24-006

Additional Damage to Buildings and Infrastructure Induced by Long-Term Surface Movements Above Longwall Mining

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ABSTRACT

After the systematic closure of Europe's coalfields in the late twentieth century, the emphasis is now clearly on industry's environmental legacy. One aspect of the latter is the long-term surface movement above abandoned coal mines. The analysis of satellite data shows that the subsidence lasts longer than generally assumed. However, a few years after the flooding of the abandoned underground coal mines, a new phenomenon was observed, i.e., the direction of the surface movement was reversed. The phase of upsidence has already lasted for several decades, and only future measurements will tell how long it continues. A key conclusion is that the regions with maximum subsidence do not necessarily correspond to the greatest upsidence. In other words, buildings and infrastructure are subjected to a different loading from this upsidence than during the subsidence phase. The long-term surface movements have an impact on vulnerable structures in the densely populated regions of the former deep coal mining areas in Europe. These movements create additional damage. This new knowledge is also relevant for mines that are still in operation or future mines that are planned.

INTRODUCTION

At the end of the twentieth century, entire coal fields in Europe were closed. In Belgium (Campine coal basin), the five remaining underground coal mines were closed between 1988 and 1992. Coal production in these mines began between 1917 and 1930. These mines applied the longwall mining method (with goaf), and most panels were situated between 500 to 1000 m depth. The average mining height per coal seam was relatively low, i.e., between 1.0 and 1.5 m. The Campine coal basin is characterized by numerous faults, causing a high degree of compartmentalization. This combined with past tectonic movements along these faults resulted in complex mining geometries, i.e., the position of the various longwall panels and their shape. In other words, mining did not follow a regular pattern. Below a given location, the total mining interval covered several hundred meters, and more than 5 seams were mined (even, sometimes more than 10). At both sides of the panels, single gateroads were excavated.

At the end of the coal mine's lifespan, the underground pumping installations were dismantled, and the vertical shafts were sealed. This meant that after the closure, the open tunnels, the collapsed goaf volumes and the surrounding rock mass or strata started to be filled with groundwater and the hydraulic gradient started to evolve towards the original hydraulic gradient. It is generally accepted that after closing the underground access, the surface movements are reversed, i.e., from a downward subsidence to an upward movement (uplift or upsidence). Examples can be found in the reference list in Vervoort 2021a. The link with the flooding of these mines was clearly established by other research (Baglikow 2011; Bekendam and Pöttgens 1995; Caro Cuenca et al. 2013; Samsonov et al. 2013). Although the direction of the additional movements has reversed, the cumulative amount of movements remains downward in comparison to the situation before the start of mining. (Further, an example is presented.) Recently, an analytical framework was successfully presented to better understand the different mechanisms and processes involved (Vervoort 2021b; Vervoort 2022a). Good correlation was observed between the measured and the calculated upsidence values along north-south transects. The crucial aspect for a good match between the two is to take into account the expansion of the goaf material when the water level is increased, but, as important, to also include in the calculations the expansion of all the strata between the excavated panels and around the mined area. It is believed that the strata layers are also drained during mining and that the pore pressure values are increased towards their original values before the mining began. A good fit with the measurements was observed for a goaf thickness equal to four times the mining height, and a stiffness ratio between goaf and the rest of the strata equal to 1 on 10.

Three different time series of satellite images are used in the study of upsidence (radar-interferometry or InSAR (interferometry with synthetic aperture radar)). The first two series, i.e., the European C-band ERS1/2 and ENVISAT-ASAR satellite images, were made available for research through a research proposal of the European Space Agency (ESA) (Devleeschouwer et al. 2008). These two series cover the periods from August 1992 through December 2000 (87 cycles of 35 days), and from December 2003 through October 2010 (72 cycles of 35 days), respectively. The third and most recent time series is made available through the European Ground Motion Service project (EGMS), which receives funding from the European Commission's Copernicus program (Costantini et al. 2021). The latter is based on the Sentinel-1 (S1) satellite mission, which was launched in 2014, and it systematically collects interferometric C-band SAR image stacks with global coverage at short revisit time (temporal resolution of 6 days). The observations available via the EGMS website cover the period from early January 2016 through end of December 2021 (i.e., a period of 6 years).

This paper discusses three topics. First, the emphasis is on surface movements over long time periods. Measurements along a survey line of about 2.5 km are presented over a total period of 65 years, i.e., from the start of mining a first longwall panel in the area until approximately 40 years after mining the last panel, of which more than 30 years are situated after the closure of the mine. The recently available EGMS data extend previously published results by more than 10 years (Vervoort 2021c). Second, the focus is on the phase of upsidence and, more specifically, on the period covered by the EGMS data, i.e., about 30 years after the closure of the mine. A comparison is made with previously published results (Vervoort and Declercq 2017). Since the EGMS data also includes horizontal east-west movements, the latter are also presented and discussed for the same site. Third, examples are presented of damage to buildings and infrastructure observed above the same mined zone after the mine closure.

SURFACE MOVEMENTS DURING THE ACTIVE LIFE OF A MINE AND THE FOLLOWING DECADES

Data are presented for a total observation period of 65 years (Figure 1). Figure 1a shows the measuring line with a total length of almost 2.5 km (Vervoort 2021c). The vertical movements were measured in comparison to a reference point approximately 900 m further northeast than point A along the same road, i.e., A-B-C. These levelling data were supplemented with recent remote sensing observations by satellites (Figure 1b). Information on the mining in the vicinity of the measuring line is included in Figure 1a. The first panels were mined in year 0, at the beginning of the monitoring period. The line is in the northern part of the mine. The mining extends to just north of point B. So, point A is situated above the virgin zone, north of the mining. Below point E, the sum of the mining heights of the 9 longwalls is 11.2 m, i.e., the largest value of the four points above the mined zone. The last panel was mined in year 27. Four years later (year 31) the mine was closed.

The phase of subsidence lasted until years 33 (Point E) and 35 (Points B, C and D). Below points B and E, the last panel was mined more than 10 years earlier (year 22 vs. 33 and 35). Below B and C, it is 8 years earlier (27 vs. 35). When interpreting these moments, the large interval between measurements must be taken into account. However, the phase of subsidence lasts much longer than the often-assumed period of 3 to 5 years. If the underground infrastructure and rock mass had not been submerged after the closure, the phase of subsidence would most likely have continued. In other words, the change in direction of movement (from downward to upward) around year 35 most likely means that the upward movement becomes larger than the additional downward movement. Comparing the total uplift to date, i.e., recorded up to year 65 (period of 30 to 32 years), with the maximum subsidence recorded, a ratio is calculated between 5.4% (Point D) and 20% (Point B). For points C and E, this ratio is 6.6% and 10.3%, respectively.

On the scale of Figure 1b, one might get the impression that there is no more surface movement after 65 years. However, when zooming in on the last 6 years (Figure 2; the EGMS satellite data), there is still a clear trend of upward movement. Above the mined zone, an additional movement of 10 to 15 mm over the period of 6 years is observed, i.e., an annual rate of approximately 2 mm. Although in the Campine basin it was observed that the extension of the upsidence or uplift zone towards the north and south increases with time after the mine closure (Vervoort 2021a), one must still be cautious when interpreting the trend for point A after year 3 (Figure 2a).

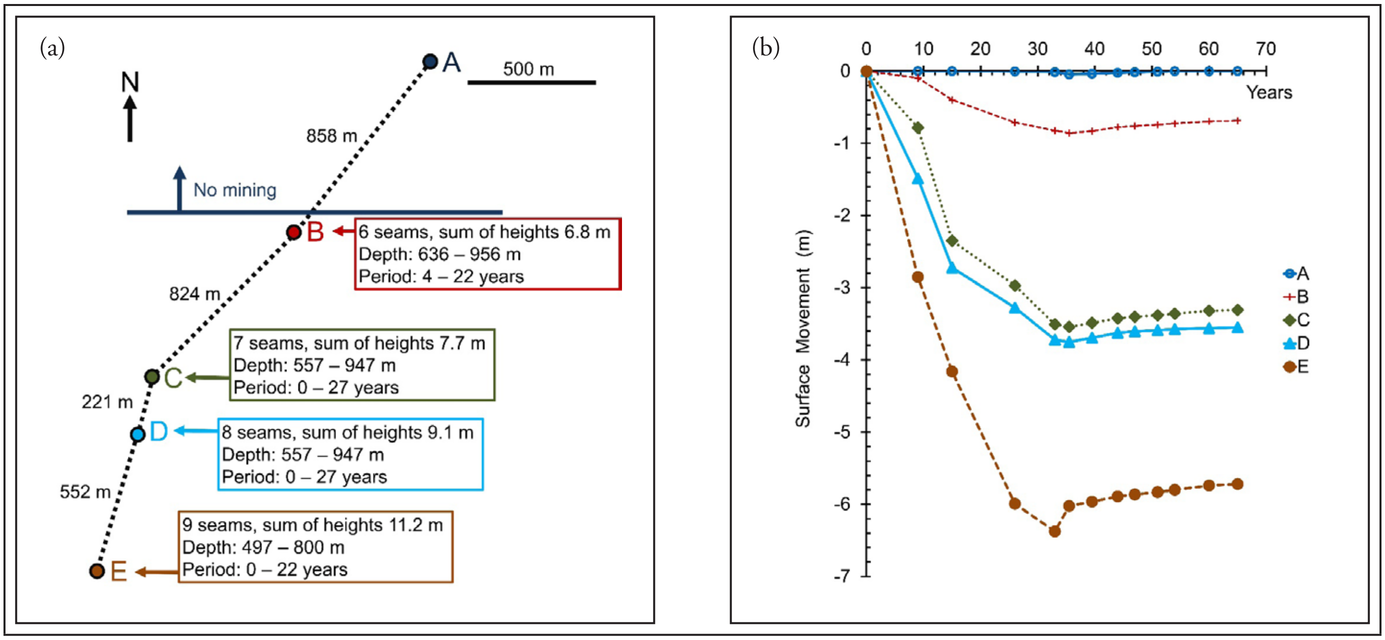

Figure 1. Surface movements along a measuring line of about 2.5 km over a period of 65 years. (Vervoort 2021c). a. Position of the monitoring points and information on mining below these points; b. Variation of surface movements (cumulative) as a function of time

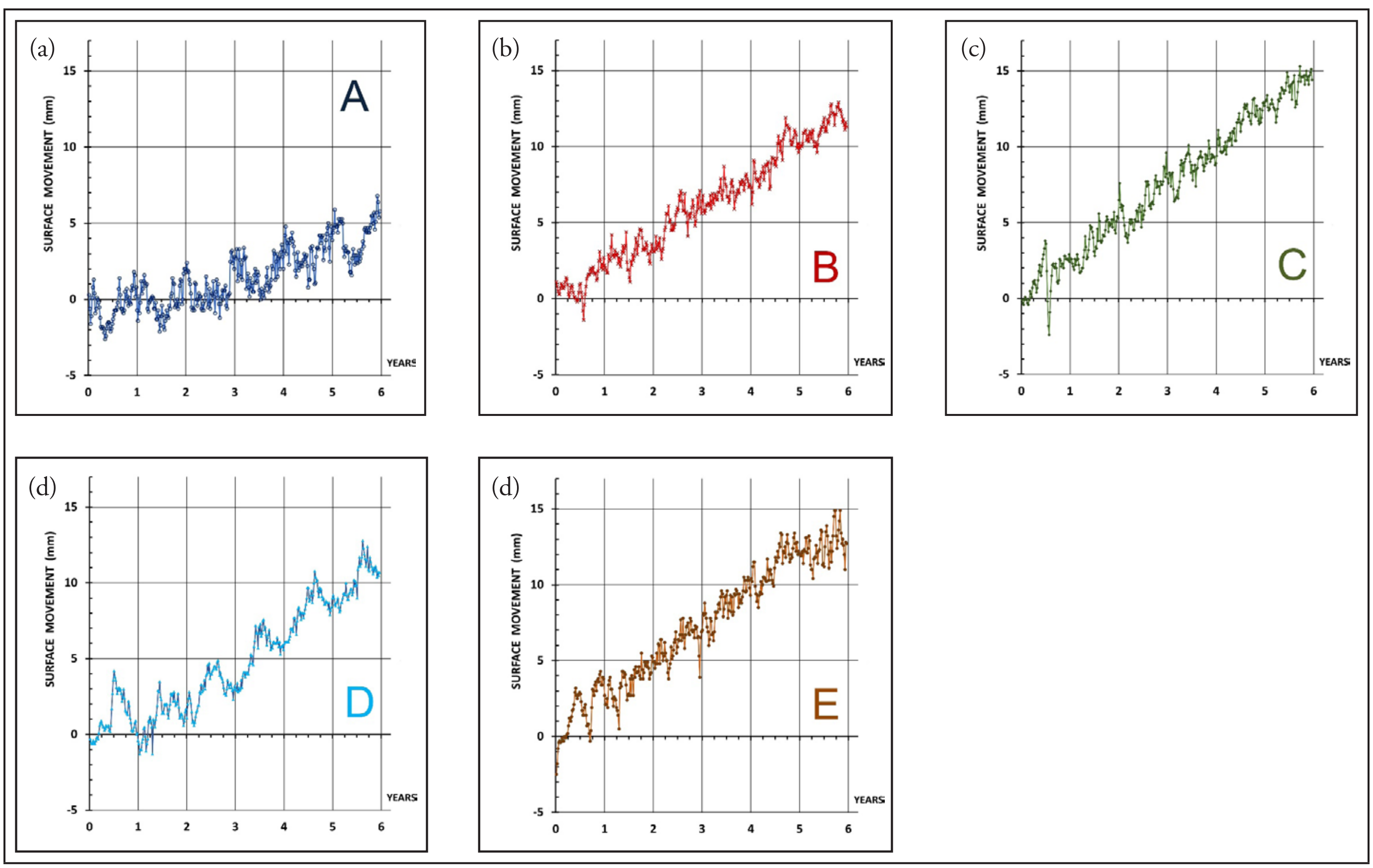

Figure 2. Variation of vertical surface movements for the five monitoring points in Figure 1, as a function of time over a 6-year period (EGMS data covers the years 2016–2021). The start of the curves corresponds to year 59 in Figure 1b.

PHASE OF UPSIDENCE ABOVE A NORTH-SOUTH ORIENTATED MINED ZONE (COAL MINES OF WINTERSLAG AND ZWARTBERG)

At the SME 2017 International Conference on Ground Control in Mining (Vervoort and Declercq 2017), a case study was presented with measurements of the upward surface movements or uplift above two neighboring coal mines (Winterslag and Zwartberg, Belgium). The Zwartberg mine was closed in 1966, and the Winterslag mine in 1988. Five years later, at the SME 2022 International Conference on Ground Control in Mining, the results of the analytical calculations and a comparison with the measurements for the same case were presented (Vervoort 2022a). Readers are referred to both papers for all details on the mining operation and the results of the analysis. This paper complements the previous analysis with the newly available EGMS-data, including the measurement of east-west horizontal surface movements. In the Campine coal basin, mining took place in a relatively narrow east-west band (with a north-south width of about 5 to 7 km and a length of about 50 to 60 km). The strata are dipping to the north. Therefore, the analysis was based on 2D north-south transects. The variation of the vertical surface movement is much greater in the north-south direction than in the east-west direction. Based on this finding, a logical assumption would be that the variation of the horizontal surface movement would also be smaller in an east-west direction than in a north-south direction. However, it must be admitted that very little is known about horizontal surface movements, associated with subsidence or upsidence over deep underground coal mines. Horizontal strain is sometimes taken into account in studies, but rather as a derivative of the vertical subsidence curve. Samsonov et al. 2013 published some results of horizontal movements above coal longwalls, recorded by satellite images.

Figure 3 shows the zone discussed in this and previous two papers (Vervoort and Declercq 2017; Vervoort 2022a). The map shows all superimposed panels. The latter are located between a latitude of 50.965° and 51.03°. A period of 5 years is chosen, i.e., from November 2016 through November 2021. In Figure 4a, all data points above the mined zone of Figure 3 are analyzed and the vertical vs. the horizontal east-west movements are compared. Most values are between an additional 6 to 15 mm of vertical movement over 5 years (or an average rate of 1.2 to 3 mm/year). Both larger and smaller values are observed, but these are almost all positive. The recorded horizontal surface movements for this zone are mainly between -1 and -9 mm over the 5-year period. A negative movement value means a movement to the east.

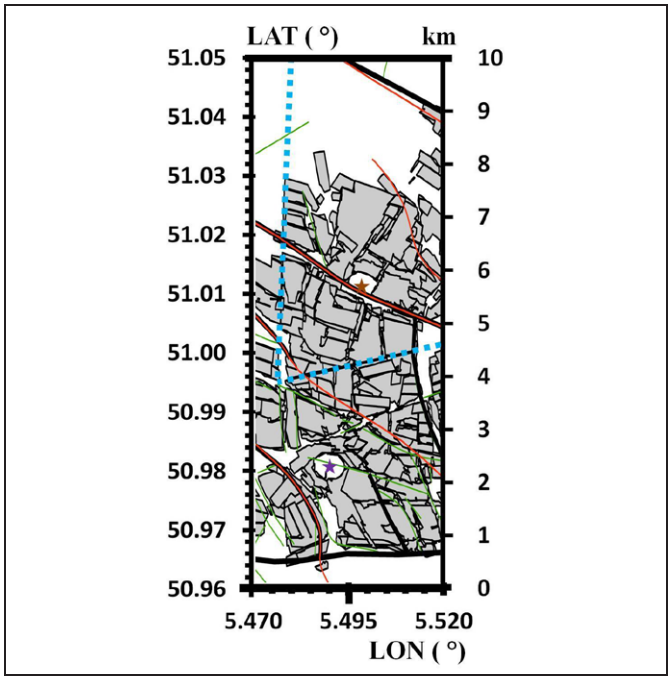

Figure 3. Map of all longwall panels mined (presented superimposed) in part of the concession of the coal mines Winterslag and Zwartberg (Vervoort and Declercq 2017); blue dotted line: border between the two mines; stars: average position of double central shafts (Winterslag in purple and Zwartberg in brown); longwall panels superimposed in grey; faults indicated in green, red and thick black lines.

Data points in a zone north and south of the mined zone are also studied (Figure 4b). Both zones are outside the zone of influence. The distribution of the horizontal movement is similar, as in Figure 4a (i.e., above the mined zone). However, the vertical movements are completely different between the two graphs. Away from the mined zone, most data points are situated between plus and minus 3 mm of vertical movement over a 5-year period, i.e., ±0.6 mm/year. In conclusion, the phenomenon of upsidence or uplift is clearly related to past mining, as previously shown (see the list of references in Vervoort 2021a). The new recent dataset clearly shows that this conclusion is still valid more than 30 years after the closure of the underground mine.

As mentioned above, the largest variation in vertical surface movements is observed in the north-south direction. Figure 5 presents data for 5-year periods from each of the available remote sensing satellite images. All reflectors situated within a 500 m band around the longitude of 5.495° are shown as a function of the north-south latitude.

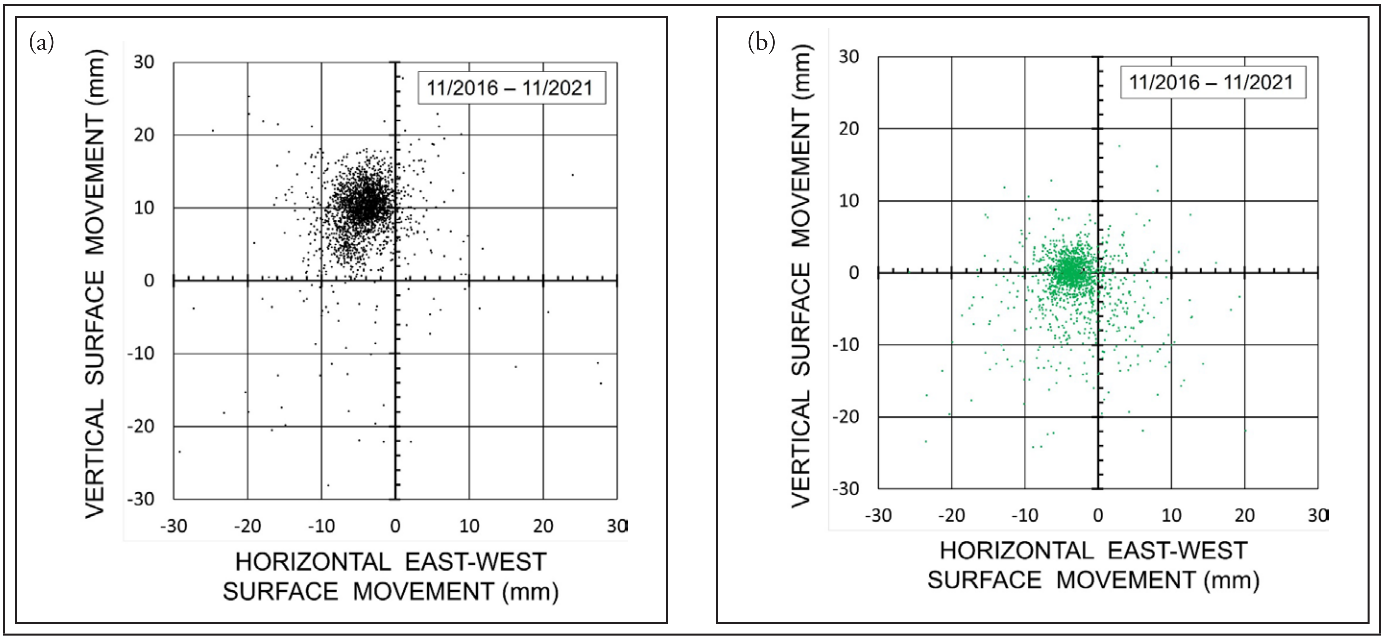

Figure 4. Vertical vs. horizontal surface movements over a 5-year period, based on the EGMS-dataset. a. Data points situated above mined zone (see Figure 3; Latitude between 50.965° and 51.03°); b. Data points away from mined zone (Latitude smaller than 50.955° and larger than 51.05°). A negative horizontal movement is towards the east.

The selection of 5-year periods within each full time series makes comparison easier. The limits of the mined zones are indicated by dotted lines in Figure 5.

The three transects confirm that the upsidence occurs over the entire mined zone and extends for a relatively short distance beyond the mined limits. However, there is no discussion that the phenomenon of upsidence is linked to the past mining. The rate of upward movement decreases as a function of time since the closure. However, thirty years after the closure of the Winterslag coal mine the upward movement is still clearly visible. The shape of the curves changes when comparing the three 5-year periods. In the period 1995–2000, there is a clear maximum in the curve, i.e., just south of the line between both concessions (blue dotted line in Figure 5a). In the period 2016–2021, there is no clear maximum and the additional movement over the mined area is approximately constant. However, the northern part of the transect lies above the Zwartberg mine, which was closed in 1966. The underground of the Zwartberg mine began to be flooded in 1966. However, this only happened partially (from a depth of 775 m downward). Although there were no man-made connections between the two underground mines, water from the Zwartberg mine flowed into the underground workings of the Winterslag mine and was pumped to the surface by the installations of the Winterslag mine. Although there are some minor differences between the data over the Zwartberg and the Winterslag mine (Vervoort and Declercq 2017), the upward movement is generally similar above both mines. For example, for the period 2016–2021, the 5-year movement above the Zwartberg mine may be a few mm smaller.

EXAMPLES OF DAMAGE TO BUILDINGS AND INFRASTRUCTURE, OBSERVED AFTER THE MINE CLOSURE

The evolution of the surface movements over time is most likely one of the most complex geotechnical problems. For the phase of short-term subsidence, text books often look at the situation in which a single panel is mined. The emphasis is on the curvature along the edges of the panel. However, even when mining in a single seam, the variation of the tilt orientation is an aspect that must be taken into account (Vervoort 2021c). If the mining geometry is as complex as observed in the Campine coal basin (Figure 3), the movements are a sequence of rotations, extension, compression, tilt, etc. For deep coal mines, the phase of short-term subsidence is always followed by a phase of long-term residual subsidence (e.g., Vervoort 2020b). Although the rate of movement is much smaller than during the phase of short-term subsidence, the additional subsidence value should not be neglected. For example, if the residual subsidence is 5 mm per year, the additional subsidence after 10 years is equal to 50 mm, which is considered in Eurocode 7 as

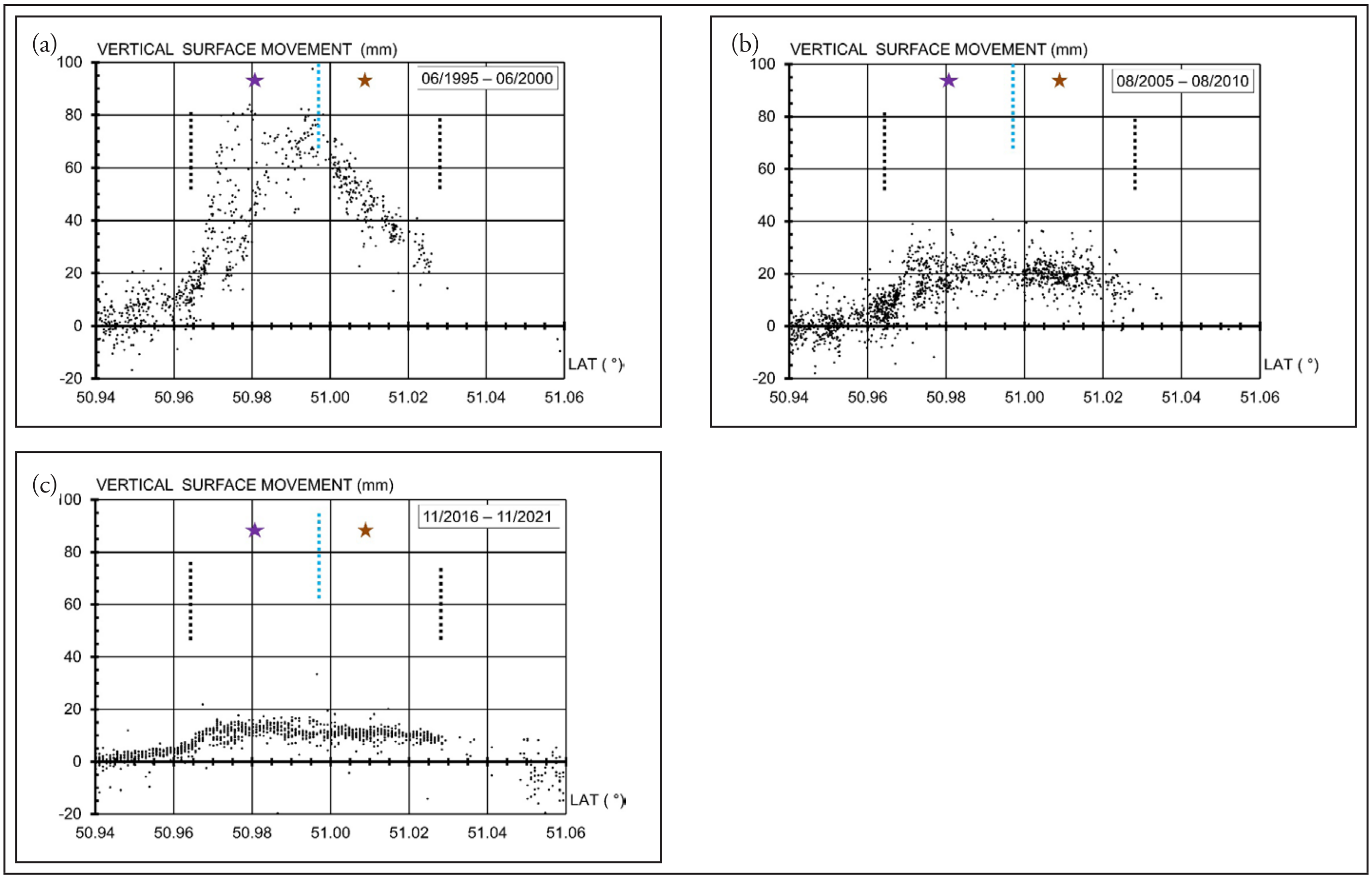

Figure 5. Vertical surface movements over 5-year periods along a north-south transect at a longitude of 5.495°. a. European C-band ERS1/2 satellite images, period from June 1995 through June 2000; b. ENVISAT-ASAR satellite images, period from August 2005 through August 2010; c. Interferometric C-band SAR Sentinel-1 images, period from November 2016 through November 2021. (black dotted lines: mining limits in N and S; blue dotted line: border between the two mines; stars: average position of double central shafts (Winterslag in purple and Zwartberg in brown)

a critical value for settlement (EN 1997-1 2004). As illustrated above, after flooding the underground infrastructure and rock mass, the downward movement is replaced by an upward movement. In most cases, the maximum upsidence is at a different location than the maximum subsidence (Vervoort 2020b). Therefore, the curvatures for the subsidence and upsidence profiles are different, meaning that the tilt and induced strains are different. It also means that the upward movement is not simply a rebound of part of the downward movement. In conclusion, there is a great variety and sequence of absolute and relative movements, rotations and tilt, etc. All these phenomena induce stresses and strains in structures (Boscardin and Cording 1989). When studying damage to buildings and infrastructure, the cumulative amount of the induced stresses and strains must be taken into account. That is why a relatively small additional movement, e.g., in the upsidence phase, is sufficient to induce new fractures, because in the previous phases a certain amount of stresses and strains have already been stored in the structure, but which did not lead to damage in the previous phases.

Some examples of damage to buildings during the phase of upsidence can be found in the literature (e.g., Baglikow 2011; Dudek et al. 2021; Vervoort 2022b). Three examples of damage are shown below (Figures 6 to 8), which are within the mined zone presented in Figure 3. The typical damage for each case is illustrated with three images. The variation of the vertical and of the horizontal movements for the 4 data points closest to the building or road section are presented as a function of time. The minimum, average and maximum movement values of these four data points are shown as a function of time (6 days frequency). These graphs present the movements for the period 2016–2021, available in the EGMS database (Costantini et al. 2021). Only this database (of the three available for the study) includes vertical and horizontal movements. The main

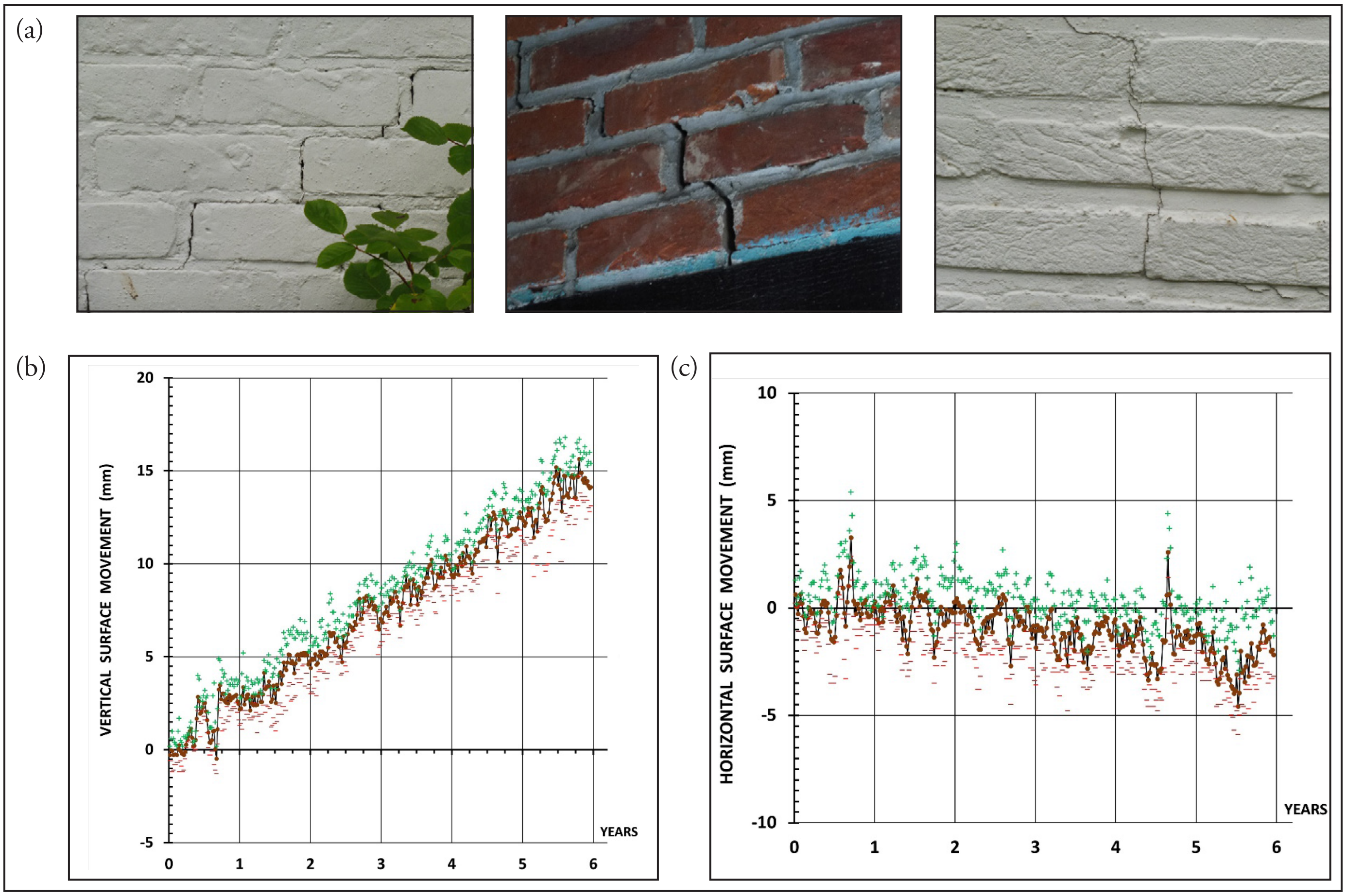

Figure 6. Examples of damage to masonry of a house, observed after the closure of the coal mines. a. Pictures; b & c. On-going vertical (b) and horizontal (c) surface movement during the period 2016–2021 (average, minimum and maximum values of four neighboring data points)

purpose to present the most recent time series is to illustrate that the movements are still ongoing. Referring to what has been discussed above, it is clear that the damage is caused by the cumulative effect of all past and current movements, and not just by the additional movements taking place in the period 2016–2021.

As indicated above, all observed damage occurred in the period after the closure of the Winterslag coal mine. Figures 6 and 7 show damage to masonry walls and refer to a single house and a large building (i.e., school), respectively. For the example in Figure 7, the new damage is a re-activation of cracks that occurred during the subsidence phase. These old cracks were simply filled with mortar and no further reinforcement was locally installed. The rate of vertical movements in these two examples over recent years is for Figure 7b about half the rate of Figure 6b. However, there is a clear trend in the variation of the horizontal movement in Figure 7c, i.e., just over 1 mm/year. For the first case, the horizontal movements are relatively small and more of a fluctuation. So far, horizontal movements above deep coal mines have only been studied to a limited extent. As mentioned above, the horizontal strain due to a curvature in the subsidence profile is calculated, but here absolute horizontal movements are measured. The latter is successfully investigated during movements towards excavations or slope instability, but so far not really above longwall panels. It is certainly a parameter which needs more attention in the future.

Figure 8 shows the damage to the road surface. The pictures cover two parallel roads at a distance of 10 to 15 m. The amount of traffic is significantly different. One road was built after the mine closure; the other was completely renovated during that period. Therefore, it can be concluded that the damage is clearly related to the upsidence. Further research is needed to relate the damaged zones to the underlying mining geometry and the position of the faults. The horizontal movement at the site is about 1 mm a year and the trend is clear (Figure 8c).

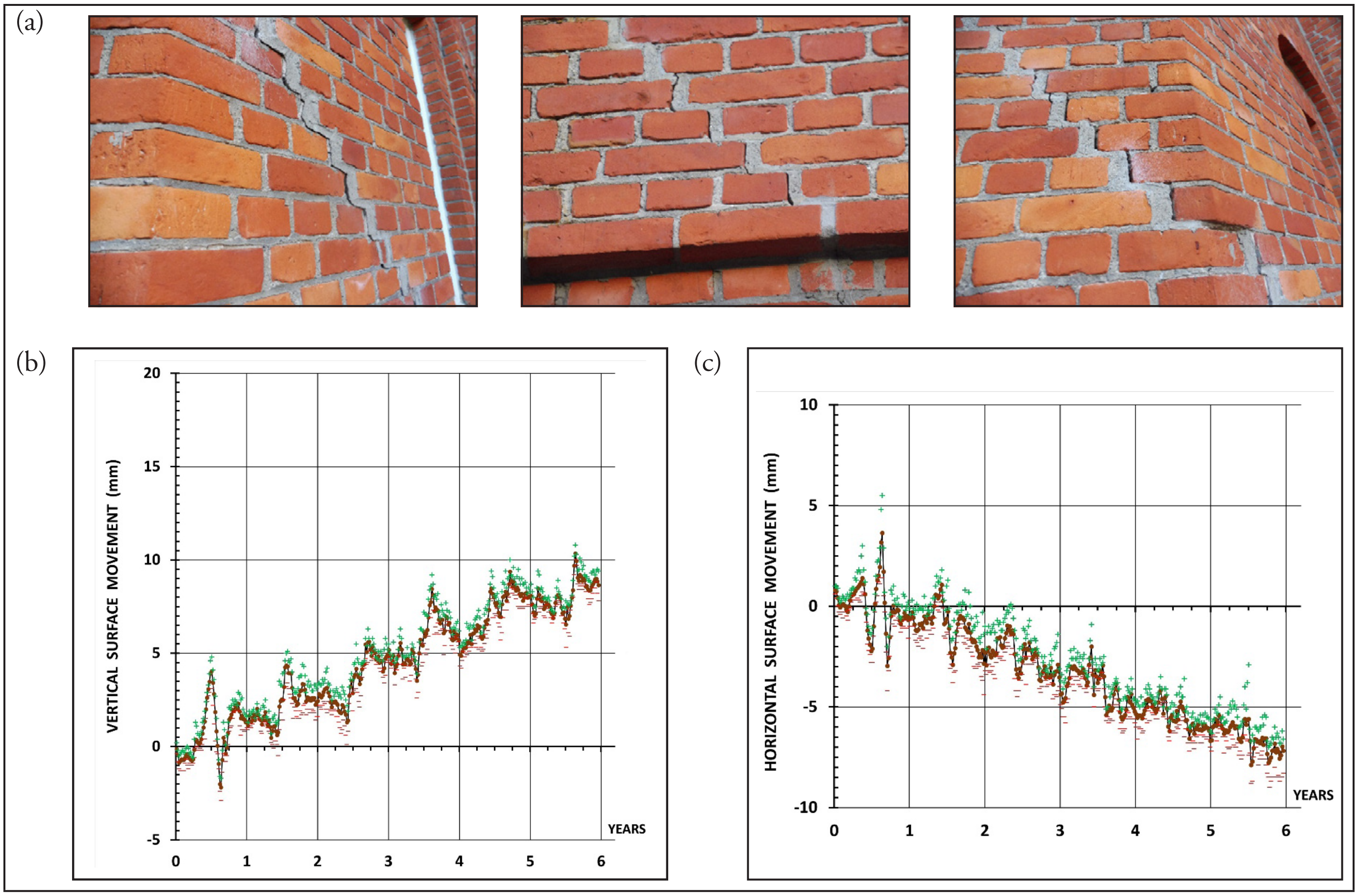

Figure 7. Examples of damage to masonry of large building, observed after the closure of the coal mines. a. Pictures; b & c. On-going vertical (b) and horizontal (c) surface movement during the period 2016–2021 (average, minimum and maximum values of four neighboring data points)

DISCUSSION AND CONCLUSIONS

The main conclusion of the presented research is that surface movements above longwall mining last much longer than the often assumed 3 or 5 years. One can even ask if it will ever stop completely (Vervoort 2020a). Or in other words, the goaf volumes and the rock mass surrounding the goaf volumes will always behave differently than the unaffected strata outside the mining concession. Results are presented for the Campine coal district, Belgium. The latter is characterized by irregular multi-seam mining over large depth intervals. These features are also observed in other European coal basins. However, for longwall mining in a single seam at shallow depth, the same conclusions may not necessarily be valid. The new insights into the long-term surface movements over coal longwall panels are a direct result of the availability of satellite remote sensing data. The latter cover large areas, and the time series are available over long periods of time. The frequency of measurements as a function of time is high, as is the spatial distribution of reflectors or data points. This can never be matched by conventional leveling campaigns. For the latter, it is virtually impossible to find the necessary funding, time and motivation, if successive measurements yield comparable results. The satellite time series showed that with movements of a few mm a year, the trend of movement only becomes clear if the time series covers five years or more.

The second conclusion is that after all underground activities have ceased and underground access is sealed off, the flooding of the underground infrastructure, goaf volumes and surrounding (non-collapsed) strata results in upsidence or uplift. In other words, the additional movements are now upward instead of on-going downward movements. The most recent available data, namely the EGMS time series of Interferometric C-band SAR Sentinel-1 images, indicate beyond doubt that this upward movement continues thirty years after the mine closure. A comparison between the vertical movements above the mined zone and the zones to the north and south shows that the observed

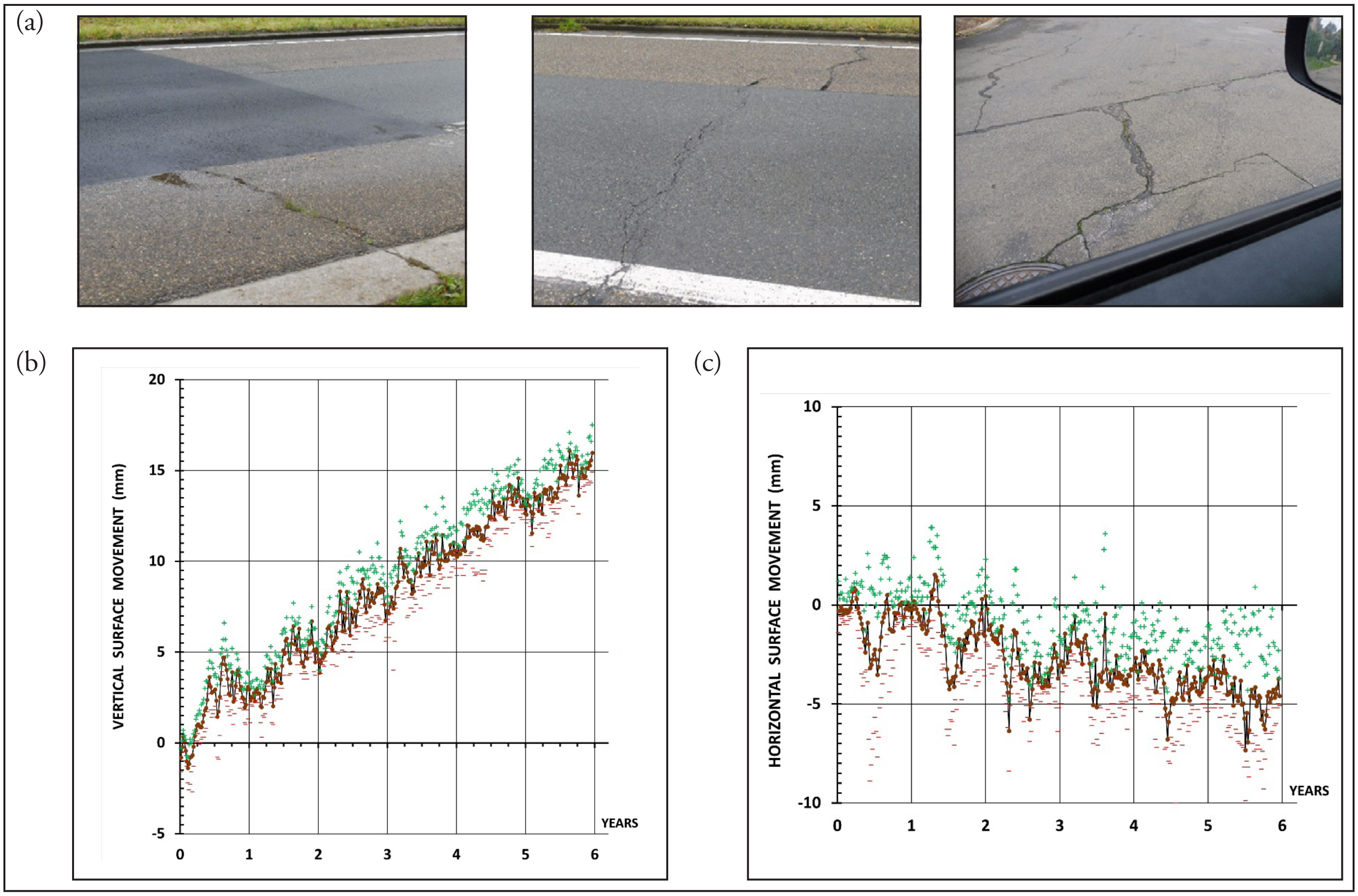

Figure 8. Examples of damage to road surface, observed after the closure of the coal mines. a. Pictures; b & c. On-going vertical (b) and horizontal (c) surface movement during the period 2016–2021 (average, minimum and maximum values of four neighboring data points)

upsidence is directly related to past mining and the disturbance of the strata. This distinction is not clear for the horizontal movements. However, examples have been given where there is a clear trend in the horizontal movements as a function of time. The interpretation of the recorded horizontal movements requires further attention.

The third conclusion is that the long-term movement can lead to new and/or additional damage to buildings and infrastructure. New damage is caused by the sum of stresses and strains stored in constructions by past movements and loading, e.g., by the impact of the short-term subsidence phase, and of the additional loading due to the long-term movements (subsidence and upsidence). The impact of horizontal movements above longwall panels is also a new research topic, and as more and more data become available, this can lead to new insights. The final conclusion is therefore that although much research has been done in the past on surface movements above longwall mining, there is still a need for further research to better understand this complex phenomenon.

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Additives for Magnetic Separation of Iron Ore Ultrafines

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ABSTRACT

Seeking to implement the Global Industry Standard on Tailings Management to improve the safety of their tailings facilities across the globe, mining companies are motivated to invest in new technologies to recover valuable minerals from tailings. One solution being evaluated is the use of magnetic separators to concentrate ultrafine tailings. However, this approach is energy intensive as it requires high magnetic fields to recover ultrafines, and usually results in low mass yields. Additives that modify pulp rheology and surface properties, or selective flocculate ultrafine particles, were tested to enhance the performance of magnetic separation. Promising results in laboratory scale testing different types of additives confirmed that it is possible to increase the mass yield, keeping the selectivity of this stage.

INTRODUCTION

The Global Industry Standard on Tailings Management sets a precedent for the safe management of tailings facilities, towards the goal of zero harm to people and the environment. Therefore, mining companies are committed to implementing new technologies to recover valuable minerals from tailings, increasing production and generating less residuals (ICMM, 2020). Also, over time, the earth's resources continue to decline, leading companies to turn to tailings recovery.

Flotation and magnetic separation are the most well-known recovery methods, but when it comes to iron ore tailings, alumina content is usually high, and that brings challenges to flotation, especially of kaolinite (Rodrigues, 2012; Ma, 2009). Taking that into consideration, magnetic separation might be a great choice to concentrate iron ore tailings. However, the intensity of the magnetic, gravity, and hydrodynamic (for wet separators) forces are mainly determined by the particle size. So, the finer the particles, the less selective this process is and the higher the energy required to concentrate the minerals. (Luo, 2016; Svoboda, 2003).

Aiming to correct that, several studies are taking place worldwide, such as the incorporation of superconductivity, and improved understanding of principles of HGMS (High Gradient Magnetic Separator), among others, as shown in Figure 1. Adding to that, we present chemical additives to enhance ultrafine magnetic separation. They provide higher economic value for the concentrate, by reducing contaminants, higher productivity, and lower residue generation, increasing mass yield.

Those additives are based on three different action mechanisms: dispersion, selective agglomeration, and rheology modification. Dispersing agents attach to the mineral surface, 'cleaning' it and making it easier for the magnetic

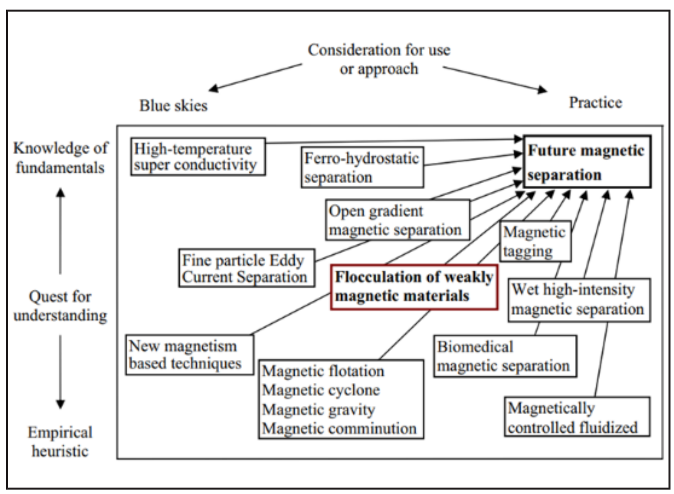

Figure 1. The future trends in magnetic separation (Luo, 2016)