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Upward surface movement above deep coal mines after closure and flooding of underground workings

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ABSTRACT

After the mass closures of entire coal mine districts in Europe at the end of the last century, a new phenomenon of surface movement was observed—an upward movement. Although most surface movement (i.e., subsidence) occurs in the months and years after mining by the longwall method, surface movement still occurs many decades after mining is terminated. After the closure and flooding of underground excavations and surrounding rock, this movement was reversed. This paper focuses on quantifying the upward movement in two neighboring coal mines (Winterslag and Zwartberg, Belgium). The study is based on data from a remote sensing technique: interferometry with synthetic aperture radar (INSAR). The results of the study show that the rate of upward movement in the decade after closure is about 10 mm/year on average. The upward movements are not linked directly to the past exploitation directly underneath a location. The amounts of subsidence at specific locations are linked mainly to their positions relative to an inverse trough shape situated over the entire mined-out areas and their immediate surroundings. Local features, such as geological faults, can have a secondary effect on the local variation of the uplift. The processes of subsidence and uplift are based on completely different mechanisms. Subsidence is initiated by a caving process, while the process of uplift is clearly linked to flooding.

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1. Introduction

After the mass closures of entire coal mine districts in Europe at the end of the last century, a new phenomenon of surface movement was observed—upward movement in the area above the past exploitation and in the immediate surroundings. Of course, most surface movement (i.e., subsidence) occurs in the months and years after mining by the longwall method [1]. This downward movement continues to occur at a smaller rate many decades after mining has been terminated when the water in the underground excavations is pumped to the surface. This is the case as long as a mine is in operation. However, after the closure and flooding of the underground excavations and the surrounding rock, this movement is reversed, and the surface is uplifted. A total uplift of about half a meter has been recorded to date. This phenomenon has been described in several different coal basins in Europe, for example, in Belgium, France, Germany, the Netherlands, and Poland [2–7]. To date, research has focused mainly on understanding the phenomenon and identifying general trends, whereby the link with the rise in water levels is an important issue [7,8]. There are several possible explanations, for example, the swelling of clay minerals in the argillaceous rocks in the coal strata [8]. However, decreases in the effective stresses also result in the relaxation or expansion of the rock, which induces an upward movement [9]. On the other hand, most coal strata rock is weakened upon contact with water and the increase in water pressure results in a decrease in the effective stress. Both aspects facilitate the fracturing of rock, which normally would result in further subsidence. So, the full explanation is complex. All of these aspects, including the long-term residual subsidence due to compaction under dry conditions, result in a net upward movement, as observed. The phenomenon discussed here is clearly different from the upsidence, sometimes observed on other continents [10]. When upsidence occurs, the rock near the surface bends and buckles upwards due to the overstressing of the floors of the valleys.

The phenomenon of upward movement was detected recently, so we do not understand all of the aspects of the underlying processes. Hence, each systematic analysis of data related to surface movement and mining characteristics should help to improve our understanding. Therefore, in this study, as in previous studies, the researchers' objective is to provide better quantification of the

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surface movement for a specific area [11,12]. This study focuses on coal mining in the Campine Basin in northeast Belgium (Fig. 1). The area that has been mined corresponds approximately to an east-west zone with a length of about 60 km and a north-south width of 5–10 km. Coal mining also has taken place to the east of this zone (in the Netherlands and in Germany).

As noted in Fig. 1, the study area in this paper is situated around a longitude of 5.495°E.

2. Case study of Winterslag and Zwartberg

A total of seven collieries were once active in the Belgian Campine Basin. Coal production started in this area in 1917 at the Winterslag Mine. The first mine closure was the Zwartberg Mine in 1966. The other mines were closed between 1987 and 1992. These mines produced more than 400 million tons of coal, with the highest annual production, about 8–10 million tons, occurring between 1950 and 1970 [13]. Longwall mining was the only mining method used in these mines. These longwalls had a single headgate and a single tailgate on each side of the panel, and, normally, no barrier pillars were left between the longwall panels. In general, the standard geometry of a panel was a rectangle that measured about 200 m by 800 m. In the early years of mining, smaller panels also were mined, and sometimes they had more complex geometries. Mining took place at depths between −450 and −1050 m. In European coal basins, a large number of longwalls in different seams were mined above each other, separated by waste rock. In the Campine Basin, this number could even be more than 10 seams. The mining height of most longwalls was between 1 and 1.5 m.

The largest variation in subsidence, as well as the largest variation in the upward movements, occurred predominantly in the north-south direction (perpendicular to the east-west axis of the entire zone mined (Fig. 1)) rather than the east-west direction. Specific local situations could be different due to the presence of faults and unmined zones. In this paper, we report the results of our study of portions of the surfaces above the Winterslag and Zwartberg mines (Fig. 2). The Zwartberg Coal Mine was active from 1920 until 1966. In 1966, production was stopped, and the underground was sealed off. Then, flooding of the underground started. The Winterslag Coal Mine began production in 1917 and was closed in 1988. The Zwartberg Mine was, on average, deeper than the Winterslag Mine. The main levels in the Zwartberg Mine were between −654 and −1010 m, whereas the main levels were between −600 and −850 m in the Winterslag Mine. Although there were no man-made connections between the two underground workings of the mines, water from the Zwartberg Mine flowed into the underground workings of the Winterslag Mine. The flow rate was estimated to be about 30 m^3/h. Therefore, it was assumed that the water level in the Zwartberg Mine stabilized at a depth of about −850 m. After the closure of the Winterslag Mine in 1988, its shafts were sealed off, and the mined-out area and the surrounding rock started to flood. At the same time, the water level in the Zwartberg Mine increased further. During the years of full production, about 7000 m^3/day of water was pumped to the surface in the Winterslag mine [14].

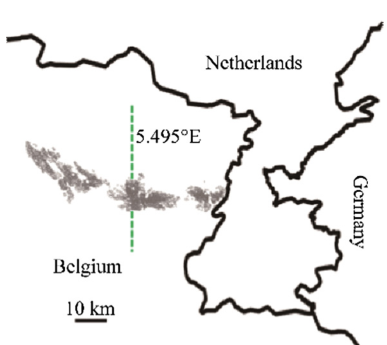

Fig. 1. Overall view of all longwall panels mined in the Campine Basin of Belgium in the 20 th century.

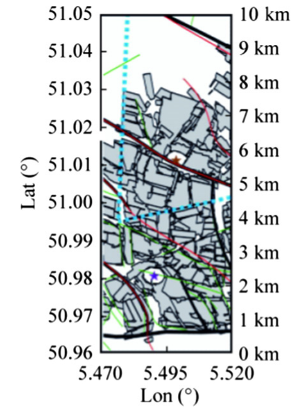

Fig. 2. Map of all longwall panels mined (presented superimposed) in part of the concession of the coal mines Winterslag and Zwartberg.

As noted in Fig. 2, blue dotted line is the concession limits, stars mean the average position of double central shafts (Winterslag in purple and Zwartberg in brown), longwall panels are superimposed in grey, and faults indicated in green, red and thick black lines.

In this paper, we concentrate our analyses on a north-south zone situated around the longitude of 5.495°E (Figs. 1 and 2). This zone is situated between the two shaft areas. Fig. 2 shows all of the longwall panels (superimposed) for an area of approximately 10 km by 3.5 km. This study is based on data from a remote sensing technique: radar-interferometry or interferometry with synthetic aperture radar (INSAR). It allows the study over a long period of time of the movement of reflectors situated in a large area. It provides measurements every 35 days at distances ranging from 10 to 20 m with accuracies of about 1 mm/year. More details are available in the literature [3,12,15,16]. The European C-band ERS1/2 and ENVISAT-ASAR satellite images made available for research through a European Space Agency (ESA) research proposal are used in this study. The images were recorded for two different periods: one period of nearly 8.5 years (87 cycles of 35 days each from August 1992 through December 2000) and one period of nearly 7 years (72 cycles of 35 days each from December 2003 through October 2010) [2].

3. Analyses of surface movement data

3.1. Global variation in the north-south direction

In the Belgian Campine Basin, two different trends have been observed for surface movement after the closures of the coal mines [2]. In the western part, residual subsidence still occurred for a period of about 10 years after the closures, but, in the eastern part, including the Winterslag Mine, upward movements already were visible at the beginning of the first observation period in August 1992, which was 4–5 years after the closures of the mines. The largest spatial variation occurred in the north-south direction. Therefore, we concentrated on a north-south transection. We took a central line that was situated between the two shaft areas and covered the concession of the Winterslag and Zwartberg mines. The central line corresponds to a longitude of 5.495°E (Fig. 2). The reflectors were not situated on a straight line, so we considered a

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