Ground Deformations Related to an Old Drainage Adit in The Abandoned Coal Concession Around Saint-Vaast (Wallonia, Belgium) Analyzed Using PS-InSAR and Piezometric Wells Time Series

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Abstract

The persistent scatterer radar interferometry technique (PS-InSAR) has revealed ground displacements since 1992 in Saint-Vaast (Wallonia, Belgium), where an old drainage adit allows mine water discharge to the Haine River. As far as our knowledge goes, the Saint-Vaast area has already been affected at least twice, by a clogging rupture in the drainage adit. This event has induced a displacement at the surface. The integration of PS-InSAR results and observations of installed piezometric wells are used to compare the water table evolutions and the ground deformations observed at the surface before, during, and after the second outbreak event in 2018.

Keywords: PS-InSAR, Clog rupture, Mine adit, Urbanized area, Coal mine concession.

Introduction

Abandoned mines often pose a threat to the environment, public health, and safety (Lee and Park 2013). Many old and abandoned mines over the world, which were often mined in the shallow depth, are prone to land subsidence (Bell and Genske 2001). Various studies have demonstrated the effectiveness of InSAR technology in detecting and monitoring land-surface linked to mining operations (Li *et al*. 2022). In this paper, PS-InSAR is used to quantify and map displacements that the earth's surface has experienced during the period 1992–2022 in the Saint-Vaast area, Wallonia, Belgium.

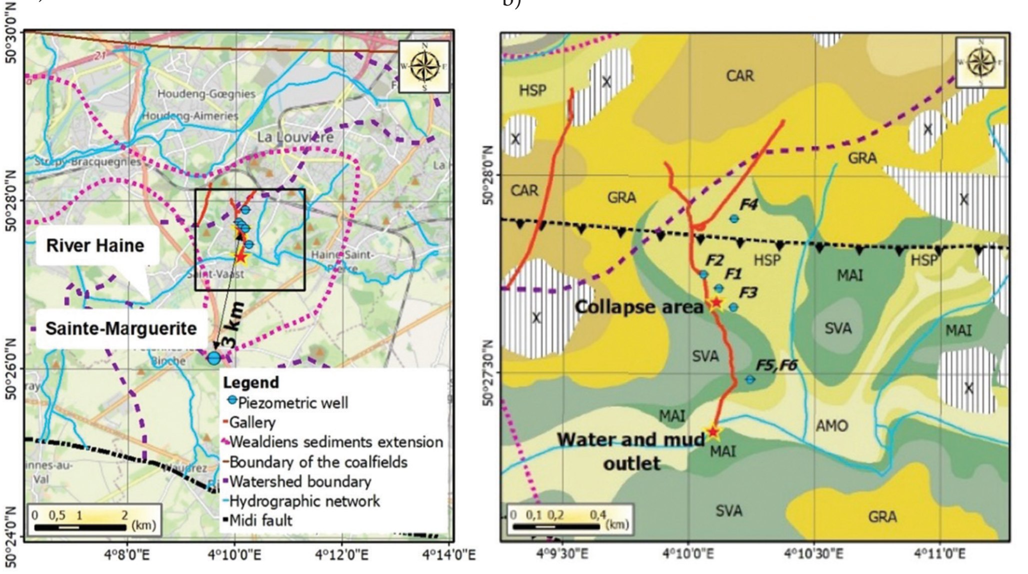
The presence of an old drainage adit at a depth of approximately 30 m in combination with a confined aquifer located in low mechanical resistance geological sublayers has so far resulted in a stream of mud and sand gushing out at least twice in 2009 and 2018. The first incident resulted in a serious collapse in a residential area in Saint-Vaast and a mud outbreak for a few hours at the outlet of the adit near the river Haine (fig. 1a). A pipeline was erected to redirect the water directly into the river, but it was clogged in 2010. Water gushed through the pipe again during the second water outbreak in 2018. However, there was no genuine issue since the pipe effectively directed water into the river and regulated the outgoing flow. Changes in deformation trend, which were observed by PS-InSAR along the network of piezometric wells set up for monitoring groundwater levels after the first water outbreak, make Saint-Vaast a perfect study site for demonstrating and interpreting the hazards associated with the abandoned coal mine area.

This study has two main objectives. First, to apply PS-InSAR on ERS1/2, Envisat ASAR, and Sentinel-1A satellite radar imagery to monitor ground surface deformations and retrieve time series of deformation in PS points in the vicinity of the collapse site to identify, quantify and map the effects of the outbreak events and second, to evaluate the relationship between water level fluctuations and deformation time series allowing one to use different techniques together as a tool for preventing future risk issues.

Geological, Geographical, and Hydrogeological Setting

The Region of Interest (ROI) is in Saint-Vaast, Wallonia, and comprises the municipality of La Louvière (fig. 1a). The area is bordered on the north by coalfields, and on the south by the Midi Fault.

a) b)



c)

Abreviation	Lithology	Formation	Hydrogeology	Epoch	Period	Era
X	Coal mine spoil (heaps), landfills of household waste and inert waste	Backfill	–	Holocene	Quaternary	Cenozoic
AMO	Gravel, sand, clays	Modern alluvium	Alluvial aquifer of the Haine	Pleistocene		
CAR	Alternation of clays and sands	Carnières	Aquitard of Eocene clays	Eocene	Paleogene	
GRA	Clayey sands	Hannut	Paleocene sands aquifer	Paleocene		
SVA	Clayey chalk	Saint-Vaast	Cretaceous Carles aquifer	Upper	Cretaceous	Mesozoic
MAI	Chalk or calcareous rock	Maisiéres				
HSP	Glauconitic chalk	Haine-Saint-Paul				
HAI	Heterogeneous sandy or clayey deposits containing fossilized plants	Gravels of Saint-Pierre	Aquiclude (Wealdian facies sediments)	Lower		
HOU	Shales, sandstones and coal seams, Phtanitesn, and limestone bed shales	Flénu to Blaton (Houiller group)	Coal bedrock	Westphalian and Namurian	Carboniferous	Paleozoic

d)

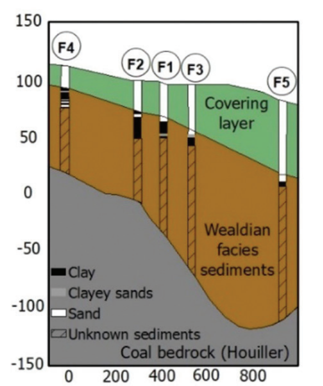


Figure 1 a) Summary of data in the study area, including the position of the piezometric wells, the border of wealdian terrains, and the location of the Sainte-Marguerite well, b) map of galleries in the region on the geological map of Belgium, c) geological descriptions, and d) The geological section which follows the (non-rectilinear) route of the drill holes F4, F2, F1, F3, and F5.

The research area's sub-surface is mostly composed of Paleozoic rock (consisting of limestone and dolomites of the Lower Carboniferous) and a Meso-Cenozoic formation (consisting of Cretaceous clays, marls, and chalks of the Upper Cretaceous), which is overlaid by Paleocene and Eocene sediments corresponding to the extension of the North Sea basin at that period (fig. 1b & c). The surface collapse took place in 2009 in the middle of the drainage adit route and water outbreaks in 2009 and 2018 took place at the adit outlet (fig. 1b).

A groundwater monitoring system was installed along the presumed route of the drainage adit after the first event in 2009 (F1 to F6 in fig. 1b). The F1 to F5 wells were installed in the Wealdian terrain, while F6 is being used for monitoring the water level in the Upper Cretaceous aquifer (covering layer in fig. 1d) to check if any connection could be identified between the different aquifers. The Sainte-Marguerite extraction well located 3 km of Saint-Vaast, started to be used for measuring levels of the Houiller water table, after 1982 (fig. 1a). In addition, because of its importance in this study as they caused the clogging of the drainage adit, the Wealdian terrain border, which is characterized by sediments of extremely diverse origin and nature, has been highlighted over the study region, even though it has no outcrops on the surface. These sediments have low mechanical resistance. The piezometric wells are only present on a small percentage of the upper Wealdian sediments (See fig. 1d). However, this representation simplifies the conceptual model of a bi-layered Wealdian terrain, with sandy top layers and clayey lower layers. The different behavior deduced from the piezometric wells, which will be shown below, confirms this fact.

Data and Methodology

InSAR. thanks to the phase difference between acquisitions, can measure the change of distance between the source and the objects backscattering the signal. This change of distance can be attributed to the deformation if different phases contributed to various sources are subtracted. Interferograms were generated in Doris (Delft Object-oriented Radar Interferometric Software) (Kampes and Usai 2003) and processed in the StaMPS (Stanford Method for Persistent Scatterers) (Hooper *et al.* 2012) software throughout the PS-InSAR technique (Ferretti *et al.* 2001). Table 1 summarizes the characteristics of the SAR image datasets used in this study.

Results and Discussions

Satellite observations revealed various deformation patterns before and after the area's collapse (fig. 2). For those PS points within a 150 m radius around the centre of the collapse area, the average ground surface uplift at a rate of 3.11 mm/y during the period associated with the ERS1/2 imagery is observed (1992-2006). The Houiller is unlikely to be connected to the Wealdian aquifer through natural hydraulic systems. Nonetheless, a regional influence cannot be ruled out due to the considerable changes in the piezometric surface of this aquifer, following the cessation of pumping operations at the previous Sainte-Marguerite mining site (even though, there is no piezometric well in the ROI that measures the water level in the Houiller). The Sainte-Marguerite piezometric well, located approximately 3 km from the first event site, showed a dramatic rise in water level after 1985 when the previously active pumping was stopped. The piezometric level rose from 261 m depth in 1983 to 50 m depth in 2022. The groundwater levels are monitored

***Table 1** Characteristics of the SAR image datasets used for the study of the Saint-Vaast region*

Satellite	Number of interferograms	Start date of spanning	End date of spanning
ERS1/2	74	26/04/1992	04/10/2006
Envisat ASAR	73	19/03/2003	13/10/2010
Sentinel-1A	179	02/04/2015	31/01/2022

in both the Sainte-Maguerite mine shaft and the well. This area is too far to the south of the ROI to be detailed in our paper, but it confirms a regional rise of the piezometric levels in the coal mining area implying a regional recharge and potentially a rebound characterized by positive LOS velocities. The presence of superficial aquifers (less than 100 m deep) associated with the Cretaceous and Tertiary sediments overlaying the hard coal Carboniferous rocks have potentially a more direct effect at the surface related to the groundwater fluctuations as well. There are no piezometric data available in the Saint-Vaast area to confirm any groundwater evolutions. It is thus very difficult to estimate if one or both aquifers could be cause the surface deformations observed during ERS1/2.

Envisat ASAR processed data from 2003 to 2010 indicates that the region is nearly stable, and within a 150 m radius around the centre of the initial event, the average LOS displacement rate for all PSs is 1 mm/y. The processed data from applying the PS-InSAR approach to the SLC Sentinel-1A data between 2015 and 2022 demonstrate that the PS points' stability has turned into subsidence, with an average displacement rate of -1.78 mm/y

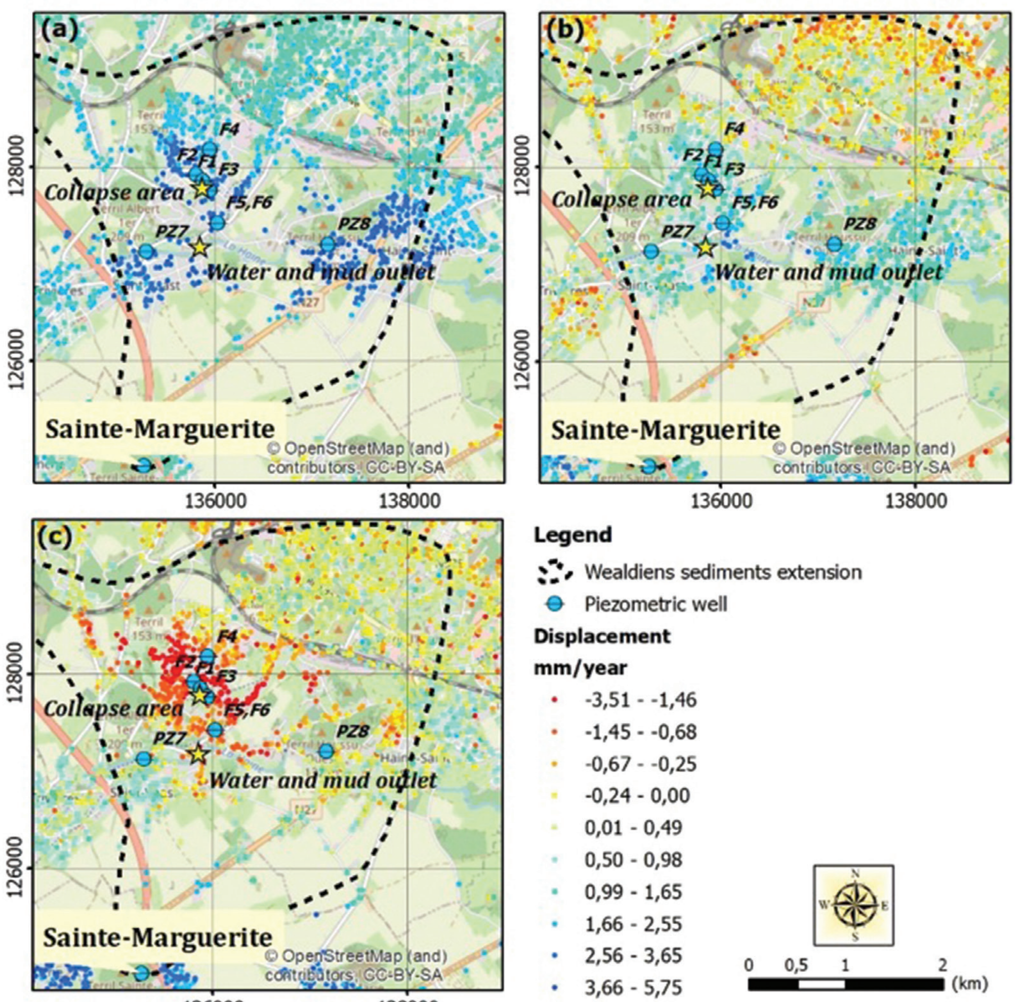


***Figure 2** LOS velocity map of PS points distributed over the ROI highlighting the collapse area and water and mud outlet locations in Saint-Vaast, derived from (a) ERS1/2 radar data (1992-2006), (b) Envisat ASAR radar data (2003-2010), and (c) Sentinel-1A (2015-2022).*

for the points within a 150 m radius from the centre of the first event. The subsidence bowl highlighted during Sentinel-1A has a clear pattern: the bowl is oriented mostly along a North-West to South-East axis in the Saint-Vaast district. The higher absolute value LOS velocities are in the centre of the subsidence bowl and the LOS velocities are decreasing symmetrically towards the SW and NE margins. This land subsidence bowl is mapped at the centre of the main extension area of the Wealdian sedimentary terrains (Wealdian sedimentary deposits coverage and extension are still uncertain and mapped from borehole descriptions) covering the hill of the Saint-Vaast district area. The interpretation of surface displacement, on the other hand, necessitates the analysis of the displacement time series (fig. 3).

The water level fluctuation rates in piezometric wells at Saint-Vaast are much higher in the Wealdian layer. This could be related to issues that arose during the piezometer's installation. Because of the confined nature of the Wealdian water table and the distance between the piezometers and the nearest water inflows, such changes are either caused by a sensor malfunction or by random mistakes. However, the combination of Figures 3 and 4 helps to understand the general trend of piezometric wells (fig. 3 and 4).

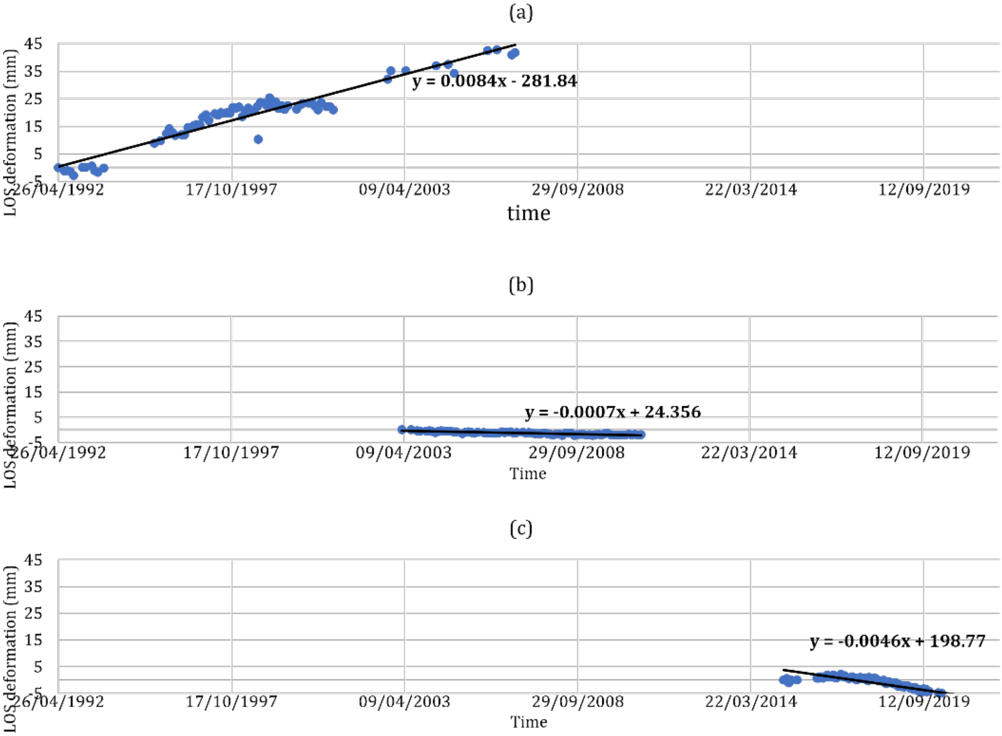


__Figure 3__ The average of LOS deformation time series for the PS points within a 150-meter radius around the centre of the collapse area observed at the surface, inferred from (a) ERS1/2 radar data (1992-2006), (b) Envisat ASAR radar data (2003-2010), and (c) Sentinel-1A (2015-2022).

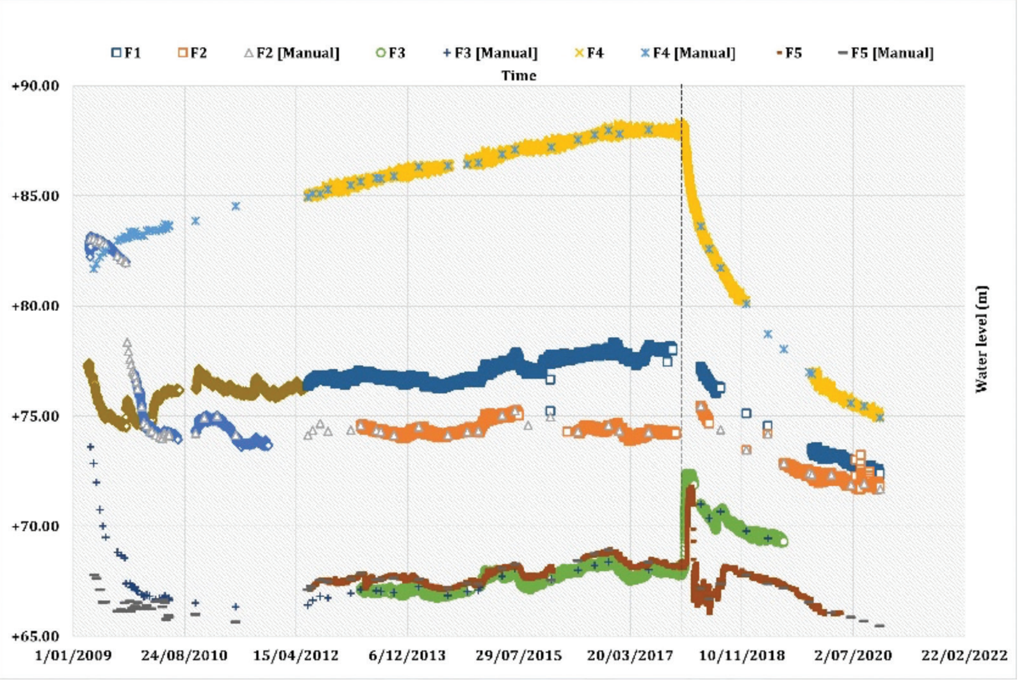


Figure 4 Time series of water level at the location of five piezometers (F1 to F5) near the collapsed area in Saint-Vaast, installed by the Public Service of Wallonia following the first event in 2009.

Even though the piezometric wells are only a short distance apart, their behavior is vastly different due to the vertical heterogeneity of the Wealdian sediments in the sublayers. On the other hand, the water level fluctuations in the first months following the installation of piezometric wells indicate declining trends. The slight decreasing trend in the time series of deformation computed by the processing of Envisat ASAR radar data from 2009 to 2010 might explain this downward tendency. However, due to the lack of piezometric wells, interpreting the Envisat ASAR time series before the first incident remains challenging. The water level in all the piezometric wells obviously began to increase again in 2010, when the water pipeline installed in 2009 for channelling water to the river was clogged. There is no PS-InSAR time series of ground movement available between 2010 and 2015. However, between 2015 and 2022, the displacement time series of Sentinel-1A data reveal a considerably decreased trend. The discovery of a large number of subsurface geological layers in the Wealdian series is potentially implying a weakening of the geological layer stability at the bottom of the sequence directly associated with the mine adit structure as a result of the first event in 2009. The water level of all piezometers dropped at the same time in 2018 because of the second water outbreak. Although there was no sudden damage since the pipeline could control outcoming outflow, it is likely that more sediments were gushed out leading to further weakening of the Wealdian sandy sedimentary layers. At the end of the time series of surface displacement associated with Sentinel-1A data, the acceleration of land subsidence in the years after 2018 confirms this process.

Conclusions

This study attempted to estimate surface displacement using the PS-InSAR technique in the Saint-Vaast residential area, where the presence of an old outbreak adit in combination with a confined aquifer in the low mechanical resistance sublayers has resulted in a stream of mud gushing out twice, in 2009 and 2018. Three separate time series datasets were used to achieve this purpose. ERS1/2, Envisat ASAR, and Sentinel-1A were the datasets used. The evolution of the water level in the piezometric wells is substantially consistent with the LOS velocity and time series of displacement acquired from radar satellite imagery. By evaluating the displacement time series generated from the InSAR technique, a more complete explanation of the behaviour of piezometric data at shorter intervals will be investigated in a subsequent study.

Acknowledgments

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