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Detection of cavity migration and sinkhole risk using radar interferometric time series

Ling Chang *, Ramon F. Hanssen

Department of Geoscience and Remote Sensing, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands

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ABSTRACT

Upward migration of underground cavities can pose a major hazard for people and infrastructure. Either via sudden collapse sinkholes, or by eroding the support of building foundations, a migrating cavity can cause the collapse of buildings, water defense systems, or transport infrastructure. The main problem for risk assessment is the lack of a priori knowledge on the location of a potentially hazardous cavity. Here we demonstrate the feasibility of satellite radar interferometry to detect a migrating cavity under the city of Heerlen, the Netherlands, leading to foundation instability and the near-collapse of a part of a shopping mall in December 2011. We exploit the data archives of four imaging radar satellites, between 1992 and 2011, to investigate the dynamics of the area and detect shear strain within the structure of the building. Time series analysis shows localized differential vertical deformation rates of ~3 mm/yr during 18 years, followed by a dramatic increase of up to ~15 mm/yr in the last few years. These results imply that the driving mechanism of the 2011 near-collapse event had a very long lead time and was likely due to a long-lasting gradual process, such as the upward migration of a cavity.

1. Introduction

Upward migrating cavities of both natural and anthropogenic origins are an important hazard in many parts of the world, able to cause sudden cover-collapse leading to sinkholes (Caramanna, Ciotoli, & Nisio, 2008; Coker, Marshall, & Thomson, 1969; Galve et al., 2009; Lamoreaux & Newton, 1986; Newton, Copeland, & Scarbrough, 1973; Tolmachev & Leonenko, 2011). Moreover, rising population densities in sinkhole-prone areas, in combination with media attention using public video surveillance and private cell phone video, have increased public awareness (CNN, 2014; Meng, 2013; Schwartz, 2013; Wines, 2013).

Apart from sudden collapse sinkholes, the consequences of migrating cavities include the lack of support of building foundations, drainage of water bodies, and the deformation or destruction of water defense systems or critical infrastructure (Gutiérrez et al., 2009).

The chief problem in the assessment of sinkhole risk is the lack of a priori knowledge on the location of the cavity (Baer et al., 2002; Wust-Bloch & Joswig, 2006). Although in situ measurements such as gravimetry (Colley, 1963), seismic (Cook, 1965) or electromagnetic surveying or ground-penetrating radar (Beres, Luetscher, & Olivier, 2001; Mochales et al., 2008) are in principle able to detect an underground void, it is not economically possible to use these techniques over vast areas. Moreover, the risk of fatalities is highest for urbanized areas (Bezuidenhout & Enslin, 1970; Frumkin & Raz, 2001), in which the built-up environment prevents getting close enough to perform these measurements. The second problem is that there is usually no data available preceding a collapse, so it cannot be assessed whether there was precursory motion, and how far ahead in time critical levels can be detected. Here we investigate the use of satellite radar interferometry to detect minute signs of impending sinkholes (Abelson et al., 2003; Nof et al., 2013). In particular, we hypothesize that precursory deformation may be occurring before sinkhole formation, potentially detectable as relative displacements using radar satellites. As this hypothesis can only be tested empirically using case studies we choose a near-collapse event of a shopping mall in Heerlen, the Netherlands, to investigate the efficacy of the method. Even though a successful case study does not prove generic applicability of the approach, it is crucial to expand the scarce empirical material available.

1.1. Study area and near-collapse event

From the late 19th century to the mid 1970s, coal mining took place in the Heerlen area, in the southeastern Netherlands, see Fig. 1 (Messing, 1988; Westen, 1971). The extraction of coal caused up to several meters subsidence of the surface, leading to damage to the build-up environment (Cuenca, 2012; Cuenca & Hanssen, 2008). After the discovery of large reserves of natural gas in the north of the country, mining ceased abruptly, and shafts and galleries were backfilled and abandoned, but possibly leaving cavities. When the overburden of the

* Corresponding author.
E-mail addresses: L.Chang@tudelft.nl (L. Chang), R.F.Hanssen@tudelft.nl (R.F. Hanssen).

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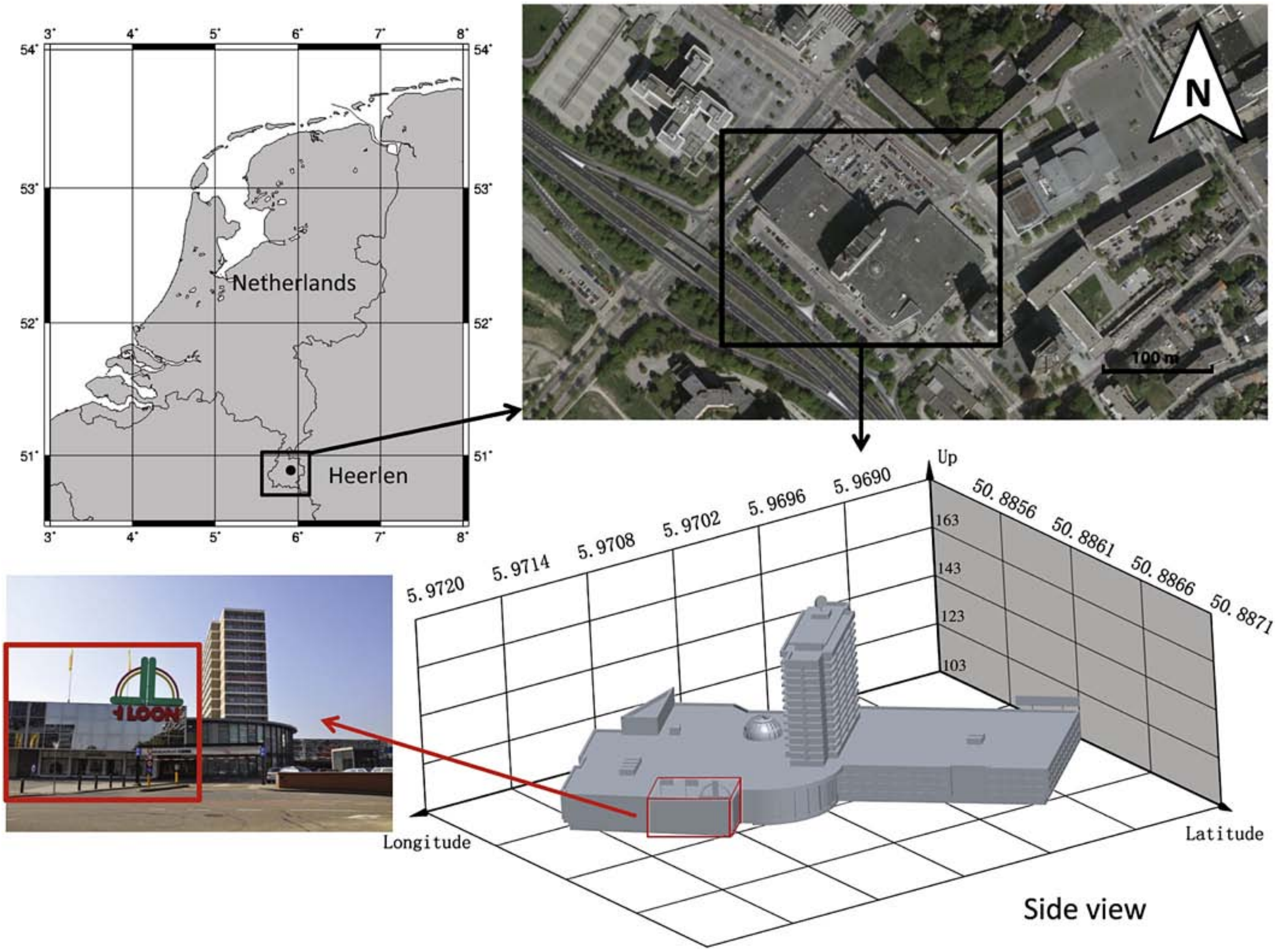

Fig. 1. Location of the study area (Heerlen, the Netherlands) and the shopping mall from airborne imagery. A 3D model of the building at the lower right was constructed using airborne lidar data and photographic information, see Fig. 3 and the ground-view photo on the lower left. The area indicated by the red square was subject to the localized subsidence. Source: Aerodata 50°53′10″N and 5°58′13″E.

mine galleries would collapse, such cavities could migrate upwards over time and eventually reach the surface.

Shopping mall and apartment building *'t Loon* in Heerlen, see Fig. 1, was built in 1965, as it later appeared some 90 m above an abandoned mining gallery. In June 2011, movements were occurring in the structure of the mall, and periodic surveys were performed to monitor their behavior (Engelbertink, Morée, & Muis, 2012). Late August 2011, cracks were observed in the columns supporting the car park below the mall, leading to the installation of support constructions and further investigations. November 29th, a significant crack was observed in the head of column D18, see Fig. 2, and parts of the floor and facade had deformed. A part of the mall was evacuated. December 3rd, an ~8 m wide and ~1.5 m deep sinkhole occurred beneath column D18, marked in red in Fig. 2 (Hordijk, 2012). The entire complex (mall and apartments) was evacuated. The municipality decided to demolish the part of the mall that was constructively affected.

In the analysis of the event, several hypotheses were formulated on the driving mechanisms for the sinkhole, such as (i) coal mining activities between 1950 and 1956 (Parise, 2012), (ii) rising mine water, (iii) surface water run-off (Sinclair, 1982), (iv) karst dissolution (Parise & Lollino, 2011), and (v) tree roots and the flushing of a broken sewer system, where it was recognized that it could also be a combination of mechanisms (Roest, 2012).

In this study, we use the Heerlen events to investigate the value of satellite radar data archives to detect potential sinkhole-prone locations over build-up areas, to assimilate various data sources, and to analyze the spatio-temporal information retrieved from the data. In Section 2 we discuss the applied methodology for multi-sensor data processing and precise geolocation, followed by the results and interpretation in Section 3. Section 4 is dedicated to the conclusions.

2. Methods

In order to investigate the hypothesis of precursory deformation preceding sinkhole occurrence, we jointly use the SAR data archives of four radar satellites (ERS-1, ERS-2, Envisat, and Radarsat-2) over a period of close to 20 years. We then apply radar interferometry via time series analysis using a persistent scatterer interferometry (PSI) method (Ferretti, Prati, & Rocca, 2001; Kampes, 2005). This yields estimates of the relative one-dimensional motion of time-coherent scatterers, here termed as PS, in the satellite line of sight (LOS) (Ferretti, Prati, & Rocca, 2000; Hanssen, 2001; Ketelaar, 2004). The periodically acquired