InSAR Monitoring of Subsidence Induced by Underground Mining Operations

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ABSTRACT
Subterranean activities such as underground mining and tunnel excavations can produce extensive subsidence of the ground surface, which in severe cases can have serious consequences. In mining, excessive subsidence can lead to blocks in production and safety issues while in urban tunneling contexts it can lead to stoppages, damage to above-ground structures and extensive project delays. The timely mapping of the extent and magnitude of surface movement is usually one of the main challenges faced by geotechnical managers in these cases.

The instrumentation used for monitoring surface deformation has generally been based on conventional survey techniques (total stations, levelling, GPS, extensometers), which provide spatially sparse measurements. The advent of satellite SAR Interferometry (InSAR) significantly changed this scenario by providing wide coverage and high density of accurate information without the need to install ground instrumentation. It is also possible to assess historical deformation by processing satellite data archives going back to the early 1990s. Furthermore, recent advances in processing algorithms have significantly reduced computational time and the advent of newer satellites with increased spatial resolution and acquisition frequency have increased information density. Near-real time InSAR monitoring is now widely applied in different applications to highlight incipient movements in areas not visible to in-situ instrumentation.

Some case studies of InSAR applied to underground mining and urban tunneling will be shown, highlighting the advantages of combining different InSAR techniques to monitor both slow and fast movements.

INTRODUCTION
Ground subsidence often accompanies underground excavation activities and monitoring surface subsidence is essential to increase safety, avoid activity stoppages and provide timely detection of incipient damage to buildings and infrastructure. It has become an essential tool for mitigating the socio-economic risks related to activities that produce ground surface deformation.

The instrumentation used for monitoring surface deformation in and around excavation operations is generally based on conventional survey techniques (total stations, levelling, GPS receivers, ground-based radars) but none of these usually offer the high density, bird’s-eye view of the movement areas provided by satellite InSAR (Synthetic Aperture Radar Interferometry).

After a brief introduction of the technique, selected case studies are presented in this paper to illustrate the use of InSAR to monitor both slow and fast surface deformation induce by underground mining and support mitigation strategies in urban contexts.
SAR INTERFEROMETRY

SAR satellites acquire images of the Earth's surface by emitting electromagnetic waves and analyzing the reflected signal. InSAR consists of the phase comparison of SAR images, acquired at different times with similar looking angles from space or airborne platforms (Gabriel et al., 1989; Massonnet and Feigl, 1998; Rosen et al., 2000; Bamler and Hartl, 1998). As SAR satellites are continuously circumnavigating the globe, a number of SAR images are collected for the same area over time.

The phase difference calculated between two SAR images acquired over the same area at different times is proportional to the surface deformation that occurs during that time interval (Figure 1) but also contains topographic and atmospheric contributions. Differential InSAR (DInSAR) refers to the interferometric analysis of a pair of SAR images to identify and quantify movement by removing the topographic contribution using a Digital Elevation Model.

Figure 1 shows the relationship between ground displacement measured along the satellite Line of Sight (LOS) and signal phase shift. This is the basic principle of InSAR for measuring ground movement.

In the mid-90s, after extensive application of the DInSAR technology, it became evident that the atmospheric contribution to the signal phase was significant, particularly in tropical and temperate areas. This led to the advent of Advanced DInSAR (A-DInSAR) techniques in the late 1990s, which are based on the statistical processing of multiple images to remove atmospheric noise and reach a higher accuracy of deformation measurements. Permanent Scatterer Interferometry, the first A-DInSAR technique, identifies and monitors point-wise permanent scatterers (PS), pixels that display stable amplitude and coherent phase throughout every image of the dataset (Ferretti et al. 2000, 2001). Permanent scatterers are objects such as rocky outcrops, boulders, manmade structures (buildings, street lights, transmission towers, etc.), and any structure that consistently reflects a signal back to the satellite. In 2011, Ferretti et al. presented a new technique known as SqueeSAR™ that also extracts information from distributed scatterers (DS), areas with homogeneous ground surface characteristics that can be grouped to extract ground surface information from non-urban areas with limited infrastructure and light vegetation.

The existence of data archives going back to the 1990s initially led to the extensive use of InSAR data to perform historical ground deformation analyses. Recent advances in processing algorithms have significantly reduced computational time and the advent of newer satellites with increased spatial resolution and acquisition frequency have

Figure 1. Basic principle of InSAR for measuring ground movement
increased information density. Near-real time InSAR monitoring is now widely applied in different applications: mining, civil engineering, natural hazard and oil&gas.

MINING APPLICATIONS

The complementary use of space-based InSAR with traditional systems has proved to be strategic for operational monitoring and risk assessment in mining operations. Successful applications to underground and open pit mines are presented by Carnec & Delacourt (2000), Raucoules et al. (2003), Colesanti et al. (2005), Jung et al. (2007), Herrera et al. (2007), Herrera et al. (2010), Espinosa et al. (2014) Iannacone et al. (2014), Paradella et al. (2015), Sanchez et al. (2016), Carla’ et al. (2018).

Two case studies of InSAR applied to longwall mining are presented, illustrating the use of SqueeSAR historical data to characterize the extent of long-term subsidence (Metropolitan Mine, Australia) and the use of DInSAR to detect short-term fast deformation (Bytom City, Poland).

Metropolitan Mine (Australia)

The Metropolitan mine is an underground coal mine located in the Southern Coalfields of New South Wales, about 40 km South of Sydney and in operation since 1888. A 3 m coal seam has been mined from the Bulli Seam (DeBono & Tarrant 2011) using longwall mining. The Bulli Seam is the top seam in the Illawarra Coal Measures (Hutton 2009), and is overlain by the Arrabeen Group (300 m of sandstones, claystones and shales), a Middle Triassic quartz sandstone and the Hawkesbury Sandstone. The depth of the cover varies from 400 to 520 m depending on the local surface topography (DeBono & Tarrant 2011).

Mining started in the area of study with Longwall 1 in 1995 and finished in April 2010 with the extraction of Longwall 18 (Figure 2). Mining progressed from the southeast towards the northwest while the extraction direction of the individual longwalls proceeded from southwest to northeast (DeBono & Tarrant 2011; Morgan et al., 2013).

The processed radar imagery consists of two archives of ENVISAT radar imagery that were processed using SqueeSAR (Iannacone et al., 2014). The data sets comprise 44 images acquired from an ascending orbit and 43 images acquired from a descending orbit and cover the period June 2006 to September 2010, corresponding to the period in which panels from Longwall 13 to Longwall 18 were mined.

Longwall mining can induce large, rapid displacements in the weeks after panels are mined out, which can lead to a loss of measurement points above the longwalls. However, the focus here was to determine the extent of the subsidence area and to correlate the timing of deformation with mining operations. The analysis of the timing of ground movement within the subsidence bowl showed measurement points located close to the mining front accelerating followed by deceleration once the panel has been mined (Figure 3). InSAR highlighted a kilometer scale subsidence bowl with displacements that extend well beyond the surface area above the longwalls, and reached a cumulative value of over 150 mm between 2006 and 2010. The extent of the subsidence bowl is usually defined by means of an angle of draw which extends upwards and outwards from the working face and varies from 8° to 45° off the vertical. The SqueeSAR results indicate a much higher angle of draw of around 64° with a wider than expected subsidence bowl. Furthermore, a significant number of measurement points located over older mining areas denoted a multiyear linear deformation trend, indicating that residual subsidence can last for many years after the mining has terminated.
Bytom City is located in the north-western part of Upper Silesian Coal Basin in southern Poland. Mining activities in this area are carried out by longwall mining. The excavated coal layer is 2.5 m thick, 250 to 400 m long, and about 680 m deep. Historical subsidence of up to 27 m over 33 years has been measured, affecting an area of nearly 300 km².

Bytom City (Poland)

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To monitor the rapid subsidence over the mine, SAR images acquired by the Terrasar-X satellite every 11 days were processed using a DInSAR approach (Colombo et al., 2018). Figure 4 shows some examples of 11-day interferograms (maps of difference in phase between two images), where coloured bands, referred to as fringes, highlight areas with

![Interferograms](image)

**Figure 4.** Interferograms over longwall coal-mining area in Bytom municipality. Acquisition dates are reported in Table 1.

<table>
<thead>
<tr>
<th>Interferogram</th>
<th>1st Image</th>
<th>2nd Image</th>
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<td>c</td>
<td>23 Oct 2011</td>
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<td>d</td>
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<td>e</td>
<td>14 Mar 2012</td>
<td>25 Mar 2012</td>
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**Table 1.** Acquisition dates for interferograms in Figure 4

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phase variations where deformation can be measured. Figure 4f shows estimates of the cumulative deformation on the surface during the observations.

While interferograms outline areas with centimetre-scale subsidence bubbles, SqueeSAR was applied to detect more subtle millimetre-scale displacements, thereby providing a more complete map of the area affected by mining-induced subsidence (Figure 5).

**URBAN TUNNELING APPLICATIONS**

InSAR monitoring of ground deformation has been applied to all phases (design, construction, and operation) of tunneling projects in both urban and nonurban areas (Bock et al., 2012; Iannacone et al., 2014; Hoppe et al., 2015). In urban contexts, where there is a higher need to monitor ground deformation associated with tunneling activities, InSAR significantly improves the quality of any monitoring program by refining and extending *in situ* observations. This is recognized by the inclusion of InSAR in the “ITAtech Guidelines for Remote Measurements Monitoring Systems” (2015), which provide recommendations and examples for monitoring projects in support of tunnel designers, contractors and owners to understand the benefits and limitations of remote measurement systems.

**Rail Tunnel (South Italy)**

The case study presented here regards a single-track 60 m² cross-section rail tunnel being excavated in a city in southern Italy. The excavation caused surface displacements above the alignment, affecting a number of buildings. InSAR was used to investigate the correlation between excavation progress and induced surface settlements (Barla et al., 2016). This information was of particular interest along a stretch of tunnel where jet grouting from the ground surface was performed in order to deal with challenging geologic and hydrogeologic conditions. These involved a highly heterogeneous calcarenite formation, ranging from well cemented to poorly cemented.
rock, that reaches from the surface down to the tunnel crown, and is underlain by a very fine sandy soil with silt, which in turn overlies the substratum (silty claystone with sandstone intervals). The water table is above the tunnel crown. Based on geological and hydrogeological studies, a low structural substratum locally acts as a drainage axis for the water flow.

Following completion of the jet grouting consolidation work, at the beginning of June 2014 tunneling advanced into this stretch. After 1 m of penetration into this area, 300 m$^3$ of water and silty sand collapsed into the tunnel, leading to the development of a subsidence trough at the surface and causing significant damage to the surrounding buildings.

The conventional topographic measurements (including a robotic total station) used along the tunnel axis were augmented by two InSAR data sets covering a time span of about 5 years before June 2014. The data were processed with the SqueeSAR algorithm to produce vertical and E-W horizontal displacement movements. An analysis of the vertical deformation progression along the tunnel alignment (Figure 6) and of the subsidence bowl development allowed to estimate the total volume of displaced material and to correlate this to amount to the volume of material that collapsed into the tunnel. The findings indicated the presence of previously unknown voids in the upper calcarenite formation that triggered further in-situ investigations to identify the possible mitigation strategies for tunnel completion.

Figure 6. Time-lapse analysis of the vertical deformation along the tunnel alignment from January 2012 to December 2013. Each map represents cumulative vertical displacement in subsequent six-month periods.

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CONCLUSION

The two cases presented here highlight the use of InSAR surface deformation monitoring to mitigate the socio-economic impact of ground subsidence induced by underground excavations.

In the Metropolitan longwall mining example the InSAR analysis of historical satellite archives revealed a significantly higher angle of draw and larger extent of the subsidence bowl than previously thought. It also highlighted that residual subsidence over mined out areas continues for many years. In the Bytom City mining example, the combined use of traditional and advanced InSAR techniques allowed both rapid and slow deformation to be precisely monitored for a complete characterization of ground deformation associated with the longwall mining activities.

These longwall mining examples highlight the capability of InSAR surface monitoring to provide precise, spatially dense data high accurate information without the need for ground instrumentation and the ability to monitor both slow and rapid movement (from millimetres to metres) by applying different InSAR techniques.

The use of InSAR in the railway tunnel excavation example in southern Italy highlighted the advantage of using highly dense, precise spatial coverage in measuring far-field deformation in an urban environment, the support provided in accurately defining possible mitigation strategies.

REFERENCES


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