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Predicting structural disasters with Radar interferometry

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Abstract

Radar interferometry is a technique which can observe the earth's surface during day and night time. It makes uses of thousands of pulses per second that are transmitted by satellites and reflected by the surface of, for instance, structures. By analyzing the data it is possible to measure displacements of the surface within millimeter precision. For the building industry this might be a promising technique, for monitoring buildings or for forensic engineering. Variables that might be monitored are the displacements of roofs, of balconies or the settlements of buildings. In addition, the technique might be a tool which can be used for forensic investigations. This paper will discuss the possibilities and limitations of radar interferometry for both building monitoring and forensic engineering. The method is expected to be especially useful for measuring soil displacements and the resulting settlements of structures.

Keywords: radar interferometry, structural health monitoring, forensic engineering, new technologies

1 Radar interferometry and structural failures

Satellite radar interferometry (or InSAR: Interferometric synthetic aperture radar) is a technique to observe the geometry, and geometry changes, of the earth's surface from an orbiting satellite [1]. The satellite orbits are designed such that they repeat exactly after a given repeat interval, typically in the order of one or two weeks. The radar samples the earth's surface and all structures on it with a spatial resolution in the order of meters. In this way, time series are constructed with a typical length of a decade per satellite mission [2]. Using radar phase measurements, the precision of measuring geometry changes is in the order of millimeters, and the estimation of strain rates can achieve precisions of better than 1 mm per year [3]. This routine form of sensing holds great promise to assess and monitor the health of structures, anywhere on earth, and independent of weather conditions or solar illumination.

Although a limited number of the resolution cells in the images is useable, given that a typical radar image has ten thousand to a million resolution cells per square kilometer, this ensures that there remain many observation points, especially over structures. Furthermore, since radar images have been archived from many satellite missions since the early 1990's, there is a huge potential for retrospective analysis.

The investigation and determination of the causes of structural failures of buildings, bridges, and other constructed facilities is called forensic structural engineering [4]. A structural failure can be defined as the inability of a structure or a structural member to fulfill the specified requirements [5]. A structural failure can manifest itself in a (partial) collapse, structural damage, material deterioration, insufficient functionality or no damage (when structures cannot fulfill the requirements, but no damage has occurred yet).

The characteristics of radar interferometry create the possibility to use it for 'forensic structural engineering', analyzing in hindsight whether a known structural failure has had precursory deformation. In addition, radar interferometry can be used for 'structural health monitoring', predicting and avoiding or mitigating incumbent structural disasters by detecting anomalous motion.

The possibility to monitor the deformation of a building night and day for a period of time without being on site, on difficult-to-access areas, is a unique feature of InSAR as structural health monitoring tool. 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.

However, there are some requirements and limitations on the use of InSAR for forensic structural engineering or structural health monitoring.

First, the deformations should be visible at the outer shell of a structure. Failures within a building, without effects on the outer shells cannot be analyzed with InSAR.

In addition, a strict requirement to achieve reliable ('coherent') time series is that the reflective characteristics of the structure do not change significantly over time. This condition of coherent, or persistent, scattering is in practice very hard to achieve. In fact, perhaps more than 90% of all resolution cells does not satisfy this condition.

Furthermore, it is important to stress that the technique is opportunistic, in the sense that one cannot control the location of the radar reflections, as this is the result of an intricate combination of the object geometry, shape, and orientation, and the satellite's orbit, viewing geometry and wavelength.

Another important aspect is the sensitivity to the radar viewing direction. Whereas the deformation vector of a (part of a) structure is effectively three-dimensional, the radar can only measure geometric changes in the line-of-sight from the object to the satellite. By combining two viewing geometries, the rank defect can be reduced from two to one, but this still implies that not all deformation components are equally well observable. Particularly the north-south component is difficult to observe.

For these reasons, the technique should be seen as a valuable complementary component to other analyses and structural health assessment techniques, particularly to get a quick and wide-range overview over a certain area. It provides a sample of structures, rather than a dedicated all-inclusive coverage.

The question now is to know what are the possibilities of radar interferometry for forensic engineering and structural health monitoring, given the opportunities and limitations of this method?

Therefore, in this paper an analysis is made of a database with 401 structural failure cases [6] to determine InSAR's potential as a forensic engineering tool. In addition, the use of InSAR for forensic engineering and structural health monitoring is illustrated with a case study about large soil deformations of a shopping mall 't Loon. Finally, a brief comparison with other measuring techniques is provided.

2 Prediction of failures with InSAR

To investigate the potential of INSAR predicting failure cases, a database with structural failures has been examined.

This database consists of 401 Dutch failure cases from 1993 until 2009 which were published in a Dutch newspaper for the building industry, called Cobouw [6]. In this database general information of the failure cases is provided, such as location, number of stories and building type. Furthermore, information about the damage is provided, like type of damage, involved materials, involved structural parts and technical cause. In addition, information on possible physical warning signs is included. Finally, information on underlying causes is presented, like the building phase in which the failure was caused and the possible human error that was made.

For the selection of cases the focus has been on buildings. The criteria that were used to determine if a case potentially could be determined by InSAR data, are

- damage should be visible on the outer shell, and
- damage should occur gradually, over a longer period of time, because the satellite only provides data every 11 days (with a sudden collapse it will be hard to compare reflection points).

These criteria result in the following subset of cases.

1. Only buildings (238 out of 401 cases, 1 redundant case has been removed).
2. Damage should be visible (so a few cases with for instance erroneous calculations possibly leading to failures of the construction are out of scope)
3. Buildings during use, during construction they usually do change too rapidly (189 out of 238 cases left)
4. No temporary structures (these are usually built and used during a too limited time, 181 cases left)
5. No accidental loads (these usually result in a very brief development time of the damage (169 cases left)
6. The damage should be visible at the outer shell. This can be directly visible (for instance with facades), or indirectly visible when the underlying structure was displaced (142 cases left)
7. Deformation in the outer shell should be visible (71 cases left)
8. Deformation in the outer shell must take more than 11 days to develop (50 cases left)

From the 50 cases that may be detectable InSAR there are 35 roof cases, 7 façade cases and 8 balcony cases.

From these 50 cases, for 18 cases it is reasonable that the damage may be detectable with InSAR, when adequate data points would be available. For 32 cases this may be possible, but the case descriptions did not provide sufficient information to give a final answer.

The analysis of failure cases from the database gives insight in the potential of InSAR data to be helpful for analyzing, or even predicting, forensic cases. Approximately 10-20% of the reported failure cases with damage (18-50 out of 238) might be analyzed with help of InSAR data, if adequate data with useful reflection points would be available. The most probable situations are damage to roofs, façades or balconies.

Deformation of roofs can be visible with InSAR. Deformation due to snow and instantaneous wind load might be hard to detect, because of limited visibility of reflection points. Displacements of complete buildings (observed via deformation of the roof), for instance caused by settlements of the foundation, are easier to detect with InSAR data.

Although facade damage can be visible, many failures did occur suddenly, for instance in the case of façade elements where the connection failed during strong wind loads.

Damage of balconies revealed by excessive deformations, may be visible. For instance, it was shown by InSAR data that deformations of balconies in summer and winter can be different due to temperature.

From this first inventory, it appeared that structural failures caused by soil settlements are especially promising to analyze with InSAR, although the Cobouw might pay more attention to more ‘spectacular’ and visible failure causes. To illustrate the potential use of InSAR for forensic structural engineering and predicting disasters, a case study has been performed on a shopping mall in Heerlen that suffered large damage due to soil settlements.

3 Case settlements shopping centre ‘t Loon

3.1 Hypothesis testing in forensic structural engineering

Shopping mall ‘t Loon was built in 1965 in an area that was used until approximately 1974 for coal mining (closure of Oranje-Nassau mine). The involved part of the shopping mall consisted of 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. The columns have shallow foundation on footings. On top of these columns there is a concrete floor which functions as a platform for two storeys of steel structure. The roof is flat. The concrete structure has a column span of approximately 7 m, and the building height is approximately 15 m.

The floor of the parking garage sagged between 12 and 15 cm in the period from 2002 to 2011 [7]. 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 led to a clearance of the building. On December 3, 2011 a column sagged into the ground and was detached from the supporting structure. Thereby the structure lost locally its carrying capacity, but did not collapse because of the second load path of the structure. One of the hypotheses of the cause of the detachment of the column was the presence of a sinkhole under the column [7].

A sinkhole can cause a failure mechanism with a translation of the ground that results in a translation of the column.

The hypothesis that the failure was caused by a sinkhole can be tested with InSAR data.

A dataset for the specific area was analyzed by Chang and Hanssen [3] and is used for this case study. 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. A dominant satellite data point is located near the location of the detached column and on another part of the structure.

Figure 1 shows the displacement of two persistent points. PS1 is near the damage location, PS2 is a point on a part that is barely influenced by the sinkhole. PS1 shows 80 mm settlement from 1992 to 2011. The data also show that the displacement increases closer to the failure, which makes it plausible that the movement of the roof was higher during the failure at the roof. PS2 shows almost no displacement because of dilatation. These results were expected and support the hypothesis of a sinkhole.

The maximum subsidence of soil, due to the sudden collapse of the sinkhole, of approximately 1500 mm over a small are of 30 to 50 m^2 [7] could not be detected with InSAR because it was inside the building and because it developed nearly instantaneous.

Figure 2 indicates why the displacement at the roof (80mm) is much smaller than the actual displacement of the soil (approx. 1500mm).

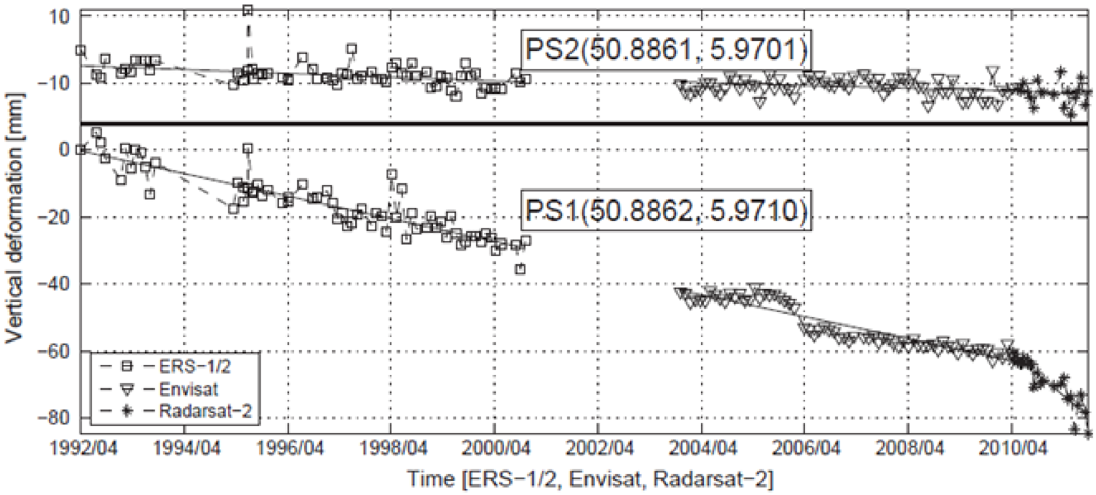

Figure 1: Displacement of two Persistent points in time monitored by different satellites. Source: Detection of cavity migration and sinkhole risk using radar interferometric time series by Chang and Hanssen [3].

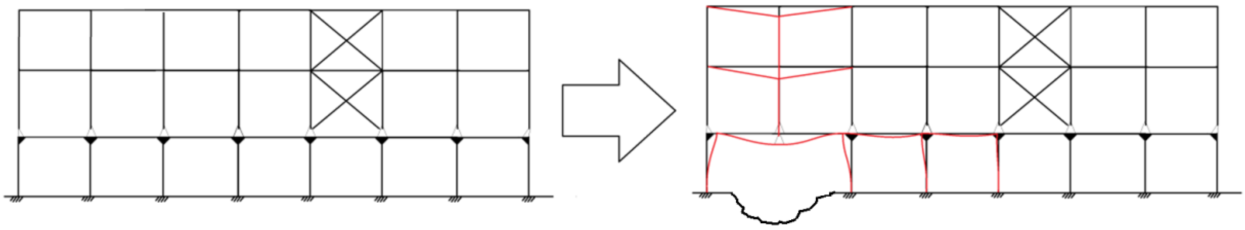

Figure 2: Theoretical simplified movement of the roof in normal condition and without the detached column (magnitude of displacement not on scale).

In red the theoretical movement can be seen. The detached column is removed from the left part of the figure. The reinforcement of the first floor connected to the columns delivered a tensile force to keep the floor in place. This redistribution of loads by the concrete part of the structure reduces the size of the deformation, while the steel structure on top follows the deformation of the concrete first floor. This explains the smaller magnitude of the measured displacement at the roof.

Hordijk [7] finally concluded, using additional information, that the cause of the failure actually was the sinkhole. In addition, he used InSAR data to verify that other parts of the structure were not moving, like the apartments located on top of the mall.

This case study shows that InSAR data can help to sustain or reject a hypothesis, although usual additional information of the actual situation is needed to interpret the data.

3.2 Predicting failure of ‘t Loon

’t Loon is a case where the failure might have been foreseen by monitoring absolute values and the displacement rate of the structure with InSAR data (see [3]).

When the vertical deformation limits according to Dutch NEN6702 code are considered for floors with a span of 7000 mm, a deformation limit of 14 mm is applicable (when crack prone walls are placed on the floor). This limit was already exceeded in 1996.

For the vertical displacement rate a value of 3 mm/year is critical [8]. If ERS-1/2 data is analyzed for 1992 to 2000, a period that ends 12 years before the failure, alarming displacement rates of about 3.3 mm/year could be observed already. Envisat data also observed a displacement rate of about 3.3 mm/year.

It can be concluded that the absolute values of the displacements were already critical and the development of the displacements occurred too fast, which could have been detected with InSAR.

4 Alternatives for radar interferometry

Displacement measurements for buildings are one of the fields in which InSAR can add value. Alternative survey techniques include Lidar, photogrammetry, levelling, and tachymetry. Table 1 shows these different monitoring techniques and their properties. [9, 10, 11, 12, 13].

Monitoring instrument	**Accuracy (indication)**	**Point spacing**	**Covered area per measurement**	**Measurement interval**	**Limitations**
Tachymetry (robotic or manual)	0.6 mm	Retro reflectors, tens of meters	50x50 m	Episodic (robotic: minutes, manual: weeks)	Surveying, benchmarks needed, free line of sight required, costly
Levelling	8 mm/$L^{0.5}$ (L=distance in km)	Tens of meters	~50m between benchmarks	Manual: weeks/months	Obstruction of elements in line of sight. Manual work: costly
GPS	20 mm	Benchmarks > 100 m	Point	Continuous or episodic	Requires benchmarks, free view to satellites
Terrestrial Laser Scanning	2 mm	> Centi-metres	Tens of meters	Episodic	Obstruction of elements in line of sight. Manual operation
Close-range photogram-metry	15 mm	Decimetres	Tens of meters	Episodic	Obstruction of elements in line of sight
InSAR	2 mm, 0.4 mm for time series	~3x3 m and coarser	Hundreds of square kilometres	different per satellite (typically weeks)	Lower density of accurate data in vegetated areas, measurement in the LOS direction

Table 1: Different monitoring techniques and their properties.

From this brief comparison it appears that the accuracy and the measurement in line of sight (LOS) direction are a disadvantage compared to monitoring techniques on site. Another possible disadvantage is the, previously described, opportunistic character of the technique. It may be possible that the location of interest is not available with InSAR data.

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. InSAR data’s ability to look back in time after an unforeseen failure has occurred, is also a unique feature that makes InSAR a useful addition to other monitoring techniques.

5 Conclusions

This research explored the opportunities of radar interferometry for forensic investigations or structural health monitoring.

It appeared that approximately one fifth of the reported damage cases in the use phase of buildings in the Netherlands between 1993 and 2009 have the potential to be studied by InSAR, presuming that satellite data is available. Failures that affect outer shell elements in deformation/displacement can be investigated, especially gradually increasing settlements. Usually, additional information from the actual structure is needed to interpret the InSAR results.

An advantage of InSAR over other measuring techniques is that it can look back after an unforeseen failure, by using historical satellite data.

The opportunities for structural health assessment and monitoring with satellite radar interferometry are growing rapidly. This is largely due to the fact that more and more radar satellites are launched, with increasingly better resolutions and revisit intervals, and that data availability, access, and cost are improving.

Full details of this study can be read in the Master thesis: Feasibility study of building monitoring and forensic engineering with Interferometric Satellite Apperture Radar, H. van Waning (2014), accessible by TU Delft's repository.

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