time and can result in tilting, subsidence, and/or shear deformation of the building.

According to Leijen and Hanssen (2007), groundwater changes and surface displacement are highly correlated and can be seen with InSAR (Figure 4.16). The susceptibility to groundwater level movement depends on the type of soil. The groundwater level can be influenced by many factors, such as rain, discharge from factories, drainage, and construction activities.

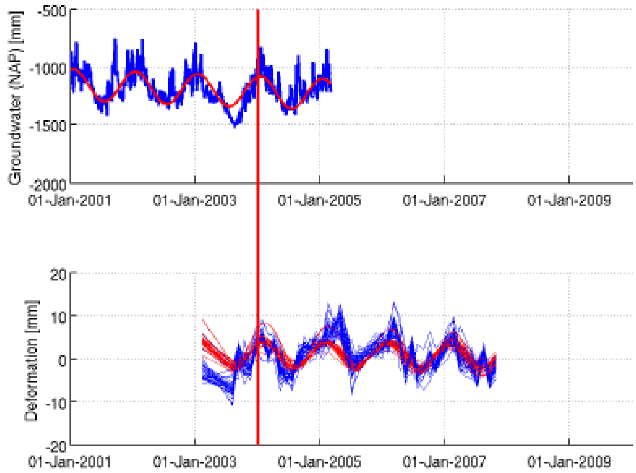


Figure 4.16, The top figure is an example of a groundwater level time series. The other graph shows a PS-point time series. In this figure, indications can be seen that InSAR can monitor the influence of the groundwater on ground deformation. Source: Leijen and Hanssen (2007)

The Eurocodes divide displacement calculations for the foundation into two categories: raft foundations and pile foundations. The variables of the Eurocode's design equations for subsidence of the foundation will be analysed to indicate which factors are of importance for deformation monitoring.

Raft foundation

A large part of the movement of a raft foundation is formed by consolidation. Consolidation is the process of soil deformation by a compressing load. Water and air are pressed out of the soil's pores. To calculate the subsidence, only vertical forces need to be used, according to NEN 9097-1 (2012).

Subsidence can be calculated with the following equations:

$$s_d = s_{0;d} + s_{1;d} + s_{2;d} \tag{4.8}$$

S_d	Total sag
$S_{0;d}$	Sag caused by shear formation (can be neglected, according to NEN-EN 9097-1)
$S_{1;d}$	Primary subsidence
$S_{2;d}$	Secondary subsidence

In the following figure (4.17) it can be seen that the consolidation process of a structure on a raft foundation requires years before stabilization. Consolidation speed depends on the type of soil (the texture and structure of the soil), the water content of the soil, the size of the load, and the influence of previous loads on the soil. The primary subsidence forms the largest part of this subsidence. The primary subsidence is the volume change caused by elastic deformation and the egress of water out of the pores. Secondary subsidence is volume change caused by plastic deformation of the soil structure caused by creep. If the soil contains different soil layers, then the consolidation of each layer within the area of influence must be calculated.

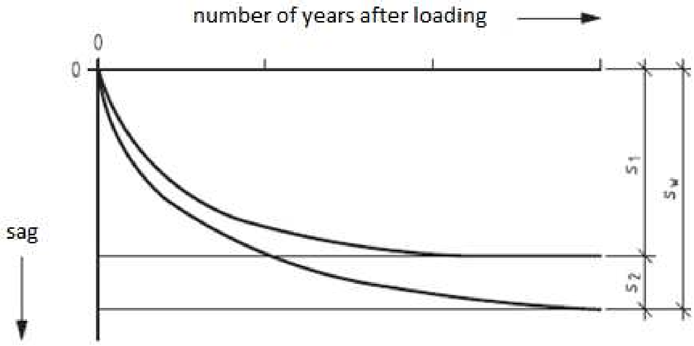


Figure 4.17, Consolidation process of a raft foundation over time. Source: Eurocode NEN-EN 9097 (2012)

Primary subsidence of raft foundation

The primary subsidence can be calculated per soil layer and must be summed; the subsidence can be calculated with the following equation:

$$s_1 = \sum_{j=0}^{j=n} \frac{C_{c;j}}{1+e_j} * h_j * log\left(\frac{\sigma'_{v;z;0;d} + \Delta\sigma'_{v;z;d}}{\sigma'_{v;z;0;d}}\right) \quad (4.9)$$

$C_{c;j}$	Compression ratio of ground layer j
e_j	Pore number of ground layer j
h_j	Height of ground layer j in metres
$\sigma'_{v;z;0;d}$	Total building weight
$\Delta\sigma'_{v;z;;d}$	Effective soil stress

In this equation the different ground layers must be summed to calculate the primary sag. The ground layers that are distinguished in codes are gravel, sand, silt, clay, and peat. Silt, clay, and peat cause the largest portion of the primary subsidence, as can be seen in the following table (4.2), because $\frac{C_{c;j}}{1+e_j}$ is for the ground layers higher than gravel and sand. This primary subsidence will not vary much over time. Renovations may change the total building weight ($\sigma'_{v;z;0;d}$), and drainage or construction activity may influence the effective soil stress ($\sigma'_{v;z;;d}$).

Soil type			Characteristic values of soil properties	
Main name	Admixture	Consis-tency	$C_c/(1+e_0)$ [-]	C_α [-]
Gravel	Weak silty	Loose	0,0046	0
		Moderate	0,0023	0
		Fixed	0,0019 0,0016	0
	Strong silty	Loose	0,0058	0
		Moderate	0,0038	0
		Fixed	0,0023 0,0015	0
Sand	Clean	Loose	0,0115	0
		Moderate	0,0038	0
		Fixed	0,0023 0,0015	0
	Weak silty, clayey		0,0051 0,0035	0
	Strong silty, clayey		0,0115 0,0058	0
Loam	Weak sandy	weak	0,0920	0,0037
		moderate	0,0511	0,0020
		fixed	0,0329 0,0230	0,0013 0,0009
	Strong sandy		0,0511 0,0329	0,0020 0,0013
Clay	Clean	Weak	0,3286	0,0131
		Moderate	0,1533	0,0061
		Fixed	0,0920 0,0767	0,0037 0,0031
	Weak sandy	Weak	0,2300	0,0092
		Moderate	0,1150	0,0046
		Fixed	0,0767 0,0460	0,0031 0,0018
	Strong sandy	-	0,0920 0,0164	0,0037 0,0007
	Organic	Weak	0,3067	0,0153
		Moderate	0,2300 0,1533	0,0115 0,0077
Peat	Not preloaded	Weak	0,4600 0,3067	0,0230 0,0153
	Moderate preloaded	Moderate	0,3067 0,2300	0,0153 0,0115

Table 4.2, Soil characteristics. Source: NEN 9097-1 (2012)

Secondary subsidence of raft foundation

The secular subsidence can be calculated per soil layer and must be summed; the subsidence can be calculated with the following equation:

$$s_2 = \sum_{j=0}^{j=n} c_{\alpha;j} * h_j * log\left(\frac{t_\infty}{t}\right) \qquad (4.10)$$

This equation is time-dependent. The rate of sag will decrease over time, according to Figure 4.18, if the height of the soil layers and the properties of the soil do not change over time. Most of the secondary subsidence occurs in the first 500 days, if it is assumed, as proposed by the Eurocodes, that the total subsidence takes approximately 27 years (10,000 days).

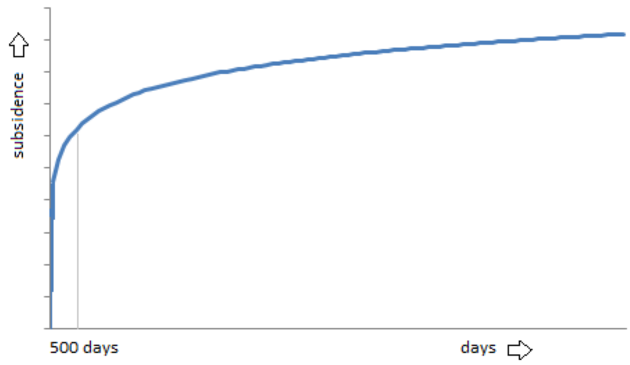


Figure 4.18, Secondary subsidence from 0 days until 10,000 days, so as to demonstrate the equation's characteristics. The subsidence is downwards (in opposite direction of the graph).

Consolidation can be a problem if the settlements are large or the settlements are unevenly distributed over the foundation area. Vertical sag caused by consolidation is the vertical portion of the movement caused at a structure's foundation. Primary subsidence comprises the largest part of a building's sag. According to design equations, it is dependent on the weight of the building and the strength of the soil layers. The secondary subsidence is only a small part of the deformation, and after 500 days most of the secondary subsidence has occurred.

Pile foundation

To calculate the sag of pressure-loaded pile foundations the Eurocodes use the following equation:

$$s = s_1 + s_2 \tag{4.11}$$

s	Sag of the top of the foundation element
s_1	Sag of a single pile
s_2	Sag of a pile group caused by the compression of soil layers under the pile tip

The pile sag (s_1) can be written as:

$$s_1 = s_b + s_{el} \tag{4.12}$$

s_1	Sag on top of a pile
s_b	Empirical value of the sag of a pile tip caused by a vertical load
s_{el}	Sag on top of a pile with respect to the pile tip, caused by the elasticity of the pile

S_b is determined by empirical tests and can be found by Figure 4.19. The sag can be found in the graph by choosing the calculated force on the pile tip ($R_{b;cal;i}$) divided by the maximum capacity ($R_{b;cal;max;i}$) on the x-axis and choosing the line that fits the pile class factor. The pile class factor depends on the installation technique. Driven piles are primarily group 1, vibrated and screwed piles are primarily group 2, and pulsed piles are group 3. It can be seen that s_b depends on the vertical load, the carrying capacity, the diameter of the pile, and the installation technique. The parameter that is most likely to change over time is the vertical load that can be caused by, inter alia, building renovations or excavations near the building. Negative skin friction can also increase the vertical load on the pile. Piles' carrying capacities are obtained from the pile point resistance and the skin friction. Due to compression of the soil, the soil may stick to the pile, causing extra weight that the pile must carry. This causes negative skin fraction.

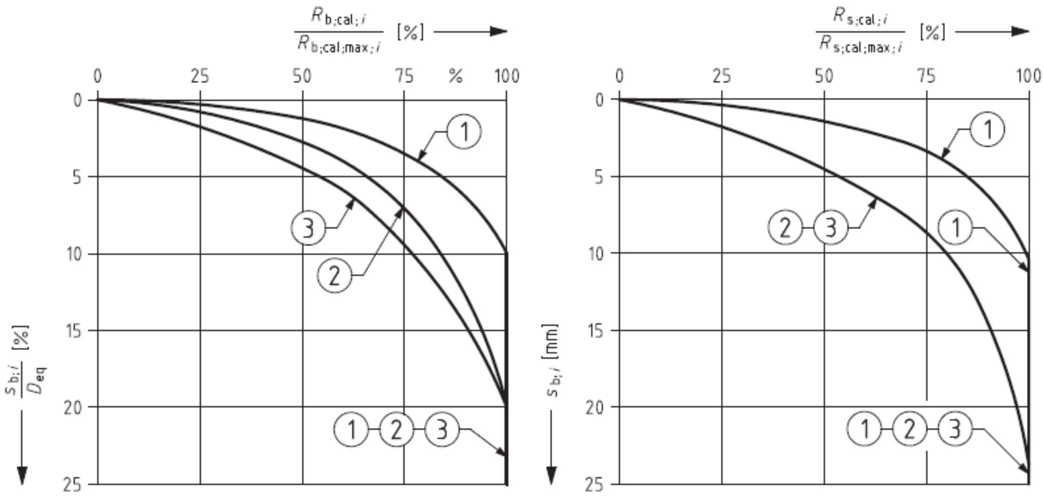


Figure 4.19, The value s_b can be determined with the graphs. NEN 9097-1 (2012)

The sag caused by the elasticity of the pile can be calculated with the following equation:

$$s_{el} = \frac{L * F_{gem,i}}{A_{schacht} * E_{paal;nom}} \quad (4.13)$$

s_{el}	Sag on top of a pile with respect to the pile tip, caused by the elasticity of the pile
L	The length of the pile
$F_{gem;i}$	Calculation value of the average normal force in the pile shaft, dependent on the total of vertical forces working on the pile and the carrying capacity
$A_{schacht}$	Area of the section of the pile shaft
$E_{paal;nom}$	The nominal modulus of elasticity of the pile shaft material

The parameter that is most likely to change over time is the normal force working on the pile that can be caused by building renovations or excavations near the building. For old, wooden pile foundations, stiffness can also change over time by devaluation of the pile caused by mold or rot.

When piles are close together, they function as a pile group, and then an extra deformation parameter is introduced: s_2. This variable, s_2, depends on the vertical force working on the influence area of the pile group, its carrying capacity, and the properties of a pile.

Next to vertical sag, a raft and pile foundation can also rotate or experience shear deformation. Rotation and shear deformation are also a part of the total movement. Movement observed by the satellite and caused by rotation is height-dependent – the taller the building, the larger the possible deflection. The rotation of the building can be calculated by comparing the horizontal and vertical forces on the building, with the resistance of the soil in both directions.

Conclusion
Movement or rotation of the building caused by sag due to changes in groundwater levels or carrying capacity of the soil can be seen by satellite, because of the often-gradual deformation rates and large deformations. Foundation problems are often caused by changes in the soil. This often affects a larger area than the building itself, and this is why foundation problems often can be recognized by PS-points that move in the same way over a larger area. If a couple of structures in the same area, founded in the same soil layer, all make a particular movement, then this might be an indication of a changing carrying capacity of the soil.

The visibility of local foundation problems caused by a loss in carrying capacity of a part of a foundation depends on the building's structural system. When the structure is monolithic, the structure might compensate for the movement by transferring the load to other parts of the foundation, and this may result in less deformation in the outer shell of the building.

4.4 DATA-DRIVEN BUILDING MONITORING

This section will deal with the other monitoring approach, data-driven building monitoring. With this type of monitoring, the structure is unknown, and this leads to a different approach than that used for object-driven building monitoring. For this type of monitoring, general indications must be made to detect possible damage. For this reason, it was chosen to assess buildings' limit values.

With data-driven monitoring, an entire area is monitored, without looking at specific structures. The first step of data-driven building monitoring is to determine the location of the PS-point and to find out if there is a building at this location. The second step is to recognize a value that might indicate damage. To give general boundary limits for these points, the maximum horizontal and vertical deformations for common building spans in the Netherlands are given in the following sections. The deformation limits are analysed on the basis of design limits in the Eurocodes. The deformation limits are split into three categories: vertical beam deformation, horizontal column deformation, and rotation and deformation of the foundation. For vertical deformation, one satellite may be sufficient. In cases of horizontal deformation or rotation, different satellite tracks are required. These deformation limits can support the search for building damage. However, a disadvantage is that almost all buildings are unique, have different spans, and therefore have different limit values.

Limits of deformation rates are unknown for vertical deformations of beams and horizontal deformations of columns. There are deformation rate guidelines for foundations.

4.4.1 VERTICAL DEFORMATION LIMITS OF BEAMS

Vertical deformation of a beam is called sag. Sag can be caused by vertical loads and temperature loading. Beams that deflect can be seen by satellite if they belong to the main supporting structure, support the roof structure, or are part of the roof structure. Floors inside a building may not result in deflection observations for the satellite. Vertical movements of the foundation will be discussed in section 4.4.3.

The sag of a beam can be calculated if boundary conditions are known. The magnitude of the sag is different for simple supported and for fixed beams. Furthermore, the magnitude of the displacement depends on the loads, the Young's modulus of the material, the moment of inertia, and the length to the third power, according to design equations. A difference in length will have the largest impact on the sag. If it is assumed that only the force changes over time**,** then sag is a linear deformation. For vertical displacement, the Eurocodes describe design limits. These limits are explained in the following figure (4.20).

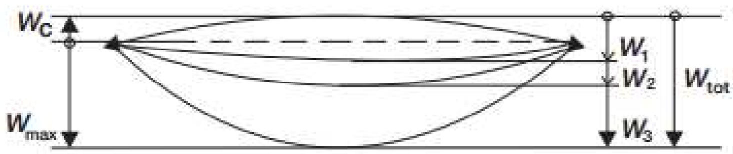


Figure 4.20, Example of vertical deflection of a floor, according to the Eurocodes. Source: NEN-EN 1990 (2002)

In this figure, (W_c) is the sheer (in Dutch: *zeeg*). (W_{max}) is the total deflection, taking the sheer into account. (W_1) is the initial deflection caused by the floor's own weight, caused by the short-time-span material properties. W_2 is the long span part of the deflection and can be calculated with quasi-persistent forces and long-span material properties. W_3 is the additional deflection caused by live loads. (l_{rep}), not shown in the figure, is the length of the span, or two times the length of the cantilever. Floors with crack-sensitive partition walls have a design limit of 1/500 part of (l_{rep}) as displacement. The displacement is W_2 + W_3. For floors and roofs that are intensively used by persons, the maximum displacement is 3/1,000 of ($l_{rep)}$, calculated with frequent load combinations. For other roofs, the deflection limit is 1/250 of (l_{rep}), calculated with the characteristic load combination.

To give an indication of displacements that are alarming, a table has been made of common building sizes in the Netherlands with the maximum design displacement, according to the Eurocodes. Agentschap NL (2012) used the sizes of common new buildings in the Netherlands to calculate energy consumption. Buildings like factories, hospitals, schools, large offices, and shopping malls are not covered by Agentschap NL. These buildings are often unique in size because of their explicit functions or because the architect tried to design a landmark. Housing made up approximately 40% of building production in 2011 and 2012 (EIB, 2012). According to Terwel (2012), 38% of cases with damage were houses with a residential function (Figure 4.21).

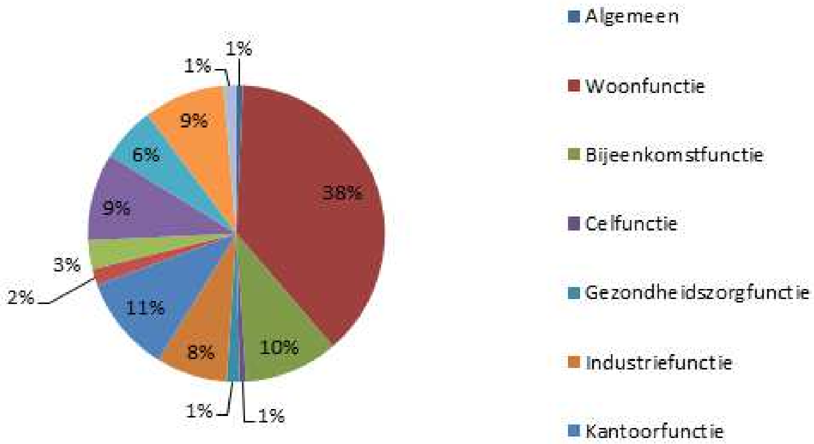


Figure 4.21, Function of damaged buildings. Source: Terwel (2012), Constructieve incidenten in Cobouw 1993-2009

Total housing production can be separated into apartments (33%), terraced houses (50%), semi-detached houses (13%), and detached houses (5%) (Agentschap NL 2012). Common widths or lengths of these building categories are used in the table to calculate the maximum allowable deflection (Table 4.3). As starting point, it was chosen to use the limits stated by the Eurocodes. Although these values do not have a structural nature, they are limit design values.

Type of building	Frequently used width in mm	Maximum vertical deflection per floor, according to code, in mm
Terraced house	5,100	10.2
Semi-detached house	5,800	11.6
Apartment building	8,300	16.6

Table 4.3, Vertical deflections of frequently used building widths. Widths are adopted from Agentschap NL (2012).

These deflections are only limited to floors and for beam spans and do not say anything about sagging columns or other parts of the structure. There are no limits in the Eurocodes for these displacements.

Another distribution for vertical displacements can be made by using the length of frequently used floor systems and the length of frequently used beam lengths. Examples of frequently used floors are: hollow core slabs, combination floors, steel deck floors, and concrete plate floors. Most of the beams in buildings are made from reinforced concrete or steel. A box girder can span up to 60 metres, but they are rarely used. Spans as long as or higher than 20 metres are seldom used in buildings. Large spans are often used in storage buildings or car parks. Frequently used floor systems, such as hollow core slabs, can have spans of up to 18 metres. This may result in a maximum deflection of 36 mm, but these are used infrequently. Modular building sizes for beams in offices with a width of 6, 7.2, 8.4, or 9.6 metres are often used. These lengths have limit deflection values from 12 mm for 6-metre spans to 19.2 mm for 9.6-metre spans.

4.4.2 Horizontal deformation limits of columns

Horizontal deflection of columns is caused by horizontal loads, temperature, buckling, and second order effects. A column may be susceptible to buckling if the element has small dimensions compared to the height of the column. The magnitude of the deflection caused by buckling cannot be calculated and is therefore unknown. If at first a column deflects by horizontal forces, then the vertical load on the column may introduce a second order deflection, because this load becomes excentric. This is a magnification of a horizontal deformation called a second order effect. This movement is a part of a horizontal movement and therefore cannot be evaluated seperatly by InSAR data.

Buildings with one building layer loaded with the characteristic combination can have a maximum horizontal deflection of h/300. The (h) is the smallest storey height. For industrial buildings, this is h/150. For buildings with more than one building layer loaded with the characteristic combination, this deflection can be at maximum h/300 per layer, and for the entire building h/500 (NEN-EN 1990 2002). The storey height is often the end of a mechanical subsystem because of diaphragm action. These provided limits are according to Bouwbesluit (2012). Although the maximum deflection has been designed on the basis of these numbers, they are not necessarily of structural nature, but were created with comfort in mind and with respect to the functioning of the building.

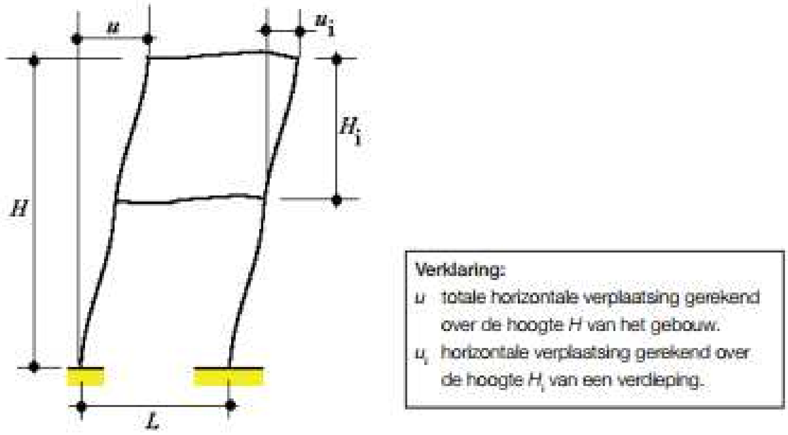


Figure 4.22, Example of horizontal deflection of a framework, according to the Eurocodes. Source: NEN-EN 1990 (2002)

For horizontal displacement, floor height is often normative for displacement calculations. The height between the ceiling and the floor must be at least 2.2 metres for new houses and 2.1 metres for existing houses, as defined in Het Bouwbesluit (2012). Offices and other buildings must have a minimum height of 2.6 metres for new buildings and 2.1 metres for existing buildings. These heights are the space between the ceiling and the floor. For the total building height, the floorsystem height and the ceilingsystem height must be added. Offices often have a lowered ceiling for installations. The total floor height for housing is estimated to be 3 metres and for offices around 3.5 metres. This makes the maximum deflection for one-storey houses 10 milimetres and for one-storey offices 11.67 milimetres. In the following graph, the maximum deflection of buildings with different numbers of floors for housing and offices are shown (Figure 4.23).

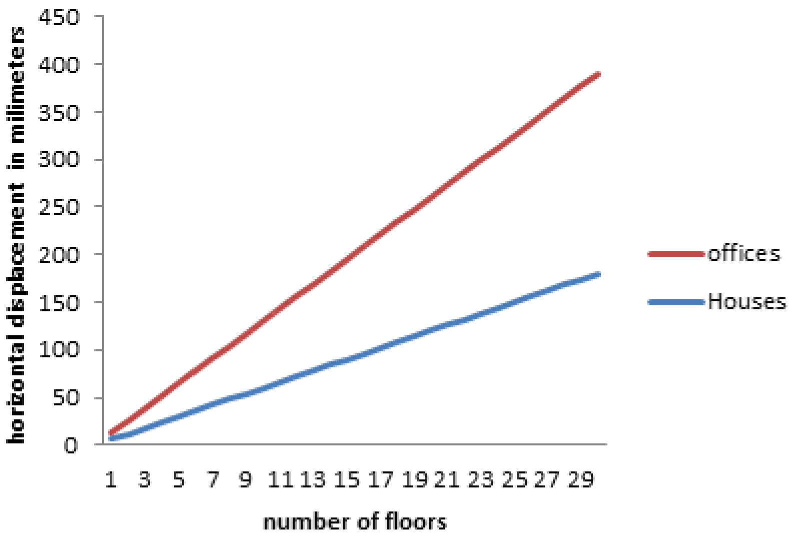


Figure 4.23, Graph of maximum horizontal displacement, according to Eurocode limits.

A deformation of 12 mm in a horizontal direction can be alarming for a one-storey high building, but is not the case for multi-storey buildings. This is why the height of the building needs to be known to interpret the data. In addition, the data for one satellite direction, if horizontal motion is assumed, is not very sensitive. A deformation of 12 mm in an easterly direction is expressed by a movement of 4.5 mm, according to the satellite. A deformation of 12 mm in a northerly direction is expressed by a movement of -1 mm, according to the satellite. This makes horizontal deformation monitoring with one satellite impossible. Monitoring with two satellite tracks of the TerraSAR-x (ascending and descending track), and assuming that the building moves in a horizontal direction and does not move in an upward direction, is still very ambiguous. A movement of 12 mm in a northerly direction is only -1 mm in satellite data for both directions. A 12 mm movement in an easterly direction is, for satellite data, 4.5 mm in the opposite direction. This makes it difficult to monitor horizontal movements in data-driven research.

4.4.3 Deformation limits of the foundation

The building can sag for different reasons, as can be seen in Figure 4.24.

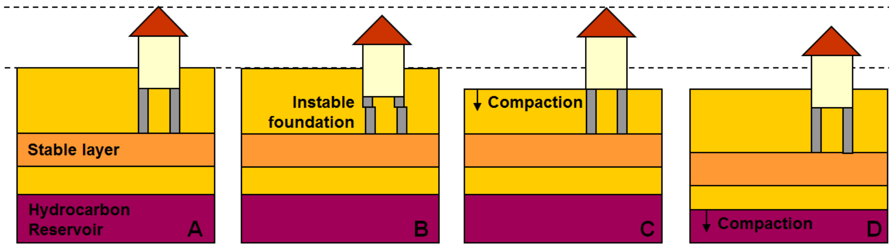


Figure 4.24, Different reasons a foundation can sag. Source: dheenathayalan (2014)

Much research has been conducted on deformation limits for foundations, in contrast to deformation of the upper structures of buildings in the Netherlands. A possible reason for this could be that, according to Stichting Platform Fundering (2010), 200,000 buildings have foundation problems. This is caused by settlement, decreasing groundwater levels, negative creep, degradation due to mold and bacteria, and design errors. Underground problems translate to sag, skew, cracks in the façade, and clamping windows and doors (Markum Stedelijke Ontwikkeling, 2010).

According to F3O (2012), the settlement rate can be divided in the following table:

Zakking [mm/jaar]	Benaming
tot 0,5	Nihil
0,5 tot 2	Klein
2 tot 3	Matig
3 tot 4	Groot
> 4	Zeer groot

Table 4.4, Settlement rates and their severity, according to F3O (2012).

According to F3O, large settlement rates (from 3 mm/year) require repair. This figure can be used as the limit for deformation velocity. According to Van Tol (2013), deformation rate differences for the same structural element need to be divided by two of F3O's limits to warrant the same severity classification for settlement rate. If there are two different PS-points on the same structural element, then deformation rate differences can be measured. Differences of 1.5 mm/year and higher are alarming.

De Lange (2011) made an overview of deformation and rotation limits of different empirical, analytical, numerical, and probabilistic studies, as well as the limits set forth in the Eurocodes. The deformation rates are not in this overview. In Table 4.5, the overview can be seen. Studies without damage criteria are left out.

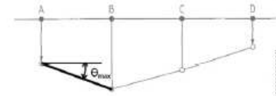
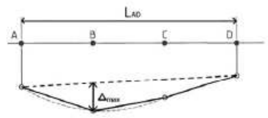
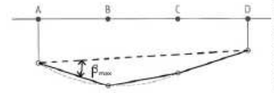
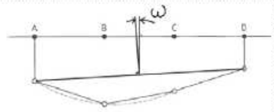
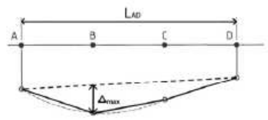
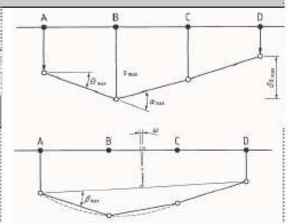
Model	Doel	Parameters	Eis	Weergave parameters
Empirische modellen				
Skempton & MacDonald (1956)	Criteria geven om schade ten gevolge van zettingsverschillen te voorspellen	Rotatie metselwerk (θ) Zettingsverschil (δs) Uitgaande dat er geen scheefstand (ω) optreedt	Constructie schade θ_{max}<1/150 Functionele schade θ_{max} <1/300 δs_{max}≤32 mm	
Polshin & Tokar (1957)	Criteria geven om schade ten gevolge van zettingsverschillen te voorspellen	Doorbuigingsverhouding (Δ/L) afhankelijk van lengte-hoogteverhouding gebouw	L/H≤3: Δ_{max}/L = 1/3500-1/2500 L/H≥5: Δ_{max}/L = 1/2000-1/500 1 bouwlaag: Δ_{max}/L ≤1/1000	
Sowers (1962)	Criteria geven om schade ten gevolge van zettingsverschillen te voorspellen, uitgaande van bruikbaarheidseisen	Totale zetting (s) Scheefstand (ω) Zettingsverschil (δs) Afhankelijk van de functie van het gebouw	Aansluitingen riolering: s≤15-30 cm Toegankelijkheid: s≤30-60 cm ω≤0.004*L tot 0.0 1*L afh. van functie gebouw Hoge doorgaande metselwerk wanden Δs≤0.0005*L tot 0.001*L 1-verdiepingsbouw metselwerk Δs≤0.001*L tot 0.002*L	
Bjerrum (1963)	Criteria geven om schade ten gevolge van zettingsverschillen te voorspellen: aanvullen van eisen van Skempton en MacDonald (1956)	Relatieve rotatie metselwerk (β)	Esthetische schade β≤1/500 Functionele schade β≤1/300 Constructieve schade β≤1/150	
Charles & Skinner (2004)	Het onderzoeken van de relatie tussen scheefstand en bruikbaarheid van een woning	Scheefstand (ω)	ω = 1/250-1/200: Merkbare scheefstand ω > 1/250: Monitoren ω = 1/100: Constructieve veiligheid komt in gevaar ω = 1/50: Constructieve veiligheid in gevaar!! Direct actie ondernemen.	
Empirisch Analytische modellen				
Burland & Wroth (1974)	Criteria geven om schade ten gevolge van zettingsverschillen te voorspellen. Classificeren van schade Op grond van LTS-methode	Doorbuigingsverhouding (Δ/L) Afhankelijk van lengte-hoogteverhouding en van buigingsvorm Uitgangspunt bij criteria: toelaatbare rek in metselwerk, ε≤0.075%	Sagging, Neerwaartse buigingsvorm / Hogging, Opwaartse buigingsvorm L/H=1: Δ/L≤1/2500 / Δ/L≤1/5000 L/H=5: Δ/L≤1/1250 / Δ/L≤1/2500	
Nederlandse Norm (nieuwbouweisen)				
NEN 6740	Het geven van vervormingscriteria voor nieuwbouw	Zetting (w) Rotatie (θ) Scheefstand (ω) Relatieve rotatie (β)	Grenstoestand 2 (=BGT) / Grenstoestand 1B (=UGT) w (m): 0.15 [1] / - θ (mm/m): 1/300 / - β (mm/m): 1/300 / 1/100 [2] ω (mm/m): 1/300 /	

Table 4.5, Overview of studies with damage criteria. This table was made by De Lange (2011).

The criteria utilized above can be explained with the following figure:

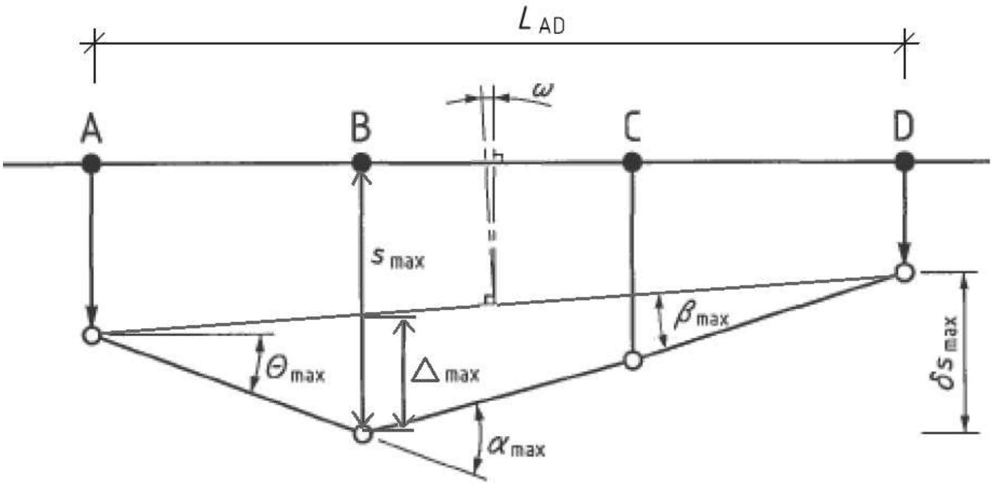


Figure 4.25, Different deformation parameters for a foundation, according to the Eurocodes and other research.

In this figure, the line from A to D is the width of a building. A, B, C, and D have different assumed sags to define the different variables. The variables are as follows:

ω	Skew (Different sag on one side of the building compared to the other side results in skew.)
s_{max}	Maximum settlement (Settlement at a location of the building)
θ_{max}	Maximum rotation (Maximum sag difference between two points on the foundation)
L_{AD}	Building length (or width) of a section
Δ_{max}	Maximum relative subsidence (Maximum subsidence minus the virtual skew line)
β_{max}	Maximum relative rotation (Maximum sag difference in reference to the virtual skew line)
α_{max}	Angular rotation.
δs_{max}	Maximum settlement difference (The difference between the foundation's lowest sag and its highest sag)

The Eurocodes have design limits for skew, rotation, and relative rotation. The design limit for settlement presented in Table 4.5 is not used anymore, because these high settlements can also originate with tall buildings. It can be noted that the Eurocodes contain the most conservative deformation criteria. In different sources of literature examined by De Lange's study, are there different design limits for structural damage. When design limits for structural damage are known, they are used as criteria for design limits for monitoring foundations.

Variables with limit value	Limit value
ω	1/100
S_{max}	150 mm (not used anymore)
θ_{max}	1/150
Δ_{max}	*Sagging:* L/H=1: 1/2,500 L/H=5: 1/1,250 *Hogging:* L/H=1: 1/5,000 L/H=5: 1/2,500
β_{max}	1/150
δs_{max}	*For multi-storey buildings:* L>32 m: 32 mm L<32 m: 0,0005*L till 0,001*L *For single-story buildings:* L>16 m: 32 mm L<16 m:0,001*L till 0,002*L
Deformation rate	*3 to 4 mm/year*
Deformation rate difference of a building element	*1.5 to 2 mm/year*

Table 4.6, Limit values for different deformation parameters from De Lange's table, with the Eurocodes as the primary source.

With one PS-point on a structural element, a settlement limit of 150 mm and a deformation rate of 3 to 4 mm/year can be used as vertical deformation limit. For other limits, at least two PS-points are needed on a structural element. The difference in sag between the two points needs to be subtracted from each other to find out if the limit of 1/150 suffices. As can be seen, larger deformations generally are allowed for the foundation, except if two PS-points are very close to each other.

4.5 Conclusion

SHM assesses a structure's condition (Cross et al. 2012) It could be said that InSAR can be a SHM technique. Deformation measurements for buildings are one of the fields in which InSAR can compete. Competitors in this field are Lidar, photogrammetry, levelling, and tachymetry. One of the main advantages of monitoring with InSAR is that large areas can be monitored with one measurement, and no one needs to be at the site. Companies that already make use of this technology are, for example, Hansje Brinker and TRE.

A specific building or an area with buildings can be monitored. In this thesis, the difference between these two approaches is described as object- or data-driven building monitoring. Building monitoring attempts to detect damage at an early stage, and this is why it looks for causes of potential failure and not for failure mechanisms themselves.

Object-driven monitoring of buildings can be done by monitoring a building and identifying explanations for building movements. The movement of a PS-point is caused by forces that work on a building and by the resistance of the building. Forces that do not change over time, and without degradation of the building elements, will not make the building move. The sum of all movements caused by different factors is, in theory, the movement of a PS-point. In theory, this is described by the following equation:

$$\Delta R_{bt}(t) = \Delta R_w(t) + \Delta R_p(t) + \Delta R_T(t) + \Delta R_{ds}(t) + \Delta R_{df}(t) + \Delta R_v(t) + \Delta R_a(t) + \Delta R_m(t) + \Delta R_s(t) + \Delta R_{gw}(t) \quad (4.1)$$

Change in movement of a PS-point on a structure ($\Delta R_{bt}(t)$), with respect to the previous InSAR measurement caused by a change in:

ΔR_w Movement caused by a change in wind load
ΔR_p Movement caused by a change in precipitation (snow and rain load)
ΔR_T Movement caused by a change in temperature load
ΔR_{ds} Movement caused by a change in total weight of the structure (dead load)
ΔR_{df} Movement caused by a change in interior load
ΔR_v Movement caused by a change in total weight of people in the building
ΔR_a Movement caused by a change in accidental loads (explosion, impact, fire, and earthquake load)
ΔR_m Movement caused by devaluation of a material or connection
ΔR_s Movement caused by a change in settlement
ΔR_{gw} Movement caused by a change in groundwater pressure

Forces that work directly on a PS-point are forces that work on the outer shell of the building. This can be changed by temperature, wind, precipitation, and accidental loading. The following forces that cause movements are described in Table 4.7.

Change in load:	Direction:	The change is:	Noticeable for PS-point:	Recognizable by:	Suitable to monitor with InSAR
Dead load	Vertical	Incidental, for example caused by renovations	Indirect	Sudden change in movement of a point	No
Devaluation	Both	In the first two years and incidental	Indirect	Gradual movement over the first years	Yes, but rarely of influence to the movement
Wind	Horizontal	Unfocused, magnitude of the wind load depends of shape and location of facades	Direct, mainly facades and roofs	Not possible to detect because of the variation in magnitude	No
Precipitation	Vertical	Throughout the year; snow only in temperatures below zero	Direct, roofs	Directly related to precipitation	No
Temperature	Both	Periodic throughout the year, changes almost every day	Direct, roofs and facades	Directly related to changes in temperature, a periodic function over the year	Yes
Weight of people	Vertical	Incidental, only noticeable with many people	Indirect	Related to number of people in the building, will mostly not influence the outer shell	No
Weight of interior	Vertical	Incidental, change in building function	Indirect	Related to changes in the interior, will mostly not influence the outer shell	Yes, but rarely of influence to the movement
Accidental	Both	Incidental, occurrence of an accident	Direct and indirect	Sudden change in movement of a point	No
Settlement	Both	Mainly first five years after construction or by construction activities near building	Indirect	Not only movement of building, also near building, gradual sag over the first years	Yes
Groundwater	Both	Depends on rainfall, ground composition, and surroundings	Indirect	Not only movement of building, also near building	Yes

Table 4.7, Properties of forces for monitoring with InSAR.

InSAR measurements are most suitable for vertical deflection monitoring because of the sensitivity of the satellite measurements. General vertical movements of a point involve temperature, precipitation, settlement, and changes in groundwater. These movements can often be derived by other data. Movements that do not shift in the same directions are not accounted for here. These are, for example, movements caused by buckling and movements caused by second order effects. For object-driven building monitoring, it is important to keep in mind that the movement of a PS-point is a collection of different variables described in the building movement equation.

In reality, it is hard to relate all movements to theoretical movements. Often not all of the forces that work on a building are known. The equations that describe the movements are an approximation of reality, and the sensitivity of the InSAR data also plays an important role.

Data-driven monitoring of buildings can be done by monitoring an area and identifying explanations for movements that may involve buildings. Horizontal movements cannot be monitored with data-driven monitoring, because knowledge of the structure is required to interpret the data correctly. Only an indication of horizontal movement can be monitored in an easterly direction. Vertical movements may be monitored by satellite. Movements of more than 17 mm should be researched. Data-driven monitoring is most suitable for monitoring foundation problems. The movements are often gradual over time, and large movements are allowed. Attention should be paid to the translation of the top structure of the movement. Movements of 3 mm/year of a PS-point in vertical direction, or 1.5 mm/year relative to another PS-point on a building, are alarming.

5 CASE STUDIES

In this chapter the three different building research methods, object-oriented building monitoring, data-oriented building monitoring and forensic research are explored with case studies.

This chapter begins with a data-oriented case study focused on Delft as research area. The main goal of this section is to test InSAR as a data-driven building monitoring tool. The object-oriented case will mainly center on the movement caused by temperature differences of the Erasmus MC. The monitored deformation is compared to the calculated temperature deformation. The chapter ends with two forensic engineering case studies. These are about shopping mall 't Loon and a building in Kerkrade. The 't Loon case analyses the relation of the structural deformation and the retrieved deformation by satellite. The case in Kerkrade looks at the research method with InSAR. These last two case studies will also look at the building monitoring possibilities in hindsight.

5.1 DATA-ORIENTED BUILDING MONITORING

For the data-oriented building monitoring study, the data from Delft was looked at. The data was made available by Hansje Brinker, who also processed the data. The goal is to find a building case in Delft by analyzing the data and to learn how the data should be interpreted.

5.1.1 GENERAL OVERVIEW DATA DELFT

Different maps, such as Google Maps, Bing Aerial and open Streetmaps can be used to project the data. The coordinates from the satellite data are coupled to these maps. Satellite data from the TerraSAR-X satellite ascending and descending are available, as is ascending data from Cosmo-SkyMed. The ascending data of the TerraSAR-X satellite spans from April 2009 to August 2012; and descending data from April 2009 until May 2012. The ascending track makes an angle of 347 degrees with respect to the north and the descending track one of 193 degrees. The incidence angle of the satellite is approximately 24 degrees. The ascending data of Cosmo-SkyMed was recorded from February 2012 until September 2012. The Cosmo-SkyMed data was not used because of the short time period.

The projection of the data is done by adding colored dots in the map. The color stands for the linear displacement rate of a point in mm/year. The linear displacement is an interpolated line from the start of the measurement until the end. This interpretation only gives correct display of the deformation rate of already gradual developing movements over the whole monitoring span. It does not give a good interpretation of the movement that started in the middle of the monitoring period. The deformation rate of the trend line could be lower than the deformation rate of the last segment of the data. A 2-month period moving average could possibly resolve this interpretation error because of the often incidental change of deformation of building damage.

In the map, the red dots indicate a downward deformation of -5 mm/year, and blue ones an upward deformation of 5 mm/year. Green represents a deformation between -1 and 1 mm/year. The color of the dots gives a quick insight of locations with high deformation rates. Next to the movement of the point in time, the quality and the height are also represented in the data. The movement in time of a point with respect to the first measurement can be viewed in a graph. The quality of the point is already described in a previous chapter and the height of the point is also represented. The height of a point can be of importance to confirm if the point is from a building.

The displacements of Delft can be seen from three subsequent years with the TerraSAR-x data sets (figure 5.1). Movements upwards and downwards are the easiest to recognize, because the data generate the same color for these directions.

Figure 5.1, the ascending data of Delft can be seen in the left image, the descending data in the right one. The data is provided by Hansje Brinker. The data for Delft is recorded with the TerraSAR-x satellite and projected on Google Maps. The color scale in the figure presents the deformation rate. Red dots represent a sag of 5 mm/year or higher. Orange represents 3 to 5 mm/year. Yellow 2 to 3 mm/year. Green between 1 mm/year sag or rise. Turquoise 2 to 3 mm/year rise. Light blue 3 to 5 mm/year. Blue 5 mm/year or higher. This color scale holds for all the representations of the data for Delft of the TerraSAR-x satellite. The scale is approximately 1:20000.

The previous chapter proposes that deformations larger than 3 mm/year can be alarming for the foundation of a building. When the data are analyzed it can be seen that large parts of the data in the south east of Delft shows sagging with a deformation rate of about 2 mm/year. This sag in relation to the reference point can be the cause of the global sag of the soil. However, this sag cannot be found in the ascending data of Delft. The global sag of the descending data can be caused by horizontal deformation; this would explain the global difference in deformation rate. Another possibility is that the differences in deformation rate of the two data sets are caused by the movement of the reference point in the descending or ascending data. It is assumed that the data is correct and the deformation is caused by horizontal deformation.

What stands out when the data is analyzed is that three relative large areas sag in both frames (red areas). This means sag according to the InSAR data. These red areas are marked on the following figure (Figure 5.2). The first area represents the new railway tunnel. The second a row of houses at the Goudenregenlaan and the third the parking lots at the Delft IKEA. These areas are discussed in sections 5.1.2, 5.1.3 and 5.1.4.

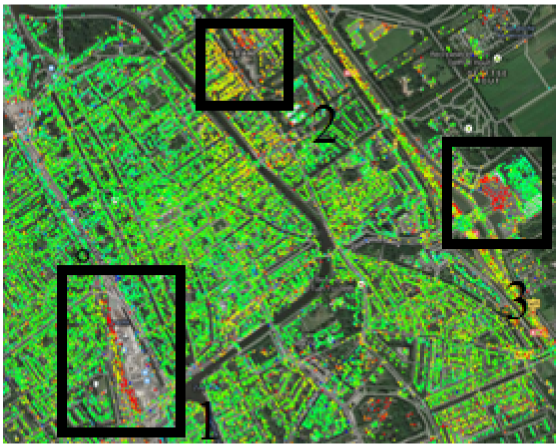


Figure 5.2, the three areas of interest. 1: The railway tunnel in Delft, 2: The Goudenregenlaan and 3: The Delft IKEA. The data is provided by Hansje Brinker. The data for Delft is recorded with the TerraSAR-x satellite and projected on Google Maps. The original scale is approximately 1:20000 (edited image).

5.1.2 THE RAILWAY TUNNEL IN DELFT

A new railway station is being built in Delft since 2009. It is expected to be completed in 2015. This station has platforms under the ground, because the railway that splits Delft in half will be placed underground. The railway tunnel was constructed with sheet piles and diaphragm walls as retaining walls. The area between these walls was excavated, the tunnel was constructed and soil was placed on top to reach surface level.

In the following figure it can be noticed that there are no data points on the railway zone. This is because this area is continuously changing because of the rebuilding of this terrain. The lack of coherent points with the same reflection causes the absence of data points (Figure 5.3). Remarkably, on the left side of the railway zone, there are red dots for both ascending and descending data. For both data the points are moving further away, this means sag of the ground. The change in water level caused by drainage and the retaining walls may explain the predominantly vertical displacement of the soil.

Figure 5.3, in the left figure the descending data of the railway tunnel of Delft. In the right figure the ascending data of the railway tunnel of Delft. The data is provided by Hansje Brinker. The data of Delft is recorded with the TerraSAR-x satellite and projected on Google Maps. The original scale is approximately 1:5000 for the left figure and 1:2500 for the right figure.

Taking a closer look at the tunnel area, there could be observed of possible horizontal displacement of the foundation of buildings near the tunnel because of the difference in direction of the deformation rate (figure 5.4). The ascending image near the tunnel shows many blue dots on the right of the tunnel and the descending image shows many yellow dots. The movement could be eastward, in the direction of the tunnel. If this is the case, then the different color explains a horizontal deformation.

Figures 5.4, the ascending data of houses near the railway tunnel are in the left figure and in the right the descending data of the TerraSAR-x satellite. The data of Delft is recorded with the TerraSAR-x satellite and projected on Google Maps. The original scale is approximately 1:2500.

When one building in particular is analyzed (figure 5.5), 15 dots are seen near the building for the ascending data. Not all these dots are reflections of the building. The height varies from -2.7 to 14.6 m. Assuming that points 5 meter lower than the highest point are not on the building makes points 2,4 and 8 no-building points. With this assumption, it is accounted for the sensitivity of the data and the possibility that the point might be on the façade. On the left, there are predominantly blue dots on the building. For the descending data the measured height seems lower, but if the same rule is applied and 9.6 metres is taken as threshold, then 10 dots suffice (figure 5.7).

Figure 5.5, Streetview of the analyzed building in the left frame and in the right frame the analyzed building in the red square. The original scale is approximately 1:2500. Source: Google Maps.

If it is assumed that the building rotates around the long side of the building parallel to the tunnel and does not move in the length direction of the building, the possible movement can be derived (figure 5.6). The equation for two satellite tracks (equation 2.5) results in an average horizontal deformation of -4.5 mm/year (x-direction, see figure 5.7) and 1.5 mm/year of vertical deformation. This means, if the foundation of the building can be seen as a whole, the building is rotating towards the tunnel. This is plausible.. The sag of the ground near the tunnel may also cause sag of foundations near the tunnel, so the cause of deformation is plausible because the development of deformation (figure 5.8) started when the building activities began at the Engelsestraat, at the end of May 2010 (website spoorzonedelft.nl). Excavations for the sheet pilings were up to 25 metres under ground level, while foundations of the buildings on the Engelsestraat are 20 metres under ground level. These excavations can influence the foundation piles

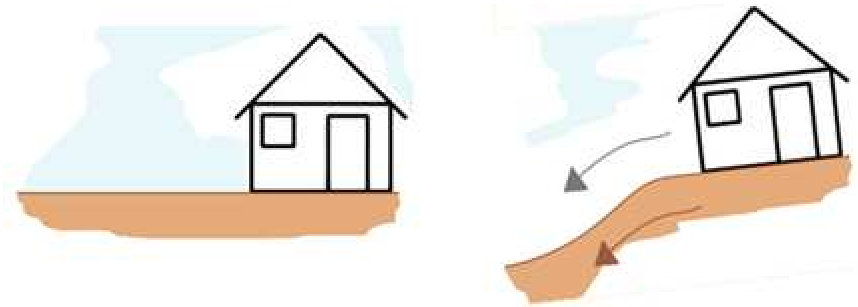


Figure 5.6, a representation of the tilting of the building caused by the subsidence of the soil, caused by the tunnel.

Figure 5.7, the data points of one specific building near the railway tunnel. In the left figure the ascending data and in the right the descending data are seen. The PS-points are numbered for each direction to get a clear overview of the data. The data is provided by Hansje Brinker. The data of Delft is recorded with the TerraSAR-x satellite and projected on Google Maps. The original scale is approximately 1:333.

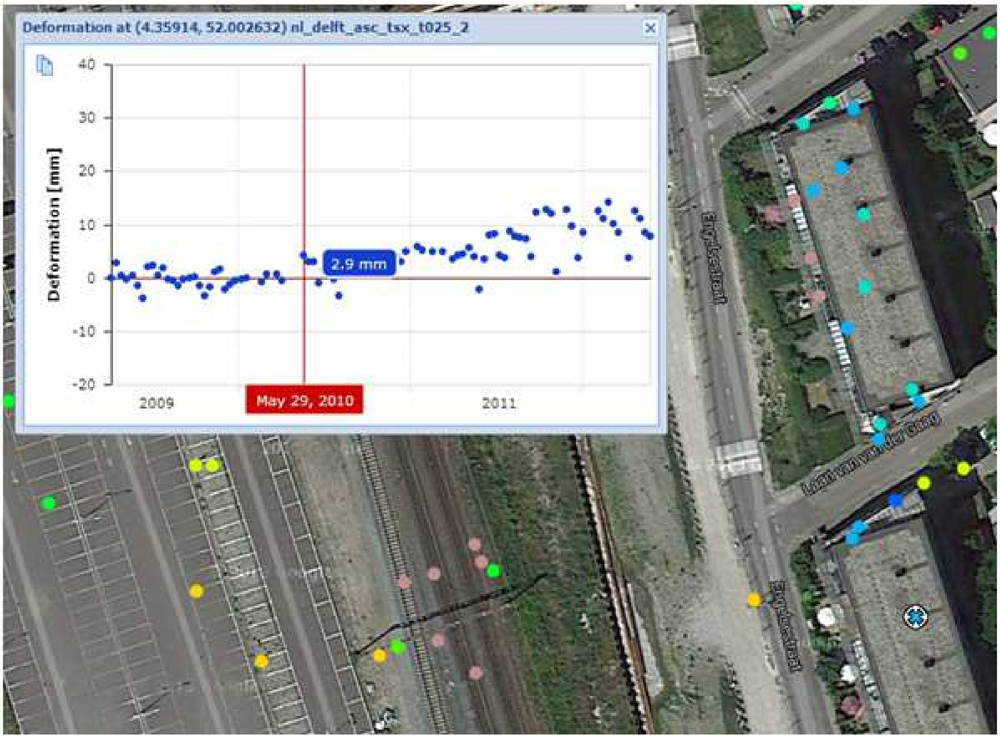


Figure 5.8, deformation of the white marked satellite point started to rise at the end of May. The data is provided by Hansje Brinker. The data of Delft is recorded with the TerraSAR-x satellite and projected on Google Maps. The original scale is approximately 1:666.

The absolute deformation of the buildings over 3 years is overall not larger than +10 mm in the ascending data and -8 mm in the descending data. The mean deformation results in a horizontal deformation of approximately -15 mm and 4.5 mm vertically, if the equation for two satellites explained in chapter 2 is used.

According to Eurocode 7 (2012) 1/300 is admissible in SLS for tilting foundations. For this particular building the width is approximately 13500 mm. In this case, 45 mm is admissible. This is more than 15 mm, which means the building suffices. The deformation rate in horizontal direction is relatively high, although it should be noted that the descending data is sagging in the entire city of Delft, which may be an interpretation error in relation to the reference point or a global horizontal movement, this needs additional research. Further development of the deformation should be monitored.

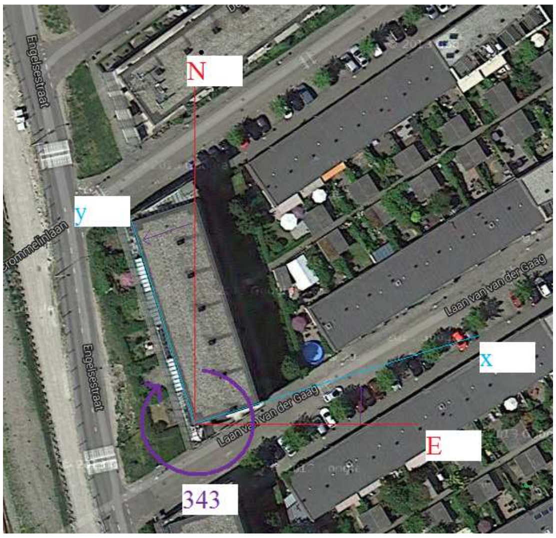


Figure 5.9, the translated directions of the building can be seen in this figure. The data is provided by Hansje Brinker. The data of Delft is recorded with the TerraSAR-x satellite and projected on Google Maps. The original scale is approximately 1:666 (edited image).

5.1.3 THE GOUDENREGENLAAN

Figure 5.10, descending data of the Goudenregenlaan can be seen in the left figure and ascending data in the right of the TerraSAR-x satellite. The buildings with large deformations are numbered. The data is provided by Hansje Brinker. The data of Delft is recorded with the TerraSAR-x satellite and projected on Google Maps. The original scale is approximately 1:2500 (edited images).

In this case the cause is unknown. The descending data got more PS-points than the ascending data, even though the ascending data also show red dots on the same buildings. The red dots on the roof of the buildings show sag up to 20 millimetres. The large area of red dots, located on different buildings, suggests that the soil under the buildings is sagging. This can result in a sagging foundation. In the previous case it was noted that buildings that do not produce

PS-points can be incoherent reflectors, because of large deformations; this could also be the case in the present analysis. A reason for these large deformations can be construction work or buildings that have only just been built, which results in a lack of coherence in the data. It can be seen on figure 5.11 that the marked building lacks PS-points. Also the row of buildings on the left side of buildings 1 and 2 are new.

Figure 5.11, building that lacks PS-points in the left image. This can mean no stable points can be found in this area, because of construction activities. The data is provided by Hansje Brinker. The data of Delft is recorded with the TerraSAR-x satellite and projected on Google Maps. The original scale is approximately 1:2500 (edited images). In the right figure a Google Maps street view of the houses at the Goudenregenlaan.

On Google Maps it can be found that the building had not yet been built in May 2009. (Figure 5.12) This confirms the hypothesis that the building was built recently. The InSAR data also confirm a relation the deformation development in figure 5.13 is looked at. Construction was started in September. Foundation work produces vibrations, settlement and may lower the groundwater level of the surrounding soil, which might cause the sag. When the construction maps are analyzed it could be concluded that, for the construction of an underground parking lot, the groundwater level of the area is affected, and that this is the most likely cause of the sag.

Figure 5.12, Google Maps street view of May 2009 of the building marked in figure 5.11.

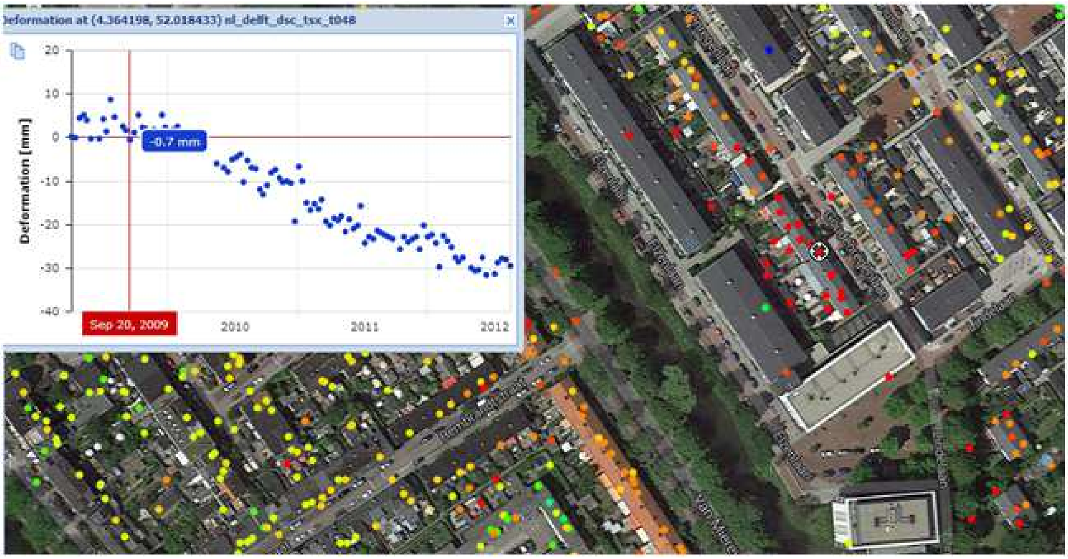


Figure 5.13, deformation development of the white marked point on building 1. The deformation started at the same time as the construction in the end of September 2009. The data of Delft is recorded with the TerraSAR-x satellite and projected on Google Maps. The original scale is approximately 1:1333 (edited images).

There are 46 PS-points near the three buildings. Not all points are reflections of the building. The height of a point is chosen as boundary. The street level is at a height of -3.5 metres. It is assumed that a point reflects a building if a point is visually on the building and is higher than 1.5 metres. 12 points satisfy these demands; slightly more than 25 percent. The first building has 6 points located on the building and these points are the most alarming since they have the highest deformation rate at -10.3 mm/year in LOS-direction. For the ascending data, only 1 point is available and this point is relatively stable. If it is assumed that the foundation moves as one object, and only deforms in x-direction (see figure 5.15) then the equation for two satellites (equation 2.5) can be used again. It was chosen to keep x-direction fixed because this direction is more or less parallel to the new building. The following deformation can be defined: -11 mm/year in x-direction and -6 mm/year upwards, if the descending data points are correlated with the ascending points. A settlement rate of more than 5 mm/year is very alarming. Foundation improvement is recommended for a settlement of more than 4 mm/year, according to criteria of settlement rates used in Amsterdam (Lecture slides A. van Tol CIE4362). The building is very susceptible to sag because of the shallow foundation (figure 5.14). The shallow foundation makes these large sags plausible.

Figure 5.14, raft foundation of buildings in the Goudenregenlaan. Source: Archive of Woningbeheer Gemeente Delft, drawingnumber: 29322 (Plattegronden en doorsneden Bomenwijk).

The situation could also lead to the wrong interpretation of the data. The width of the measured buildings is relative small (7 metres); this makes the data susceptible to interpretation errors. The measurements can be a reflection of the backyard of buildings 1 and 2. Large sag will not be surprising of the backyards, since the backyards of these buildings are practically construction sites. This building and its deformation need to be inspected visually to find out if there are really deformation problems.

Figure 5.15, the translated directions of the building can be seen in this figure. The data is provided by Hansje Brinker. The data of Delft is recorded with the TerraSAR-x satellite and projected on Google Maps. The original scale is approximately 1:666 (edited image).

5.1.4 The Ikea of Delft

Figure 5.16, ascending data of the Ikea can be seen in the left figure and descending data in the right of the TerraSAR-x satellite. The data is provided by Hansje Brinker. The data of Delft is recorded with the TerraSAR-x satellite and projected on Google Maps. The original scale is approximately 1:6666.

If the data at the Delft Ikea is analyzed, it can be seen that the red PS-points do not reflect the building, but the parking area. The parking area may be subjected to settlement, while the Ikea is probably founded on a stable soil layer under the ground. The reason for the sag of the parking area is not further researched. At some places the parking area has sagged up to -40 mm in three years; this may cause inconvenience but is not unsafe and is out of the scope of the thesis.

It can be seen that for the ascending data there are many PS-points at the front of the building on the side of the parking lots, while for the descending data there are a lot of points at the backside of the building. This phenomenon is caused by the direction of the satellite track and is called double bounce points (Figure

5.16). If we look at the points on the building that have a height of 10 metres or higher, it can be concluded that the deformation is not higher than (-)2.0 mm/year for any given point, and for almost all points not higher than (-)1.0 mm/year. The deformations of the building may be caused by temperature, rain and other loads; this may cause the difference in deformation of the structure. The sensitivity of the satellite also contributes to deviation in deformation.

5.1.5 CONCLUSION DATA-ORIENTED BUILDING MONITORING RESEARCH

The areas with the largest deformations in Delft are looked at. The difference in deformation rates between the ascending data and the descending data from Delft suggests a global horizontal deformation in relation to the reference point. Movements of a large area are often foundation problems; this makes these failures the most notable for data-driven building monitoring. For all cases, the movement monitored by the satellite was plausible. The general workflow of data-oriented building monitoring used in this case study can be summarized in a diagram (figure 5.17). When the data are alarming, a quick visual investigation on site is suggested to confirm the data before alarming stakeholders about the possible state of the structure.

Single-point anomalies with a high deformations rate can also be studied. The disadvantage of studying the alarming points is that these deformations are often not the reflection of a building. This makes searching for single alarming points on buildings less suitable for data-driven building monitoring.

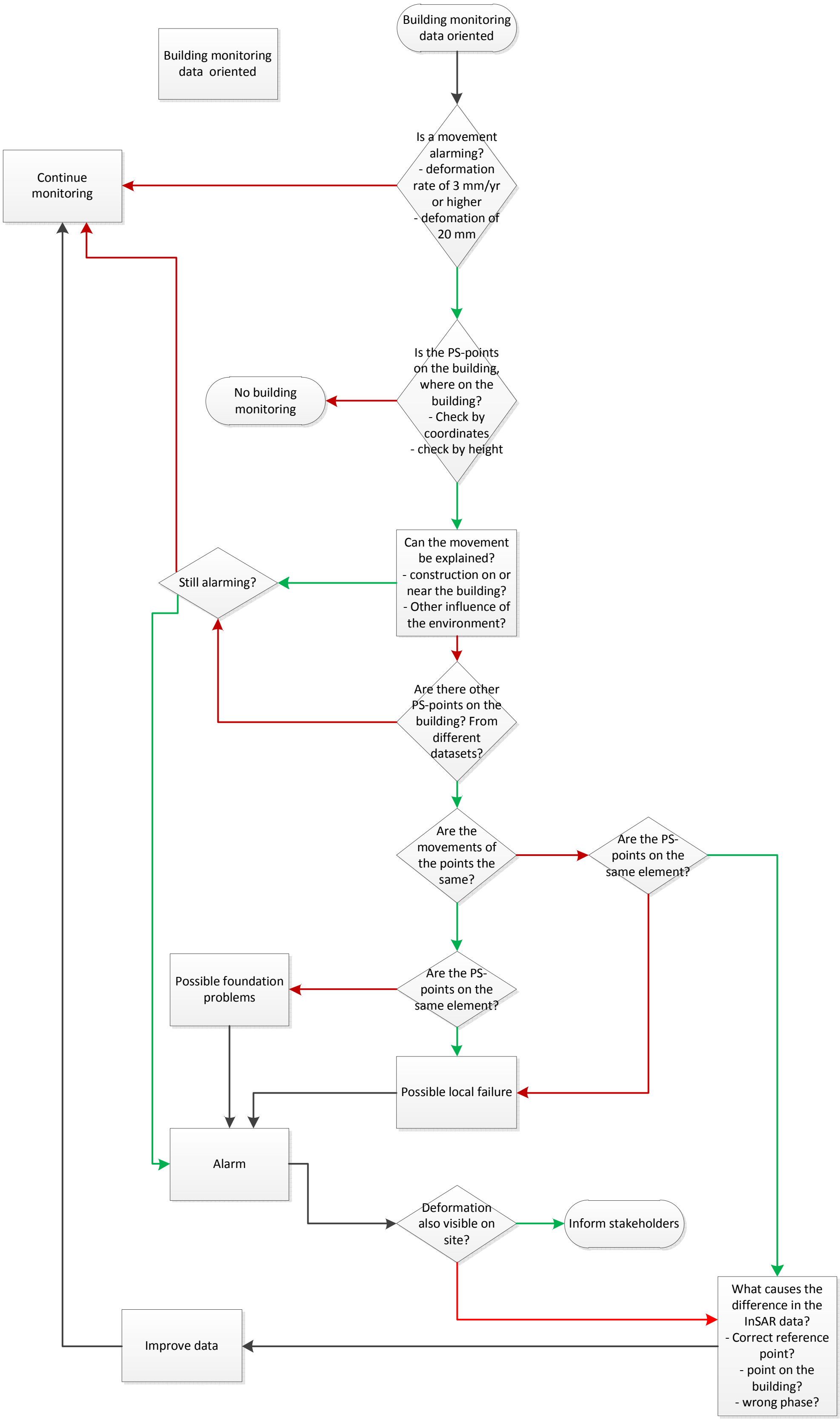


Figure 5.17, the decision tree for using InSAR in data-oriented building monitoring. Diamond shapes are decisions, rectangle a process, red arrows are negative and green arrows are positive.

5.2 OBJECT-ORIENTED BUILDING MONITORING

A movement equation was proposed in chapter 4 for monitoring with InSAR. The present section explores the visibility of one of the entities where the movement is influenced by the known load on a building. Data of temperature movements at Erasmus MC, Delftse Poort, the Millenniumtower and the World Port Center were shown. In this chapter, data of the rooftop of Erasmus MC is analyzed (figure 5.18).

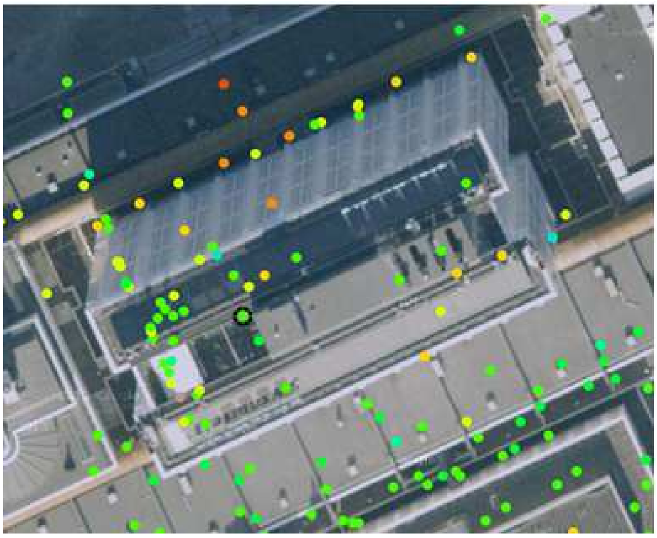


Figure 5.18, top view of the Erasmus MC tower, at 114 metres. Source: Hansje Brinker, ascending data of the TerraSAR-x satellite.

A clear influence of temperature can be seen for almost all points on the roof of this building. This influence can be recognized by the periodic movement caused by the change in temperature throughout the year. The data of the circled point of figure 5.18 is studied. In figure 5.19 the periodic movement can be seen. In the summer the movement is upwards, because of expansion and in the winter downwards, because of contraction.

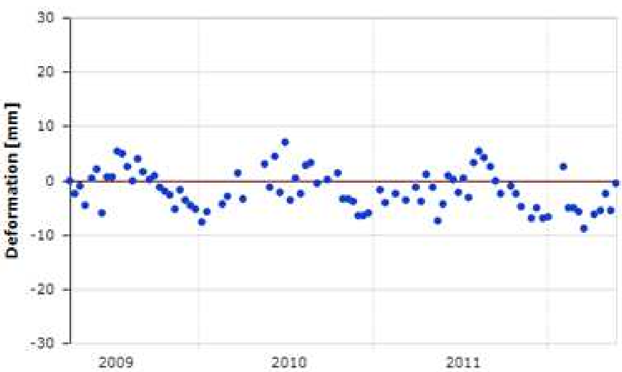


Figure 5.19, deformation data of Erasmus MC from April 2009 until May 2012 monitored with TerraSAR-x, data provided by Hansje Brinker.

The deformation caused by temperature can be compared to the displacement for each date monitored by InSAR. The KNMI provides the temperature for the city of Rotterdam per day. The deformation can be calculated with the temperature equation mentioned in 4.3.6:

$$\Delta l = \alpha * \Delta T * l \qquad (4.5)$$

The thermal expansion coefficient of concrete is considered ($10*10^{-6}/^{\circ}C$), together with a length of 120 metres, and for the difference in temperature the change of temperature in reference to the first measurement is taken. According to the theory, a change in temperature should be linked to the deformation in a linear form, if the influence of the direct radiation of the sun is neglected. In figure 5.20 the monitored displacement and the theoretical deformation by temperature per measurement can be seen.

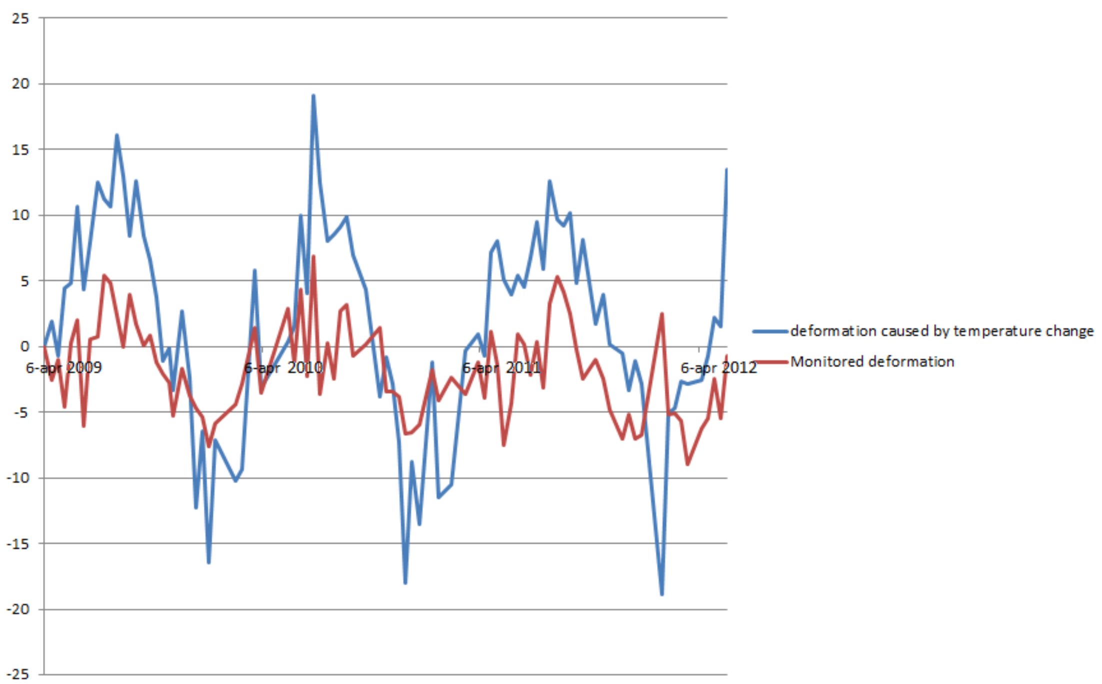


Figure 5.20, Graph of the relative temperature and the displacement per measurement. In red the monitored displacement and in blue the calculated movement by temperature difference. The data is provided by Hansje Brinker. The data of the satellite is recorded with the TerraSAR-x satellite. The temperature is from the KNMI.

The graph confirms the same global trend: If the temperature rises the building expands, if the temperature decreases the building shrinks. The magnitude of the calculated deformation is three times higher in most places. The change in deformation by outside temperature is damped according to the InSAR data. This may be correct, because the temperature inside the building is not accounted for. When the outside temperature is combined with the inside temperature, set at 20 °C (this value can be contested), this results in a deformation that is almost equal to the monitored deformation that can be seen in figure 5.21.

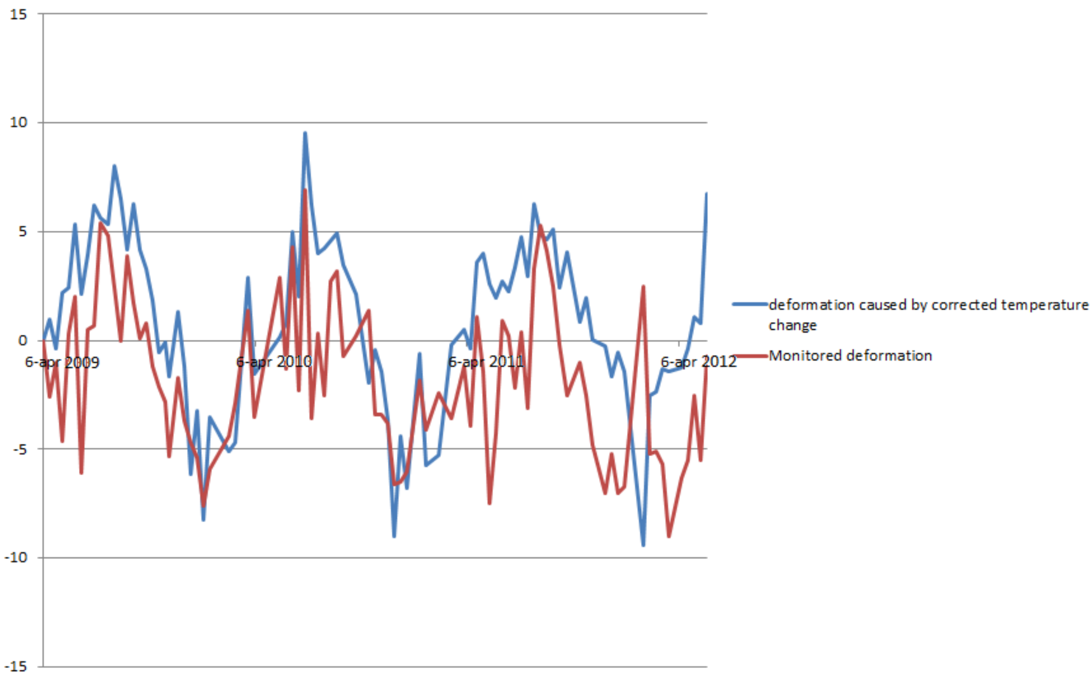


Figure 5.21, calculated corrected temperature deformation is the blue, observed deformation with InSAR in red. The data is provided by Hansje Brinker. The data of the satellite is recorded with the TerraSAR-x satellite. The temperature is from the KNMI.

The deviation in the data may be caused by the incorrect difference in temperature between inner and outer temperature, the radiation of the sun, other movements or the sensitivity of the InSAR data. The observed deformation and the calculated deformation are approximately correct until June 2010. From June 2010 and until the end of the measurement period, the differences between the data become larger. The difference in movement may be explained by movements of the foundation. A new high-rise as built near Erasmus MC. This may cause movements in the foundation of the Erasmus MC complex. The foundation activities for the 3 building parts which began in 2010 continued until April 2012. These activities may explain the difference in deformation between 2010 and the rest of the monitored period. (Figure 5.22)

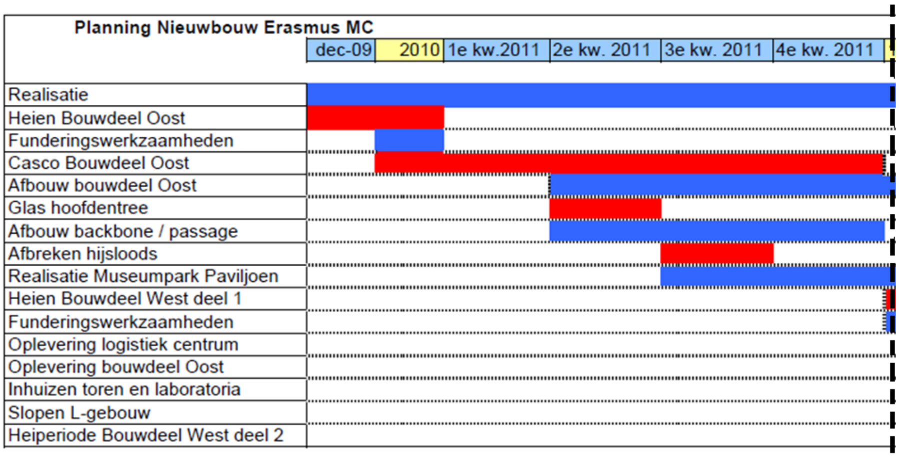


Figure 5.22, planning of construction activities for the eastern part of the new high-rise. Source: Erasmusmc.nl/nieuwbouw.

The clear relation of the temperature in the first part of the monitored deformation ensures that a clear relation can be found between changing loads and the deformation on the building.

5.3 FORENSIC RESEARCH: 'T LOON

One of the motivations of this thesis was that the damage at 't Loon could have been detected with InSAR data, because the sag of the columns developed throughout a long period. The feasibility of using InSAR data was already tested by Chang and Hanssen (2014). A case study with the proposed approach for forensic research is discussed in this chapter, together with what the satellite should have detected based on the known damage. The relation between the data and the expected deformation is put into practice in this case study. The damage is analysed as it was developing and InSAR could be used as spatio-temporal building monitoring tool.

Figure 5.23, shopping mall 't Loon. Source: deondernemer.nl.

5.3.1 Background

Shopping center ‘t Loon was partly damaged on 3 December 2011. A column detached from the supporting structure built in 1965; thereby the structure lost locally its carrying capacity, but did not collapse because of the second load path of the structure. The detachment of the column was caused by a sinkhole under the column (Hordijk, 2012) (figure 5.24).

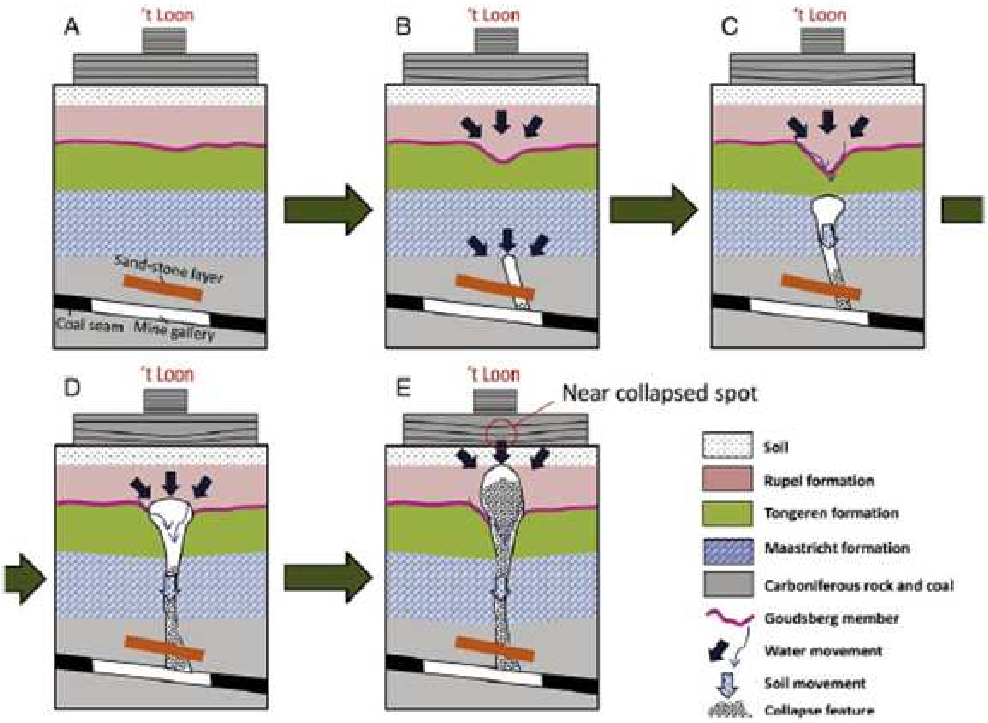


Figure 5.24, developing of the sinkhole in time, source: Detection of cavity migration and sinkhole risk using radar interferometric time series by Chang and Hanssen (2014).

Hordijk (2012) has studied the development of the damage at ‘t Loon. Signs of structural damage were already found in 1989, cracks in the columns of the parking garage could be seen. The structural damage was researched throughout the years by different engineering companies. In 2000 Van der Werf and Nass reported for the first time that the damage may be caused by the foundation footings, and consulted Geoconsult for information about the foundation. Geoconsult suggested that settlements could have been caused by mining activities. They suggested further research and did not mention the possible formation of a sinkhole. On the basis of different researches in the following years, multiple repairs were performed and multiple columns reinforced. The origin of the displacements, namely the, until then unknown, forming of a sinkhole, was not dealt with. This caused further development of cracks in the concrete. During repairs in 2011 a part of a column crumbled and was directly reinforced with a temporary structure (figure 5.25).

Figure 5.25, temporary structure. Source: Dossier Hageman 7998 sinkhole winkelcentrum 't Loon in Heerlen, 2012.

The floor of the parking garage sagged between 12 and 15 cm in the period from 2002 to 2011 (Hordijk, 2012). From November 2011 onwards, 12 columns were monitored for further displacements with an optical cord of 2 metres. The monitoring system measured substantial displacements in a short time and this lead to a clearance of the building. On 3 December a column sagged into the ground and was detached from the building. Hordijk used InSAR data to verify that other parts of the structure were not moving, like the apartments located on top of the mall.

The structure of the shopping mall can be divided in six parts, as can be seen in figure 5.26. The separation is made by function and foundation type. Most of the structure has a shallow foundation; only the two shop parts seen on the left in figure 5.26, which are highlighted in pink with the words 'winkels' have a pile foundation. The part of interest to the present work is the top right part. This part of the structure contained the sinkhole and a shallow foundation on footings. There is a parking area on the ground floor and two layers of shops above. The parking lot is a monolithic concrete structure with larger column heads. On top of these columns there is a concrete floor with two floors of steel structure. The roof is flat. The concrete structure has a column span of approximately 7000 millimetres. The building is approximately 15 metres in height.

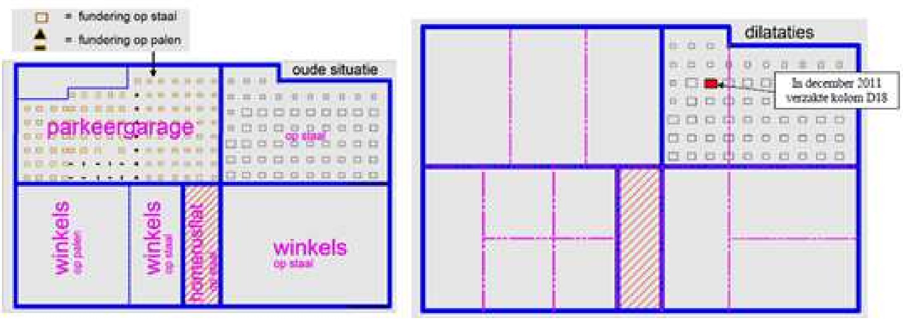


Figure 5.26, the floor plan of the structure with dilatations. Source: Dossier Hageman 7998 sinkhole winkelcentrum 't Loon in Heerlen, 2012.

5.3.2 HYPOTHESIS OF THE MOVEMENT

When a building is damaged and it is necessary to find out how the damage occurred with forensic engineering, InSAR can be used if the damage resulted in movement of the outer shell and took a period of time to develop. The case of 't Loon meets these conditions, which makes research with InSAR possible. An advantage of InSAR for forensic research is the possibility to go back in time and find out how the building moved prior to the damage. InSAR can help to test the hypotheses of what caused the damage. To do so, the expected movement in time of the structure needs to be known.

The cause of the failure is already known and that is why it is not necessary to test different hypotheses, in contrast to the proposed forensic research process in chapter 3. The movement is caused by a sinkhole; this failure mechanism is a translation of the ground that results in a translation of the column. The report of Hordijk (2012) stated that an area between 150 and 200 m^2 subsided approximately 230 mm in a process of years before the damage could be seen. A small part of 30 to 50 m^2 in the middle of the subsiding area subsided approximately 1500 mm in days or hours. The area can be seen in the following figures (figure 5.27).

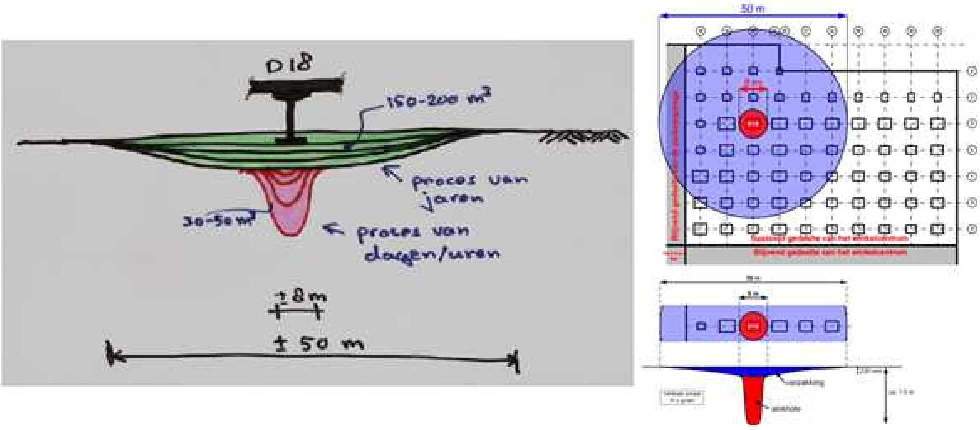


Figure 5.27, right: sketch of the subsidence of the column in time and left: the area around the column that sagged. Source: Dossier Hageman 7998 sinkhole winkelcentrum 't Loon in Heerlen, 2012.

The short development period and the high deformation rate of the actual sinkhole make it difficult to interpret this part of the movement with the satellite. The deformation of the large area may be noted by the satellite data. The gradual movement can be described as presented in figure 5.28 out of the Hordijk report (2012).

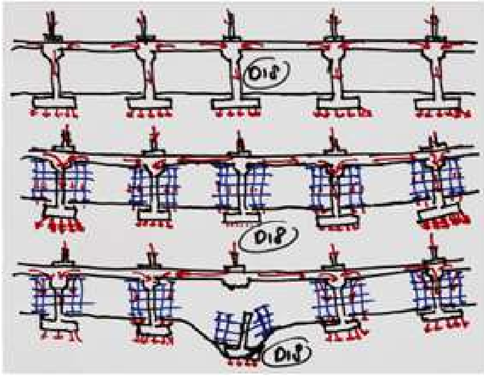


Figure 5.28, schematic presentation of the development of the sag of the column. Source: Dossier Hageman 7998 sinkhole winkelcentrum ’t Loon in Heerlen, 2012.

When the building was constructed, the forces were equally distributed over all columns. In time, a sinkhole began forming under the foundation of column 18. The stiffness of the soil was reduced and this resulted in a reduction of carrying capacity. Therefore, other columns near column 18 had to carry a larger amount of the load. The distribution of forces was caused by the structural redundancy of the building (monolith structure). Structural redundancy is the ability of the structure to redistribute the loads over other parts of the structure without failing, if the original load path fails and thereby loses its carrying capacity (Starossek & Haberland, 2008). The redundancy of the structure results in a smaller movement on the roof above column 18. The reinforcement of the first floor connected to the columns delivered tensile force to keep the floor in place. The size of the reduction cannot be calculated easily because it depends on many different factors, like the connection, stiffness and strength of the elements. The steel structure on top of the concrete structure can be seen as a more hinged structure and will largely follow the deformation of the first floor. The movement of the roof will thereby be a damped movement of the parking floor.

The report of Hordijk (2012) shows the movement of the floor between 2002 and 2011, before the sinkhole was formed. (Figure 5.29) If the movement developed in linear fashion in time, then the linear deformation per year would be 15 mm/year; this is very large.

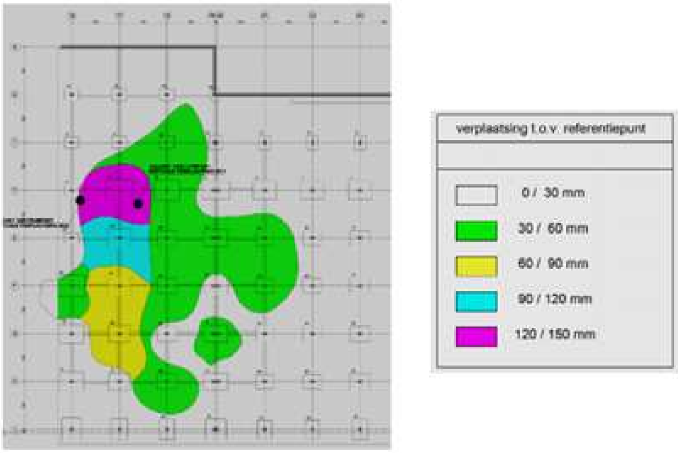


Figure 5.29, the movement of the parking floor according to Dossier Hageman 7998 sinkhole winkelcentrum 't Loon in Heerlen, 2012

The carrying capacity of the foundation was changing locally with time. This movement is related to the development of the sinkhole. When the cavity in the ground grew, the column sagged deeper into the ground. According to Ahmed (2013) the development of the displacements of sinkholes depends on many factors and can have different deformation developments, this means that a general curve that describes the development of deformation is not known. The vertical movement can have different development curves; two points are certain on the curve, and are marked with the crosses in figure 5.30.

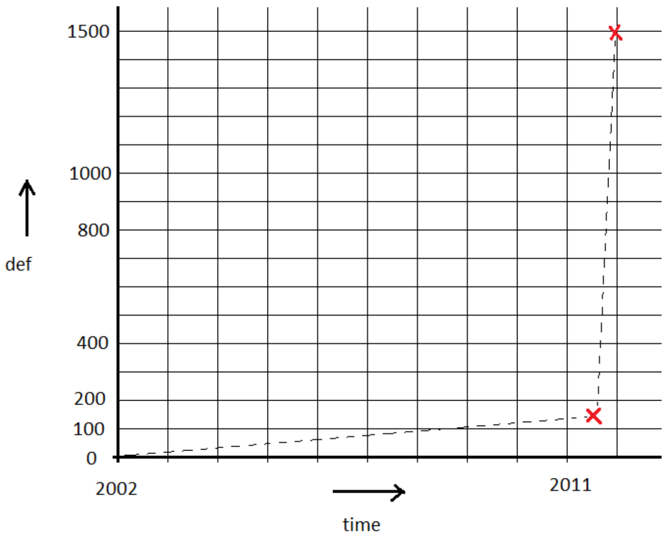


Figure 5.30, graph of certain movement of the column of shopping mall 't Loon at the floor of the parking lot. Deformation is in millimetres.

The dotted lines can have different forms. The dotted line that is interesting for this research is the dotted line between 2002 and the first cross. This deformation looks small, but is already more than 100 mm. To find the damage movement with InSAR, the data need to be understood. The data in LOS-direction can be described as follows:

$$InSAR\ data = \Delta R = \Delta R_{movement\ at\ the\ roof} + \Delta R_{noise} \quad (5.1)$$

The movement at the roof is of interest, because the PS-points of the satellite are mostly on the roof. The ΔR is used because the data is in LOS-direction. In this context the following is meant with noise:

$$\Delta R_{noise} = error\ InSAR\ data + other\ movements\ of\ object \quad (5.2)$$

The error of the InSAR data is already discussed in chapter 2. It is important to note that this error is not constant in time. The main parts of this error are interpretation errors and have a standard deviation of about 3 mm. The 'other movements' that result in a vertical movement are only relevant for this case, although horizontal movements also influence the deformation in LOS-direction. The 'other movements' of the building (object) are caused by movements described previously in chapter 4. If the loads causing a certain movement differ significant in time, this will result in an additional movement of the building.

The movement caused by temperature can be calculated. The movement caused by rain (and snow) load can be calculated, if assumptions are made about drainage. The movement will be close to 0 mm if the drainage of the roof works properly or can have a peak value to the order of about 5 mm with no drainage. It is assumed that the drainage works. The movement of the structure caused by wind, furniture, people and dead load is unknown. What is known is that the movement caused by furniture or people will not cause a large movement on the roof and this is therefore assumed to be 0. The structure was renovated several times, but no large changes were implemented in the building, this is why the movement by own weight of the structure is also assumed to be 0. The movement caused by devaluation of the structure is assumed to be 0, because no devaluation processes of materials are known in hindsight. The general subsidence of the soil and movement can be subtracted from the InSAR data. Around 't Loon, the soil movement was of some millimetres in upwards direction, as can be seen in figure 5.31. The development of this movement is assumed to be linear.

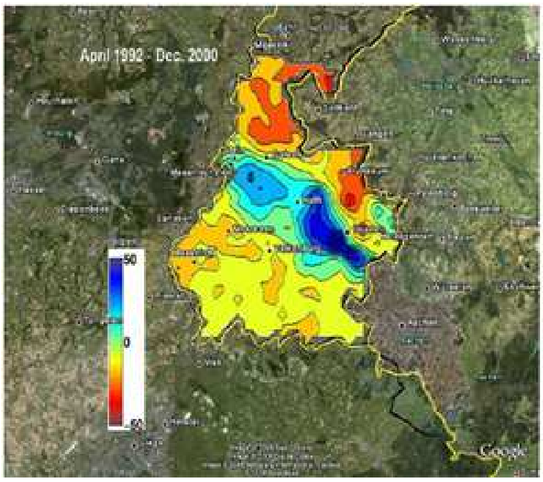


Figure 5.31, soil movement in southern Limburg. Source: Dossier Hageman 7998 sinkhole winkelcentrum 't Loon in Heerlen, 2012.

The movement of the damage on the roof can be described as follow:

$$\Delta R_{movement\ at\ the\ roof} = \mathrm{i}_{redundancy} * \Delta R_{movement\ of\ the\ ground\ floor} \quad (5.3)$$

The movement of the ground floor is the measured movement of figure 5.29. Not the total movement will be seen in the roof, this is caused by the earlier described structural redundancy ($i_{redundancy}$). Theoretically, the total movement of the roof can be estimated by comparing the theoretical sag of the roof in undamaged state and the sag of the first floor without column 18 (Figure 5.32).

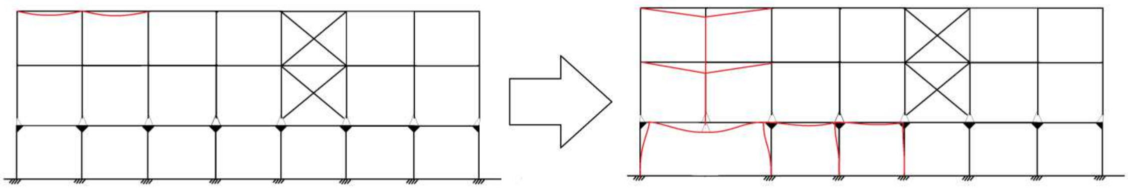


Figure 5.32, theoretical movement of the roof in normal condition and without column 18. The size of the movement is not on scale and is only to give an impression of the movement.

The steel structure on top of the garage is assumed to be connected by hinges, this means that the sag of the first floor results in approximately the same sag on the roof. This makes the stiffness of the first floor beam and the connection of the beams to the roof leading in the translation of the movement. The movement of the beams around column 18 is neglected, because this movement is dominantly horizontal. The way the movement of the sinkhole plays a role in the movement of the roof is the loss in stiffness of the foundation.

$$\begin{gathered} total\ movement\ of\ the\ damage\ at\ the\ roof = \\ total\ sag\ of\ the\ first\ floor\ without\ column\ 18 \end{gathered} \quad (5.4)$$

An approximate calculation of the total maximum deflection of the roof can be calculated, if it is assumed that the beams do not deflect; that design loads reflect the actual loads; and that the steel structure has hinged connections. The sag is not exact calculated with 3D software, because of the scope of this research. A more realistic deformation on the roof is found with 3D software, because the concrete floor will redirect the extra loads in all directions; this will cause a smaller deformation on the roof. Figure 5.33 shows the starting principles for the linear calculated model of MatrixFrame. In figure 5.34 an indication of the expected sag according to MatrixFrame can be found. A deformation of 126 mm can be expected above the column according to this model. This deformation is an estimation to give an idea about the magnitude of the displacement and how the structural system works. Also the loss in stiffness of the other columns is not accounted for. This deformation is not in LOS-direction.

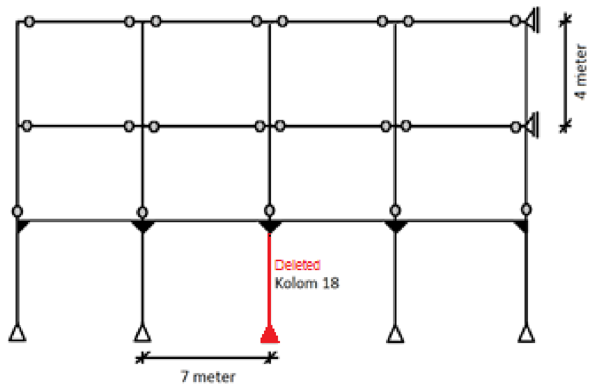


Figure 5.33, starting principles for model in Matrixframe.

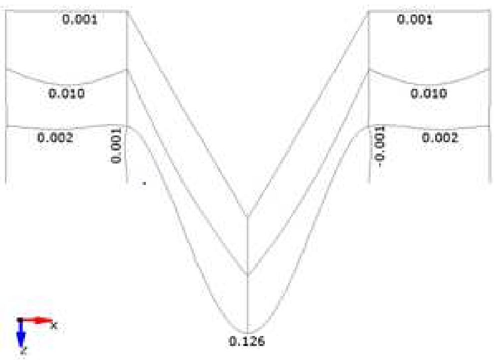


Figure 5.34, sag calculated with MatrixFrame without column 18. The deflection is enlarged to highlight the magnitude of the deflection. Assumed dimensions: (real dimensions unknown) Concrete structure 700x300 mm (columns and first floor), concrete class c25/30. Steel structure I-beam 360x370x134 mm, Steel strength S235. Load on the floors 4 kN/m^2, on the roof 1 kN/m^2. A span of 7 metres in both directions is assumed.

In the InSAR data shown later in this work, a total deformation of 80 mm was found; this is smaller than the estimated 126 mm. The difference in deformation can be attributed to different factors: The assumptions and limitations of the simple calculation. The material properties, the foundation, the spans and the loads are all simplified and estimated for the calculation. The 2D calculation does not take 3D effects into account of the carrying capacity. Further, the measurement period: The InSAR data ends in October and not at the actual failure of December 2011.

The dilatations of the building play a role if the deflection of the roof is looked at. The expansion joints between elements split the structure into different structural elements. If the sinkhole was only present locally at column 18 and there was no other sag in the foundation, then the only movement on the roof could be seen in the yellow hatched part of the following figure. The sag of the soil was an area of 50 metres; this means that surrounding roof areas could potentially have moved as well (Figure 5.35). This movement on the roof was not significant when the InSAR data was analyzed.

Figure 5.35, the yellow part of the structure is the part where sag can be expected on the roof. The green parts of the structure are the parts where sag can also be expected because of the magnitude in diameter of the sinkhole under the structure.

5.3.3 THE DATA

First the data processed by Hansje Brinker was examined. This dataset did not have PS-points on the yellow part of the structure. The datasets processed by Chang (Chang and Hanssen, 2014) were used for this research. The satellites used in this data are ERS-1/2 from 1992 until 2011, Envisat from 2003 to 2010 and RadarSAT from 2010 to 2011. Only one satellite is needed at the same time to detect the dominant vertical movement. In figure 5.35 the PS-points used can be seen in the red squares. There is no data for when the damage actually occurred. Figure 5.36 shows a representation of the damage.

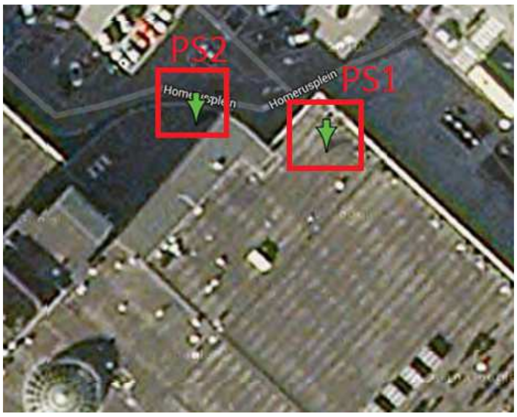


Figure 5.36, the used PS-points by Chang and Hanssen (2014). PS-point 1 is near column 18 and PS-point 2 is on another part of the building.

PS 1 shows -80 mm deformation from 1992 to 2011 near the location where the damage occurred. The data also show that the deformation increases closer to the failure, which makes it plausible that the movement of the roof was higher during the failure at the roof. PS 2, located on another part of the roof, shows almost no deformation because of dilatation. These results were expected and it was what Hordijk (2012) concluded for the apartments.

The data processed by Chang proves that InSAR can be a useful tool to locate building movement, if a hypothesis is made about the expected movement on the roof. It should be considered that the deformation on the roof is different than the movement at the failure; this is because of the structural system. The monolith parking garage works as a bridge above the sinkhole, if the building was hinged, larger deformation could be expected. An important conclusion to this section is that the movement of the failure should always be translated to the location of the PS-points for the right interpretation.

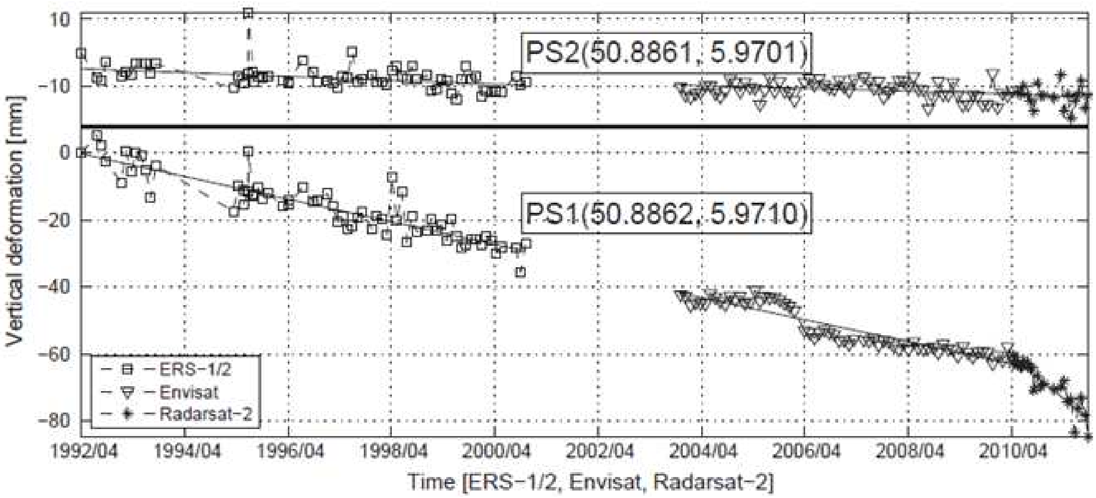


Figure 5.37, the deformation of the two PS-points in time monitored by different satellites. Source: Detection of cavity migration and sinkhole risk using radar interferometric time series by Chang en Hanssen (2014).

5.3.4 BUILDING MONITORING IN HINDSIGHT

Data-oriented monitoring
With building monitoring there is an attempt to detect possible building damage in an early stage to prevent it from worsening. When a building is monitored with InSAR, the deformation should sound the alarm for the failing structure. This deformation has to lead to deformation in the outer shell. The design limits for a failing foundation is a vertical deformation rate of 3 mm/year or more. If ERS-1/2 data is looked at for 1992 to 2000, a period that ends 12 years before the failure, alarming deformation rates of about 3.3 mm/year could be seen then already. Envisat data also observed a deformation rate of about 3.3 mm/year. When the vertical deformation limits of the Eurocodes are looked at with a span of 7000 mm, a deformation limit of 14 mm is the design limit. This limit was already exceeded in 1996. Data-oriented monitoring with InSAR could have detected the damage at an early stage.

Object-oriented monitoring
This is done with one-satellite monitoring. This means InSAR can only monitor the vertical deformation with accuracy. The monitoring of the building could have started already in 1993. In that year, the building was already 28 years old. After 28 years no large settlements are expected if there are no construction activities near the building, although it was known that the soil in Heerlen rises. This should be subtracted from the monitored movement. The periodic movement of the structure by changes in temperature would not be larger than 3 mm. When extra deformation occurs by precipitation, removals or by accidents, this could be anticipated in the data if differences in deformation are found. In hindsight it could be predicted that the large movements of the structure were caused by the foundation or by devaluation of the structure. This should have been researched.

Figure 5.38, Deformation of the parking garage after failure. Source: Dossier Hageman 7998 sinkhole winkelcentrum 't Loon in Heerlen, 2012

5.4 FORENSIC RESEARCH: CAMPUS KERKRADE

This section is moved to confidential appendix 5.

6 CONCLUSION AND RECOMMENDATIONS

This chapter is divided in two parts. In section 6.1 the conclusion of this research are found. In section 6.2 the recommendations are presented.

6.1 CONCLUSION

The main research question is solved by answering the formulated sub questions in chapter 1. This section concludes with the research objective obtained.

Interferometric Synthetic Aperture Radar

- *Sub-question 1: How should deformations measured by InSAR be interpreted?*

InSAR can periodically measure deformation of a certain location in the LOS-direction. Buildings are often stable reflectors. The direction is mainly vertical; this makes deformation measurement of vertical displacements the most suitable for InSAR. Horizontal deformation measurement with InSAR is interpretation sensitive; this makes InSAR less suitable for horizontal deformation monitoring. An indication of the direction of the data can be derived when multiple satellite datasets are available of the same element in the same time period. With two satellites one building direction has to be assumed as constant. The sensitivity of the deformation depends on its direction. To avoid ambiguity of the data a maximum deformation per measurement of 7.5 mm is allowed for x-band satellites. The deformation rate can be measured with millimetric accuracy. The accuracy of the location of the measurement is to the order of a metre.

Forensic engineering

InSAR can be used as forensic engineering tool. Forensic engineering researches engineering failures. The database of building deformation before research is initiated makes InSAR a unique tool for research. Information about the movement prior to the failure can be retrieved. The database gives the possibility to link activities in time that might instigate the failure. Failures that present deformation in the outer shell can potentially be researched by InSAR. Deformation hypotheses that relate to the failure and the PS-point have to be explored before researching a building with InSAR in order to find out whether InSAR can contribute to validate the hypothesis. The relation between the failure and the deformation of the outer shell is important. Deformations of failures that cause deformation of the main supporting structure of monolithic buildings can be damped.

- *Sub-question 2: What kind of damage can the satellite recognize, and how do these failure mechanisms express themselves in deformation?*

Damages caused by torsion, inelastic deformation, fracture, second order effects and buckling are hard to see with InSAR. Damaged caused by translation, rotation and elastic deformation got the potential to be researched. Deformation caused by these failures needs to be visible on the outer shell of the structure. The magnitude and the development of the deformation caused by the failures cannot be predicted.

- *Sub-question 3: Is InSAR's potential contribution to damage research of significance?*

One fifth of the damage database cases in the use phase of buildings in the Netherlands 1997 and 2009 have the potential to be researched by InSAR if satellite data is available. Failures caused by structural errors and aging can be researched with InSAR. Failures that affect outer shell elements in deformation can be researched.

Building monitoring

- *Sub-question 4: What are the potential advantages and disadvantages of InSAR as compared to conventional monitoring techniques?*

The area that one satellite observation can measure is very large, which makes InSAR unique as a monitoring tool. The possibility to monitor the deformation of a building night and day for a period of time without being on site is another unique feature of InSAR as a monitoring tool. The accuracy and the measurement in LOS-direction are a disadvantage compared to monitoring techniques on site.

- *Sub-question 5 and 6: What is the procedure and how can InSAR data be interpreted for use in object-driven building monitoring?*

Which parts of a building and what kind of deformation can be monitored in object driven monitoring can be determined in advance. Which parts can be monitored by PS-point location depends on the number of PS-points, datasets and time period of monitoring. Deformation of the monitored object can be explained by the movement equation of a building (Equation 4.1). On the basis of this equation, deformation limits can be determined for each element monitored. Deformation caused by changes in temperature, ground-water and settlements can be monitored with InSAR. More important is that this equation highlights that most deformations monitored by InSAR are often influenced by different movements. The failure needs to develop over a longer period of time, to use InSAR as an early detection tool for possible failure. Sudden failures caused by accidental loads cannot be predicted by InSAR.

- *Sub-question 7 and 8: What is the procedure for data-driven building monitoring with InSAR and is there a potential general threshold to indicate building damage?*

Data-driven building monitoring is difficult, because a great amount of non-building related PS-points have larger deformations than the proposed deformation limits. The vertical deformation rate limit for the foundation is alarming for all buildings when it is larger than 3 mm/year. This makes data-driven monitoring of foundations damage suitable to be performed with InSAR. An additional advantage is that foundation damage often influences multiple PS-points. Deformations near construction activities can often be detected by the lack of coherent points on the constructed building. When a point is alarming further analysis of the point is required, is the point really on a building, is the deformation rate plausible, what could be the cause of deformation and are more points on the building deforming?

- *Main research question: How can InSAR data contribute to forensic engineering and building monitoring?*

InSAR can become an addition to conventional monitoring techniques for building research. For forensic engineering InSAR can indicate which parts of building elements were influenced by the failure, and when deformation started to develop. InSAR can support evidence for the possible cause of the failure, when the failure is expressed in deformation. For building monitoring InSAR may support the indication of the development of deformation that may cause damage. The monitoring of vertical deformations is limited by the sensitivity and the phase ambiguity. These boundaries make InSAR most suitable for monitoring gradual deformations, often found in deformations of foundations. Building elements with warning of deformation may be detected by InSAR for further inspection with conventional techniques.

This research gives a global indication of the potential of InSAR as building research tool. Starting principles for monitoring in different building research fields are formulated and outlines of the monitoring process with InSAR are proposed. This research is a first step for the interpretation of InSAR data as a building research tool.

6.2 RECOMMENDATIONS

This section will start by illustrating and discussing the insights of this thesis. Most of the research limitations were already discussed in Chapter 1.2.1. This section concludes with recommendations for follow-up studies.

InSAR is an evolving technique that is still developing. InSAR data processing is becoming more and more accurate, and the number of satellites available to measure InSAR data is still increasing. The sensitivity of current InSAR horizontal deformation measurements is susceptible to interpretation errors. A deformation Insensitivity of 34 mm in North direction for the Envisat satellite in a horizontal direction is significant. This makes horizontal deformation detection unreliable, although sensitivity will become better in the future. This could make horizontal deformation monitoring possible for InSAR. At this time, InSAR can only suggest the presence of horizontal deformations.

The location of the PS-point can cause interpretation errors. Sometimes the point does not reflect the building while the projection is on the building. This can be caused by the interpretation errors discussed in Chapter 2. These errors sometimes give the impression that the building is deforming, while in actuality it is the ground near the building that is deforming. Information about height can help minimize these interpretation errors. The possibility of selecting data by height might add value, because often the highest PS-points are from buildings.

For forensic research, the possible relationship between the damage and the PS-point must be analysed. When the PS-point is uninfluenced by the damage, this may help to indicate undamaged parts of the building.

With InSAR monitoring the danger of viewing a black-box can arise. The understanding what is monitored, a building, is lost. This can give a false impression that a structure's deformation limits suffice, while parts of the inner structure are damaged. Infrastructure and hydraulic structures have the advantage that they do not need to make this interpretation, this result in a more global coverage of possible monitored failures. Another disadvantage for the monitoring of buildings is that buildings can be made of brittle material. Brittle materials do not show much deformation before failure, and this means that damage development is often not possible to research.

The proposed theoretical movement equation (Equation 4.1) is difficult to utilize in practice. On the one hand, the magnitude of the factors that play a role in building deformation is often unknown. On the other hand, it is hard to interpret the movement of a PS-point if it is influenced by horizontal deformation. A research possibility could be to monitor a structure in a somehow controlled environment, and with other techniques, to learn more about the interpretation of the deformation of PS-points.

Recommendations for follow-up studies
A research study is recommended to test the feasibility of InSAR for only one element or for one failure mechanism. In this research, all possibilities have been described in general. The recommended research could examine the subject in greater depth. It is suggested that such a research study could focus on deformation failure mechanisms in foundations.

The failure database of Terwel was tested using the basic principles of InSAR research. The database should also be tested with InSAR data to validate the assumptions that have been made.

InSAR adds value by monitoring areas with an increased risk for foundation deformation. An increased risk could arise because of the formation of possible other cavities in Zuid Limburg or because of the sag of buildings due to gas extraction in and near Groningen. Another way InSAR adds value is by monitoring difficult-to-access areas. Yet another advantage of InSAR is its ability to completely monitor large structures with a single measurement. For onsite measurement techniques, this is often impossible or else very time-consuming and expensive. Additional study should be undertaken in the fields of business and legal studies on how InSAR can be a future profitable building research tool.

For data processing, it is recommended to subtract movements caused by temperature load and groundwater level changes. The subtraction of these variables may make other causes of PS-point movements more visible in data-driven research.

Other possibilities for measuring the deformation rate should be tested. For example the use of a linear model for variable time periods. Data-driven building monitoring should be further explored. Single PS-points with alarming deformations should be researched, and more clear indications of alarming deformations should be researched as well. Also, the processing possibilities for comparing deformation differences of neighbouring PS-points located on the same structural element should be further examined.

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List of symbols

Chapter 2

λ	Radar wavelength
$B_{\perp}$	Effective distance
B_T	Temporal baseline
A	Earth’s atmosphere
D	Deformation
S	Surface
$\Delta\varphi_t$	Total phase shift
$\Delta\varphi_{topo}$	Phase shift due to shift in topographic phase
$\Delta\varphi_{def}$	Phase shift due to deformation
$\Delta\varphi_{atm}$	Phase shift due to the atmospheric delay
$\Delta\varphi_{geom}$	Phase shift due to a change in the scatter characteristics of the Earth’s surface
$\Delta\varphi_{noise}$	Phase shift due to noise (e.g. thermal noise, co-registration errors, and interpolation errors)
ΔR	Deformation
ΔR_U	Deformation in Up direction
ΔR_N	Deformation in North direction
ΔR_E	Deformation in East direction
α_h	Heading of the satellite
θ_{inc}	Incidence angle
γ	Angle of an object in a local coordinate system in reference to the global coordinate system
ΔR_X	Deformation in x-direction of a local coordinate system
ΔR_Z	Deformation in z-direction of a local coordinate system

Chapter 3

S_d	Load on a structure
R_d	Resistance of a structure

Chapter 4

U_x	Horizontal translation
U_y	Vertical translation
ω_{xy}	Rotation
ε_{xx}	Deformation in x-direction
ε_{yy}	Deformation in y-direction
γ_{xy}	Deformation in x and y-direction
ΔR_w	Movement caused by a change in wind load

ΔR_p	Movement caused by a change in precipitation (snow and rain load)
ΔR_T	Movement caused by a change in temperature load
ΔR_{ds}	Movement caused by a change in total weight of the structure (dead load)
ΔR_{df}	Movement caused by a change in interior load
ΔR_v	Movement caused by a change in total weight of people in the building
ΔR_a	Movement caused by a change in accidental loads (explosion, impact, fire, and earthquake load)
ΔR_m	Movement caused by devaluation of a material or connection
ΔR_s	Movement caused by a change in settlement
ΔR_{gw}	Movement caused by a change in groundwater pressure
ΔR_{mold}	Movement caused by mold
ΔR_{rot}	Movement caused by rot
ΔR_{corr}	Movement caused by corrosion
ΔR_{creep}	Movement caused by creep
ΔR_{shrink}	Movement caused by shrinkage
s	Representative snow load
μ_i	Snow load shape coefficient
C_e	Exposure coefficient
C_t	Thermal coefficient
s_k	Characteristic value of the snow load
$p_w(x)$	Characteristic value of the present rain load on position x on the roof
$d_{hw}(x)$	Water level on the non-deformed roof
$d_n(x)$	Water level caused by the deflection of the roof, as caused by water accumulation
γ_w	Volumetric weight of water (10 kN/m^3)
α	Thermal expansion coefficient
ΔT	Difference in temperature
L	length
ΔL	Difference in length
u	Vertical shortening of a column
F	axial load
E	Young's modulus
A	Area
Δ_n	Column shortening of an entire building
h_i	Storey height
S_d	Total sag
$S_{0;d}$	Sag caused by shear formation
$S_{1;d}$	Primary subsidence
$S_{2;d}$	Secondary subsidence
$C_{c;j}$	Compression ratio of ground layer j
e_j	Pore number of ground layer j
h_j	Height of ground layer j in metres
$\sigma'_{v;z;0;d}$	Total building weight
$\Delta\sigma'_{v;z;;d}$	Effective soil stress

$C_{a;j}$	Secundaire compression ratio of ground layer j
t	Time
s	Sag of the top of the foundation element
s_1	Sag of a single pile
s_2	Sag of a pile group caused by the compression of soil layers under the pile tip
s_b	Empirical value of the sag of a pile tip caused by a vertical load
s_{el}	Sag on top of a pile with respect to the pile tip, caused by the elasticity of the pile
s_{el}	Sag on top of a pile with respect to the pile tip, caused by the elasticity of the pile
L	The length of the pile
$F_{gem;i}$	Calculation value of the average normal force in the pile shaft, dependent on the total of vertical forces working on the pile and the carrying capacity
$A_{schacht}$	Area of the section of the pile shaft
$E_{paal;nom}$	The nominal modulus of elasticity of the pile shaft material
W_c	Sheer (in Dutch: *zeeg*)
W_{max}	Total permissible deflection
W_1	Initial deflection caused by the floor's own weight
W_2	Long span
W_3	Additional deflection caused by live loads.
l_{rep}	Length of the span, or two times the length of the cantilever.
ω	Skew (Different sag on one side of the building compared to the other side results in skew.)
s_{max}	Maximum settlement (Settlement at a location of the building)
θ_{max}	Maximum rotation (Maximum sag difference between two points on the foundation)
L_{AD}	Building length (or width) of a section
Δ_{max}	Maximum relative subsidence (Maximum subsidence minus the virtual skew line)
β_{max}	Maximum relative rotation (Maximum sag difference in reference to the virtual skew line)
α_{max}	Angular rotation.
δs_{max}	Maximum settlement difference (The difference between the foundation's lowest sag and its highest sag)

APPENDIX 1: STRUCTURAL SAFETY

When a building (partly) collapses one of the first questions that comes to mind is; '*why was the building not safe enough*?' To answer this question an introduction is given of the definition of structural safety. When an accident occurs often an extensive research by stakeholders is done. In cases of large damage public debate can instigate political intervention. According to the book 'Leren van instortingen' (Herwijnen, 2009) this was the case in 2003 when balconies came down in Maastricht. Several investigations were started by the government, how the structural environment could be safer. This brought multiple platforms to life, like VN-constructeursplatform and the CUR-commissie, who launched platform structural safety and the ABC-meldpunt. This public attention emphasizes the actuality of structural safety. In A1.1 an introduction will be given about structural safety. In A1.2 an introduction is given to the norms that support structural safety. In chapter A1.3 the roll of the structural engineer is introduced with respect to structural safety. To define structural safety a lot of use is made of chapter 2 of the upcoming doctoral dissertation of Terwel (2014) and the master thesis of Boot (2010) about structural damage.

A1.1 INTRODUCTION

The collapse of a construction mostly leads to economic damage and can cause injuries and even loss of life(s). By means of the building regulations the probability of failure is kept under a socially acceptable limit. It would be expected that there is structural safety if the probability of failure is zero. But absolute safety does not exist. The lecture notes of steel 2 (Bijlaard, 2006) gives a description of the term structural safety:

"The safety philosophy underlying structural safety is based on the probability that circumstances may arise that (may) lead to failure of a structure during the period of use. The probability of failure of a structure (caused by insufficient strength or instability) is influenced by the statistical variations in the loads on the structure and the statistical variations in the capacitance (variations in the strength of materials, cross-sectional dimensions and straightness of elements) of the structure. The size of the probability of failure that is socially accepted is directly related to the consequences of the failure of a structure (personal injury, economic loss)."

A lot of slightly different definitions can be found. So is, according to Hollnagel (2006) safety the sum of accidents that do not occur. According to the Dutch Building Decree (Bouwbesluit 2012) the definition of structural unsafe is defined as the chance of failure of a construction. These definitions raise two questions according to the book Basis Constructieleer (2001). Namely, what chance of failure is acceptable and how large is the chance that a structure fails during its use period? These questions make the term structural safety partly subjective. What chance of failure is acceptable? One may think something is completely safe but the other may think it is unsafe. The answer to the other question is not that easy to answer, how is the chance of occurring of failure calculated? Which factors are used for the calculation and what uncertainties can be foreseen? The building decree tries to answer these questions in an objective manor. It gives minimal guidelines to make a safe structure. By following these guidelines not always a safe structure will be created. In the distant past structural safety was determined by trial and error. If the construction did not collapse it was safe. Nowadays the structural safety depends on several factors. There are five factors that influence the structural safety according to the book 'Leren van instortingen' (2009):

1. *Knowledge of mechanics and structural engineering;*

With the knowledge of mechanics the behaviour of a building in different circumstances can be predicted. This makes the calculations more accurate. This will increase the structural safety. According the discussion 'Kasteel of Kaartenhuis' (2007) this knowledge is decreasing in the last decade, the cause is the quality of education and decreasing practice knowledge according the discussion. A downside in the increase of knowledge and the more advance calculation methods is the decrease of robustness in the calculation according to the report 'instortingen van lichte daken' (2003). This means a lower safety margin.

2. *Tools for making the calculations;*

The more advance engineering software on the market and the increase of computer memory makes the calculation time lower and able to visualize the structure, this also increases the safety. It should be noted that the engineer should always be aware that the software does not become a black box. This induces the danger of interpretation mistakes.

3. *Submission of new and stronger materials;*

With the use of conventional materials the physical and mechanical properties are known. This is less the case with the use of newer materials, though these newer materials aim to possess higher and more equal quality.

4. *Communication and information provision;*

With the use of more advance software, computers and telephones the communication and information provision is getting better. On the other hand an overload of information may contribute to unclear communication. This overload of information is generated by the ease of producing new drawings and information. There may also be a loss of communication in the classic tender, when the project is transferred from architect to constructor.

5. *Economic and technological development;*

There is also a clear relation between the economic and technological development of a country, the higher the development the higher the demand for safety. An increasing chance of failure usually means a less expensive structure.

These structures are in more developed countries not socially accepted. The selection criteria during a tender is another economic factor that influents the quality. The selection of an architect, consulting engineer and other consultants is often price driven. The quality of the service is less important (Vambersky, 1997)

Besides the five discussed factors, Boot (2010) also states that the lack of professional principals, the owners of the structure and the increase of complexity of structures influence the structural safety. The principal is often assisted by various consultants. The selection of these consultants is often poor though; they underestimate the importance of the designing party and assume that safety is guaranteed. (Vambersky, 1997) Architects always seek more challenging designs like, tilting facades and cantilevers. The structural engineer needs to make a very complex structure to realize the design; these challenges bring risks with them. (Vambersky and Terwel 2009)

Vambersky and Terwel (2010) categorized the factors that influence the structural safety in three categories: micro, meso, and macro level. (Figure A1.1)

- Micro level: Causes by mistakes or insufficient knowledge of the person involved. If another person would not have made this mistake than there can be spoken of a cause on micro level.
- Meso level: Causes located in the organization, and management of a project, like communication or coordination. If another organization would bring the project to a good result than there can be spoken of a cause on meso level.
- Macro level: Causes located in the regulations, the culture of the industry or other external conditions. If another regulation, another culture or other external conditions had led to a good result than there has been a cause at the macro level.

Figure A1.1, possible influencing factors. Source: Vambersky and Terwel (2010)

All these factors contribute to the structural environment. To express the structural safety the required safety level of a building needs to be known. The safety level depends on the chance an event may occur and the value of a building. In formula this means:

$$R = P * S \leq A$$

R is the risk, P the chance of occurrence of an undesirable event, S the amount of damage and A the acceptance. With the acceptance the economic value is meant, also the possibility of loss of life and the danger for society if a building is damaged falls under this term. The higher the risk, the lower is the chance of occurrence for an accepted safety level. "Safety is a psychological concept that is strongly related to risk. One might say that safety is operationalized through the concept of risk." (Kuijper et al. 1997). In the building codes there are several guidelines that express this security level by the height of desirable safety factors. This will be discussed in the next chapter.

A1.2 Norms in the Netherlands

When realizing a building plan in Holland one must meet the requirements of the building decree (het Bouwbesluit, 2012). These requirements are safety, health, usability, energy efficiency and environment for different types of buildings. The building decree refers to a variety of standards and regulations which a structure should meet. As a functional demand for structural safety Building Decree states: "a proposed structure shall be sufficiently resistant to the forces impinging upon it." (het Bouwbesluit, 2012) and "a load-bearing structure shall not collapse, during the designed useful life referred". The authorities need to check the building application in line with these regulations. The accountability for structural safety is always the responsibility of the applicant of the building permit. The authorities test the requirements with a preventive test, the so called BRIStoets. The authorities will also monitor whether the implementation is carried out in accordance with the permit and building regulations after the permit is granted. (Banga, 2012)

A building must be structurally safe. The building decree 2012 specifies this requirement. The structure may not collapse or deform in such way that unsafe situations occur. In The Netherlands the framework for technical building regulations is set in the Housing Act (in Dutch: Woningwet) Further the building decree refers to the new construction standards, the Eurocodes for structural safety. The Eurocodes are European standards and guidelines for the construction industry. These norms are established by engineers, scientists, users and professionals in practice. There are currently 10 Eurocodes. In Eurocode 0, which refers to NEN-EN 1990, the main principles of structural design are discussed. (NEN is short for 'Nederlandse normen' and EN for 'Europese Norm'.) This includes the basic standards that refer to the use of load combinations with the corresponding load factors for different situations to calculate the ultimate limit state. The ultimate limit state of a structure is needed to require a particular level of safety. Besides that the structure should be designed and calculated to possess sufficient structural resistance, serviceability and durability. The Serviceability Limit State (SLS) covers situations like local damage, unacceptable deformations and excessive vibrations. The Eurocode works with the main design principal that the resistance of a structure should be larger than the effects of the loads. (Terwel, 2013) In the case of fire, the structural resistance must be sufficient for the prescribed duration of the fire. To assess extraordinary situations the following is stated: The structure shall be designed and constructed in a way that it will not be destroyed by events such as explosions, shock loads and the effects of human error to an extent disproportionate to the original cause.

In Eurocode 1, which refers to NEN-EN 1991, the loads are given that should be used in different cases, like snow, wind, extraordinary load and roof- and floor load. In Eurocode 2 to 6 and 9 design rules for different materials are introduced. Eurocode 7 is related to geotechnical design and Eurocode 8 to earthquake resistant structures.

The required reliability of structures within the scope of NEN-EN 1990 must be required by designing and calculating the structure in accordance with NEN-EN 1990 until NEN-EN 1999. The fundamental reliability according to het Bouwbesluit (2012) is defined as the limit state which should not be exceeded during the estimated referential period, while respecting the pre-determined amount of reliability. Reliability covers safety, serviceability and durability of a structure. In the vision of Eurocode structural safety is just one aspect of reliability. To determine the reliability the Eurocode (NEN-EN 1990, 2002) uses two different classes. Full probabilistic methods (Level III), and first order reliability methods (FORM) (Level II) are used. The full probabilistic methods (Level III) give in principle correct answers to the reliability problem as stated. The level II methods make use of certain well defined approximations and lead to results which for most structural applications can be considered sufficiently accurate. In both the Level II and Level III methods the measure of reliability should be identified with the survival probability P_s.

$$P_s = 1 - P_f$$

Where P_f is the failure probability for the considered failure mode and within an appropriate reference period. If the calculated failure probability is larger than a pre-set target value P0, then the structure should be considered to be unsafe. Level III methods are seldom used in the calibration of design codes because of the frequent lack of statistical data. (NEN-EN 1990, 2002) Level I calculation is a part of level II calculations. As stated by Terwel (2013) Level I calculations are based on the assumption that an element is sufficiently reliable if a certain margin is present between the representative values of the resistance and the loads. The use of partial safety factors in the design ensures this. With these factors, uncertainties in materials, geometry, calculation models and loads are covered. The Partial safety factors for loads are dependent on the reliability class (RC) and the limit state. The different reliability classes may be adopted for the structural resistance and usability. The reliability classes with regard to structural resistance and usability can be achieved by using characteristic values of loads and the choice of partial factors during constructive calculations. For the structural calculations these reliability classes are introduced based on the assumptive consequences of a failure. (Table A1.1)

Reliability classes	definition	Building examples
Reliability class 3	Great risk for the loss of life, and/or great economic and social consequences or consequences for the environment.	High-rise Grandstands Exhibition halls Concert halls Large public buildings
Reliability class 2	Moderate consequences with respect to the loss of life, and/or significant economic and social consequences or consequences for the environment.	Residential buildings Office buildings Public buildings Large industrial buildings
Reliability class 1	Slight consequences with respect to the loss of life, and/or small or negligible economic and social consequences or consequences for the environment.	Agricultural buildings Greenhouses Small residential buildings small industrial buildings

*Table A1.1, the reliability classes according to the Eurocodes. (*NEN-EN 1990 2002*)*

According to Terwel (2013) the current Eurocode philosophy to ensure safety is a combination of two approaches. First, calculations have to be made in which the resistance of a structure should be larger than the effect of the loads, to meet the acceptable failure limits. Second, quality management is suggested to provide reliable design and construction processes.

A1.3 The structural engineer

Creating structural safety is more than creating a design that meets the standards. The designing engineer will always have to check if the design is feasible and also whether the safety is sustainable. All parties involved in the construction process, including the government as evaluative party affect the assurance of structural safety. However, the main responsibility lies with the principal structural engineer and the contractor. The principal can have a great impact on the quality of the project, hence the structural safety. A careful selection of the parties who are involved can be chosen depending on the complexity of the specific project. The client has to decide whether or not to monitor during execution is important for the project. (Banga, 2012)

During the design process the principal structural engineer is the one who should ensure the structural safety. During the construction phase it is the contractor who should ensure the final structural safety. During the design the strength and stability are examined for the final phase of a building, the contractor must ensure that also for the construction phase measures have been taken to ensure the strength and stability. In addition, the principal structural engineer should already in the design phase take into account the manufacturability of a construction. For more complex structures the engineer has to give the drawings and calculations of the different stages to the contractor. The phase of detailing is the most critical to the structural safety. This is mainly because there are many different parties involved and the communication to the contractor is in the final phase. If there are wrong details produced and the contractor follows these, unsafe situations may occur. (Banga, 2012)

In order to ensure that the safety of a structure is sufficiently large, the structural engineer should always keep the following two things in mind according the book Basis Constructieleer (2002):

- Preventing collapse and minimizing the chance of collapse.
- Limiting the damage in case the structure (or a structural element) still fails.

Preventing collapse
The structural engineer can reduce the chance of collapse by designing a construction with sufficient strength and stiffness. The size and the effect of the load can also be influenced. For example loads can be avoided by adopting special facilities to the structure. Think of a guardrail construction to absorb a load by a collision.

Limiting the damage
It is the responsibility of the structural engineer to limit the consequential damage if a structure (part) still collapses. This can be done by applying a second load path to avoid cascading failure or by designing a structure which warns before the collapse may occur. A structure that warns is a structure that shows a large deformation or a lot of cracks before it collapse. The structure warns the users of the building that there is a dangerous situation arising. The effectiveness of this warning is obviously increased if there is also a good evacuation plan. The possession of a warning mechanism for a structure is very important for this research. The satellite may also note the deformation of a building before collapse.

Contribution of InSAR
Monitoring buildings with the satellite can increase the structural safety, because if we look back at the following formula and assume that this formula expresses the risk related to structural safety:

$$R = P * S \leq A$$

Than there can be assumed P stays equal, because it will not influence the events leading up to a damage case, but damage that can be expressed in displacement will be discovered earlier, this will limit the damage, and thereby limit the costs (A) and the risk (R). The contributions of the satellite start at the use phase and will not have a contribution to the structural safety until this phase.

It can be said that if the satellite can discover a part of the damage cases in an early stage of the damage, that this will increase the structural safety. This does not immediately answers the second sub-question, because a first conclusion about the possibilities of the satellite can only be made after the case research.

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APPENDIX 2: FAILURE MODES

The aim of the chapter is to describe what kind of failure mechanisms can occur in buildings. To do so there is looked back to the basics of failure mechanisms. A failure mechanism is how a material, a part of a structure or an entire structure fails. On the one hand there is the load that works on the structure on the other hand there is the resistance of the structure to withstand the load. The different failure mechanisms that arise are dealt with in this chapter. The chapter is written by using books and lecture notes of different courses. The used lecture notes are Steel Structures 2, Concrete Structures 2, Structural Mechanics 3, Building Structures 2 and Constructive Design 1 and 2. Other books that are used are The High Rise Manual, Constructieleer BASIS and the building decree.

The building decree makes demands on the capacity of a structure. There is demanded that some ultimate limit states may not be exceeded. The ultimate limit state is a limit state applicable to the assessment for the structural safety. Overwriting an ultimate limit state occurs when there is insufficient strength or an inadequate stability of a part of the construction. In the ultimate limit state the strength criterion applies. In general the following equation holds:

$$S_d \leq R_d$$

S_d is the load, force or stress acting on the structure (S stands for sollicitance). R_d is the resistance (R for resistance) of the structure, in other words R_d the limit load (The d stands for design). To assess whether the stated requirements are met, the Building decree refers to the assessment methods in the material-specific standards. The serviceability limit state is also tested. This is a boundary condition applicable to the assessment of the requirements for the predetermined use and sustainability. The serviceability limit state mainly relates to the stiffness.

The structural engineer tries to estimate which failure mechanisms can occur and tests with calculations in the design stage if the structure suffices. The structure should provide sufficient resistance to any load that may occur over its lifetime. A solid construction has to meet the following three main requirements; Sufficient strength, sufficient stiffness and sufficient stability. In general this means that a structure needs to contain the ability to sustain the applied loads to satisfy in strength. The resistance against deformation is called stiffness. Stability is the ability of a structure to maintain position and geometry. For buildings with a small height the strength is often governing. For medium high buildings this is the stiffness and for high rise the stability is often governing.

This chapter will describe different failure mechanisms sorted in different levels. First this is assessed on a material level, followed by element level and finally at system level. Mainly failure modes that are present in concrete and steel structures will be discussed.

A2.1 Strength

The strength is the degree of resistance applied on an object. According to the book Basis Constructieleer (2001), mainly four factors determine the strength:

- The strength of the material
- The size of the cross-section of the structural element
- Shape of the cross-section of the structural element
- The structural system

These factors will be part of the different levels that will be discussed below.

Material level

Material strength is measured by a stress level at which there is a persistent significant change in the materials' load carrying ability caused by compression and tension. This is the case when a material deforms too much and the deformation is irreversible. The stress at which a material begins to plastically deform, is the yield stress. (see figure A2.1) The material will not return in its' original shape and will lose its' strength capacity.

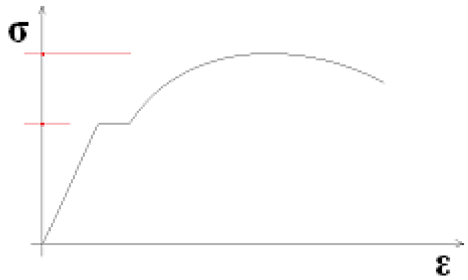

Figure A2.1, A stress-strain diagram of steel. Marked in red is the plastic capacity

The ultimate stress is the stress level that introduces fracture or buckling. The ultimate stress has got a tension and a compression component. The strength of a material is expressed by (ultimate) tensile stress and (ultimate) compression stress. In the following table A2.1 the compression stress and tensile stress can be seen for different materials. The higher these values, the stronger the material is against these forces. Concrete is particularly used for structures loaded under compression. Steel is mainly used for structures under tension. The compression strength of steel is higher than that of concrete, but buckling can occur more easily, because of the slender profiles of steel elements. This disadvantage lowers the compression stress. To avoid buckling the area of the steel must be designed larger. This gives the steel element the disadvantage of becoming too expensive when it is used in compression.

Material	Compression strength N/mm^2	Tension strength N/mm^2
Stone	2-6	<0,5*
(soft)wood**	12-15	7-10
Construction steel	235-355	235-355
Reinforcing steel	435	435
Prestress steel	inapplicable	1520-1690
Unreinforced concrete	9-36	0,9-2,2
High strength concrete	50-120	2,5 -3,0

** The bond strength of grout*

*** The strength parallel to the grain*

Table A2.1, compression strength and tension strength of different materials. Source: Constructieleer Basis (2001)

A structural engineer can calculate the strength of a material under pressure or under tension with the design value of a material. The design value of the compression strength of concrete in the Eurocodes is:

$$f_{cd} = \alpha_{cc} f_{ck} / y_c$$

y_c is the partial safety factor for concrete, α_{cc} the coefficient that takes hold with long-term effects on the compressive strength and f_{ck} is the characteristic value of the cylinder compressive strength obtained after 28 days from laboratory research. The design value of the tension strength of steel is:

$$f_{ctd} = \alpha_{ct} f_{ctk0,05} / y_c$$

the coefficient α_{ct} takes hold with long-term effects on the tension strength and with the adverse effects the way the structure is loaded. $f_{ctk0,05}$ is the characteristic lower limit value of the tensile strength of concrete.

Failures that may occur on the material level of strength are often failures that are caused by materials that not suffice the strength properties that are used during calculations. This could be instigated by different reasons, like wear and production errors. Example of wear is corossion that decrease the strength and the ductility of steel. Creep and relaxation are also caused by wear. Creep is a persistent deformation of a material which is under stress for a long period of time. Larger deformations are introduced by equal stress. Relaxation is a decrease of the stresslevel in steel, also caused by stress that is applied for a long period of time. There is also a persistent deformation, but the strain stays equal in contrast to creep. Lamenar tearing is an example of a production error. This failure mechanism occurs in steel structures. Lamenar tearing is caused by the absence of non-metallic inclusions like sulfide, silicates and oxides. These failures are local. Relaxation and creep can be measured by the satellite because of the long period of time this failure mechanism take to develop.

Element level
The strength of an element is measured by the amount of load that an element can withstand before reaching a certain damage level, such as persistent deformation or complete collapse. For example, the strength of a beam could be measured in terms of the maximum distributed load that is carried before large irreversible deformation occurs

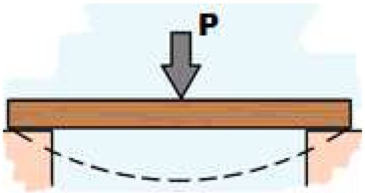

Figure A2.2, example of possible deflection of wooden beam as dotted line.

The assessment of strength occurs by the so-called unity-check. This means that one should fulfil the following requirement:

$$R_{sd} \,/\, R_{ud} \leq 1$$

R_{sd} is the design value of the moment or the force which occurs in the cross-section under consideration. R_{ud} is the design value of the capacity of the cross-section. A value lower than or equal to 1 indicates that the cross-section suffice with regard to the strength. The strength of a girder is determined by the capacity of the cross-section of the beam, the cross-section capacity, with respect to the moment, shear force, normal force, torsion and the interaction between these capacities. This leads to the most basic design equations:

For normal force:

$$N = \sigma * A$$

In this formula the N is the normal force, σ the stress and A the area.

For the shear force:

$$V = \frac{\tau * b * I}{S}$$

In this formula the V is the shear force, τ the shear stress, S the static moment, b is the thickness and I the moment of inertia.

For the bending moment:

$$M = \sigma * W$$

M is the bending moment and W the section modulus.

These three simple design formulas give an indication how important the dimensions of an element are. This dependence is expressed in the formulas as the cross-section (A), the moment of inertia (I) and the section modulus (W). The height of an element is in particular important. This can be seen for example by a rectangular profile, the height is to the third power for the moment of inertia and for the section modulus it is squared.

For calculating the strength of steel structures the plastic capacity is also included in the assessment. According to the theory of elasticity the cross-section calculation is based on a linear relationship between the stress and strain. Only the elastic part of the stress-strain diagram is used and is limited by the yield stress. The non-elastic branch of the diagram is also used when calculating with the theory of plasticity. After reaching the yield point, there is still a reserve capacity available. The term of use of plasticity theory is that the material is ductile. This is the case when stress does not decrease with an increasing strain. This is when steel and reinforced concrete are used. The reserve capacity is caused by the hardening of the material with increasing yield and the favourable redistribution of stress. The second effect is the source for the calculation of the plastic capacity. The reinforcement is ignored in the calculation, which always means an additional reserve is present in the steel.

Failures that may occur on the element strength level are ductile fracture, brittle fracture, concrete crushing and punching shear failure. These failure modes are introduced by shear forces, normal forces and bending moments.

System level
System strength is measured by the amount of load that a system can sustain before reaching some damage level, such as persistent deformation or complete collapse. The collapse of a system typically involves a sequence of element failures, called progressive collapse. A well designed system may experience severe damage in many elements before collapsing, while continuing to sustain higher loads. To introduce enough structural integrity in a system, second load paths for susceptible parts for damage of the structure are designed.

Under the influence of a lack of strength a material can translate, rotate, fracture or deform. The displacement cannot be linked directly to the strength. There is also not a universal ratio, because of the incoherence of different structures.

A2.2 Stiffness

A force on a structure will always cause a small displacement. This displacement is inevitable. A structure that does not bend when loaded under varying loads, will show cracks and parts may break off. The resistance to deformation of a structure is called the stiffness. The stiffness (k_d) of an elastic body in relation to displacement can be expressed as follows:

$$k_d = F / \delta$$

The F is a load and δ is a displacement. This formula shows that the stiffness is a ratio between force and displacement. There can be said that an increase in the force and an unchanged stiffness means a displacement. The resistance against rotation that is caused by a bending moment is called the rotational stiffness and is expressed as follows:

$$k_r = M / \theta$$

This second formula shows also that the stiffness is a ratio, this time between the bending moment and the rotation. The stiffness is the relation between a force (or a derivative thereof) and the displacement (or derivative thereof). The term stiffness depends on the forces that work on the structure. If a normal force works on the structure the stiffness is the extensional stiffness (EA) with the unit Newton, derived from $\varepsilon = N / EA$, ε stands for strain ($\varepsilon = du/dx$). For bending there is the bending stiffness (EI) with the unit Newton times metres squared, derived from: $\kappa = M / EI$, (κ) stands for curvature ($\kappa = d\delta/ds$). When the structure is loaded with shear force than there is spoken of the shear stiffness (GA). (G) is the shear modulus. The shear stiffness is derived from $\gamma = V / GA$, the γ stands for shear distortion ($\gamma = dv/dx$).

The following four factors affect the stiffness according to the book Constructieleer Basis (2001):

- The construction system: structures loaded by pure axial forces (tension or compression) behave stiffer than constructions loaded by bending.
- The elasticity of the material of the structure.
- The size of the cross section: In case of pure tension or pressure, the resistance to deformation is proportional to the size of the cross section (A). For pure bending the resistance against deformation is directly proportional to the moment of inertia.
- The structural member height: The higher the element, the stiffer the element. The construction system determines to a significant extent, the slenderness ratio of a structural member.

These factors will be part of the different levels that are discussed below.

Material level

Stiffness is most commonly expressed in terms of the modulus of elasticity: the ratio of stress to strain in the linear elastic range of material behaviour (see figure A2.3). This is described in Hook’s law $\sigma = E\varepsilon$.

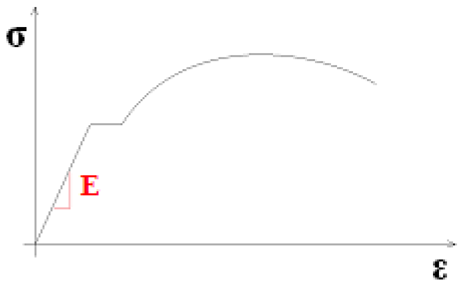

Figure A2.3, a stress-strain diagram of steel. Marked in red is a part of the linear range of the stress-strain diagram. This can be expressed as the Young's modulus.

The young modulus is in this equation the stiffness. The stiffness is material depended. In the following table (table A2.2) different young's modulus for different materials can be seen. The young's modulus describes the linear relation between stress and strain (the first part of the graph in figure A2.4) the non-linear part is called the ductility. Ductility is an element of stiffness; it is the amount of inelastic deformation before failure. It is commonly expressed as a ratio of the maximum strain at failure divided by the yield strain. In the table can be seen that steel is much stiffer than other materials. A larger area is needed of the other materials to get the same bending and extensional stiffness. Because when materials are getting stiffer the slenderness of an element also increases (slenderness = height / width), but deform more easily.

Material	E (N/mm^2)
Stone	3000-20000
Wood	7000-20000
Concrete	20000-35000
Aluminium	70000-80000
Steel	210000

Table A2.2, young's modulus for different materials. Source: Constructieleer Basis (2001)

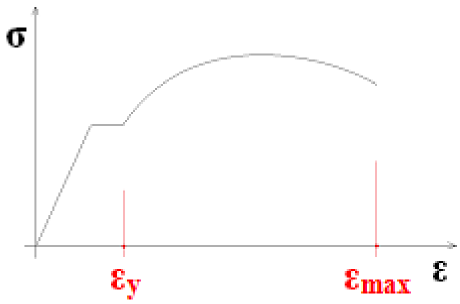

Figure A2.4, a stress-strain diagram of steel. Marked between the red dots is the ductility.

Element level

Element stiffness is measured by the ratio of a displacement on an element and an applied load. The verification on stiffness of an element in a building can be divided in two elements according to Doel-Grondsma (1969):

1. Vibration requirement: the structure may not vibrate too much. A beam should be resistant against low frequency vibrations. The structure should not resonate and has to feel safe. This will not be further discussed, because of the short time of these deformations.

2. The deflection: There is a distinction made between additional displacement and final displacement. The final displacement is the displacement caused by persistent load and live load. The additional displacement is the displacement caused only the live load. The final deformation of a beam can be influenced by the use of camber, a pre-given curvature. The deflection requirement is:

$$\frac{\delta_{max}}{\delta_{limit}} \leq 1$$

(δ_{max}) is the maximum displacement the element and (δ_{limit}) is the limit that is given in the Eurocodes. The total deflection should be lower than 1/400 of the length of the element. The deflection of a beam can be calculated with so called 'forget-me-nots'. The forget-me-nots works with the bending stiffness, this makes the stiffness depended on the young's modulus and the moment of inertia. Failures that may occur by low element stiffness are too large deflections and too large vibrations.

System level

System stiffness is measured by the total deflection of a building. The stiffness of the system is important in high rise, because of the large horizontal wind loads that works on the slender structure. This means that this property is often governing in tall buildings. There is made use of lateral load resisting systems to make sure the building have enough stiffness and stability. (See figure A2.5)

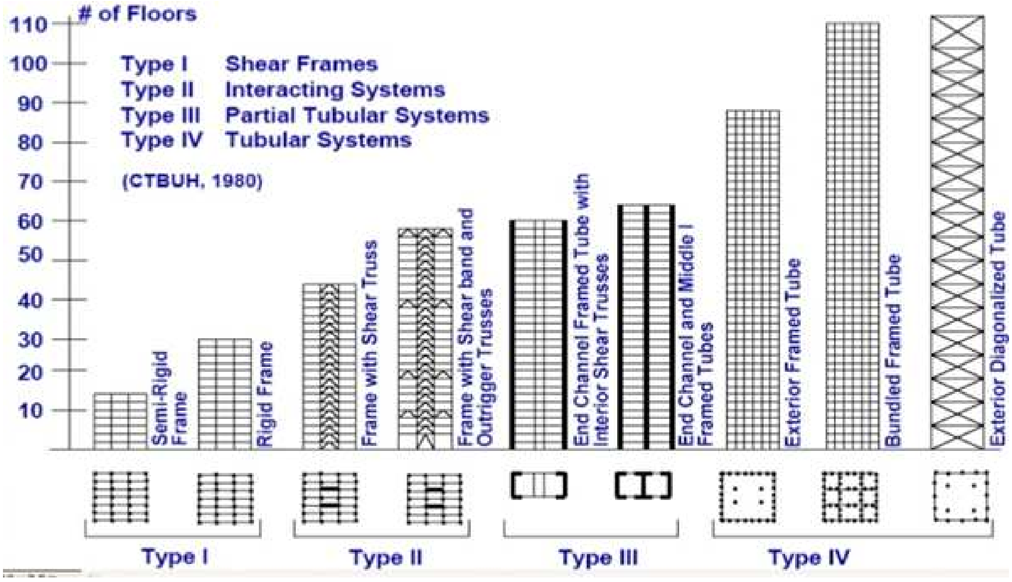

Figure A2.5, stability systems of buildings. Source: Lecture slides of Building structures 2

A core is one of the first measures that can be taken in higher buildings to provide extra stiffness. The core is often a lot stiffer than the other elements of the building because of a larger diameter and bracings. One of the most important structural properties is transferring the horizontal loads to the foundation. This is effective until 50 floors. To gain an extra 10 floors outriggers can be added to the core. These outrigger elements contain a huge bending stiffness. The highest buildings are made with the structural principal called 'Mega structure'. These structures are relative simple structural principles, like a truss, but amplified to make the span bigger.

The stiffness can be linked to deformation. Because of the differences of possible structural systems no hard values can be linked to different deformations, this is case dependent.

A2.3 Stability

An unreliable balance is called unstable. If a small force can knock down a structure then there is spoken of an unstable structure. The stability of a structure is related to the resistance to horizontal and vertical forces. Horizontal forces have to be processed by the system stability-structure. This is done by for example the foundation, moment resisting frames, diaphragm-action and braces. Instability caused by vertical forces exists mainly out of slender structures under pressure load. To assess the stability of a structure there is looked at a structural part or the whole structure.

Element level
Element stability concerns the ability of the element to maintain its shape and position. The stability can be internal or external. External instability means that

an element can move by applying a force. An example of external instability is an I-girder that topples because of a horizontal force at the upper flange. External instability is often caused by a connection that does not suffice.

Internal instability is a failure mode that occurs at slender elements such as steel and is often caused by bending and normal forces. There are three main internal instability mechanisms for beams loaded by compression: buckling, torsion and torsional buckling. For beams loaded by bending, lateral torsional buckling and folding are the main stability failures.

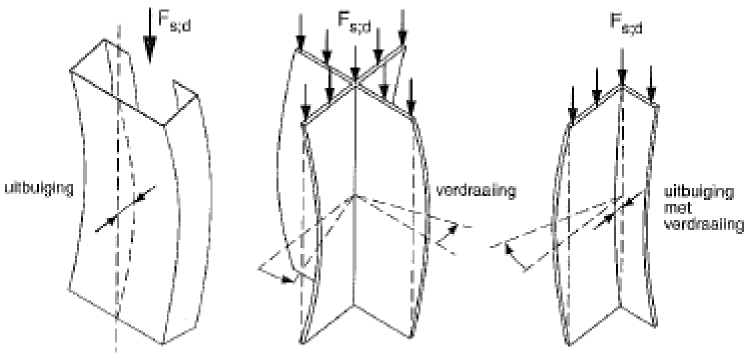

Figure A2.7, beams loaded with compression. Beam left: buckling, middle beam: torsion and right beam: torsional buckling. Source: Reader Construeren A (2001)

Buckling

When the equilibrium of a centric pressure-loaded bar becomes unstable, than there can be spoken of buckling. Buckling goes together with significantly increasing displacements perpendicular to the member axis. This finally results in failure. The buckling can occur in the two main directions of a bar. The load at which buckling occurs is called the buckling load. The buckling load is an upper limit for the capacity of a centric pressure-loaded bar and is derived from Euler's formula for buckling. The buckling load is:

$$F_e = (\pi^2 * EI)/l_{buc}^2$$

(l_{buc}) is the buckling length of a bar, this is the length between two inflection points. According to the Eurocodes the structure should suffice the following regulation:

$$\frac{N_{c;s;d}}{\omega_{buc} * N_{c;u;d}} \leq 1$$

($N_{c;s;d}$) is the calculation value caused by the load. ($N_{c;u;d}$) is the calculation value for the ultimate absorbable pressure force for the given section. (ω_{buc}) is the buckling factor and stands for:

$$\omega_{\,buc} = 1 / \lambda_{rel}^2$$

λ_{rel} is the relative slenderness and is derived from:

$$\lambda_{rel} = \lambda / \lambda_e$$

λ is the slenderness of the beam and can be expressed by:

$$\lambda = l_{buc} / i$$

(i) is the radius of Gyration. The radius of gyration is a factor between the moment of inertia and the area. The direction with the smallest radius of gyration is the buckling direction and can be expressed as:

$$i = \sqrt{(I/A)}$$

The factor (λ_e) relates to minimal slenderness ratio obtained with the formula for Euler's buckling stress. The factor is a relation to the yield stress (f_y) and the young's modulus. The factor (λ_e) factor can be expressed as:

$$\lambda_e = \pi * \sqrt{(E / f_y)}$$

Torsion
Torsion stability is the degree to which a bar is susceptible for instability resulting from a rotation-deformation of the bar over the longitudinal axis caused by a compression force. The analysis of torque is only necessary if a straight bar is double symmetric and loaded with a compression force. The torsion should suffice the following unity-check:

$$\frac{N_{c;s;d}}{\omega_\theta * N_{c;u;d}} \leq 1$$

The torque factor (ω_θ) depends on the relative torsion-slenderness, which in turn is dependent on ($N_{c;u;d}$) (the ultimate absorbable pressure force for the given section) in relation with the Euler-torsion force. The formulas for this are not further described, since this does not fall within the scope of the research. The following failure mechanisms will also not be expressed in formulas, because of the scope of this research and the complexity of these formulas.

Torsional buckling
Torsional buckling plays a role in cross-sections with a small torsion stiffness and relative large bending stiffness. This is the case with thin-walled open profiles. With torsional buckling a bar twists under the influence of centric pressure force, which is smaller than the buckling load.

Lateral torsional buckling
With lateral torsional buckling the moment of inertia in the main directions differ a lot in magnitude. This can be the case with slender beams of a great height. If the beam is loaded in the plane of the beam with the largest stiffness, than the beam can suddenly move and rotate out of his plane. Torsional buckling and lateral torsional buckling both deal with a combination of bending and torsion.

Folding
Buckling in plates is called folding. Folding occurs under the influence of pressure and shear forces in the plane of the plate. At a certain load displacements perpendicular to the plane of the plate appear. The plate looks wavy when folding takes place.

System level
System stability concerns the ability of a structure to maintain its position and shape. System stability can also be internal or external. External instability is caused by external factors that directly influence the stability of a structure. This is the situation if one of the preconditions changes. This can be the case if the soil around the foundation changes caused by an earthquake.

Internal system stability is influenced by the stability system of a building. The stability systems that are used are briefly described under system stiffness. These systems also provide stability. The stability of the most buildings can be redirected to four simple stability systems according to the lecture notes of Building Structures 2. These are (see Figure A2.8):

1. Columns fixed to the foundation.
2. Moment resisting frames
3. Shear walls or shear cores, fixed to the foundation
4. Load bearing facades

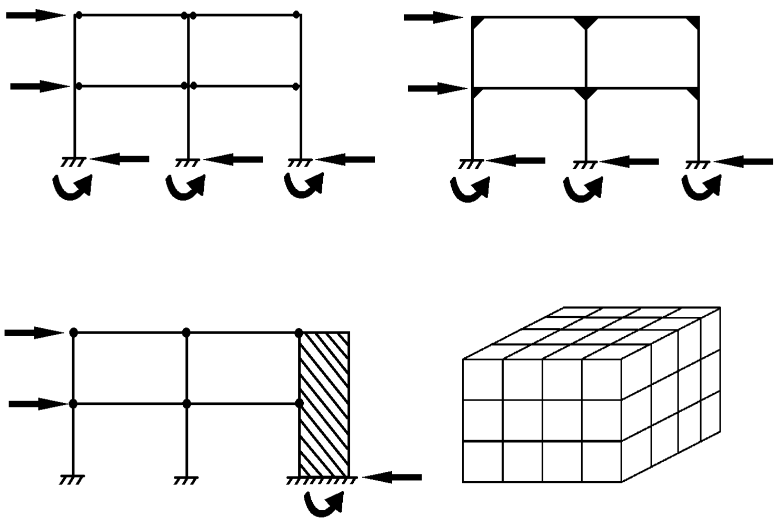

Figure A2.8, different stability systems, from left to right: column fixed to the foundation, moment resisting frame, shear walls or shear cores, fixed to the foundation and load bearing facades.

These systems lead the horizontal forces to the foundation. The first system got a foundation with a large bending stiffness that processes the horizontal load. The supporting column should be stiff enough to prevent large deflections. The second system works with moment resisting connections or cross bracings that transfer the horizontal and vertical loads to the foundation. The third system works partially in the same way as the first system. The difference is that the horizontal forces are lead to one very stiff element; this may be done by the diaphragm action of the floors. The final system is built up out very stiff elements that can lead the horizontal forces to the foundation; this is a different implantation of the second system. This system can be made with stiff prefab façade elements.

Second order effects can also influence the stability of a structure. This displacement is introduced by tilt of a structure that makes the vertical load eccentric on the structure, this effects especially slender structure.

APPENDIX 3: STRUCTURAL HEALTH MONITORING STARTING PRINCIPLES

"Structural Health Monitoring offers an automated method for tracking the health of a structure by combining damage detection algorithms with structural monitoring systems" (Melkonyan, 2008).

The guidelines how structures should be monitored are widely discussed in literature. (Farrar et al. 2001) defines the SHM process in terms of a four-step statistical pattern recognition model. This following four-step process includes:

1. "operational evaluation,
2. data acquisition, normalization and cleansing,
3. feature selection and information condensation
4. statistical model development for feature discrimination."

According to Farrar (et al. 2001) operational evaluation attempts to answer four different questions regarding the implementation of damage identification capabilities.

"(i) What are the life-safety and/or economic justification for performing SHM?

(ii) How is damage defined for the system being investigated and, for multiple damage possibilities, which cases are of the most concern?

(iii) What are the conditions, both operational and environmental, under which the system to be monitored functions?

(iv) What are the limitations on acquiring data in the operational environment?"

For an adequate monitoring process these questions have to be answered first before addressing the next step. Monitoring with InSAR may contribute to a safer environment, if damage can be prevented. Definitions of different type of damage will be discussed in chapter 3. The limitations of InSAR will be discussed in chapter 2. The second step begins with data acquisition, as data can be measured under varying conditions; the ability to normalize the data becomes very important to the damage identification process. Data cleansing is the process of selectively choosing data to pass on to or reject from the feature selection process. Some data can be irrelevant by measurement errors or during specific circumstances. This brings the process to step three where abnormalities are mapped out. These two steps are taken care of by 'Hansje Brinker' by their data processing software of InSAR data. Step four is getting insight how often the monitored figures arise. Finding alarming values is one of the goals of this research to determine on which threshold a structure possibly damages.

Worden (et al. 2007) tries to give a list of principles for structural health monitoring. These seven axioms are formulated as a starting point in monitoring research:

"Axiom I: All materials have inherent flaws or defects.

Axiom II: The assessment of damage requires a comparison between two system states.

Axiom III: Identifying the existence and location of damage can be done in an unsupervised learning mode, but identifying the type of damage present and the damage severity can generally only be done in a supervised learning mode.

Axiom IVa: Sensors cannot measure damage. Feature extraction through signal processing and statistical classification is necessary to convert sensor data into damage information.

Axiom IVb: Without intelligent feature extraction, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions.

Axiom V: The length- and time-scales associated with damage initiation and evolution dictates the required properties of the SHM sensing system.

Axiom VI: There is a trade-off between the sensitivity to damage of an algorithm and its noise rejection capability.

Axiom VII: The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation."

These axioms are very general statements about monitoring and speak fairly for themselves. With the monitored data there is tried to detect damage. According to Farrar et al. (2007) damage can be defined as changes introduced into a system that unfavourably affect its current or future performance. As the damage grows, it will reach a point where it affects the system operation to a point that is no longer acceptable to the user. This point is referred to as failure. Damage detection methods can generally be classified as one of two types: local-based or global-based damage detection methods. "Local-based damage detection methods attempt to identify damage based on screening structures at their component or subcomponent length-scales. Global-based damage detection refers to numerical methods that consider the global vibration characteristics (e.g. mode shapes, natural frequencies) of a structure to identify damage." (Lynch and Loh 2006) InSAR can be seen as a global based damage detection technique, global design rules should form a guideline for alarming values. The local-based damage detection techniques ask for multiple measurements for one element on different location or inside an element to monitor the state of the element.

The damage state of a system can be described as a five-step process along the lines of the process discussed in Rytter (1993) to answer the following questions.

1. "Existence. Is there damage in the system?
2. Location. Where is the damage in the system?
3. Type. What kind of damage is present?
4. Extent. How severe is the damage?
5. Prognosis. How much useful life remains?"

Answering these questions give a good indication of the severity of the damage. These questions are for buildings situation depended. The location of the damage can be derived from the PS-point with the data that indicates damage. With the

SHM process defined by Farrar and the axioms of Worden the structure can be assessed.

Sources:

C.R. Farrar, S.W. Doebling and D. A. Nix, Vibration-based structural damage identification.Phil. Trans. R. Soc. A 359, 131–149, 2001

K. Worden, C. R. Farrar, G. Manson and G. Park, The fundamental axioms of structural health monitoring, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, Published online 3 April 2007

C. R. Farrar and K. Worden, An introduction to structural health monitoring, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, Published online 27 Januari 2007

A. Rytter, Vibrational Based Inspection of Civil Engineering Structures, Phd. Thesis, University of Aalborg, Aalborg, Denmark, 1993

APPENDIX 4: MONITORING IN THE NETHERLANDS

Monitoring of most structures in the Netherlands is not required, though a building owner has to guarantee the safety of a building. This can be supported with monitoring. How the monitoring should occur or what should be monitored is not defined by norms, only NEN 2767 (2008) specifies guidelines for condition measurements for buildings. This is performed by means of a defined measuring and recording method. The registration is done by a certified inspector. The inspector states what the possible defects of each material, every element and every detail could be and what the extent and the intensity of the defect could be. Combining the determined defects of the elements of the structure leads to a condition score. The score ranges from 1 to 6, 1 is a very good condition and 6 is a very bad condition. The norm does not describe what score is sufficient for a structure or if a specific score means a part needs be repaired.

Although NEN 2767 (2008) describes a monitoring system, it does not completely satisfy the monitoring what is aimed at in this research. The monitoring proposed in NEN 2767 is not continuous in time and only periodic. Also the condition of a building is examined by an inspector and not by sensors. This means that warning for (partly) failure is only done by chance and not by continue measurements of the structure. Ideally, health monitoring of civil infrastructure consists of determining, by measured parameters, the location and severity of damage in buildings or bridges as they happen. (Chang et al. 2003) This norm is rarely used in the Netherlands.

Sources:

NEN 2767: Conditiemeting van bouw- en installatiedelen, Normcommissie 351 261 "Conditiemeting van bouw- en installatie delen", 2008

P.C. Chang, A.F. and S.C. Liu, Review Paper: Health Monitoring of Civil Infrastructure, Sage Publications, Vol 2(3): 0257–267, 2003

APPENDIX 6: SUITABLE DAMAGE CASES FOR FORENSIC ENGINEERING WITH INSAR

The residual buildings are the following; under the table the difference in colour is explained: The first column with green and yellow is outer shell? Green means the damage is visible in the outer shell and yellow means it is indirect visible in the outer shell. The next column answers the question if movement is possible. Green means yes and yellow means maybe, not sure. The last coloured column answers the question if the development of the deformation is shorter or longer than a successive measurement. Green means yes and yellow means maybe, not sure.

On the next page the cases can be seen. The description is in Dutch.