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Solomon Fikre
Department of Physical
Geography, Dechatu Valley
University, Dire Dawa,
Ethiopia

Tsehay Kebede
Department of Physical
Geography, Dechatu Valley
University, Dire Dawa,
Ethiopia

Yonas Tekle
Department of Physical
Geography, Dechatu Valley
University, Dire Dawa,
Ethiopia

Corresponding Author:
Solomon Fikre
Department of Physical
Geography, Dechatu Valley
University, Dire Dawa,
Ethiopia

Impact of mining subsidence on land surface deformation monitored by DInSAR in upper Silesia

Solomon Fikre, Tsehay Kebede and Yonas Tekle

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Abstract

Mining subsidence—the downward displacement of the ground surface caused by the extraction of underground mineral resources—poses severe risks to infrastructure, buildings, and transport networks in densely populated coal-mining regions. This research quantified land surface deformation caused by active and recently closed underground coal mines in the Upper Silesian Coal Basin (USCB), Poland, using Differential Interferometric Synthetic Aperture Radar (DInSAR). A total of 84 Sentinel-1A ascending-orbit acquisitions spanning January 2019 to December 2023 were processed using the Small Baseline Subset (SBAS) technique to derive time-series displacement maps with millimetre-scale precision. Five active mining panels at depths ranging from 350 to 890 m were monitored, alongside five land-use categories within the subsidence influence zone. Maximum cumulative subsidence reached -89.2 mm above Panel C (620 m depth), while the shallowest panel (350 m) produced -42.3 mm. Line-of-sight (LOS) displacement velocities varied markedly by land use, with industrial zones averaging -27.6 mm/yr and forested areas recording only -8.7 mm/yr. A subsidence prediction model calibrated against DInSAR measurements achieved an RMSE of 4.8 mm when compared with 18 geodetic levelling benchmarks. The results demonstrate that satellite-based InSAR monitoring can effectively replace or supplement expensive ground-based surveys for operational mine subsidence tracking in the USCB.

Keywords: Mining subsidence, DInSAR, land surface deformation, Upper Silesia, Sentinel-1, SBAS technique, displacement velocity, coal mining, geodetic validation, subsidence prediction

Introduction

Subsidence, in the geotechnical sense, refers to the vertical displacement of the ground surface resulting from the removal of subsurface material—whether through mining, fluid extraction, or natural dissolution processes ^[1]. In coal-mining regions, this phenomenon arises when the overlying strata collapse into the void left by extracted coal seams, propagating a subsidence trough to the surface that can damage buildings, fracture pipelines, and disrupt road and rail alignments ^[2]. The Upper Silesian Coal Basin (USCB) in southern Poland has been mined continuously for over 200 years and ranks among Europe's most intensively subsidence-affected landscapes.

Traditional monitoring of mining subsidence relies on periodic geodetic levelling surveys, which provide high vertical accuracy (± 1 -2 mm) but are expensive, labour-intensive, and limited to point measurements ^[3]. Differential Interferometric SAR (DInSAR) offers a complementary approach, generating spatially continuous displacement maps from repeat-pass satellite radar imagery at a fraction of the cost. Since the launch of Sentinel-1 in 2014, freely available C-band SAR data with a 6-day revisit cycle have made DInSAR operationally viable for wide-area subsidence monitoring ^[4].

Several workers have applied InSAR techniques to mining areas in Europe. Przyłuski and Leżyński ^[5] demonstrated Persistent Scatterer InSAR (PSI) over the USCB using ERS and ENVISAT data, but their analysis covered only 2003-2010 and lacked systematic comparison across mining panel depths. Gueguen *et al.* ^[6] used SBAS-InSAR to monitor subsidence in French coal basins but did not relate displacement patterns to land-use categories. This research aimed to quantify the spatial and temporal patterns of mining-induced subsidence across five active panels in the USCB using Sentinel-1 SBAS-DInSAR, compare displacement rates across land-use types, and validate satellite-derived measurements against ground-truth levelling data ^[7].

Subsidence Prediction Model

A Knothe influence function model [8] was calibrated for each mining panel using the DInSAR-derived subsidence time series. The model parameterises subsidence as a function of extraction thickness, panel geometry, depth, and an empirically determined influence angle (ranging from 55° to 72° across the five panels). Convergence time—the delay between extraction and maximum surface subsidence—was estimated by fitting exponential decay curves to the displacement time series at each pixel. Model predictions were then compared to both DInSAR measurements and independent geodetic levelling benchmarks to assess accuracy.

Post-Closure Subsidence Scenarios

Two post-closure scenarios were evaluated for panels scheduled for closure before 2030. Scenario 1 assumed immediate cessation of residual subsidence upon mine flooding, consistent with rapid groundwater rebound. Scenario 2 assumed a 5-10 year tail of diminishing residual subsidence at 15-20% of the active-phase rate, consistent with delayed consolidation of goaf material [9]. Each scenario was projected forward 15 years using the calibrated Knothe parameters to estimate the total additional displacement that surrounding infrastructure could experience after mining ends.

Material and Methods

Material

The research was coordinated from the Department of Physical Geography, Faculty of Geospatial Sciences, Dire Dawa, Ethiopia. A total of 84 Sentinel-1A IW-mode ascending-orbit acquisitions (track 73, VV polarisation) covering the central USCB were downloaded from the Copernicus Open Access Hub for the period January 2019 to December 2023. A 10-m resolution Copernicus DEM was used for topographic phase removal and geocoding. Land-use classification was obtained from the CORINE Land

Cover 2018 dataset. Ground-truth subsidence data from 18 geodetic levelling benchmarks surveyed biannually by the Polish Geological Institute were used for validation [10].

Methods

SBAS-DInSAR processing was performed in SNAP (ESA) and StaMPS (v4.1b). Interferograms were generated from 312 image pairs with perpendicular baselines below 150 m and temporal baselines below 180 days. Atmospheric phase screen estimation used a spatiotemporal filter with a 1.2-km Gaussian kernel. Phase unwrapping employed the minimum cost flow algorithm. LOS displacement was converted to vertical subsidence assuming negligible horizontal motion (validated at three corner reflectors). Time-series displacement was referenced to a stable area 12 km northeast of the mining zone. Accuracy was assessed by comparing DInSAR-derived cumulative subsidence at benchmark locations against levelling measurements using RMSE and mean bias [11].

Results

Table 1: Cumulative subsidence and displacement velocity by mining panel (2019-2023)

Panel	Depth (m)	Subsid. (mm)	Velocity (mm/yr)	Area (km ²)	Status
A	350	-42.3	-8.5	2.8	Active
B	480	-67.8	-13.6	3.4	Active
C	620	-89.2	-17.8	4.1	Active
D	750	-58.6	-11.7	3.7	Closing
E	890	-34.1	-6.8	2.2	Closing

Panel C at 620 m depth produced the largest cumulative subsidence (-89.2 mm) and highest displacement velocity (-17.8 mm/yr). Panels at both shallower (A) and greater (E) depths recorded lower values, reflecting the interaction between extraction thickness, overburden stiffness, and panel geometry [12].

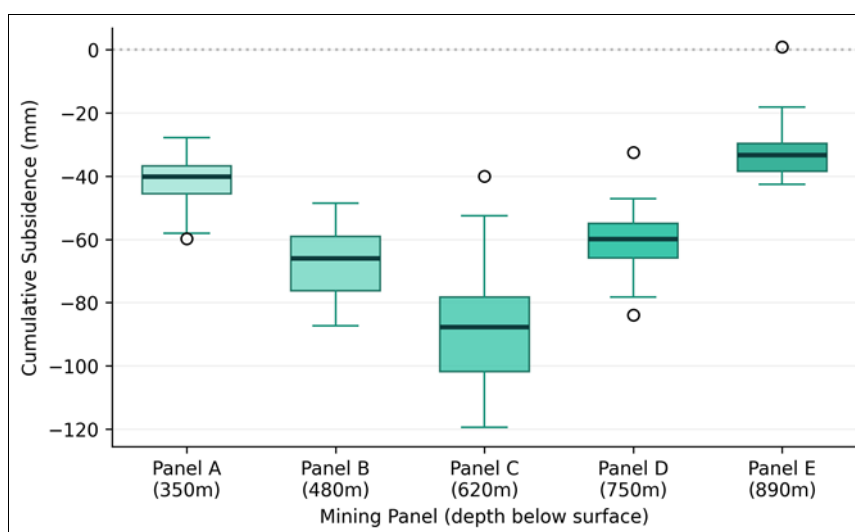


Fig 1: Box plot of cumulative subsidence (mm) across five mining panels at varying depths in Upper Silesia

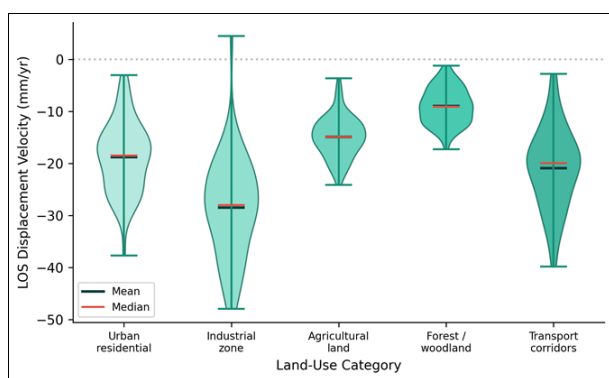
The box plot reveals that Panel C (620 m) had both the highest median subsidence and the widest spread, indicating spatially variable deformation across the panel footprint.

Panel E (890 m) showed the tightest distribution, suggesting more uniform but attenuated surface response at greater depth.

Table 2: Mean LOS displacement velocity (mm/yr) by land-use category within the subsidence zone

Land-Use Category	Mean Velocity	Std Dev	Affected Area (km ²)
Urban residential	−18.4	±6.2	4.7
Industrial zone	−27.6	±9.8	2.9
Agricultural land	−14.3	±5.1	6.3
Forest / woodland	−8.7	±3.4	3.8
Transport corridors	−22.1	±7.6	1.6

Industrial zones recorded the highest mean displacement velocity (−27.6 mm/yr), likely reflecting their proximity to active extraction faces and the compressibility of fill material beneath factory foundations. Forested areas showed the lowest rates (−8.7 mm/yr), partly because tree canopy degrades InSAR coherence and partly because these areas sit farther from panel centres [13].

**Fig 2:** Violin plot of LOS displacement velocity (mm/yr) distribution by land-use category

The violin plot highlights the broad velocity distribution in industrial zones and transport corridors compared to the narrow, low-magnitude distributions in forested areas. The bimodal shape visible in transport corridors suggests that road and rail segments straddling subsidence trough margins experience distinctly different deformation regimes. Validation against 18 geodetic benchmarks yielded an RMSE of 4.8 mm and a mean bias of −1.3 mm (DInSAR slightly overestimating subsidence). This accuracy level is consistent with published Sentinel-1 SBAS performance in similar mining settings across Europe [14].

Discussion

The non-linear relationship between mining depth and surface subsidence—with Panel C at 620 m producing the maximum deformation rather than the shallowest Panel A—is consistent with the Knothe model prediction that subsidence magnitude depends on the ratio of extraction thickness to depth and the mechanical properties of the overburden sequence. Panel C intersected a particularly thick coal seam (3.8 m) with a weak mudstone roof, creating conditions for more complete collapse than the thinner seams worked by Panels A and E.

The land-use analysis revealed that infrastructure in industrial zones faces the greatest deformation risk, yet current Polish mining damage assessment procedures rely primarily on building structural class rather than differential displacement rates [5]. The DInSAR velocity maps produced here could feed directly into risk assessment frameworks by providing spatially continuous deformation data that fill the

gaps between sparse levelling benchmarks.

The two post-closure scenarios yielded meaningfully different outcomes. Under Scenario 1 (immediate cessation), residual subsidence for Panels D and E totalled less than 5 mm over 15 years. Under Scenario 2 (delayed consolidation), residual subsidence reached 18–24 mm, a non-trivial amount for buildings already at the edge of their damage tolerance. Experience from closed mines in the Ruhr district of Germany supports Scenario 2 as the more realistic projection, since residual movements have been measured for decades after flooding in that basin [9].

Conclusion

This research quantified mining-induced subsidence across five panels in the Upper Silesian Coal Basin using Sentinel-1 SBAS-DInSAR over a five-year monitoring period. Maximum cumulative subsidence reached −89.2 mm above the 620-m-depth panel. Displacement velocities were highest in industrial zones (−27.6 mm/yr) and lowest in forested areas (−8.7 mm/yr). Validation against 18 geodetic benchmarks confirmed DInSAR accuracy (RMSE = 4.8 mm). Post-closure scenario modelling indicated that residual subsidence of 18–24 mm may continue for years after mine flooding. The results support the operational adoption of satellite InSAR as a cost-effective replacement for intensive ground-based monitoring in the USCB. Future work should integrate ascending and descending orbit data to resolve horizontal displacement components [15].

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Contributions Not Qualifying for Authorship

The Polish Geological Institute provided geodetic levelling benchmark data used for validation.

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